COMPREHENSIVE MODEL FOR HUMIDITY TESTING CORRELATION

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ABSTRACT

This paper reviews all published life in humidity conditions vs life at 85C/85%RH for epoxy packages; 61 data points are used. An acceleration formula is described which provides direct extrapolation from test results in autoclave tests at up to at least 140C to low-humidity down to below 30%RH. This formula compares favorably with previously-published formulae. The possible effect of the Tg of the epoxy is recognized, and other high-temperature and low-humidity effects are disclosed. Recommendations are made for future tests, replacing 1000 hours at 85C/85%RH with a 20-hour test at 140C/100%RH, to reduce test time and increase test usefulness.

INTRODUCTION

Reliability testing in humid environments will apparently be with us for a very long time. Improvements in processing quality have essentially eliminated sodium contamination from complex chips. Better understanding of electromigration has provided design limits which should essentially exclude problems with this failure mechanism. Other mechanisms are being controlled through continuing studies of reliability physics, but new concerns may still arise from failure mechanisms intensified by new VLSI design rules.

And yet, the pressures of increasing pin-outs and size, together with the economics proven long ago, require that we continue to use plastic packages of one form or another. The concomitant risk of failures resulting from the effect of humidity on the chip metalization will continue to require testing in high humidity and temperature for accelerated-stress testing, to (1) evaluate package and chip materials and design, and (2) provide efficient acceptance testing on completed product.

The standard test for the effect of humidity has been, for many years, the electrically-biased test of components in 85C temperature and 85% relative humidity. At the initial use of this test, it was considered a design-and processing-control type of test. Specification writers and device manufacturers felt that, if they could meet the usual requirement of 10% failures in 1000 hours for this test, the devices would operate as reliably as others in general-use conditions. Attempts were not made to determine a relationship between 85C/85%RH (85/85) test results and expectation of life at some other environmental condition.

Since about 1970 we have seen the results of various laboratories' efforts to understand such a relationship for plastic-encapsulated semiconductor devices. These efforts are frequently based on a small number of tests at only a few conditions of humidity and temperature, which is not surprising considering the long testing time for any condition much less severe than 85/85. A mathematical model is then postulated which seems to fit these points. Serious thought should tell us, of course, that there must be variation around each of the measured median lives, including sampling variation, changes in the encapsulation properties from time to time, contamination, and many other factors. Hence, a model which perfectly fits a few data points may still not be correct. So there is a continuing effort to find a model which provides confident extrapolation to low stress conditions, but with little expectation that any one facility could mount a large enough effort to provide data over the necessarily large range of stress, with known factors for repeatability.

Another modeling and testing objective is to reduce the testing time from the usual 1000 hours at 85/85, particularly since median lives of present epoxies are around 5000 hours, with very low standard deviation, so that the 1000 hours tells little about the long-life properties of the epoxy, and can only measure the freak level. Testing at a more severe stress is becoming more common, particularly with the use of an autoclave above 100C and with controllable percent saturation. Other techniques to shorten test time, such as soaking before biasing or the use of a prior salt exposure, have been reported, but these complicate the extrapolation of the pure temperature-humidity bias results to low-stress conditions, and these conditions are not considered here. This does not say that they do not have advantages for the objective of reducing test time for a chosen test.

It is the purpose of this paper to review all the published data on humidity testing over the entire stress range, both above and below 85/85 stress, in the hope that either the existence or non-existence of a good correlation between autoclave testing and 85/85 could be established, and that at least a model could be fitted to all the data from stress less than that of 85/85.

The use of data from a wide range of stress minimizes the impact of sampling and testing variations at any one point. If autoclave testing provides valid acceleration, test times can be drastically shortened, the frequency of testing can be improved, and predictions to low humidity conditions could be made, if at all, then from a more solid base.

EVALUATION PROGRAM AND RESULTS

A survey was made of all published median-life data on electrolytic corrosion failures of aluminum metalization (with the inclusion of one batch of data on nichrome fuse electrolysis) in epoxy packages, from available sources[1-14], avoiding that data which did not provide median life measurement at 85/85. A few exceptions were made where the 85/85 median could be estimated from nearby conditions with a minimum of probable error. The 85/85 life being the base, the ratio Ro of observed median at some other condition to that at 85/85 was determined. As lives both longer and shorter than at 85/85 were involved, this ratio provides a consistent set of numbers which do not conflict. Ro is the Acceleration Factor (AF) from 85/85 to lower stress condition, but 1/Ro would be the AF from higher-stress to 85/85; to show AF for both conditions on one plot would be confusing.

Acceleration and Deceleration

The IEEE Transactions on Reliability, in Nov 1970, published definitions which include:

"Acceleration Factor: The ratio between the times necessary to obtain a stated proportion of failures for two different sets of stress conditions involving the same failure modes and/or mechanisms."

Note that this definition does not distinguish between

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(t_1/t_2) and (t_2/t_1), but calls either one an acceleration factor. In this author's opinion, this is a good practice. If, in going from an observed life at low stress to a shorter life at high stress by a factor, e.g., of 175, then 175 is the acceleration factor(AF). One divides the long life by 175 to obtain the life at accelerated stress. If one then has an observed life at the high stress condition and wants to predict life at low stress, it is undesirable to have to remember that the Deceleration Factor (DF) is 0.0057142; it is only required to remember that the AF is 175, and one multiplies by it rather than dividing by the DF. Only a single AF between two conditions is required if one uses it appropriately.

Also defined is:

"Accelerated Test: A test in which the applied stress level is chosen to exceed that stated in the reference conditions in order to shorten the time required to observe the stress response of the item...(identifying a common failure mechanism)..."

This implies that the life at the higher stress is the accelerated life, and is normally obtained by dividing the long life by the AF. In the present review, the ratio of median life at some other condition to that at 85/855 is used, giving an AF when treating lower stresses, and a DF when treating higher stresses. The total AF between a stress below 85/85 and that above 85/85 would be the AF below 85/85 divided by the DF from the higher stress.

Modeling and Model Results

The modeling involved in this program is to postulate a relationship between life-and-temperature and life-and-humidity so that the product of the two separable factors between a given condition and 85/85 provides a calculated ratio Rc, according to the model, which best matches the observed ratio, Ro. A plot of Ro vs Rc is used to determine regression parameters and the linearity and uniformity of the regression.

The lognormal distribution of life was assumed, as it was in all the data reviewed. The standard deviation estimated in all tests ranged from 0.4 to 0.5, showing remarkable uniformity. Ro and Rc also have lognormal characteristics, as does the ratio Ro/Rc. The use of the life ratio allows the consistent comparison of data from 5-volt and 70-volt operation, from test structures and from commercial devices, and from different time periods.

Figure 1 shows the plot of 61 data points, with Ro on the vertical axis and Rc on the horizontal, the 45° line representing a 1:1 correlation. The relationship shown here is:

$$\text{time-to-failure} \quad (RH)^n \exp(E_a/kt)$$

where the exponent n in Figure 1 is -2.66, and E_a = 0.79eV. The resulting acceleration calculation is relatively insensitive in the range of n from -2.5 to -3.0 and of E_a from 0.77 to 0.81eV, using the regression parameters and the distributions of Ro/Rc above and below 85/85 (medians and estimates of standard deviation) as criteria. Thus there are seven measures of fit, and not all are optimized at any one choice of n and E_a. The following combinations are suggested as nearly equivalent (and optimum) in results:

E_a	n	correlation coefficient
0.79	-2.66	0.986
0.81	-2.50	0.985
0.77	-3.00	0.987

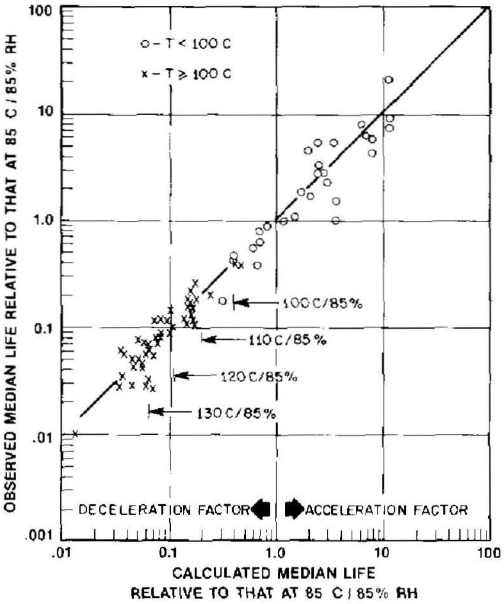

Figure 1 Ratios of life in reported humidity tests to that in 85C/85%RH are shown, comparing the observed ratio Ro to the calculated Rc from the model. The ratios for various test conditions are shown for perspective.

Linearity of the regression was gauged by eye from Figure 1; distributions of Ro/Rc are shown later. Linear regression analysis provides the intercept on the Ro axis at 0.917 + or - 0.064, and the slope as 0.994 + or - 0.04, the tolerances being determined from the standard deviation of error. Removal of one maverick point changes these numbers to an intercept of 0.982 and a slope of 1.026, with the same tolerances as before.

There was also some suspicion that the earliest data may not have represented the best-controlled test conditions, and that later data might give better results. For data published in 1979 or later, the combination of E_a=0.81eV and n=-2.66 has a correlation coefficient of 0.988, with intercept and slope of 1.013 and 1.012, and with the best standard deviations of distribution above and below 85/85 (0.175 and 0.281 respectively). Optimization was not explored, for the sample size for Rc>1.0 is then only seven and more data should be obtained before this is studied further. There is the potential for reducing the confidence intervals for extrapolation to low-humidity conditions.

It is apparent, however, even from existing data, that a single relationship can be used to relate stresses both above and below 85/85, making viable a direct extrapolation from autoclave test results to life expectations at low-stress conditions. Further, publication of more data at autoclave stresses should be strongly encouraged, in order to define the model more precisely for modern test facilities, and to determine a measure of repeatability. The lines at the lower left of Figure 1 show the DF obtainable at some conditions. The acceleration of 130/85 over 85/85 is almost 20:1, and 100%RH increases that. It is interesting to note that , for all the fears about humidity testing at or near 100C or 100%RH, the data show only marginal influence of these limits; 16 of the 61 data points are within 5% of these limits, and all are within the range of the other data, with the exception of one point at 100%RH, from 1972, at the lowest relative value of the distribution in Figure 2 below.

Uniformity of Model Match

An even division of Ro above and below Rc reflects a uniform match of the data with the model through the entire range of the data; a visual review of Figure 1 shows this. Figures 2 and 3 show the distributions of Ro/Rc for Rc<1.0 and Rc>1.0 respectively. The medians of these distributions are at 0.919 and 0.963, both being satisfactorily close to 1.0 A further breakdown to smaller segments of the range of data would show

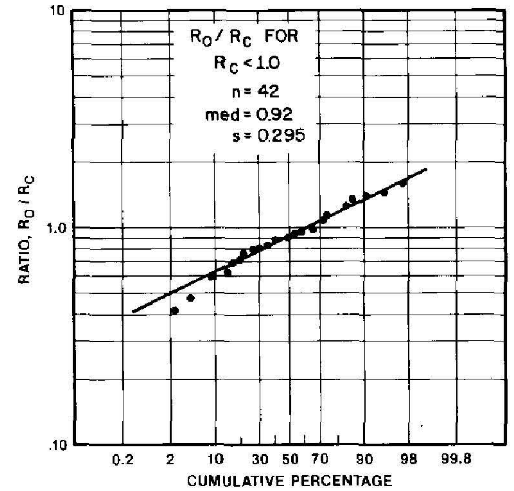

Figure 2 The distribution of deviations (Ro/Rc) from the model for stress greater than (life shorter than) at 85/85.

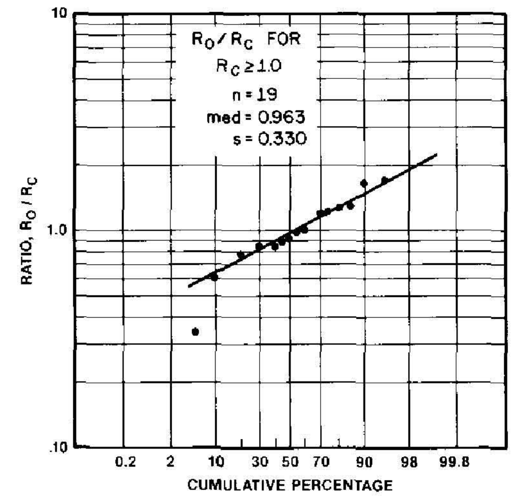

Figure 3 The distribution of deviations (Ro/Rc) from the model for stress less than (life greater than) at 85/85.

distributions of similar uniformity. The data from stresses higher than 85/85 have a better distribution and a smaller estimate, s, of the standard deviation. The confidence intervals (90%) for the standard deviation above 85/85 are 0.25-0.36, and are 0.26-0.46 for lower stress. These are not greatly different, but suggest that the distribution at higher temperature may be somewhat better. This is not surprising, considering the shorter test times, with less opportunity for test condition perturbation.

In the data of figure 2, six results represent 100%RH conditions; if these results are eliminated, the resulting distribution has an improved median of 0.956 and an s of 0.281. Deletion of these points does not change the correlation coefficient of the model, but improves the Ro intercept from 0.982 to 0.999, and the slope from 1.026 to 1.020. This suggests that, while 100%RH is useful for reducing the time of routine tests, it may be desirable to avoid this condition if one wants to optimize extrapolation to low stress levels. Further, testing in modern equipments should be aimed at determining if this fine distinction is significant at the present time.

High-Temperature Limitations

Several factors may be involved in determining a temperature limitation for testing. One of them can be disposed of quickly, for it may not be a real problem; investigators should be aware of it, in case it shows up. An anomalous result appeared in testing of silicone-molded devices with Ti-Pd-Au metalization at temperatures in the range of 150-250C and at 80% saturation [15].

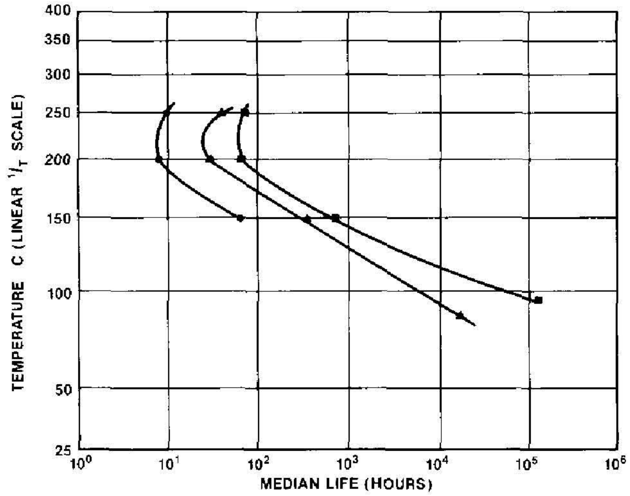

Figure 4 Examples of possible anomalous life behavior at high temperature in 80% saturation (as seen in silicone encapsulations).

This is shown in three examples in Figure 4 as a reversal in the temperature effect, giving better life at 250C than at 200C. This may not be a problem in present testing because of the difference in temperature capabilities of the materials. If, however, improvements allow testing beyond 150C, this effect might possibly appear. It was not investigated at the time (1969), so there is no background for judging its possible presence in other materials.

There are other evidences of notable behavior at 150C. Figure 5 shows an addition to figure 1, adding data for 150C results for several epoxy devices[15]. At 80% saturation these results, together with those at 200C on silicone encapsulations, show both quite longer and quite shorter life than would be predicted by the present model which appears so effective up to that stress. These data were obtained in the late 1960's and may simply reflect the lack of understanding at that time of proper testing procedures in autoclaves. One might guess, however, that anything done "wrong" might tend to shorten life rather than lengthen it. Therefore, the regime of testing at 150C and above, for epoxies, is one which should be re-examined when it can be done safely with respect to glass transition temperature.

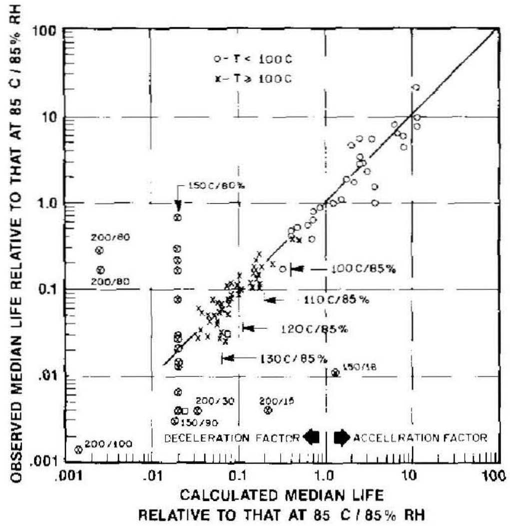

Figure 5 Comparison of Ro and Rc, including data at 150C and 200C showing variable behavior at high temperature, and divergent results at low humidity. (ca 1969)

One effect of the glass transition temperature, Tg, is indicated in Figure 5; two points, marked by squares, represent data taken on product with a stated Tg of 145C[6]. The 130C data at point (0.03, 0.07) (Ro,Rc) is on the low side of the distribution, but not outside it. The 150C data, shown at point (0.004, 0.025) is almost a factor of ten below the calculation. The work of Vanderkooi and Riddell[16] in 1976 showed that the permeability of epoxy by water vapor, while it increases slowly as temperature approaches Tg, takes a 30% jump at Tg, and then proceeds faster than before as a function of temperature. This would lead one to expect a more rapid access of moisture to the aluminum at and above the Tg, resulting in faster corrosion and shorter life.

The paper of Merrett et al[7], however, shows results on the product of Mfr. C at 131/90 (as estimated from the other data) as falling well within the range of the model, although with a stated Tg of 127C; also, the presumed humidity-reduced Tg's for Mfrs. B and F (128C and 125C) did not affect the results at 131/90 enough to put them outside the expectation from the model. In the latter cases there is the possibility, indicated by people in the epoxy manufacturing business, that the supposed reduction of the Tg in humidity exposure is not a real effect with respect to moisture permeability, and that the original 136C measurement still applies; then, the 131C tests might not be expected to have an effect. There appears to be some uncertainty about the effect of Tg, or the temperature interval of the effect, on the corrosion test results. Tests should be made well on either side of the measured Tg prior to humidity exposure, to establish the degree to which this epoxy parameter (or some modification of it) will limit testing temperature, or invalidate the model.

Low-Humidity Effect

Something else can possibly be learned from testing at high temperatures --- an answer to the question: "at what low %RH does corrosion effect diminish more rapidly than the model?" The statement is often made that "below some level of %RH we don't have to worry about corrosion", but data are not available. Some models are offered to apply "down to 25%", but without explanation. It is, of course, very difficult to take the time to run a test at 10% or 20%RH at normal use temperatures, or even at 85C. The lowest humidity level in the data used here for epoxies was 50%, and the 50-60% data are spread reasonably about 1.0 for Ro/Rc.

The B.E.T. curves as shown by Koelmans[17] show that the drastic reduction in surface conductivity (vs RH) takes place at about 5%; at this condition, at 150C the life should be 36 times that at 85/85--an untestable time. Even at 200C, the AF at 5% is 3.66, still a poor test time. At 20%, however, the ratio to life at 85/85 is 0.91 at 150C, so there is some opportunity to observe the actual life ratio if we can otherwise be satisfied with the testing capability at 150C. At 150/10, the ratio should be 1.96, so that any extension of life beyond that calculation would require an unacceptably long test time.

On the other hand, the question can be raised as to the practical value of such investigation. In an application at 30/20, the acceleration to 85/85 is over 4900; a 5000-hour epoxy median life in 85/85 becomes $2.5x10^7$ in 30/20, and the failure rate will be less than 1 FIT for 300 years. At 40/20, the AF is 1877, providing a failure rate below 1 FIT for 50 years. These calculations do not even provide for any increase beyond the calculated value, and already the question is of only academic interest.

APPLICATIONS

Extrapolations from Autoclave Test Results

The consistency of the T and RH effects from T<85C through T>85C (and, perhaps more importantly, above and below 100C) suggests that there is no reason we should not be able to extrapolate directly from results above 85C and predict failure rates at the low humidity stress of an application (keeping in mind the pessimistic calculation below 25 or 30%RH). If the model proposed here holds up with further testing, or can be fine-tuned satisfactorily, then the distribution of Figure 2 can be translated, according to the model, directly to the low-stress condition. It might also be expected that, with improved equipments and operating practices, and known Tg's, even a tighter distribution will be found.

The upper 90% confidence level of the standard deviation of results about the calculated ratio Rc, for stress above 85/85 is 0.360 (Fig.2). For this lognormal distribution, then, the central 90% of the distribution is included within a range around the median defined by a multiplier and divisor of 1.8 (1.7 with deletion of 100%RH data). The measured life in this condition can be extrapolated by the model to a low-stress condition, and the median life there should be within a factor of 1.8 from the calculated value, with 90% confidence. The regression line passes through Ro axis at 0.982, and the central value of the distribution of Ro/Rc is at about the same point, saying that the regression bypasses 85/85 by only 2-3%, and matches the low-stress extrapolations of Figure 1.

Such predictions can not be applied to low failure percentiles, which may include freaks which can vary in a given sample from the freak level of the population, and has been seen to be as high as 10% in some published data. Similarly, estimates of median lives from test data only to early failure percentiles can be made only after careful treatment to eliminate freaks; otherwise the median estimate could be grossly distorted.

Since the data used herein were obtained by different groups of experimenters over a period of over 10 years, it is amazing that even this degree of consistency could be found. The 90% confidence for median life about the sample value, from a homogeneous population, for samples of 50 (which most of these were), and with a of 0.5, is a factor of 1.12, leaving a factor of 1.6-1.7 to account for the accumulated vagaries of these humidity tests. And this does not even consider the variability in the 85/85 test which is the base for the calculations. There a temporary drop in temperature of 4C could result in condensation which could reduce life in a chamber not designed to protect against condensation on the devices.

There is an unquestioned usefulness for the model shown for direct extrapolation from autoclave results to low humidity stress, for product similar to that included in this review. (Some data from phenolic and silicone encapsulations also match the model, but were not included in the calculations). Significantly different insulating materials and encapsulations should be evaluated separately.

A paper by O. Hallberg[18] came to light as this was being finished. It used 51 points of data from different sources, in a similar fashion to that of Figure 1 here, but without that statistical comparison of the models discussed. The comparison being suggested, Appendix A is added to treat this subject.

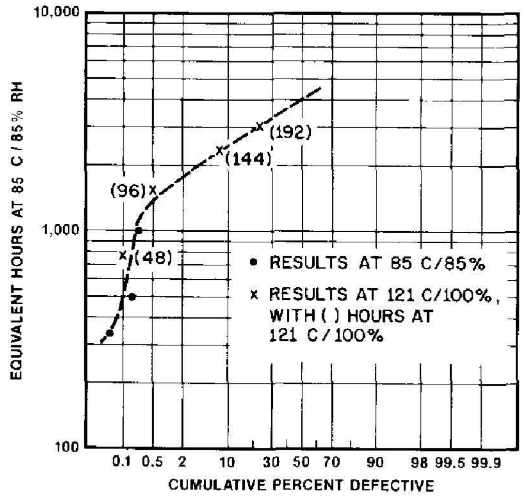

Figure 6 Composite life distribution from 85/85 and 121/100 tests.

Establishing Humidity Test Conditions

Figure 6 is an example of the combined test results of both 85/85 and 121/100 conditions (on the basis of the equivalent time at the 85/85 conditions) from many samples from the same production period of a semiconductor product. During the 1000 hours at 85/85, only the freak level of the product was measured (but the same result could have been obtained in 48 hours at 121/100, or in 28 hours at 135/100). Further, the important information that the product had a median life of about 4000 hours at 85/85 was completely unavailable except by testing up to about 3000 hours at 85/85, 200 hours at 121/100, or 84 hours at 135/100.

Which test is the more desirable? The shortest test provides the quickest feedback for control, the greatest throughput of samples, and the greatest incentive for frequent testing.

The answer also depends on what the user of the product needs[19]. If the application is in a severe environment of 40C/95%, the 4000-hour (85/85) product will have a failure rate of 500 FITs in seven years, and 8000 FITs in 10 years. A product similar to the above, but with a different epoxy date, was tested in the same time period, the 121/100 test showing a probable 85/85 median life of 7000 hours. This would have operated comfortably in the 40/95 environment, and with a tested performance in only 200 hours in the 121/100 conditions. An appropriate test condition for that application should be able to distinguish between the two products.

There are now some data available on epoxy and die surfaces which will provide from 10,000 to over 20,000 hours median life in 85/85. These times put 85/85 testing out of the question for control or acceptance purposes. At 140/100, however, the 20,000-hour equivalent is only 400 hours, and a test allowing less than 50% defective could be established in a shorter time.

If Military conditions are a real objective, then perhaps something like 38C/98% might be an extreme condition, in lieu of a specification. For a maximum 50-FIT failure rate for 10 years in this environment, a median life can be determined [19], and the acceleration factor indicates that the corresponding median life at 85/85 would be 24,000 hours. This could be established by a requirement of 10% failures in 465 hours at 135/95, or 350 hours in 140/95 (or 60 hours in 150/100 with 5% defectives allowed).

With the indication in these data of the possible need to stay under the Tg of the epoxy, these conditions may put pressure on the selection of materials for the encapsulation. The tremendous advantage, however, of reducing test times from unreachable numbers to quite modest numbers of hours, might warrant some cost for the Tg. Even if the material systems are not yet available to meet the most severe requirements, the testing facility should be validated and calibrated, since it seems within the industry capability.

According to the present model, acceleration factors over 85/85 results include the following:

Condition	Acceleration
121/100	16
135/94	30
140/94	40
140/100	50
150/100	77

The equivalent of 1000 hours at 85/85 could be 20 hours at 140/100, allowing this test to be completed within one day. This would only be a measurement of the freak level in the product, but could very well be a specification requirement, since it will control the early failure rates. In a relatively short time (5 to 20 days) one could describe the median life of any present epoxy system, or of one which might meet Military requirements.

CONCLUSIONS

First, there is available here a relationship between temperature, humidity and life for electrolytic corrosion of aluminum metalization, which can be used to extrapolate autoclave testing results, accounting for the possible effect of the epoxy Tg, directly to expected life at low stress down to about 30%RH, below which life may be longer than indicated by the model. Avoiding testing at 100%RH may give a slight improvement in the confidence limits of the extrapolation, from past data; the possible effect with modern equipments should be explored further.

Second, this relationship allows the establishment of very-short-time tests to replace the present 1000-hour, 85/85 tests, and this should be done immediately. More test results should be reported at both below and above 85/85 stress. Low-stress tests are needed to improve the statistics in that area, and the high-stress tests should emphasize measures of repeatability, particularly at 100%RH. There appears to be no other reason not to use this condition for routine testing, except for the reproducibility of ratio to 85/85, compared to that of lower RH.

Third, the existence of epoxy packaging systems for semiconductor devices with median lives greater than 20,000 hours has been suggested. Such devices could have acceptable performance in Military applications, and the autoclave results discussed here indicate that they could be qualified in reasonable time periods. Formulation of humidity- test requirements for these applications may now be timely.

APPENDIX A

A paper by O. Hallberg[18] also reviewed published data on the ratios of median life in other conditions to median life in 85/85, and plotted 51 points of data according to the $(RH)^2$ model of Lawson[20,21] and the (T+RH) model of Reich and Hakim[22]. This work was effective in reducing the number of models, but did not use distributions of the observed ratios about the calculated ratios as a measure of fit, which is felt here to be the better method of comparison, together with the regression parameters.

REGRESSION PARAMETERS

$$\log Ro = a + b (\log Rc)$$

	CORRELATION COEFFICIENT	a (Ro INTERCEPT) (ACTUAL Ro)	b (SLOPE)
REICH & HAKIM 1972 ·	.974	.780	.911
PECK & ZIERDT 1973	.956	.670	1.18
LAWSON 1974-1984	.950	.775	1.09
PECK 1986	.986	.982	1.03

Figure 7 Regression parameters for four humidity test models.

This Appendix, then, compares the following models;
1. Reich and Hakim 1972
2. Peck and Zierdt 1973
3. Lawson 1974-1984
4. Peck 1986

Figure 7 shows the regression parameters for the 61 points of data collected. Figures 8 and 9 show the distributions of the deviations of the observed data from each model, as numbered above.

Since all the models except 4 evolve from limited data, it is not surprising that they show regions where the model is relatively far from observed fact, although none are off by extreme ratios. For example, the Reich and Hakim model evolved largely from the Panama tests in high humidity, and the model fits well in that area, but does not provide as good an extrapolation to the low-humidity-stress region.

The present model provides the tightest distribution of fit to all the data used.

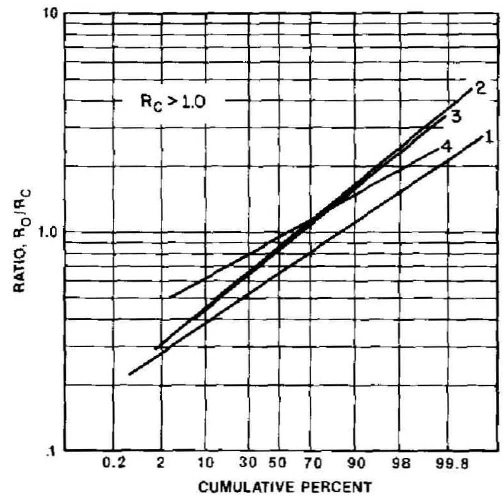

Figure 8 Distributions of deviations from the model for the models of Figure 7, for stresses less than 85/85.

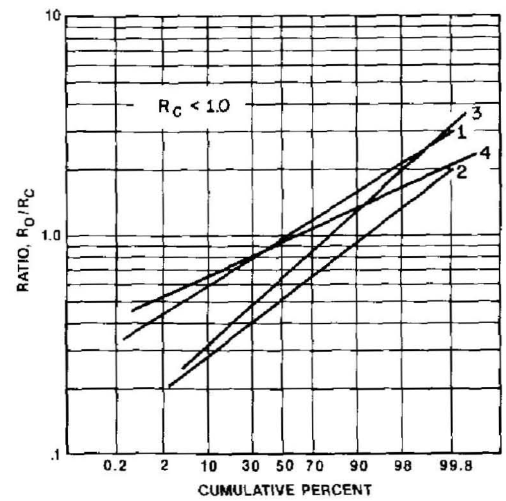

Figure 9 Distributions of deviations from the model for the models of Figure 7, for stresses greater than 85/85.

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