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RECENT HUMIDITY ACCELERATIONS, A BASE FOR TESTING STANDARDS

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SUMMARY

Accelerated humidity test data on plastic ICs are analysed, showing higher thermal acceleration and longer life for modern components compared to older ones. Accelerations for total test time in humidity are given, and the effect of assumed moisture ingress time through the plastic is also treated. A procedure for formal qualification of moisture life is proposed.

KEY WORDS Moisture Humidity Corrosion Acceleration factors Testing

INTRODUCTION

The introduction of epoxy moulded encapsulations for semiconductor devices, to replace the more costly hermetic packages, brought with it the introduction of the failure mechanism of metallization corrosion as a major concern. These failures occur because of the diffusion of humidity through the epoxy, or along the lead frame, increasing the surface conductivity of the insulator between adjacent metal lines under bias, causing corrosion and failure, The failure distributions are a function of the bias, temperature and relative humidity at the insulator surface. The relationships of time to failure and the temperature and humidity have been the subject of much testing effort.

Until recently, each study of these relationships was limited to a few tests run in a single laboratory, comparing life under special test conditions to the life at 85°C and 85 per cent RH (85/85), which has been the standard test condition for many years. A recent evaluation was made of a large number of tests, looking for an overall relationship not limited by small numbers of tests which individually led to widely different relationships. The quality of epoxies has been improving, and test procedures were stabilizing, so another review of the data mass was deemed necessary.

BACKGROUND

In 1986, a paper[1] was presented at the International Reliability Physics Symposium which used 61 points from the published data available to the author.[2–15] These compared the median time-to-failure, t_m, at conditions of temperature and relative humidity (T/RH) with the t_m at the reference condition (85/85), using the lognormal distribution plot to obtain the estimate of t_m after the removal of freak failures[16] from the distribution. The observed ratio, R_o, of t_m (T/RH) to t_m (85/85) was then compared with the calculated ratio, R_c, according to the formula being investigated. The ratios were examined to obtain the smallest standard deviations and the highest correlation coefficient between R_o and R_c.

Since the same electrical bias conditions were held through each study, the ratios normalize the effects of test-to-test variations in bias, device structure or contamination level.

A common relationship was found to be optimum for stresses both higher and lower than the reference (85/85) from 158°C down to 50°C and from 100 per cent RH down to 50 per cent RH, the range of the available data. The formula has the form

$$t_f = A(\%\mathrm{RH})^n \exp\left(\frac{E_a}{kT}\right) \qquad (1)$$

where A is a constant, $n = -2{\cdot}66$, $E_a = 0{\cdot}79$ eV and k is Boltzmann's constant, $8{\cdot}615 \times 10^{-5}$ eV/K.

This relationship shows that, for example, 1000 h of testing at 85/85 can be replaced by a test of 20 h at 140/100, allowing the 'standard' test to be done in one day instead of six weeks. The 100 per cent RH test results, however, although within the distributions for the ratios, were always at one end, so that an RH value providing a ratio somewhat lower might be desirable for more accuracy. A test at 140/95 can still be done in 24 h for equivalency, however. These results point to one or more of several possibilities:

1. Short tests for product acceptance, with more frequent testing, and less interference with shipment schedules.
2. Increasing the test time to the equivalent of

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several thousand hours at 85/85, consistent with the availability of better epoxies, and possibly proving the reliability level needed for general military and telecommunications usage.

3. For applications in general, the prediction of moisture failure rates in application environments.

CURRENT DATA

The data used in this current analysis are taken from publications from 1979 to 1987,[7–15, 17–27] using a total of 87 data points of comparisons of the ratio R_o of t_m (T/RH) to t_m (85/85) to the calculated ratio R_c according to an assumed formula. Data published before 1979 were not used because they represented sporadic attempts, frequently on home-made equipment, and with variable attempts at cleanliness of equipment or test items. Furthermore, it was recognized that the chloride content of the epoxy could be critical, and that later products might be more useful for future use. This will be discussed later.

Figure 1 shows the plot of all R_o vs R_c points, as in Reference 1, but resulting from the range of data from 158°C down to 20°C and from 100 per cent RH down to 20 per cent RH. The data optimally fit equation (1) with the following parameters:

$$n = -3{\cdot}0;\ E_a = 0{\cdot}9\ \text{eV}$$

Correlation coefficient: 0·985; R_o intercept: 1·010; Slope: 0·98

This compares with the earlier correlation coefficient of [illegible]6 for the 61 data points of 1986.[1]

Extreme points taken from data at 85/20 and 20/58 conditions were from unencapsulated devices,[17] but the R_o/R_c ratios were well scattered in the distribution from all the data. The 15 h t_m at 85/85 allowed data to be obtained at low stress within 15, 000 h. The time required would have to be far too much longer for encapsulated units. Moisture tests on these unencapsulated devices were performed using glass exsiccators giving adequate protection from external impurities. The failure criterion on these devices was visual evidence of corrosion.

Using new parameters, the equation for relative life at T RH to that at 85/85 can be written as

$$\text{Rellife} = \frac{85^3}{\text{RH}^3}\exp\left[\frac{0{\cdot}9\ \text{eV}}{k}\left(\frac{1}{T+273} - \frac{1}{358}\right)\right] \quad (2)$$

This is written as 'relative life' because it amounts to a deceleration factor from higher stress to 85/85 and an acceleration factor of 85/85 over a lower stress condition. Figure 2 shows the distribution of the ratio of the observed relative lives to those calculated according to equation (2) for each data set.

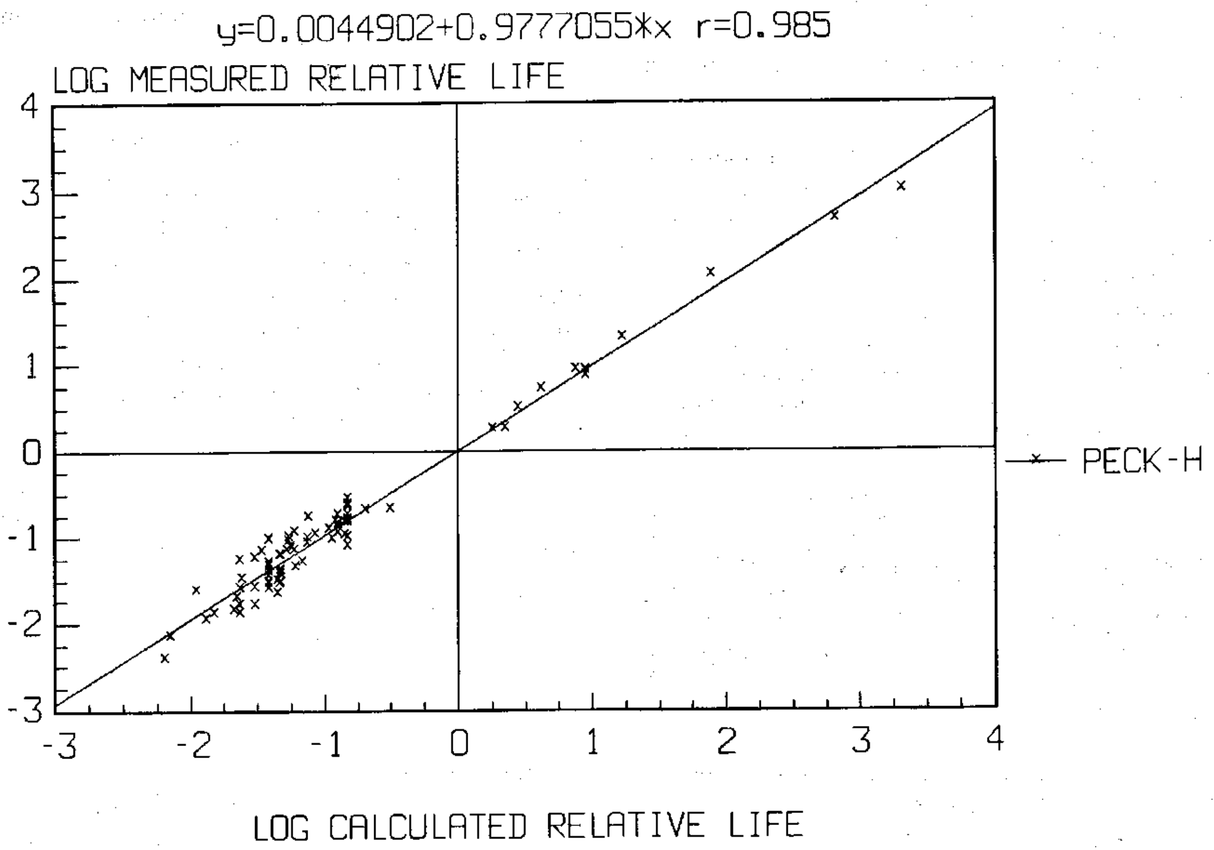

Figure 1. Correlation diagram over calculated and measured relative lives in moisture tests

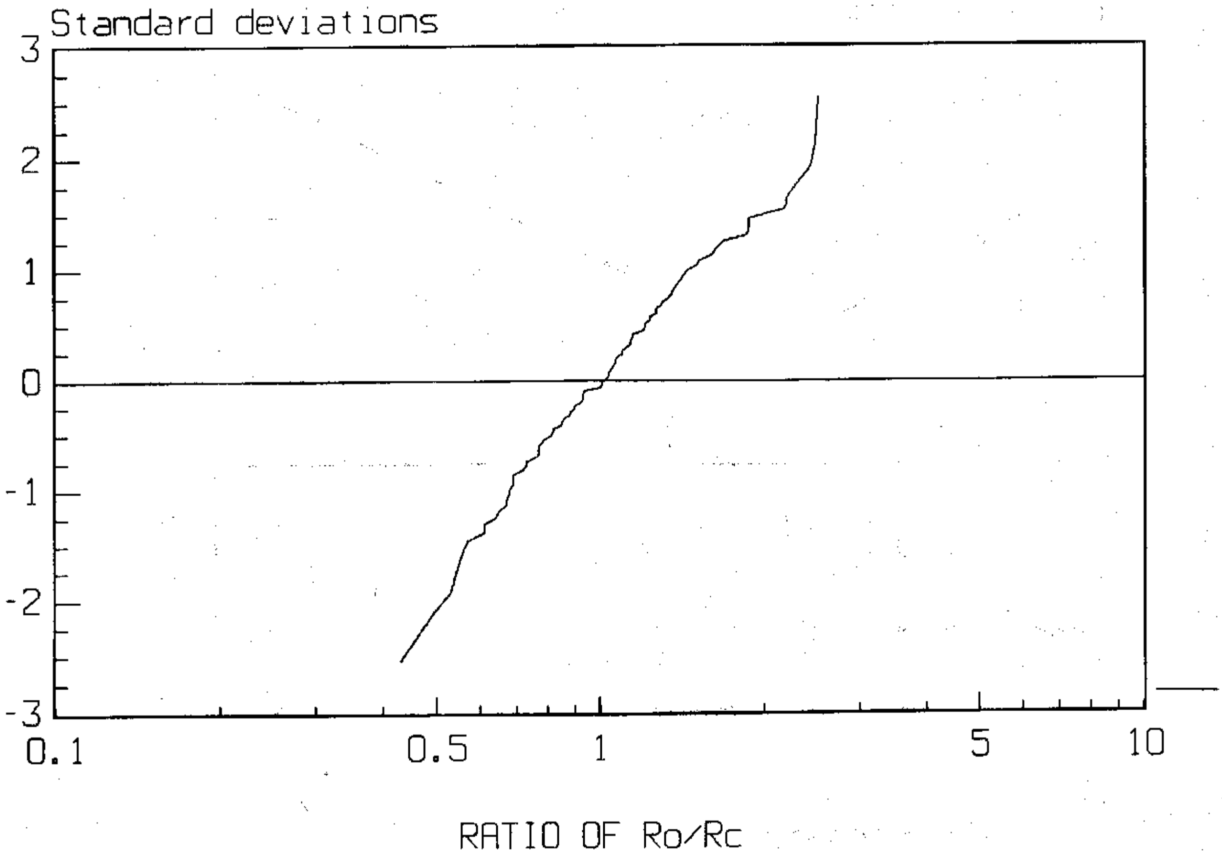

Figure 2. Distribution of the ratio R_o/R_c for $n = -3$ and $E_a = 0{\cdot}9$ eV

Figure 3 shows the ratios of t_m to that at 85/85 vs %RH and T drawn through actual data points.

There appears to be no strong interdependency etween temperature and humidity in Figure 3, suporting the form of the acceleration formula.

Figure 4 shows group average activation energies rom all tests versus median life at 85/85. An average alue for long lived products seems to be 0·9 eV.

About 60 per cent of the individual data points ame from products with t_m (85/85) between 2000 h nd 9000 h but about 30 per cent were below 1000 h many around 200–400 h), indicating that the presnce of lead leakage paths may have affected the esults for some of those samples, see e.g. Reference 2. The data used for the 1986 summary[1] would also ave been affected since the product was generally f earlier vintage with shorter life and lower actiation energy. Short life could also be caused, of ourse, by poor quality of the glassivation coverage, llowing short surface paths between metals. Gusafsson and Lindborg[28] show that a failure percentge of 2500 h exposure at 85/85 drops linearly from 0 per cent at a chlorine content of 70 ppm to ssentially 0 per cent at 0 ppm; see Figure 5. This s such a significant change, as is the reduction in pm chlorine in epoxy since about 1979, that it may ell mask any other changes in quality during that eriod. This supports the use of the parameters of he longer-life product as probably representing the evices of the future.

The data processing was carried out on those tests only having t_m (85/85) greater than 1000 h or 3000 h, with the results shown in Table I.

The differences in intercepts and slopes have very little effect on t_m ratios within the range of the data (from 0·001 to 1000). The improved correlation coefficient is indicative of the probability that the proposed relationship is more appropriate for current and new dual-in-line, or similar, products. Here it can be expected that the only path for introduction of humidity to the die surface will be through diffusion through the epoxy and glassivation. Also, the estimate of the standard deviation (s) of the distribution of R_o/R_c drops from 0·41 for the full 82 points to 0·31 for the 37 items where t_m at 85/85 exceeds 3000 h:

$s = 0{\cdot}41$, $n = 82$; $0{\cdot}355 < s < 0{\cdot}484$ 95 per cent confidence limits

$s = 0{\cdot}31$, $n = 37$; $0{\cdot}255 < s < 0{\cdot}400$ 95 per cent confidence limits

Since the tests included in the data are on dual-in-line packages, the lifetimes will theoretically be reduced when the epoxy thickness, from atmosphere to die surface, is reduced. This reduction may increase the possibility of epoxy cracks, and will reduce the length of the epoxy-to-lead frame leakage path, increasing the possibility of poor adherence and humidity leaks. These effects will cause short

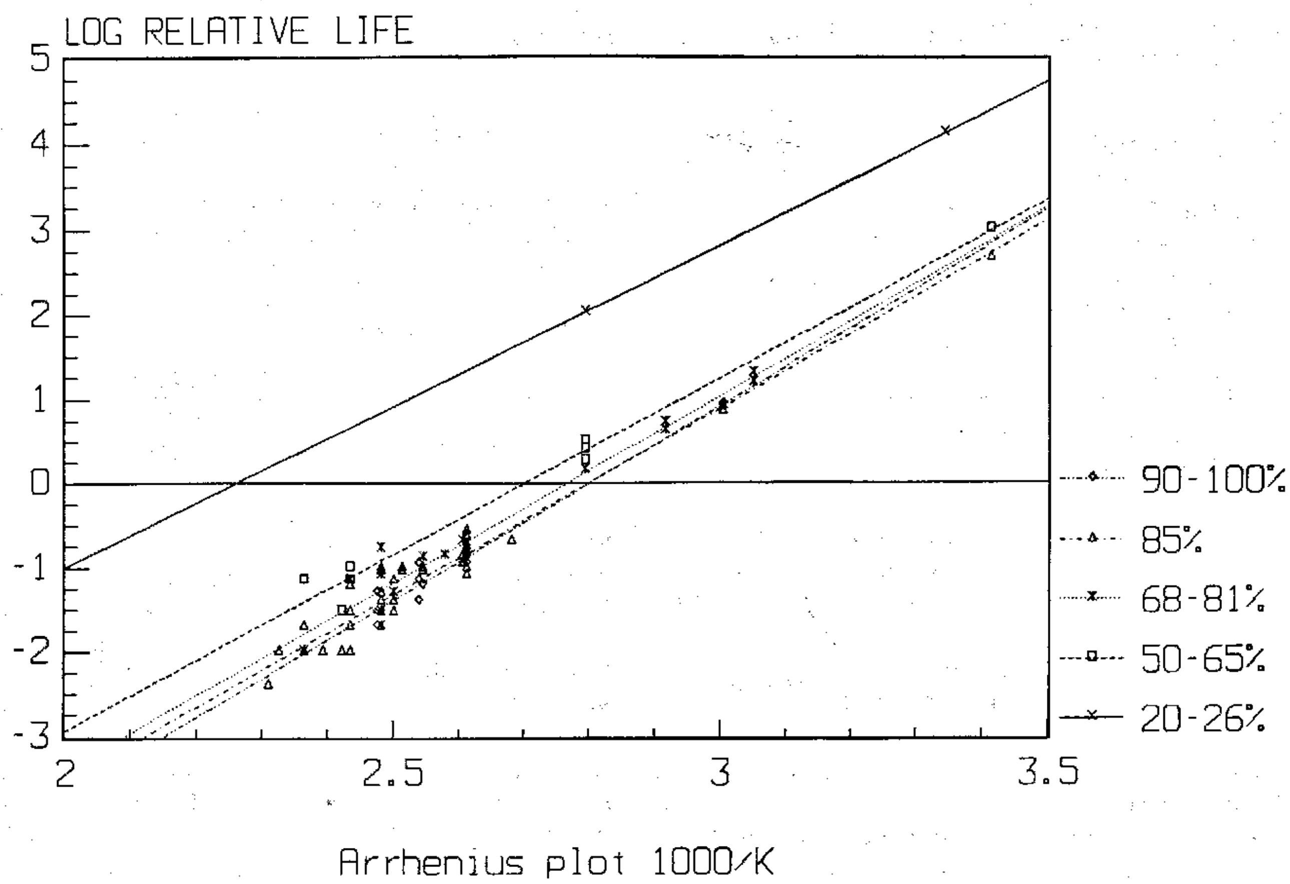

Figure 3. Summary of published moisture test lives relative to life at 85/85

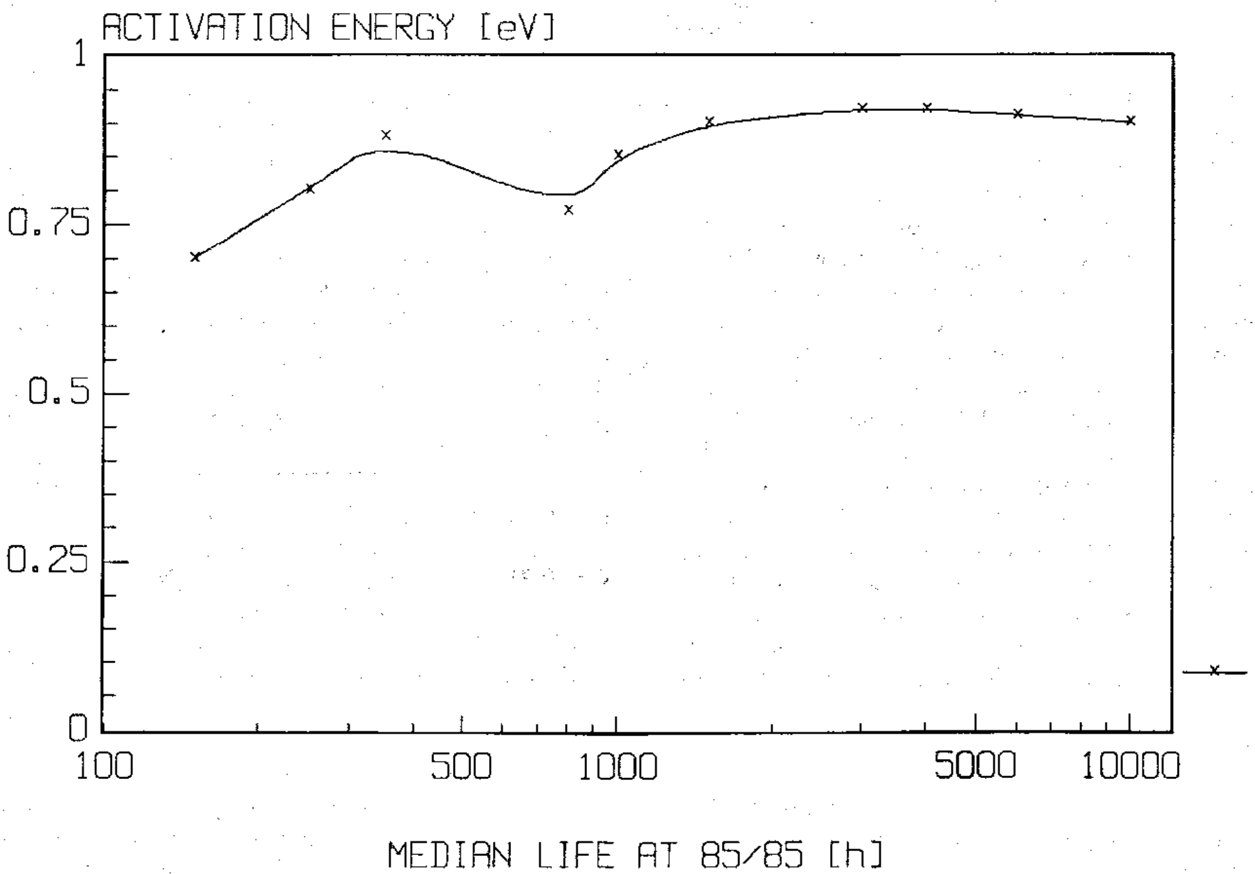

Figure 4. Average activation energy in moisture tests versus median life at 85/85

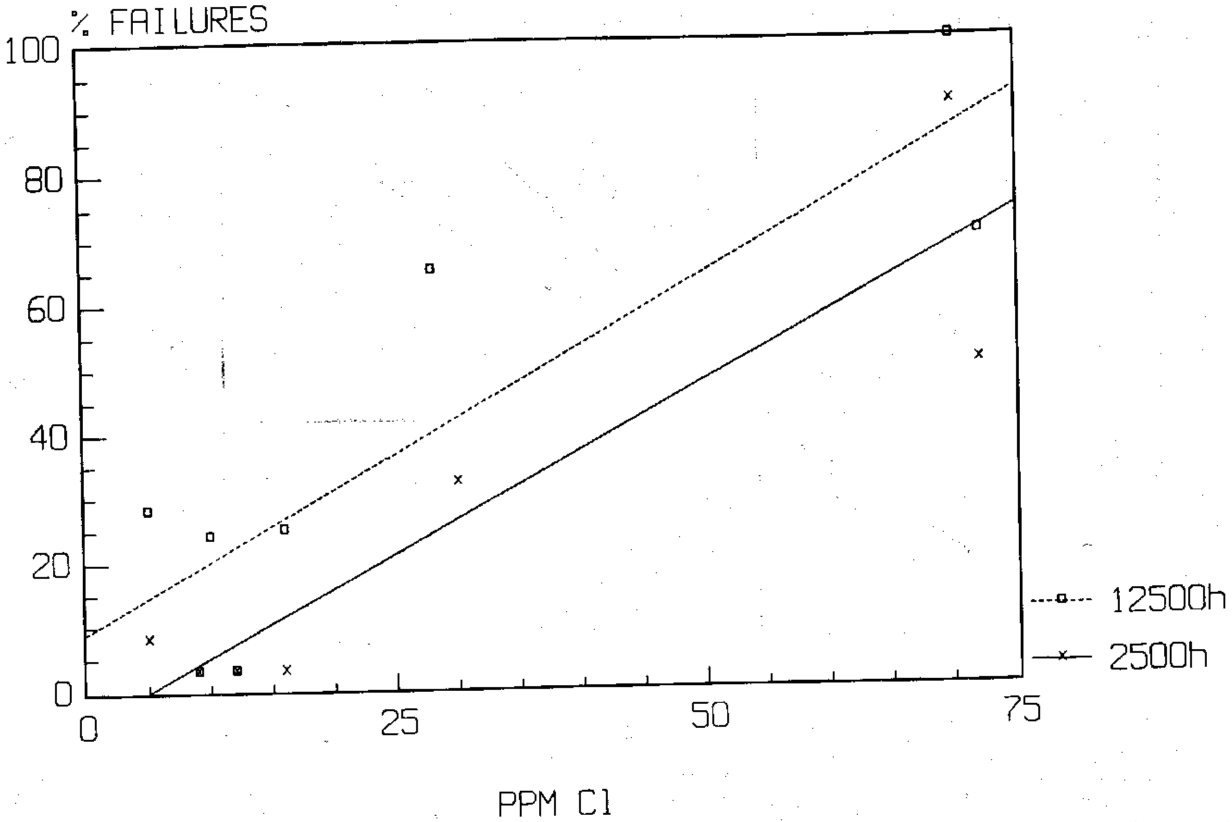

Figure 5. The percentage failures for test circuits after 2500 h and 12,500 h at 85°C/85 per cent RH as a function of the chlorine content of the moulding compound (from Reference 28, Figure 6; Replotted by permission of the authors)

Table I

	All data	t_m >1000 h	t_m >3000 h
Correlation coefficient	0·985	0·985	0·993
Intercept	1·010	1·031	1·123
Slope	0·978	0·993	0·992
Sample size	82	58	37

life, and the acceleration determined will remain the same only if these failure mechanisms are eliminated. The life in the test environment can then be related directly to the expected life in the application environment. The failure rate at any given time in that environment can be calculated, knowing the median life and the standard deviation of the lognormal distribution.[16]

COMPARISON WITH OTHER MODELS

No paper on moisture acceleration would be complete without a comparative study of other proposed models. Our material has been used to see how well different published models fit the data. Figure 6 shows the correlation between measured and calculated relative lives according to different models as they were determined with limited data.

Our material shows that REICH-H gives more scattered data than PECK-H. EYRING and LAWSON predict shorter life than measured at low stress and longer life than measured at high stress. SBAR-K predicts shorter life than measured at high stress and gives very scattered data. The present model, with optimized parameters is compared to the other models as published from limited data, to show the danger of such a process. To optimize all the models to present data would require more effort than available, or justified, considering that those models all have RH in an exponential relation.

It is also important to note that the models differ rather much at low humidity stress. This is shown in Figure 7, which plots relative lives vs RH at a constant temperature.

INFLUENCE OF MOISTURE INGRESS TIME

Many observations have indicated that a length of time is required for moisture to get from outside the plastic encapsulation to the chip surface, in order to start the corrosion process. If such a time can be determined as a function of the condition of stress, and subtracted from the total time to failure, a more precise determination of the corrosion parameters alone might be obtainable.

Figure 8 shows the calculated moisture density increase at the chip surface within a PDIP as a function of time and temperature.

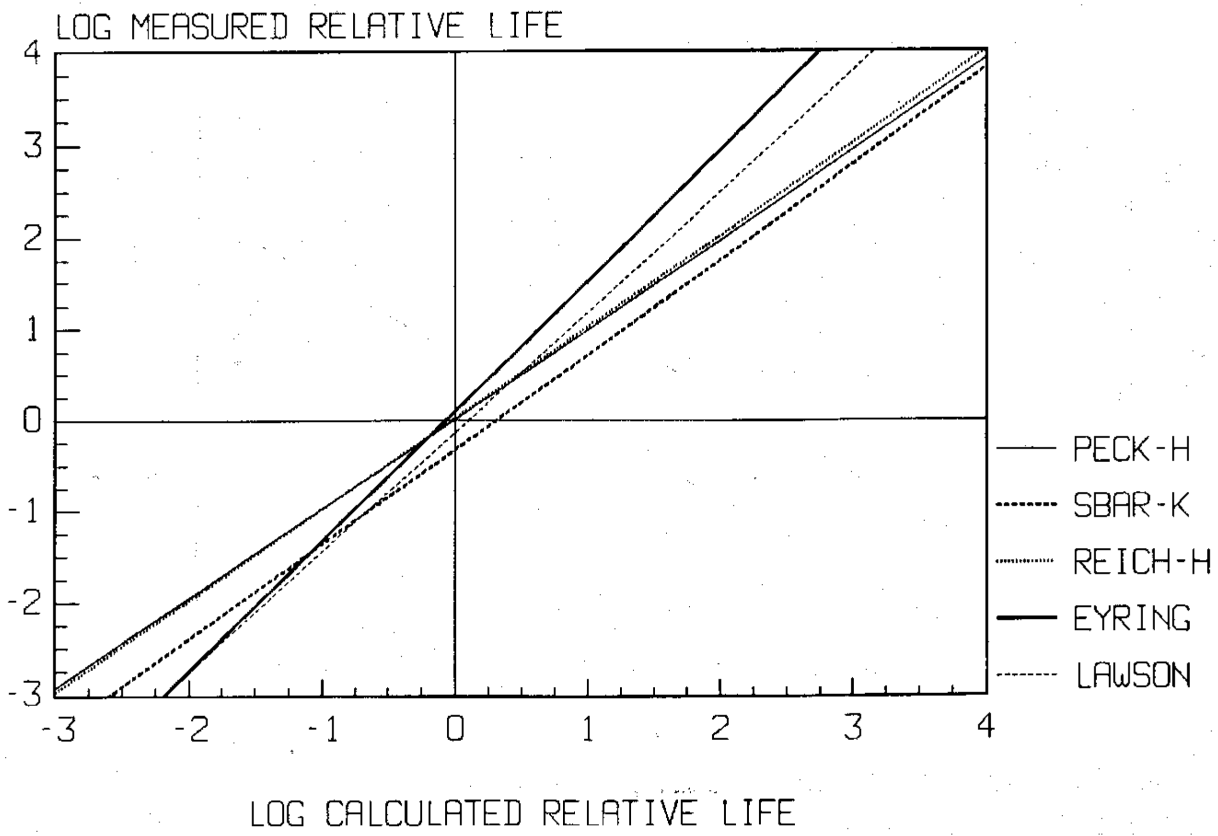

Figure 6. Correlation between measured and calculated relative lives for different models. LAWSON: $A = \exp[0{\cdot}6/kT - 0{\cdot}00044(\mathrm{RH})^2]$. EYRING: $A = \exp[(0{\cdot}65/kT) + (304/\mathrm{RH})]$. REICH-H: $A = \exp[-0{\cdot}073(T[°\mathrm{C}] + \mathrm{RH}[\%])]$. SBAR-K: $A = 10 \uparrow [0{\cdot}41/kT - 18.69\mathrm{RH}/T + 0{\cdot}00819\mathrm{RH}]$. PECK-H: $A = \exp(0{\cdot}9/kT)(\mathrm{RH})^{-3}$

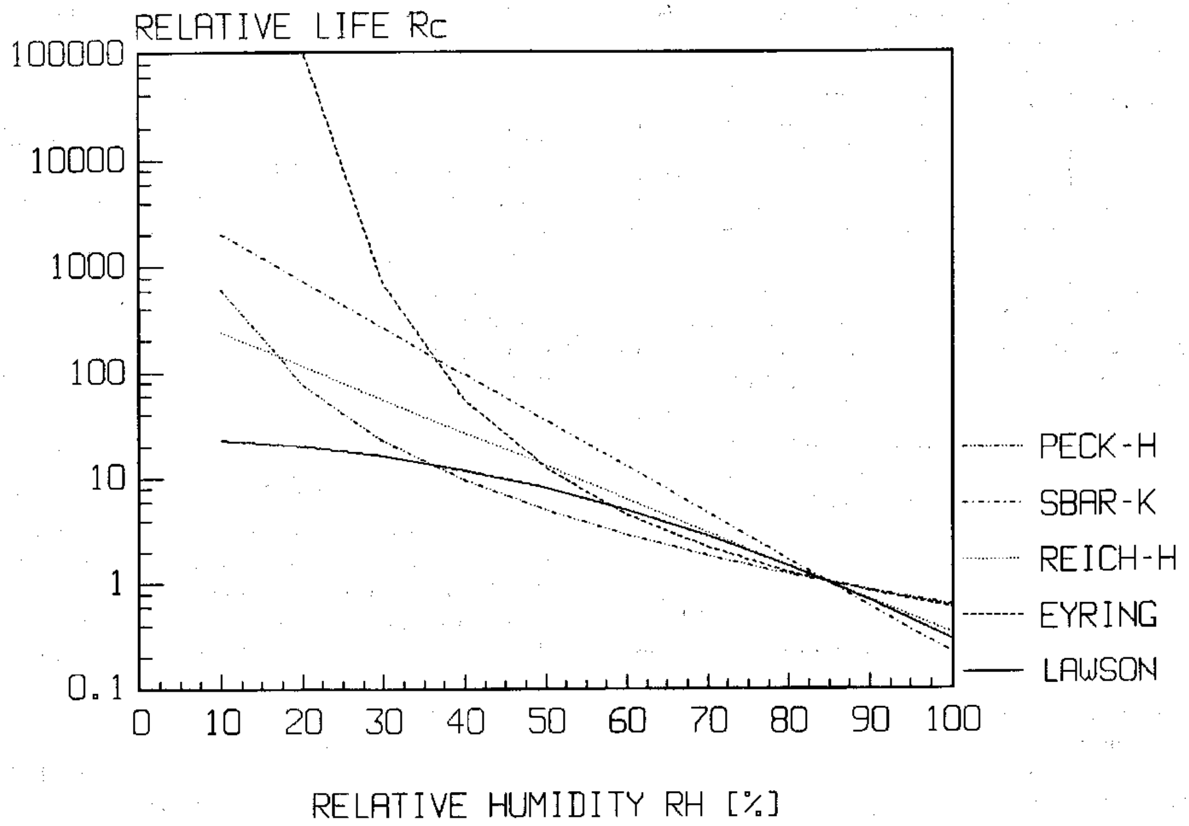

Figure 7. Relative lives versus RH according to different published models normalised to 85 per cent RH

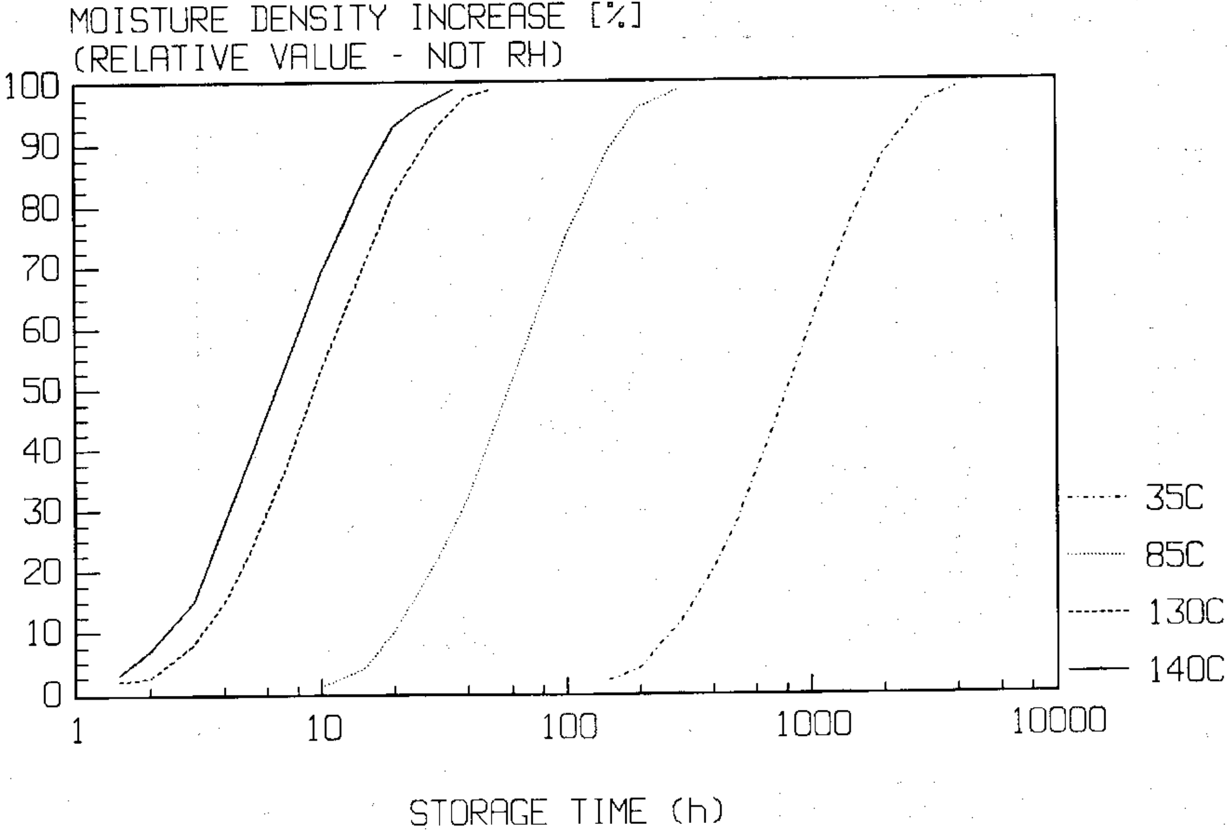

Figure 8. Moisture density increase at the die surface expressed as a percentage of the final static increase of moisture absorption relative to initial conditions. Calculated from the diffusion equation

Reference 18 reports the moisture ingress time through an IC package to a charge-spreading transistor to be 36 h at 121°C/100 per cent RH and around 500 h at 85/85. Yerman and Burgess[21] tested a tripple-track pattern and found a delay time to increased leakage current of 17–18 h at 130/85 in a 'clean adherent' (to the epoxy) lead frame, but only about 2 h for 'poor adhesion'. This shows the difference between the assumed diffusion through the plastic and the leakage of moisture along the lead interface with poorly adhering plastic. Dycus[23] also reports 'massive failures' at 25 h in 121/100 conditions, but he also assumes that failures occur as soon as the RH level at the chip reaches a certain level. Other examples can be found of observations of an ingress time for moisture prior to the significant start of the corrosion process.

Contaminated chips, of course, would be expected to corrode at low levels of RH, so that failure could occur before the chip surface sees the final moisture density. The existence of leaks along the lead–plastic interface is of course always another possibility. Unfortunately, the published works seldom identify such conditions, but the results themselves may identify those tests which may be suspect.

With the exception of particularly short-life ICs, it can be assumed that moisture reaches the chip surface by means of diffusion through the epoxy from the exterior surface. This is driven by the partial pressure of ambient water vapour. The moisture density follows the equation corresponding to an infinite suppy of moisture at the surface:

$$\rho(t,x) = \frac{4}{\pi}(\rho_f - \rho_i)\sum \frac{1}{n}\exp\left[-D\left(\frac{n\pi}{2h}\right)^2 t\right] \sin\left(\frac{n\pi x}{2h}\right) + \rho_i,\ n = 1, 3, 5\ldots \qquad (3)$$

where ρ_f is the final moisture density, ρ_i is the initial moisture density, h is the thickness of plastic over the die, x is the distance from the surface of the package, D is the diffusivity of water in the epoxy and t is the time since the start of exposure.

The temperature dependence of the diffusivity of water into plastic has been reported to have an activation energy of 0·5 eV. On the other hand the solubility of water into plastic has a negative temperature dependency of about −0·38 eV.[29] Therefore the amount of water absorbed at saturation is not increasing as strongly by temperature as the partial pressure of water does in air. This was calculated and is shown in Figure 9. This diagram may be used to define storage conditions that are compatible with maximum moisture uptake that is of importance (e.g. to avoid package cracking during soldering of PLCCs).

Many simulations were performed on the data to use a range of delay times, consistent for each test condition, in order to isolate the 'corrosion time' from the total observed test time. In every case,

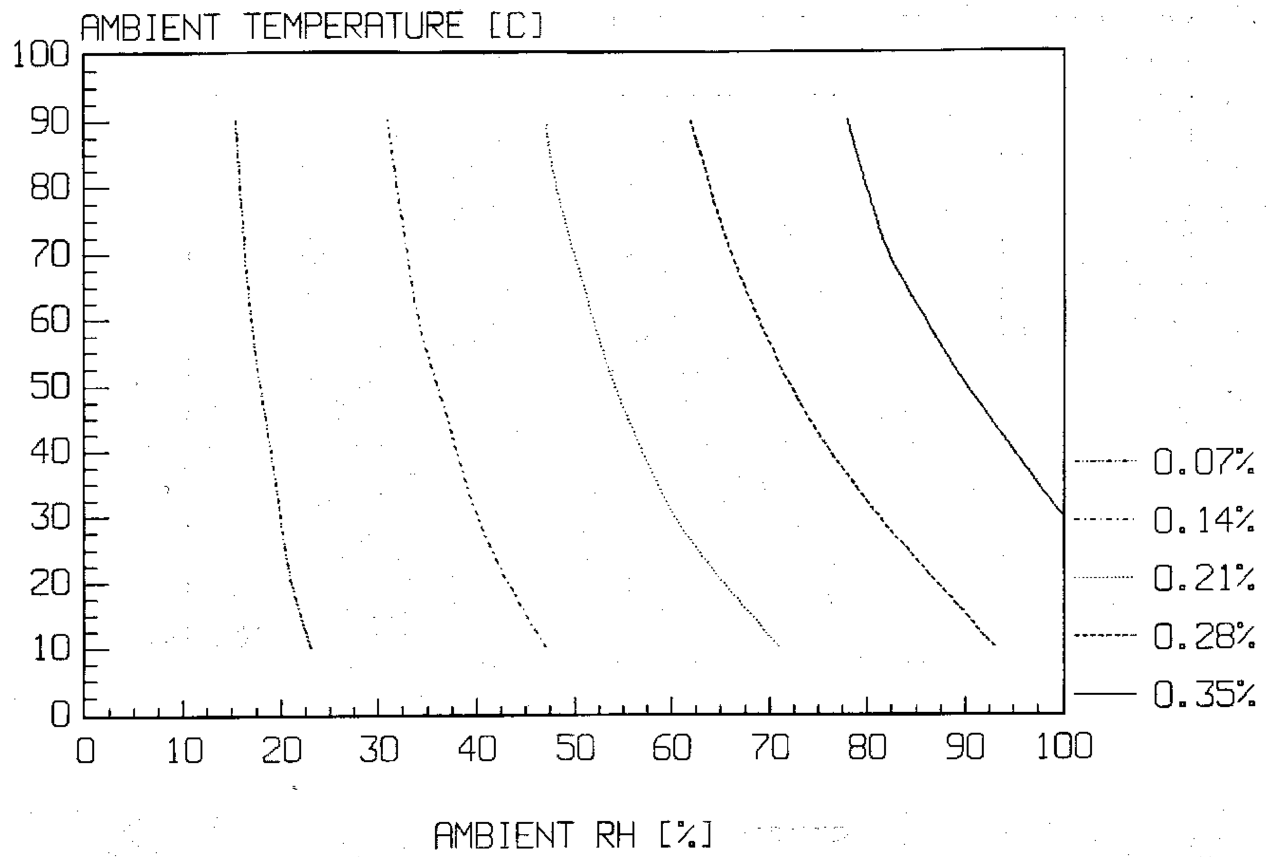

Figure 9. Saturated moisture level (weight %) in a PLCC vs temperature and RH. Calculated using the model from Reference 29 adjusted to test results at Ericsson for 85/85

the correlation coefficient of the resulting 'corrosion time' was degraded from that for the total test time. Apparently there is a wide variation between lots of material regarding the moisture density level at which corrosion starts. Considering the range of product, this is not surprising. For example, in HAST testing at 130°C, the environment at the chip surface is changing during the test time, and a stable environment is not reached until 24 h; the median failure time of the samples in the data varied from 18 h to 400 h with 60 per cent below 85 h. Some corrosion may well start before the saturation.

As a result it is concluded that with present product, the total test time gives the best statistical representation of the product for life extrapolation to any other environmental condition.

APPLICATION OF RESULTS

The first tool for controlling the median life at low stress is to establish the median life required at that stress. Determining the acceleration factor allows one to establish the median life required at a test stress in the following formal way:

1. Determine the expected operating life, the maximum failure rate and the average field use condition T/RH.
2. Establish a median life for the components, t_m, to provide a failure rate that is below the maximum allowed.
3. Establish a life-testing requirement to ensure a life that is long enough in the application using a low percentage of the allowable failures to control the critical part of the distribution.

This procedure is simplified by the fact that all humidity tests on at least recent products have shown a typical standard deviation (s) range from 0·25 to 0·5 (as the natural logarithm of the ratio of the t_m to $t_{0\cdot 16}$). The effect of this 'tight' distribution is that the failure rate does not gradually rise to its maximum value but is quite low until time approaches $0\cdot 1t_m$, when it goes up very rapidly (see also Reference 30). Hence, in the absence of freak failures, there is a long 'failure-free' period before the failure rate increases relatively rapidly. One must remember, of course, that we are talking about field use times of more than 10^5 h, so that the t_m of interest may well be in the order of 10^6 or 10^7 h. Figure 10 shows the demonstrated failure rate at 20 and 40 years as a function of failure-free test time (survival time) at 85/85 when $\sigma = 0\cdot 5$.

In the case that there is a power dissipation during field use the chip temperature will increase and the humidity density will decrease at the chip surface. A power dissipation P will increase the chip temperature by PR_{th}°C, where R_{th} is the chip thermal resistance. The reduced water density close to the chip may be modelled as an effective RH_c if the surrounding RH in the test chamber is RH_T

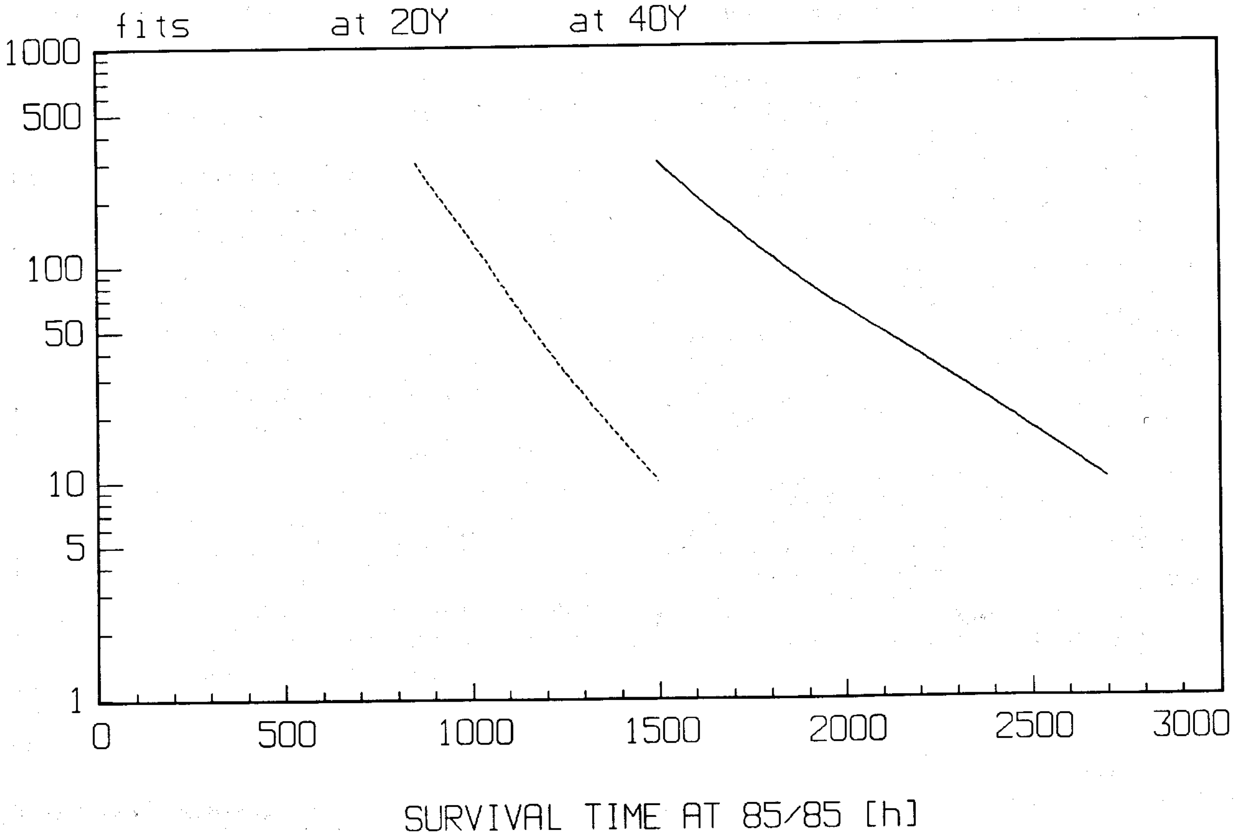

Figure 10. Demonstrated maximum failure rate at 20 and 40 years vs failure-free test time at 85/85

$$\mathrm{RH_c} = \mathrm{RH}_T \exp\left[5235\left(\frac{1}{273+T+PR_{\mathrm{th}}} - \frac{1}{273+T}\right)\right] \tag{4}$$

It is important to point out that one has to do the same calculation also for the accelerated moisture test. Figure 11 shows how the required test time at 85/85 is reduced as the operational internal heating is increased in the application, assuming that the device can be tested at very low power dissipation (as CMOS in a static condition). For a chip that has a temperature increase of +10°C in usage the required test time at 85/85 drops to about 600 h if power dissipation during the test can be neglected. For modern high-quality plastic packaging this should not be difficult to meet.

LIFETIME TEST

If the life requirement is 40 years, 10 fits due to humidity will be obtained at 40 years if the median life t_m is 200 years;[16] 100 fits will be reached if t_m is only 120 years. At an application of 35°C/60 percent RH 200 years is equivalent to a t_m of 5411 h at 85/85. With further acceleration into the HAST testing region, the t_m requirements are as in Table II.

Table II

Test condition	t_m, h
130/85	201
130/90	178
140/85	107
140/90	91

With $\sigma = 0{\cdot}5$ the time to 5 per cent failures is down from the t_m by a factor of 2·3, so the test time for that requirement could be 40 h at 140/90 testing. A way to control statistically the failure level requirement is to use the LTPD (lot tolerance percentage defective) table, which states that the given sample size and the number of defects allowed will ensure that the lot from which the sample was taken has only a 10 per cent chance of having a higher percentage of failure. A requirement of 5 per cent LTPD would also provide some protection against any significant level of freaks, and could be done with samples of $n = 77$, $c = 1$ or $n = 105$, $c = 2$. Finally, it would be desirable for some portion of the test samples to be continued until the median life is confirmed, together with σ, the standard deviation of the distribution.

Table III gives test times necessary to verify different failure rates due to humidity with a sample of 77/1. The test can also be used to qualify against early failures. The 85/85-data in Table III is also shown in Figure 10.

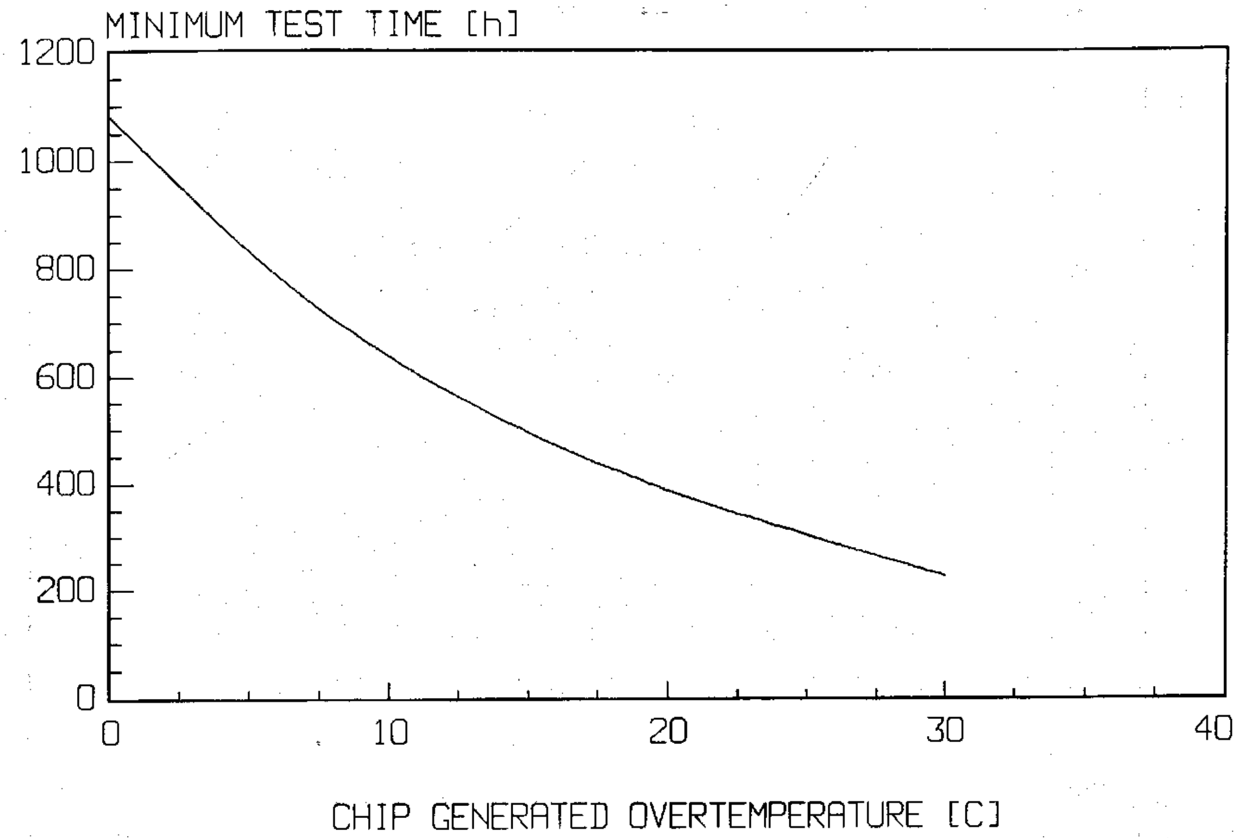

Figure 11. Minimum test time at 85/85 with low power dissipation to simulate 40 years at 35/60 versus self heating during field use

EARLY FAILURE LEVELS

A quality monitoring procedure generally calls for a short test that can be performed within a few days or even shorter. Passivation integrity tests may be seen as a wafer level reliability test related to corrosion resistance. A HAST at 130/85/*B* (*B* denoting nominal bias) for 48 h could be used as a quality monitoring procedure. Failures that are found in this test represent early failures and give information on assembly process quality, especially related to the adherence between plastic and the die or the quality of the glassivation layer. As the moisture diffusion time to the die may be of the order of 24 h for a dual-in-line package one should not normally expect corrosion during the test. A moisture test that might be regarded as non-destructive should not be longer than about half the time to reach 50 per cent of saturation. It is also important to avoid external damage during such a procedure.

A recommended quality monitoring procedure would thus be a weekly HAST test at 130/85/*B* for 48 h on 76 units. If no failures are found this corresponds to acceptance at an LTPD of 3 per cent. As the time passes the early failure level will soon be quantified.

An important part of any measure of early failure levels, as with any test failures, is a failure analysis, to establish the type of aberrations in assembly, lead treatment, control of epoxy cleanliness and flow characteristics, or any other controllable feature which contributed to a failure. If this information can be gathered as part of an ongoing program, data can quickly develop to provide better monitoring procedures and long-term failure rates.

Table III. Minimum test time to assure less-than-specified failure rates at use condition 35/60

Failure rate	at 40 y	at 20 y	at 40 y	at 20 y
(fits)	(h)	(h)	(h)	(h)
Test:	85/85		130/85	
300	1300	750	48	29
100	1600	900	58	35
30	2000	1110	74	42
10	2350	1300	91	50

CONCLUSIONS

1. The relationship between HAST conditions and the normal 85°C/85 per cent RH testing is sufficiently demonstrated that HAST testing should replace the present 85/85 testing, in order to reduce testing time and improve feedback as well as shipment times.
2. Moisture life extrapolation from 85/85 can be done by

$$A = (85/\mathrm{RH})^3\exp(10{,}444[1/(T+273)-1/358]$$

where T is in °C and RH in per cent.

3. The moisture ingress time has been calculated for a PDIP indicating delays before HAST test conditions stabilise. The delay should be considered when evaluating very short HAST tests.
4. The life of ICs made with high standards of cleanliness and epoxy purity, as now available, seems to be long enough for most indoor applications taking into account the new acceleration factors and recent advances in materials and wafer manufacturing.
5. Standard sample sizes and minimum $t_{5\%}$ life-test times have been provided for long-life telecommunications use for the case of an average use condition of 35°C and 60 per cent RH that is relevant to heated indoor premises according to Ericsson standard.[31]
6. The effect of internal power dissipation has been obtained, showing that devices having internal heating at uses of more than 10°C may be qualified in less than 600 h at 85/85 if power dissipation in the test can be low.

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Örjan Hallberg received an M.Sc. degree in Electrical Engineering in 1966 from Chalmers' University of Technology, Gothenburg, Sweden. He then joined the Swedish Telecommunications Administration, working with component evaluation and standardization. Between 1971 and 1981 he was managing the quality and reliability evaluations of electronic components within ELLEMTEL. Between 1981 and 1987 he worked as quality manager within RIFA AB. Since 1987 he has been with Ericsson Telecom AB, being responsible for qualification and vendor assessment activities.

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D. Stewart Peck was born in Grand Rapids, Michigan on 19 October 1918. He received the B.S. (E.E.) and M.S. (E.E.) degrees from the University of Michigan in 1939 and 1940, with membership in Tau Beta Pi, Eta Kappa Nu, Phi Kappa Phi and Sigma Xi.

He was involved in reliability studies for transistor applications as early as 1955, and in 1961–1962 was responsible for the selection of all components for the Telstar satellite programme, including selection of transistors for high-dosage ionizing-radiation environment for Telstar II.

He established reliability control procedures for transistors for the Nike-Zeus ABM systems, including the computer and the MSR and PAR radars, and for the first electronic switching centres for the Bell System.

He established the pattern for life-test control of reliability of semiconductor devices purchased for Bell System use. Published papers include the first definitive work on temperature acceleration in the early 1960s, with major papers later on life distributions, failure rate predictions, the special recognition of infant mortality failures, and handling of field failure data, using a major variant of the Duane plot.