CAN BURN-IN SCREEN WEAROUT MECHANISMS?: RELIABILITY MODELING OF DEFECTIVE SUBPOPULATIONS - A CASE STUDY

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Abstract

We often encounter reliability situations associated with defective subpopulations. Consider a total of n operating units. Suppose only m of these units, where $m \leq n$, are susceptible to failure, because the conditions necessary to initiate failure are not present in the remaining $n - m$ units. For example, only the m units contain a type of defect that induces failure. Then, m/n is the maximum fraction failure observable for the mechanism under consideration.

If only a fraction of units can eventually fail, analysis done assuming all units are susceptible to failure is generally inappropriate and may be misleading. We discuss procedures to model defective subpopulations and present a case study involving mobile ionic contamination in integrated circuits. We show that burn-in may be effective in screening some wearout mechanisms associated with defective subpopulations.

Introduction

Data from reliability experiments is generally analyzed under the assumption that all units under stress are susceptible to failure for a specific mechanism. Yet, in many cases, failures occur that are caused by defects existing in only a fraction of the devices under test. Units with the potential for failure are referred to as mortals. Those units that do not have the fatal flaw never fail for the defect related mechanism and are called immortals.

This situation has been considered in the literature [1]. However, application of these ideas, while basically simple, does not appear to be widely practiced among reliability investigators.

The model for the distribution of failure times for the total, mixed population of mortals and immortals can be written as

$$\text{CDF} = (\text{fraction mortals}) \times \text{CDF(mortals)},$$

where CDF is the cumulative distribution function of failure times for all units. For example, suppose 20% of stressed units contain a defect leading to failure, and the mortal life distribution has a median time to failure T_{50} of 1,000 hours. Then, at 1,000 hours, the expectation for the observed cumulative percent fallout for the total sample will be approximately 10%. The maximum expected fallout for the defect induced failure mechanism will be 20%.

If the data is analyzed without considering the presence of defective subpopulations, then the conclusions may be misleading since the observed cumulative percent fallout does not provide a direct estimate of the CDF for the mortals. Incorrect analysis using probability plotting, for example, may lead to plots which do not appear linear, and consequently, fits to the data may be poor and cause inaccurate field projections.

In this paper we present a specific industrial reliability study involving mobile ionic contamination of integrated circuits. We conduct experiments to investigate the reliability implications for field usage. We verify the existence of defective subpopulations. We determine the failure distribution for the failure mechanism. We calculate an activation energy and develop a model for expected field behavior. We check our models for goodness of fit. We generate curves that allow any product user to project expected field behavior based on historical performance.

This investigation illustrates several important principles of designing and analyzing an experiment to determine if defective subpopulations exist. We also address some previously questioned issues concerning spontaneous recovery of failures and the results of different bake (time and temperature) conditions on healing failures.

An intriguing and surprising consequence of this study is the possible application of burn-in to screen out potential failure mechanisms associated with defective subpopulations, even if those mechanisms have a constant or increasing (wearout) failure rate.

Case Study

It is routine practice among integrated circuit manufacturers to conduct reliability testing periodically on actual products. In the case that generated this study, one of the burn-in monitors revealed a high fallout level on a lot consisting of a specific type of a bipolar integrated circuit. The burn-in results after 168 hours of static stressing at 125°C ambient showed over 50% of the devices rejected. The units fully recovered after a bake at 150°C for 24 hours. The failure cause was traced to sodium contamination of some wafers due to a combination of factors. Specifically, a glass bead (the source of the sodium) blast procedure was employed to remove excess metal films from platens used for metal deposition. In this instance, the platens subsequently received a marginal cleaning process and then an insufficient initial metal coating. The preclean sputter etch operation prior to deposition in the same chamber depleted some of the initial coating, thereby allowing sodium to penetrate the thinned metal film and deposit on wafers. Subsequent wafer runs were less affected, because of the increased coating thickness on the platen from the deposition process itself.

Since typically only a sample of lots are run through burn-in evaluation, other possibly defective lots of this product were already in early field usage. After proper notification to these customers, the concern was to estimate the potential reliability exposure for product installed in the field. Because units from the untested lots were not available, we designed a reliability study to develop a model that would allow the assessment of future risk from present performance.

Reliability Design

One of the difficulties in conducting reliability studies is the normally scarce number of failures for analysis. However, in this situation, we were fortunate (a mixed blessing!) to have a lot with over 50% failures for experimental material. There were several purposes for this investigation. The objectives were to determine:

1. The appropriateness of modeling based on defective subpopulations (mortals versus immortals).
2. The applicable failure distributions (for example, lognormal) and the parameters.
3. The presence of true acceleration [1].
4. The activation energy for calculating acceleration factors.
5. The recovery kinetics associated with bake recoverable failures.

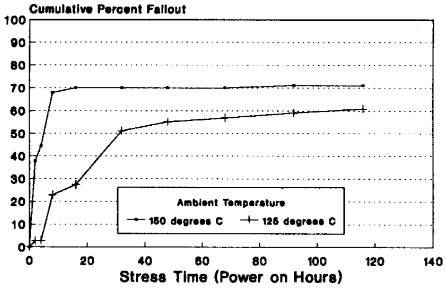
We were able to obtain 299 units from the affected lot. To determine the activation energy, two temperatures were selected. Following appropriate statistical procedures to ensure minimum variation of estimated parameters [2], we decided to stress 179 units at 125^{o}C and 90 units at 150^{o}C. We retained 30 units for control, which would be kept at room temperature but tested along with the stressed units at every readout. Since we wanted to determine the distributions and parameters as accurately as practical, frequent readouts were specified; the times were 2, 4, 8, 16, 32, 48, 68, 92, and 116 hours.

The modeling procedures involved analyzing cumulative percent failures versus time (the empirical CDF's) using both linear and probability plots. For the stress cells, the fraction of mortals for each temperature could be estimated by the plot value that the cumulative percent fallout approached asymptotically. Since the units had been allocated randomly to each temperature, it was important to verify also that no statistically significant difference occurred between the mortal fractions observed at the two temperatures. Based on the reduced sample size of mortals alone, the lognormal probability plots of cumulative percent fallout at both temperatures provided a check for linearity and equality of slopes. We also used statistical software to confirm graphical observations and provide confidence bounds on parameter estimates.

Results

The linear plot of the cumulative percent fallout versus time for the two temperatures is shown in Figure 1. No rejects occurred among the control units. We see that the 150^{o}C cell generated failures rapidly and reached a saturation point near 70% fallout in under 20 hours. The 125^{o}C cell showed more gradual fallout, crossing the 60% point at the 116 hours readout but still slowly increasing.

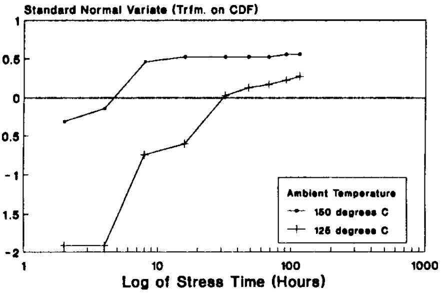
Figure 1. Linear Plot of Empirical CDF
All Units



Sample Sizes: 150oC = 90; 125oC = 179

The lognormal probability plot in Figure 2. indicates non-linear behavior and considerable differences in possible slopes visualized by eye. The evidence was strong that defective subpopulations were present. In fact, the level of mortals could be estimated as approximately 71% in the high temperature cell and about 63% in the low temperature cell. The difference in mortal fractions was not statistically significant, and as expected, could be ascribed to chance from the initial allocation of units.

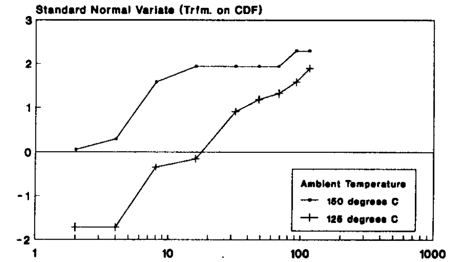
Figure 2. Lognormal Probability Plot
All Units Considered Susceptible to Fail



Sample Sizes: 150oC = 90; 125oC = 179

Thus, we concluded that there were 64 defective units under stress at 150^{o}C and similarly 113 at 125^{o}C. Creating a probability plot for just the mortals, we obtained Figure 3. The data appears linear and the slopes seem approximately equal, indicating true acceleration.

Figure 3. Lognormal Probability Plot
Mortals Only



Mortal Sample Sizes: 150oC=64; 125oC=113

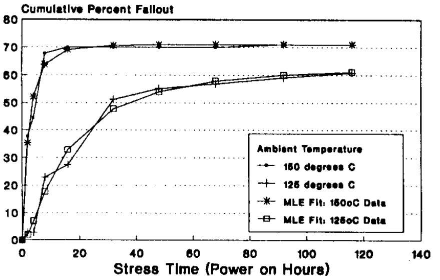
To check the validity of the graphical results, we performed maximum likelihood analysis using reliability analysis software for the lognormal distribution. The lognormal distribution is characterized by two parameters: the median (T_{50}) and the shape parameter (sigma), which is the standard deviation of the logarithms of failure times. The maximum likelihood analysis allowed us to estimate the median life T_{50} and sigma for each cell and test for equality of sigmas between the two temperature cells. Statistical hypothesis testing procedures verified the equality of sigma's between the cells, and so a single, pooled sigma was estimated. Table 1 shows the program output.

Table 1. Maximum Likelihood Estimates
(Confidence Bounds at 90%)

Cell	T_{50}	Sigma	T_{50} Low	T_{50} High	Sigma Low	Sigma High
125°C	15.08	1.09	12.68	17.94	.972	1.207
150°C	2.02	1.09	1.56	2.63	.972	1.207

The results showed T_{50}'s of 2.02 hours and 15.08 hours for the 150°C and 125°C cells, respectively, and a common sigma of 1.09. A check of the model fit against the data is shown in Figure 4. We were pleased with the goodness of fit.

Figure 4. Linear Plot of Model Fit
Empirical CDF and MLE Estimates



Sample Sizes: 150oC = 90; 125oC = 179

Projection to Field Conditions

The acceleration factor (AF) is defined [1] as the ratio of equivalent CDF percentiles between two stress cells. Typically, the 50th percentile is used and thus,

$$AF = \text{ the ratio of } T_{50}\text{'s.}$$

The acceleration statistics are developed by first estimating the acceleration factor between the two cells; here, $AF = 15.08/2.02 = 7.465$. The activation energy ΔH is found from the following equation [1] based on the Arrhenius model for thermal activation:

$$\Delta H = k\left[\ln\left[\frac{T_{50_{125}}}{T_{50_{150}}}\right]\right]\left(\frac{1}{T_1}-\frac{1}{T_2}\right)^{-1}$$

$$\Delta H = k[\ln(AF)]\left(\frac{1}{T_1}-\frac{1}{T_2}\right)^{-1}$$

where T_i, $i = 1,2$, is the junction temperature in degrees Kelvin and k is Boltzmann's constant (8.617×10^{-5} eV/°K). In this case, the junction temperatures of the devices under stress were approximately 35°C above ambient, and the acceleration factor lead to an estimated activation energy of 1.375 eV.

Therefore, under true acceleration, the field T_{50}, based on the use junction temperature of 55°C ambient calculates to: T_{50}(field) = 18,288 hours. Using the estimated field T_{50}, and the best estimate of sigma = 1.09, we can now project the expected lognormal distribution of mortals in use. However, one element is missing and that is the actual fraction of mortals in any given field installation.

User Data

The model for field fallout is:

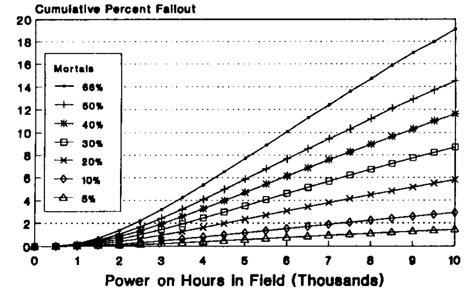
CDF(field) = (fraction of mortals) x CDF(mortals).

It is possible to generate a series of curves for the field CDF by assigning various values to the mortal fractions in combination with the CDF for mortals. If the product user can provide a measure of the observed cumulative percent fallout to date, then the matching of the field performance to a specific curve in the series would allow estimation of the future fallout. Such a series of curves appear as Figure 5. For example, if the customer has observed 20 returns from approximately 1,000 units (2%) installed in the field for roughly 7,000 hours, then from Figure 5, we estimate the mortal fraction as 10% and expect future behavior to follow the second curve from the bottom.

Bake Recoverable Kinetics

It was noted that failed units remained rejects after unbiased storage of 72 hours at room ambient. No spontaneous healing occurred. Similarly, we learned that unbiased baking at 150°C for a half hour caused the devices to fully recover. Thus, 24 hour bakes may be excessive to return failed units to operation.

Figure 5. Projection to Field Use
Various Percents of Mortals



Ambient Temperature: 55 deg C

Screening a Wearout Mechanism

If only a subpopulation of manufactured units contain a defect and consequently are mortal for a specific failure mechanism, a burn-in may cause the mortals to be culled out. The remaining product would be essentially free of defects related to that failure mechanism. However, sufficient acceleration is required to screen out the failures, which may have any failure rate characteristic: decreasing, constant, or increasing. Thus, surprisingly, it may be possible to screen wearout mechanisms associated with defective subpopulations.

Conclusions

We have illustrated the design and analysis of an experiment involving a defective subpopulation of mortals. We have used an actual case study to estimate the expected field behavior for a specific failure mode. We believe the procedures discussed have wide applicability to reliability evaluations.

[1] P. B. Tobias and D.C. Trindade, ***Applied Reliability***, New York: Van Nostrand Reinhold Company Inc., 1986
[2] T. J. Kielpinski and W. Nelson, "Optimum censored accelerated life-tests for the normal and lognormal life distributions," ***IEEE Transactions on Reliability***, 1975, R-24(5):310-320.

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