Modeling and Adapting Production Environmental Stress Testing at Alcatel-Lucent

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1.0 Introduction

In this article, we describe the PSEST process and the offline analysis conducted at Alcatel-Lucent. Some of the key characteristics and parameters of the test are described. The analytical process is based on two types of regression model that link a dependent variable (the log of time to failure in each dwell, or the log of the number failed in each dwell) to independent variables like temperature and age. These two types of regression are known as Weibull Regression [1] and Poisson Regression [2]. Using the estimated regression coefficients, expressions for the probability distribution of a unit under test can be written down and used to optimize the test duration.

2.0 Background

Environmental stress tests (EST) are commonly applied during the design and manufacture of telecommunications and electronic equipment to screen for design and manufacturing defects. In these processes, environmental stresses are applied to the units under test. Design EST (DEST) usually occurs during the product development process, with the objective of correcting design flaws, thereby 'ruggedizing' the hardware. Production Sampling EST (PSEST) is typically used as an in-line manufacturing check, often on a sampling basis, to precipitate and detect latent process-related defects, thereby eliminating so-called infant mortality failures. It also provides early information on field performance and information on design improvement opportunities. ALU conducts DEST and PSEST procedures on network products, whether the network is optical, copper or wireless based

It should be emphasized that ALU sees PSEST as the second part of a two-stage activity, with DEST as an essential preceding activity. The company is a committed supporter of DEST, of which Highly Accelerated Life Testing (HALT) is a major part [3]. The production analogue of HALT is Highly Accelerated Stress Screening (HASS). While HALT has become a common activity in the design phase of most electronic products, HASS is still rarely employed in manufacturing test.

At a time when most product manufacture is outsourced to large contractors, ALU found that few of these contractors have sufficient capacity to perform HASS in medium to high volume production on a continuous basis. Because of the lack of economies of scale, it is difficult to justify employing HASS unless the product is of very small dimensions or low volume.

Companies which already use traditional chambers with mechanical refrigeration may also be unwilling to make the large investment required in HASS chambers, which require liquid nitrogen cooling for rapid transitions and have high running costs. On the other hand, HALT activities during design can be scheduled and performed conveniently by a contractor with the required specialist equipment, such as Anecto (http://www.anecto.com/).

ALU has continued to perform PSEST within the parameters of the older style of testing. While this means a lesser level of stress applied to production packs, the company has found that, if accompanied by effective analysis, PSEST can be just as successful as HASS in the long term..

3.0 PSEST Programs at ALU

ALU designs and manufactures many types of telecommunications products. The products covered here are the circuit packs installed in customized cabinets to make up a network infrastructure. Circuit packs consist of at least one Printed Wiring Board (PWB) with mounted electronic components attached by means of Surface Mount (SM) or Plated Through-Hole (PTH) technologies. In size, packs may be a few square inches in size, or up to two square feet, and in weight from a few grams to a few kilograms. Packs may be installed in backplanes or boxes for home, curbside, remote countryside or Central Office use in customer applications.

PSEST is carried out after initial test and before final test. Failed units are repaired and retested from the start of the test. Upon completing the full duration of the test failure-free, the packs are shipped to customers. In early product life there may be emphasis on defect screening, but information on product performance is also used for design improvement.

Some of these circuit packs are assembled and tested in ALU's own factories; others are assembled and tested by subcontractors. Not all packs undergo PSEST. Much of the diversity in manufacturing and testing is due to the succession of company takeovers in the late 1990's. The circuit packs are classified according to the level of temperature cycling stress applied during PSEST:

- High. Packs that are installed outdoors which are placed into an environment temperature cycled between low temperatures such as -40C or -20C and high temperatures such as 60C.
- Medium. Packs that are installed in Central Office environments, and which are temperature cycled between low temperatures such as -5C and 0C and high temperatures such as 50C.
- Low. Some central office packs receive only an elevated temperature or room ambient burn-in. This article will not deal in detail with these pack types.

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Random Vibration does not form part of PSEST testing but does form an important part of the DEST suite of tests.

Packs are mounted in environmental chambers with temperature controlled by mechanical cooling and heating equipment. Packs are mounted is a fashion close to customer installations e.g. using special racks that duplicate backplane mounting or box installation. Most packs are monitored continuously by software during PSEST, some with their own self-test. However, for some packs, power is switched off during temperature changes ("ramps'') and switched on when the temperature is constant ("dwells'').

When the product is new, the test setup is designed to ensure a roughly equal temperature rise and fall for every pack to ensure each receives approximately equal stresses. The setup remains the same for the product's entire life cycle. To keep a constant thermal mass in the chamber, a roughly homogeneous temperature is maintained among the packs. For maximum efficiency, the chamber is generally full during testing.

The circuit pack in the example of this paper is the control pack of an outdoor-installed Asymmetric Digital Subscriber Line (ADSL) product. The test in this case was an 8-hour test, with an initial 0.5hr (30 min.) period at 25C, followed by 10 cold and hot dwells at -20C and 65C of 0.31hr (18.6 min.) duration respectively. An outline of the temperature cycle is shown in Figure 1.

Troubleshooting and repairs are carried out in-house by repair technicians. The next level of hardware analysis if carried out by engineers who monitor the repair data continuously and gather information that may provide opportunity for product improvement. In this particular case, a component was sent for further analysis by the supplier and subsequently replaced by a similar, more reliable device. Early in the pack life cycle, design engineering participates in this activity, and may take samples of failing packs for further analysis.

It is important to emphasize that PSEST refers to production 100% testing, not laboratory testing, which comes under the DEST heading in our parlance. In our experience, if PSEST and DEST have been effective, then the defects seen in customer service should be different from those seen in design and production. We find it is impossible to duplicate all the conditions on customer use, so we recommend investigation of field returns as an important part of any reliability program.

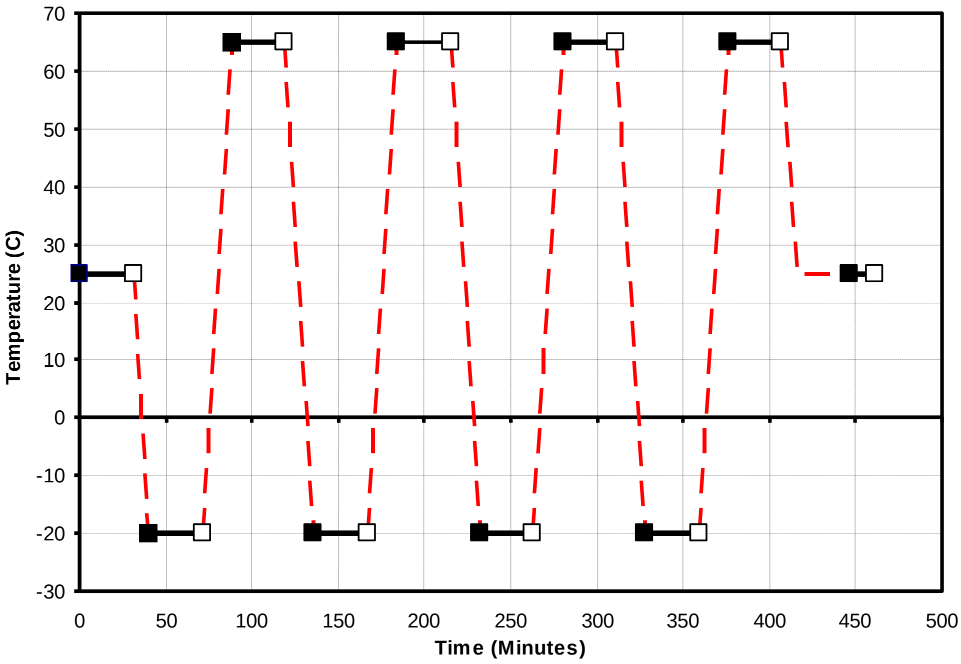

Figure 1: An outline of the temperature cycle of the example pack. Black squares and the full line indicate when the product is switched on; white squares and broken lines when it is turned off.

4.0 The Risk Set Model

The key to a good understanding of PSEST is the concept of the "risk set'', which captures the dynamics of the test. This term did not originate here [5], and has been used before in slightly different forms [6].

The risk set consists of a subset of the population with weaknesses that have arisen from the manufacturing process. Examples are weak solder joints, bad assembly, or loose hardware. These weaknesses are in addition to defects which may have arisen from components or from design, to which all the units in the general population are susceptible. In a single short test, units with manufacturing weaknesses may be indistinguishable from the general population, but under environmental acceleration, the latent defects become actual failures and they are detected by the test software.

It is possible for a member of the risk set to (apparently) re-join the general population if the environmental acceleration is insufficient to precipitate it all the way to failure. This could happen if the test is ended prematurely. Sometimes such units are detected in a subsequent test, but they can also survive to reach the field.

Note also that the risk set for PSEST contains only a subset of the general population affected by miscellaneous manufacturing-related defects. The general population also contains problems relating to design or components that are undetectable in PSEST, and may also reach the customer.

Hence it is important to have both design and manufacturing controls, of which DEST and PSEST are key features.

5.0 Development of the model

It is clear from the foregoing that the risk set should diminish over the duration of the test. Otherwise, it would be constant or increasing, which negates the concept of a limited risk set and suggests an epidemic condition, generally beyond the scope of PSEST. It is true that PSEST sometimes detects epidemic conditions before they reach the field, but that is not its prime purpose. Other controls such as adequate qualification of design and component changes are recommended in preference.

For simplicity, assume only packs with a single defect type are in the Risk Set. Then the failure function in PSEST is:

$$F(t \mid PSEST) = qF_{RS}(t \mid PSEST) \qquad (1)$$

where q is the proportion of the defect in the population ($0<q<1$), $F_{RS}(.)$ is the cumulative failure function associated with the defect, and t is a time variable.

An elaboration of this simple assumption is that the Risk Set is composed of packs with M defect types. A simple model that corresponds to the model of Section 4.0 is given by:

$$F(t \mid PSEST) = \sum_{i=1}^{M} q_i F_{RSi}(t \mid PSEST). \qquad (2)$$

where q_i is the proportion of the ith defect type in the population ($0<q_i<1$), $F_{RSi}(.)$ is the cumulative failure function of the ith defect type, and t is a time variable.

The assumption here is that no packs fails with more than a single failure. This is reasonable when the total percentage of failed packs is less that 10%. i.e. the probability of a pack with two distinct defects is << 0.01. This is true in the case of Alcatel-Lucent packs. The model can be fitted to each defect type, and the failure function of Equation (2) constructed accordingly

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6.0 Fitting a parametric model to each section.

The model chosen was a Weibull regression model [7] with the regression equation:

$$\begin{aligned} Ln(t_p \mid x, \beta) &= \beta_0 + \underline{\beta}.\underline{x}' + \sigma \Phi^{-1}(p) \\ &= \beta_0 + \sum_{j=1}^{s} \beta_j x_j + \sigma \Phi^{-1}(p) \end{aligned} \qquad (3)$$

Here, t_p is the pth quantile, $\underline{x}$ is a vector of covariates [$x_1 \ldots x_s$], $\underline{\beta}$ is a vector of coefficients estimated from the data [$\beta_1 \ldots \beta_s$], β_0 is a parametric constant, and σ is a parameter of the Weibull distribution (=1/α, where α is the shape parameter) and $\Phi^{-1}(p)$ is the p quantile of the Weibull distribution = Ln[Ln(1-p)]. The regression coefficients ($\underline{\beta}$, β_0,σ) are estimated from the data using the methods of Weibull regression described in [1].

The PSEST data are broken into separate and sequential sections, the survivors from the preceding section forming the units under test for the incoming section. Thus for *K* sections of testing (ramps, dwells etc.), the data is treated as coming from *K* distinct tests with a regression parameter that captures the age of the unit going into the test. The regression parameter captures the difference between the tests. It can be thought of as a growth parameter because at each successive test, the packs are more “resistant” to the stresses.

For each pack, information is extracted from the records database regarding test history. For each section of the test, a pack is recorded as having failed at a certain time in the section, or has a censoring time at the end of the section. For each section, the temperature and the time elapsed to the start of the section, which we call the *age* variable, are known.

For the *k*th section, the times to failure are given by t_k and the covariate values given in the *k*th section by x_k:

$$Ln(t_{kp} \mid x, \beta) = \beta_0 + \sum_{j=1}^{s} \beta_j x_{kj} + \sigma \Phi^{-1}(p) \qquad (4)$$

After some experimentation, the covariates chosen were

- Absolute Temperature, suitably transformed to give figures in the region [-10,10],
- Ramp/ Dwell, a categorical variable = 0 for a dwell and =1 for a ramp,
- Age, being the time survived before entering the current section.

Using this structure, the data was submitted by the survreg() function of the package **survival** [8] in the freeware statistical software R[9], which provided estimates of the coefficients $\underline{\beta}$, β_0 and σ

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7.0 Example

A typical pack has a PSEST of 8 hours duration, during which it experiences 10 temperature dwells at hot and cold. Testing is carried out only during the dwells so no data is available on the ramps. Table 1 exhibits data from a sample of 717 packs.

Section No.(k)	a_k (hrs)	#Packs	Failure Times in Section	Temp	r_k
1	0.67	717	0.13. 0.22	25C	0.9972
2	1.47	715	0.12, 0.13, 0.15, 0.15, 0.15, 0.15, 0.17, 0.18, 0.2, 0.22, 0.22, 0.22, 0.23, 0.23, 0.3	-20C	0.9790
3	2.28	700	0.13, 0.15, 0.17, 0.27, 0.28	60C	0.9929
4	3.08	695	0.15, 0.15, 0.2, 0.25, 0.27	-20C	0.9928
5	3.88	690		60C	1
6	4.70	690	0.08, 0.1, 0.1	-20C	0.9927
7	5.50	687	0.03	60C	0.9985
8	6.32	686	0.07, 0.1, 0.15	-20C	0.9956
9	7.12	683		60C	1
10	7.93	683		-20C	1

Table 1 : Production Environmental Test data for 717 packs; a_k means the end of section k; r_k is the survival fraction in section k. These failures were classified as component failures (see Section 3.0).

For dwell k, the model is:

$$Ln(t_{pk}) = \beta_0 + \beta_1 \boldsymbol{Temp_k} + \beta_2 a_{k-1} + \sigma\, Ln[-Ln(1-p)] \qquad (5)$$

Temp is the temperature variable, suitably transformed:

$$\boldsymbol{Temp_k} = 10^8 \left\{ \frac{1}{273.16 + f} - \frac{1}{273.16 + c_k} \right\} \qquad (6)$$

Here, f is the temperature outside the chamber 9taken to be 25C), c_k the temperature inside in C during section k.

a_{k-1} is the endpoint of the previous dwell, or the "**age**" of the pack entering section k.

t_{pk} is the pth quantile in section k measured from the start of the section.

Data is presented in a form suitable for the **survreg** function in the R package **survival**. Each pack is coded as a distinct entry with the covariate values in each dwell with censoring code = 1 for a failure, and 0 for a passing pack.

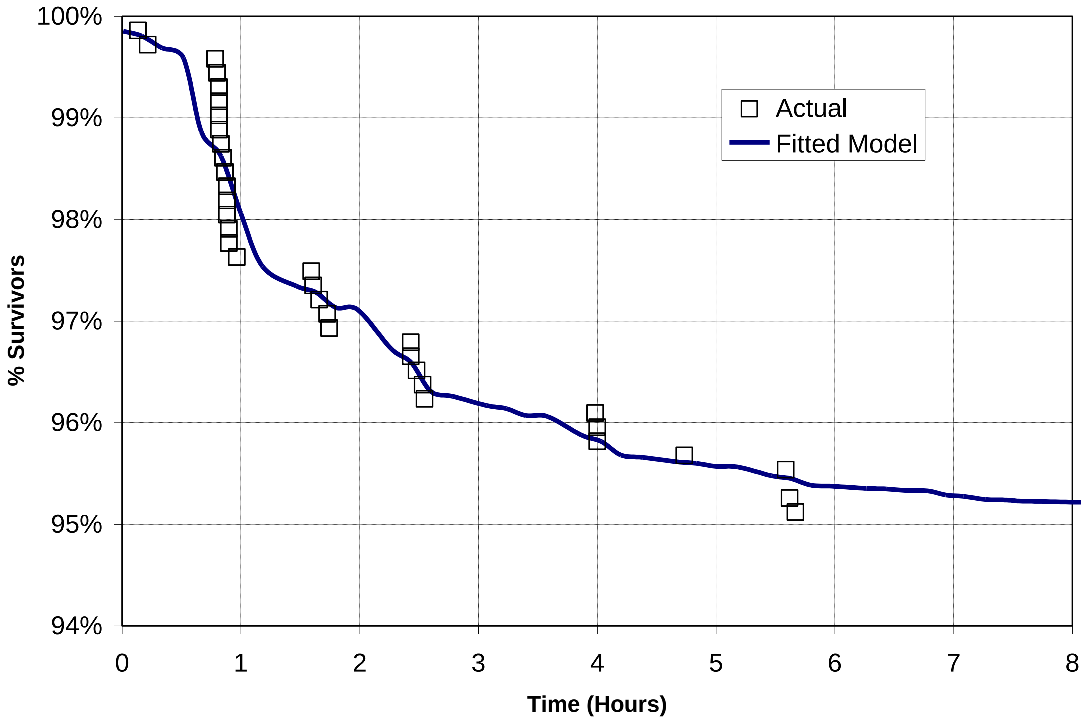
The coefficient values for this model are estimated as:

Coefficient	Estimate
β_0	9.9535
β_1	-0.0844
β_2	0.7303
σ	1.570

Note that the coefficient of **Temp** is negative as it tends to reduce time-to-failure, which the coefficient of **age** is positive as it tends to lengthen it.

The Weibull shape parameter, $\alpha=1/\sigma$, in this case equals 0.6369.

Figure 2: Reliability function of PSEST data and fitted model. The squares give the plot of the empirical failure function, plotted from the data. The full line is a plot of the fitted reliability function.



8.0 Simplification of the model

A simpler model investigated was based on Poisson Regression from the class of Generalized Linear Models [10]. In this model, the natural log of the failure count is linearly dependent on the covariates. In test section *k*,

$$\boldsymbol{log}(N_k) = \beta_{g0} + \beta_{g1}\boldsymbol{Temp_k} + \beta_{g2}a_{k-1} + \boldsymbol{log}(S_{k-1}D_k) \qquad (8)$$

N_k is the number of failures in section *k*.

S_{k-1} is the number of survivors from section *k-1*.

D_k is the length of section *k*.

The others are defined as in Equation (7).

Again, using the glm() function in R, the following estimates were obtained:

Coefficient	Estimate
βg_0	-5.0982
βg_1	0.0590
βg_2	-0.4328

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This model is simpler to handle as it only requires the results of each individual section of the test. Also, it is possible to show with some algebra that the models given by Equation (7) and Equation (8) are identical when *1-r_k* is small, and $\beta_{pi} = -\beta_{wi}\alpha$.

A further development of this model is apparent by putting $N_k / S_{k-1} = 1 - r_k \approx -\boldsymbol{log}(r_k), N_k > 0$. The Equation (8) can be written in the form:

$$\boldsymbol{log}[-\boldsymbol{log}(r_k)] = \boldsymbol{log(}D_k\boldsymbol{)} - \beta_{g2}D_k + \beta_{g0} + \beta_{g1}\boldsymbol{Temp} + \beta_{g2}a_k \quad (9)$$

This is a linear equation in the form $y = b_0 + b_1x_1 + b_2x_2$ with covariates temperature and time.

Using the data from Table 1, the following estimates were obtained from an ordinary least squares fit:

Coefficient	Estimate
βg_0	-5.3462
βg_1	0.0476
βg_2	-0.3122

These are close to the estimates obtained above, though the fit of the model is not as good, R^2 = 0.8342. However, this linear model is quite useful for exploratory analysis.

Further, Equation (9) can be adapted:

$$r_k = \boldsymbol{exp}\left[-\boldsymbol{exp}\left(\frac{a_k - \eta_k}{\delta}\right)\right] \quad (10)$$

Here, $\delta = 1/\beta_{g2}$, $\eta = -C - \beta_{g1}\boldsymbol{Temp}_k$, and $C = log(D_k) - \beta_{g2}D_k + \beta_{g0}$ from Equation (9).

This is the cumulative distribution function of a Extreme Value (or Gumbel) distribution. Therefore, as $k \to \infty, r_\infty \to 1$, which implies that eventually the units that have survived all preceding sections of the test, will survive with probability 1 in the test. This is the Risk Set model.

Equation (10) can be used to estimate *q* because the reliability at the end of section *k* is the multiple of the preceding reliabilities:

$$F(t \mid PSEST) = qF_{RS}(t \mid PSEST) = 1 - \prod_{i=1}^{k} r_i \text{ , where } t = a_k \qquad (11)$$

Therefore, using the estimates of r_k, the estimate of q is:

$$\hat{q} = 1 - \lim_{k \to \infty} \prod_{i=1}^{k} \hat{r}_k \qquad (12)$$

In the example we have used, the estimate is $\hat{q} \approx 5\%$. The limit for *R(.)* can be estimated graphically from Figure 2. Using the estimate $\hat{q} \approx 5\%$, the actual % failure is $33/717 = 0.46\%$, giving an estimate of escapes as *0.4%*.

9.0 A Simple Cost Model

If τ is the end of test, then the fraction of Risk Set escapes from test at time $t > \tau$ is given by $\Delta E(t) = qF_{RS}(t \mid t > \tau) - qF_{RS}(\tau \mid PSEST)$. If *w* is the end of the warranty period, then we can assume that $F_{RS}(w) = 1$ so that $\Delta E(w) = q[1 - F_{RS}(\tau \mid PSEST)]$

Let the non-Risk Set failures by given by $F_{NRS}(t), t > 0$, where $F_{NRS}(\tau) = 0$. Since a non-Risk Set defect can occur on any pack, the failure function in the field is:

$$F(t \mid Field) = [1 - F_{NRS}(t)]\Delta E(t) + F_{NRS}(t),\ t > \tau \qquad (13)$$

In particular, at the end of warranty:

$$F(w \mid Field) = [1 - F_{NRS}(w)]\Delta E(w) + F_{NRS}(w),\ w > \tau \qquad (14)$$

Then a model for the total cost of failure in test and warranty is given by:

$$TC(\tau) = AI(\tau) + B\tau + CqF(\tau \mid PSEST) + DF(w \mid Field) \qquad (15)$$

Here, *A* = Fixed Cost of Test, *B* =Variable Cost of Test per hour, *C* = Cost of an Internal Repair, *D* = Cost of a Warranty Repair and $I(\tau)=0$ when $\tau=0$, $I(\tau)=1$ otherwise. Equation (15) can be minimized to give an optimum length of PSEST. In this case, duration of 6 hours for PSEST was shown to be optimal.

10.0 Conclusions

The models described here essentially capture the transient period at the start of a product's lifetime when it is subject to weaknesses that have arisen from the manufacturing process. Problems that might arise in the longer term from intrinsic design, component weaknesses or extrinsic influences such as corrosion are best addressed by testing at the design stage.

Therefore, for longer term reliability tests, suitable acceleration models such as the Coffin-Manson model for the number of cycles to failure are better employed [11]. However, some initial studies have shown that the models described here are also applicable after the onset of wearout.

The models described in Sections 6 through 10 have been applied across a large sample of pack types. The results of this work have been of significant benefit to ALU for the management of PSEST, and have formed the basis for a rationalization of the process. Analytical modeling and cost modeling was included in all process and product reviews to ensure efficient testing.

PSEST is a significant process bottleneck, and the model ensures its continuing efficiency and effectiveness. The test can be shortened progressively as the product matures and yield improves, as is the norm.

Significant savings arise from faster throughput times, reduction in operator support, shorter queues and lower in-process inventory. Other savings are in power usage and maintenance costs.

From the definition of test escapes, $\Delta E(t)$, it is clear that test cannot be reduced without a small percentage increase in the shipment of packs that will fail prematurely in the field. Obviously, this is kept as small as possible. However, the small increase is usually offset by the gradual product improvement that comes from PSEST.

In 2006-07 alone, savings of the order of $5M were estimated from optimized PSEST, with minimal impact to field reliability. On top of that, the company has gained significant learning on the topic of production environmental testing:

10.1 Key Learning

(1) PSEST is a natural follow-on from a DEST/ HALT program.
(2) PSEST can ensure cost-effective detection and repair of early life failures which would otherwise occur at the customer site.
(3) Despite being often compared unfavorably to HASS, PSEST (i.e. with lower level stresses than HASS) is worth retaining as a manufacturing screen or sample check, provided it is accompanied by effective management and analysis.
(4) PSEST can adapt to changing circumstances; duration can be shortened; sampling
can be introduced; the test can be eliminated.

(5) The most successful PSEST operations use Temperature Cycling. Optimization is achieved by tailoring the number of temperature dwells to ensure a cost effective test.
(6) Management of PSEST is most effective with full cooperation of Managers, Test Engineers and Reliability Engineers.

10.2 Recommendations for a successful PSEST program

(1) Temperature Cycling with a temperature "delta" of at least 50C is recommended. This removes any distinction between types of temperature cycling mentioned in section 3. The stresses should be the maximum possible in the circumstances. They should not be based on expected field conditions.
(2) Make the temperature delta as large as possible, as large as the equipment can provide. It is acceptable to go outside the pack specification limits. In making these decisions, be guided by the DEST/ HALT experience, or at least with consult with someone who has experience of DEST & HALT.
(3) Maximize the number of cycles in the time available i.e. use the "best" rate of change the equipment can provide. If the rate of change is low, carry out at least two full cycles.
(4) Ensure the dwell time is sufficient to allow all the packs (at full chamber load) reach the maximum and minimum temperature, plus time to test all the packs.
(5) Ensure the chamber is characterized at full load using a chart recorder.
(6) Ensure a good data gathering system
(7) The software must capture the time to failure. This is essential for any assessment of PSEST effectiveness. The models used here demand at least the number of dwells (hot and cold) before failure.
(8) Ensure data on packs removed for repair are recorded and stored for retrieval.
(9) Knowing the types of defects captured is essential for a good program
   - Analyze/ compare defects with field failures. The Risk Set model implies that if the percentage fallout in PSEST is close to the estimated *q*, than the problem types seen in PEST should not be repeated in the field. This has been observed at ALU.
   - Start modeling when the process is stable i.e. yield stable, appreciable numbers of packs are in the fields without major problems. This may take up to a year to achieve.

(10)Repeat the analysis periodically and act according to its results.

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Biographies

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Simon Wilson is Professor of Statistics at Trinity College, Dublin. He received his PhD in Stochastic Modeling from George Washington University in 1993. His research interests are the use of Bayesian methods in reliability and other fields of science and engineering.

Shirish Kher is Technical Manager of Optics Reliability Group responsible for reliability of optical products in Alcatel-Lucent. He has a PhD in Engineering Mechanics from Pennsylvania State University. He has received multiple Bell Labs Presidents' Awards. Dr. Kher has wide-ranging interests and experience in the field, from reliability physics to network architecture and analysis.

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