A Multi-Stress Accelerated Life Tests Method for Smart Electricity Meter Based Upon the Life-Stress Model

Bangyan Qi, Yufeng Sun, Weiwei Hu, Xiaoxue Ding
School of Reliability and System Engineering
Beihang University
Beijing, China
bangyanqi@gmail.com

Abstract—**Current Accelerated Life Tests (ALT) mainly focuses on the single stress type of models. This article has delivered a type of ALT model named as the "Life-Stress Model", which is based upon the Weibull distribution and Peck's Temperature-Humidity Model. Also an actual ALT test on the DDZY33C-Z Smart Electricity Meter is performed to make a precise estimation of the Time Till Failure or TTF of the meter. This method has been proved to be efficient for the reason that it takes much less time and samples to make a life evaluation than other life testing methods. And it has guaranteed the result of the samples' life since a confidence level of 50% is given.**

Keywords—***ALT;Smar Meter;Weibull Distribution;Peck Model***

I. INTRODUCTION

The main principle of Accelerated Life Tests (ALT) is to urge the samples by increasing the environmental stress in a short term but without introducing any new kind of failure mechanism [1]. Samples are subjected to the higher levels of environmental stresses more quickly and thus reduce the cost and time needed for the tests. The results of the analysis of the failure data obtained at the stress levels are then extrapolated to normal levels. The type of environmental stress typically includes temperature stress, humidity stress, vibration stress, voltage stress and load stress, etc., or the combination of some of them. It is vital for the tests design to arrange the type and magnitude of the environmental stress applied in the tests [2]. This case becomes extraordinary obvious when it comes with some expensive smart electricity meter, say, the smart electricity meters. Usually it is out of possibility to have such a large amount of samples tested that it will strike the company's budget. Accordingly, we need a relatively reasonable and practical tests method which could reflect more failure information but at lower cost. The smart electricity meter is among the important equipments of the electricity grid, and has a very long operating life. Consequently it is necessary to find a way to apply the constant stress accelerated life tests to those meters in a relatively short period.

II. FAILURE MODES ANALYSIS

Most failures of smart electricity meter are caused by temperature stress and humidity stress. Since the meter is always fixated, the stress such as vibration should not be considered. Load stress actually exists in the normal operation environment of the meter, but its effect on the meters seems trivial as the meter is designed not to burden on so much loads. According to the result of the reliability enhancement tests before the formal ALT, the failures caused by temperature stress and humidity stress constitutes the majority and has taken up over 75% percent of all. Here is a typical failure mode meter measuring device classification based on a certain type of smart meters from the accelerated life test [3]. As follows:

TABLE I. FAILURE MODES OF A TYPICAL SMART ELECTRICITY METER

No.	Failure Modes Analysis		
	Failure Classification	***Label***	***Failure Depiction***
1	Communication	C	Communication between user/utility and meter e.g. payment token transfer, accessing meter registers, remote data exchange, input/output pulse, test output.
2	Measurement Processing	P	Measurement and processing e.g. signal capturing and processing, software execution.
3	Memory	M	Data storage by meter e.g. consumption register, credit register.
4	Indicating	I	User-interface indicating elements e.g. light emitting diodes (LED's), liquid crystal display (LCD), beeper/buzzer.
5	Enclosure	E	Meter housing, printed circuit board seating, LED light guides, LCD window, nameplate or cover.
6	Power Supply	P	Power supply to all functions excluding "Enclosure".

978-1-61284-666-8/11$26.00© 2011 IEEE

No.	Failure Modes Analysis		
	Failure Classification	***Label***	***Failure Depiction***
			Includes surge protection components.

The main purpose of classifying a failure mode by linking it to one function only is that the most obvious one should be selected by eliminating the other possibilities, which is of less important. This selection might be assisted by a detailed analysis of utility from the manufacturer of this type of smart electricity meter, or from the result of the previous reliability enhancement tests. If the failure can be linked to more than one function, it must be described as two or more failures and classified separately. Actually the failures of the DDZY33C-Z Smart Electricity Meter exposed in the reliability enhancement tests were mainly linked to three failure modes: Communications, Measurement Processing and Indicating. Furthermore, Humidity Stress became a dominant factor in the tests.

III. The Life-Stress Model Of Accelerated Life Tests

A. Weibull Distribution

The Weibull distribution is among the most commonly used distribution types in reliability engineering. Its main application includes modeling material strength, time to failure data of electronic and mechanical components, equipment or systems [4]. Hence it is introduced as the most appropriate model to describe the life characteristics of the smart electricity meter.

The Weibull probability density function of the time to failure is given as:

$$F(t) = 1 - e^{-(\frac{t-\gamma}{\eta})^{\beta}} \tag{1}$$

with $t \geq \gamma, \beta > 0, \eta > 0, -\infty < \gamma < +\infty$,where

- β is the shape meter;
- η is Weibull characteristic life or scale parameter;
- t is the operating time to failure in hours;
- γ is the location parameter in hours.

The data obtained in the ALT comes with a time to failure form. A Fit Weibull distribution test should be applied to make sure if the life characteristic of the sample population could be depicted by the Weibull distribution. There are some research have given the method of the fit of Weibull distribution [5] [6], while it is not in the realm of concentration in this paper.

B. Life-Stress Model

The Life-Stress model describes the relationship between the environmental stress applied to the testing samples and its life characteristics. As what is expatiated in the section Ⅱ, the temperature stress and humidity stress weigh heavily against other factors affecting the reliability behaviors of the meters. Accordingly, a model involving both temperature and humidity factors should be considered. The Peck's model is appropriate for both temperature stress and humidity stress driven ALT, or their combination. It's better to apply both temperature and humidity stress to samples because more stress involved could lead to more failures and shorter time-span needed to expose the weakness of the meter. In this case, the Peck's acceleration factor is:

$$AF = \left(\frac{RH_u}{RH_s}\right)^{-n} e^{\frac{E_a}{k}(\frac{1}{T_u}-\frac{1}{T_s})} \tag{2}$$

where

- RHu is the percent relative humidity at use conditions;
- RHs is the percent relative humidity at stress conditions;
- Tu is the temperature in K at use conditions;
- Ts is the temperature in K at stress conditions;
- k is the Boltzmann constant (8,617 × 10–5 eV/K);
- Ea is the activation energy in electron volts (Ea is in the range of 0,3 to 1,5, typically Ea = 0,9);
- n is a constant (n is between 1 and 12, typically n = 3)

In order to evaluate the degree of linearity of the model, at least 3 levels of stress should be adopted in one accelerated life test. From these levels, 3 combinations are made at which the test will be performed. These are denoted as TmaxRHmax, TmaxRHmin, TminRHmax. Ea and n are the two coefficients of the model. To allow the calculation of the acceleration factor parameters n and Ea, the least squares regression should be introduced [7]. And the Peck's acceleration factor has to be transformed into a linear form. Beginning with the equation (2) , we obtain:

$$\ln(AF) = -n\ln(\frac{RH_u}{RH_S}) + \frac{E_a}{k}(\frac{1}{T_u} - \frac{1}{T_s}) \tag{3}$$

According to equation(3), at the highest stress combination level, the acceleration factor equation defined by Tmax and RHmax is:

$$\ln(AF_{T\max RH\max}) = -n\ln(\frac{RH_u}{RH_{\max}}) + \frac{E_a}{k}(\frac{1}{T_u} - \frac{1}{T_{\max}}) \tag{4}$$

The acceleration factor equation at the stress combination level defined by T and RH is:

$$\ln(AF_{TRH}) = -n\ln(\frac{RH_u}{RH}) + \frac{E_a}{k}(\frac{1}{T_u} - \frac{1}{T}) \quad (5)$$

As

$$\frac{AF_{T\max RH\max}}{AF_{TRH}} = \frac{\eta_{TRH}}{\eta_{T\max RH\max}} \quad (6)$$

Finally we have:

$$\ln(\frac{\eta_{TRH}}{\eta_{T\max RH\max}}) = \ln\left(\frac{AF_{T\max RH\max}}{AF_{TRH}}\right) = -n\ln(\frac{RH}{RH_{\max}}) + \frac{E_a}{k}(\frac{1}{T} - \frac{1}{T_{\max}}) \quad (7)$$

Here equation (7) is the Life-Stress Model, which then could be written in the form of

$$C = nA + E_a B \quad (8)$$

with the values of C,A and B at each stress combination level represented in the following Table :

TABLE II. VALUES OF LIFE STRESS MODEL

Stress	Values of Life Stress Model		
	C	*A*	*B*
$T_{\max}$, $RH_{\min}$	$\ln(\frac{\eta_{T_{\max}RH_{\min}}}{\eta_{T_{\max}RH_{\max}}})$	$-\ln(\frac{RH_{\min}}{RH_{\max}})$	0
$T_{\min}$, $RH_{\max}$	$\ln(\frac{\eta_{T_{\min}RH_{\max}}}{\eta_{T_{\max}RH_{\max}}})$	0	$\frac{1}{k}(\frac{1}{T_{\min}} - \frac{1}{T_{\max}})$

According to the least squares regression principle, the best fitting straight line to these data is the straight line :

$$C = nA + E_a B \quad (9)$$

and the minimum function F is:

$$F = \sum_{i=1}^{N}(nX_i + E_a Y_i - Z_i)^n \quad (10)$$

where n=2. By solving the combination of equations:

$$\begin{cases} \frac{dF}{dn} = 0 \\ \frac{dF}{dE_a} = 0 \end{cases} \quad (11)$$

we have estimation of Ea:

$$E_a = -\frac{\sum_{i=1}^{N} B_i C_i \sum_{i=1}^{N} A_i^2 - \sum_{i=1}^{N} A_i C_i \sum_{i=1}^{N} A_i B_i}{(\sum_{i=1}^{N} A_i B_i)^2 - \sum_{i=1}^{N} A_i^2 \sum_{i=1}^{N} B_i^2} \quad (12)$$

and estimation of n:

$$\hat{n} = \frac{\sum_{i=1}^{N} A_i C_i - \sum_{i=1}^{N} A_i B_i}{\sum_{i=1}^{N} A_i^2} \quad (13)$$

here N=2.

IV. PRACTICAL INSTANCE

This article takes the constant stress accelerated life tests of the DDZY33C-Z Smart Electricity Meter as an example. The given normal temperature stress is 20°C (absolute temperature 293.17), and the humidity stress is 72%(as the usual average percent of relative humidity in most parts of north China). Through the analysis of this kind of meter's and its counterparts' failure mechanism, together with the results of several dependable try-tests, three different stress combination levels are determined, where 85°C-95% as Tmax-RHmax, 85°C-75% as Tmax-RHmin, 65°C-95% as Tmin-RHmax. Then the tests were deployed with 30 smart meters for each test. An online environment was built to assure the each meter was just under a normal operating condition. An automated recording equipment was responsible for testing the state of the target meter and recording all the potential failure information. Given a confidence level of 50%, the failure data obtained in the test were carefully treated using median ranks to make the unreliability estimates. If the some meter ceased in the test, the original rank needed to be adjusted, with the equation:

$$AdjRank = \frac{(\Pr eAdjRank - 1) + (n + 1)}{\operatorname{Re} vRank + 1} + n + 1 \quad (14)$$

Where AdjRank is the adjusted rank; PreAdjRank is the adjusted rank previous to the present rank, beginning with 0; n is the number of meters.

The failure times and their corresponding unreliability estimation of an independent failure mode exposed in the tests are represented through the TABLE Ⅲ to the TABLE Ⅴ. The column of "Adjusted Ranks" shows the adjusted ranks of the failure data. Column "TTF in hours" shows the time till failure of the samples in the form of hours. Column "F(TTF)" contains the estimation of the unreliability corresponding to each TTF, which derives from a rank table under the confidential level of 50%. The Column of "x" and "y" contains the parameters needed for Fit Weibull distribution, where

$$x = \ln(TTF) \quad (15)$$

and

$$y = \ln\{-\ln(1 - F(TTF))\} \quad (16)$$

Then a Fit Weibull distribution test is applied. This article has adopted a graphical method to evaluate the shape parameter and the scale parameter of the sample population. Figure1 to Figure 3 has shown the Weibull fit result of the three tests respectively. For each figure, the left subfigure represents the failure data obtained in the correspond test in a reference frame of TTF-F(TTF). And the right one represents the failure data transformed to fit the Weibull distribution and their regression line.

TABLE III. FAILURE DATA OF THE TMAX-RHMAX TEST

Adjusted Ranks	Failure Data of the Tmax-RHmax Test			
	TTF in hours	***F (TTF)***	***x***	***y***
1	6.05	0.0228	1.8001	-3.7695
2	8.05	0.0553	2.0857	-2.8667
3	42.85	0.0881	3.7577	-2.3835
4	46.57	0.121	3.841	-2.0482
5	50.33	0.154	3.9186	-1.7883

TABLE IV. FAILURE DATA OF THE TMAX-RHMIN TEST

Adjusted Ranks	Failure Data of the Tmax-RHmin Test			
	TTF in hours	***F(TTF)***	***x***	***y***
1	19.3	0.0228	2.9601	-3.7695
2	115.7	0.0553	4.751	-2.8667
3	130.2	0.0881	4.8691	-2.3835
4	139.6	0.121	4.9388	-2.0482

TABLE V. FAILURE DATA OF THE TMIN-RHMAX TEST

Adjusted Ranks	Failure Data of the Tmin-RHmax Test			
	TTF in hours	***F(TTF)***	***x***	***y***
1	13.3	0.0228	2.5828	-3.7695
2	19.3	0.0553	2.9601	-2.8667
3	67.75	0.0881	4.2158	-2.3835
4	109.75	0.121	4.6982	-2.0482
5	173	0.154	5.1533	-1.7883

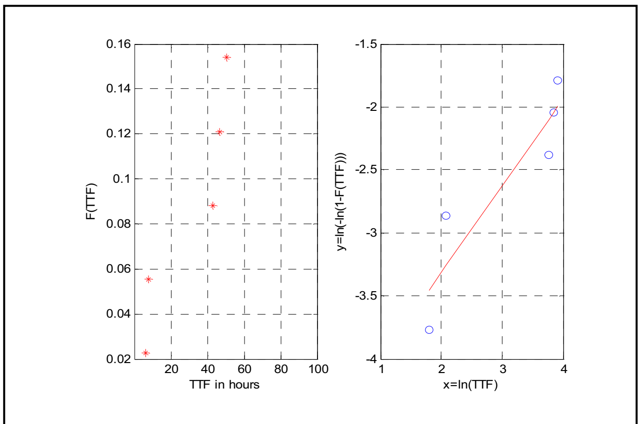

Figure 1. The Fit of Weibull Distribution for the Tmax-RHmax Stress Level

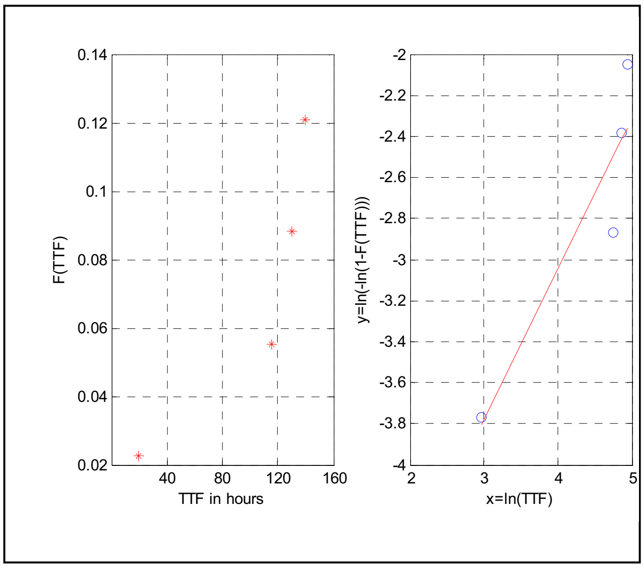

Figure 2. The Fit of Weibull Distribution for the Tmax-RHmin Stress Level

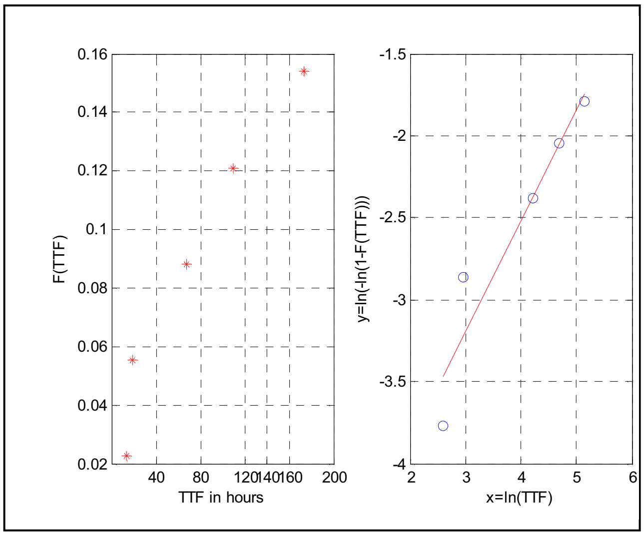

Figure 3. The Fit of Weibull Distribution for the Tmin-RHmax Stress Level

For each regression line, assuming its expression is:

$$y_i = Ax_i + B \tag{17}$$

where x_i and y_i are defined by equation (15) and equation (16), thus we have:

$$\begin{cases} \beta = B \\ \eta = e^{-\frac{A}{B}} \end{cases} \quad (18)$$

For a confidence level of 50%, estimation by least squares regression of fit of Weibull distributions gives the following results:

TABLE VI. RESULTS OF FIT OF WEIBULL DISTRIBUTION

Test No.	Results of Fit of Weibull distribution			
	T(°C)	***RH***	***Beta***	***Eta***
1	85	95	0.69	909.87
2	85	75	0.73	3527.71
3	65	95	0.67	2297.74

The equation (9) of the ratio of the Life Stress model (as described in section Ⅲ.B) gives the following table:

TABLE VII. RATIO OF LIFE STRESS MODEL

Stress	Ratio of Life Stress Model		
	C	***A***	***B***
T_{max} , RH_{min}	1.3559	0.2364	0
T_{min} , RH_{max}	0.9273	0	1.9165

According to equation (12) and equation(13),

$$E_a = 0.4839$$
$$\hat{n} = 5.7357$$

and the maximum Acceleration Factor (or AFmax, which means the accelerator factor at the maximum stress level) is:

$$AF = \left(\frac{RH_u}{RH_s} \right)^{-n} e^{\frac{E_a}{k}(\frac{1}{T_u} - \frac{1}{T_s})} = 159.13$$

Here the normal condition is defined as Tu=20 °C, and RHu=72%.

V. CONCLUSION

To estimate the parameters of the Life Stress model, a group of 3 tests under different levels of stress combination have been carried into execution. A fit of Weibull distribution is applied to the data obtained in those tests to give the estimation of the shape parameter and scale parameter of the Weibull distribution, to which the samples' population obeys. With the method of least square regression, an estimation of Ea and n could be given. With the accelerated factor defined by the Peck model, TTF at each stress level could be then extrapolated to the normal condition. By applying the Weibull distribution fit to those data, the estimation of the TTF of the samples under normal condition could be made. By adopting this method in the ALT of the DDZY33C-Z Smart Electricity Meter, the testing time is remarkably reduced to 4.5 days on average, which is only 50% of the time need for a traditional life test of the electricity meters designed to normally operate more than 10 years. Numerical instance has shown the failure data of just one independent failure mode of the meter and has given a data processing instance. The final result of the TTF of the DDZY33C-Z Smart Electricity Meter under normal condition is 16.5 years, which goes along with the previous market statistics of its operating time.

REFERENCES

[1] Nelson, W., Accelerated Life Testing - Step-Stress Models and Data Analyses. Reliability, IEEE Transactions on, 1980. R-29(2): p. 103-108.

[2] Mengmeng, L., R. Zhanyong, F. Yun, L. Dandan, Z. Zhaoyang. The methodology of life prediction and validation of electronic products based on accelerated degradation testing. in Electronic Packaging Technology & High Density Packaging (ICEPT-HDP), 2010 11th International Conference on. 2010.

[3] IEC, Electricity metering equipment–Dependability in Accelerated reliability testing–Elevated temperature and humidity 2008.

[4] Hribar, L., D. Duka. Weibull distribution in modeling component faults. in ELMAR, 2010 PROCEEDINGS. 2010.

[5] Cousineau, D., Fitting the three-parameter weibull distribution: review and evaluation of existing and new methods. Dielectrics and Electrical Insulation, IEEE Transactions on, 2009. 16(1): p. 281-288.

[6] Hasegawa, M., Y. Yanagitani. Analysis of Contact Resistance Data with Weibull Distribution Function. in Electrical Contacts, 2008. Proceedings of the 54th IEEE Holm Conference on. 2008.

[7] Siew-Leng, T., Y. Kwee-Poo, A least-squares approach to analyzing life-stress relationship in step-stress accelerated life tests. Reliability, IEEE Transactions on, 2002. 51(2): p. 177-182