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Constant-step stress accelerated life test of VFD under Weibull distribution case*

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Abstract: Constant-step stress accelerated life test of Vacuum Fluorescent Display (VFD) was conducted with increased cathode temperature. Statistical analysis was done by applying Weibull distribution for describing the life, and Least Square Method (LSM) for estimating Weibull parameters. Self-designed special software was used to predict the VFD life. Numerical results showed that the average life of VFD is over 30000 h, that the VFD life follows Weibull distribution, and that the life-stress relationship satisfies linear Arrhenius equation completely. Accurate calculation of the key parameter enabled rapid estimation of VFD life.

Key words: Vacuum Fluorescent Display, Accelerated life test, Constant-step, Weibull, Average life

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INTRODUCTION

Vacuum Fluorescent Display (VFD) is a vacuum display device evolved from vacuum tubes. As a self-luminescent display, the brightness is created when the anode fluorescent is bombarded with electrons. VFD is now widely used in many fields, such as household electric appliance, instruments and meters, communication device, OA, and so on.

Many consumers select goods by considering their design and reliability, so the reliability of the product directly represents the trust in the producer (Park *et al*., 2002). VFD is an electronic device with high reliability and long life of usually up to several ten thousand hours. Higher reliability of VFD is now required because of the rival market and special applications, such as military. It is almost impossible to conduct the conventional life test because the designed VFD speed has become more rapid, and long test time and high test cost has become a heavy burden, so accelerated life test of VFD is urgently needed for rapid estimation of VFD life. To the author's knowledge, so far there are no research reports on VFD accelerated life test.

Compared with the step-stress accelerated life test (step-test), the constant-stress accelerated life test (constant-test) has some merits as follows: simple test methods, ripe theory, and precise test data. The step-test can shorten test time, because a unit is placed on test at an initial low stress, and if it does not fail in a predetermined time, the stress is increased (Khamis and Higgins, 1998). Two constant tests and one step test were performed in this work. Estimation of VFD life was achieved by Weibull distribution function, Least Square Method (LSM) (Soman and Misra, 1992) and self-designed software. The obtained VFD failure pattern and life distribution can serve as basis for further study on VFD life.

TEST PLAN DESIGN

Failure criterion

According to specifications provided by the

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manufacturer, the VFD failure time can be defined as the duration when the VFD luminance decreases to below 210 cd/m^2 (green phosphor powder).

Plan design

1. Selection of the accelerated stress

The cathode temperature chiefly affects the VFD life, so the filament temperature (monitored by voltage) was selected as the accelerated stress level.

2. Selection of the accelerated stress level and number

In order to ensure test accuracy, there must be a great range interval between the maximum stress level and the minimum. The maximum stress level being not greater than the limited stress level depends on the material and the manufacturing technique, so that new failure mechanism can be avoided. The cathode temperature should in general be not more than 850 °C. In this study, the test samples were divided into four stress levels: T_1=1023.00 K, T_2=1055.56 K, T_3=1087.85 K, T_4=1123.33 K, and then constant tests (T_1, T_3) and the step test ($T_1 \rightarrow T_2 \rightarrow T_3 \rightarrow T_4$) were carried out. It is necessary to explain that the normal working stress T_0 of this type of VFD is 923.95 K.

3. Test end time

Complete life test was carried out in that all samples were up to failure criterion.

STATISTICAL ANALYSIS ON TEST DATA

Basic assumptions

Assumption 1 When the temperature stress is T_i (i=0,1,2,3,4), the VFD life follows Weibull distribution. The cumulative distribution function (cdf) can be written as follows

$$F_i(t) = 1 - \exp[-(t/\eta_i)^{m_i}], \quad t>0 \ (i=0,1,2,3,4) \tag{1}$$

here m_i and η_i are respectively shape parameter and scale parameter at T_i.

Assumption 2 The VFD failure mechanism keeps constant at each temperature stress. Because the shape parameter m embodies the failure mechanism, it means

$$m_0=m_1=m_2=m_3=m_4=m \tag{2}$$

If estimated values of the shape parameter are respectively $\bar{m}_1, \bar{m}_2, \bar{m}_3, \bar{m}_4$, the shape parameter m can be expressed as follows:

$$m = \sum_{i=1}^{4} n_i \bar{m}_i \bigg/ \sum_{i=1}^{4} n_i \tag{3}$$

here n_i is the total number of the samples at T_i.

Assumption 3 The VFD accelerated model satisfies the linear Arrhenius equation. Namely, the scale parameter η and the temperature stress T satisfy the following equation

$$\ln\eta=\alpha+\beta/T \tag{4}$$

where α and β are undetermined acceleration parameters, and T is the absolute temperature in Kelvin unit.

Assumption 4 Nelson principle (Nelson, 1980): the cdf is $F_i(t_i)$ when the product is working at time t_i under stress T_i, correspondingly, the cdf is $F_j(t_j)$ at time t_j under stress T_j, then one can get

$$F_i(t_i)=F_j(t_j) \tag{5}$$

Statistical analysis of constant-stress accelerated life test data

Eq.(1) is transformed as follows

$$\ln\ln[1-F_i(t)]^{-1}=m_i\ln t-m_i\ln\eta_i \tag{6}$$

If

$$\ln\ln[1-F_i(t)]^{-1}=y,\ \ln t=x,\ m_i=a_i,\ -m_i\ln\eta_i=b_i, \tag{7}$$

so the linear relation can be obtained as follows:

$$y=a_i x+b_i \tag{8}$$

After the failure at time t_j at T_i is sequenced, the corresponding cdf $F(t_j)$ is calculated by the following median rank formula

$$F(t_j) = \frac{j-0.3}{n_i+0.4} \quad (j=1,2,\cdots,n_i) \tag{9}$$

Then the test data can be obtained as follows:

$$(t_j, F(t_j)) \quad (j=1,\ldots,n_i) \tag{10}$$

According to Eq.(7), Eq.(10) can be converted into the linear model

$$(\ln t_j, \ln\ln[1-F_i(t)]^{-1})=(x_j,y_j) \tag{11}$$

Applying LSM to Eq.(11), one can obtain the coefficients as follows

$$a_i = \frac{\sum_{j=1}^{k} x_j y_j - \left(\sum_{j=1}^{n_i} x_j \sum_{j=1}^{n_i} y_j\right) \Big/ n_i}{\sum_{j=1}^{n_i} x_j^2 - \left(\sum_{j=1}^{n_i} x_j\right)^2 \Big/ n_i},$$

$$b_i = \sum_{j=1}^{n_i} y_j \Big/ n_i - a_i \sum_{j=1}^{n_i} x_j \Big/ n_i \tag{12}$$

Combining Eqs.(7) and (12), the estimated values of the shape parameter m_i and the scale parameter η_i at T_i are respectively obtained as

$$m_i=a_i, \quad \eta_i = \mathrm{e}^{-b_i/a_i} \tag{13}$$

Statistical analysis of the step-stress accelerated life test data

With the aid of Eqs.(1), (4), (5), the acceleration factor can be expressed as follows (Tebbi *et al.*, 2003)

$$\tau_{T_i-T_1} = \exp\left\{\beta\left(\frac{1}{T_1}-\frac{1}{T_i}\right)\right\} \tag{14}$$

where $\tau_{T_i-T_1}$ is the acceleration factor with T_i (i=2,3,4) vs T_1; β is the slope coefficient of Eq.(4), which can be calculated by LSM after digital points ($1/T_i$, $\ln\eta_i$) are formed.

Using the step-stress failure time and Eq.(14), one can get the failure time of the samples in each step stress level. The applied stress model of the step-stress test ($T_1\rightarrow T_2\rightarrow T_3\rightarrow T_4$) is plotted in Fig.1 showing obviously that the failure time in the step i includes accumulative effect of the step $i-1$. So the failure time in the step $i-1$ should be converted into one in the step i.

At first, one can convert the step-stress failure time into the one at the stress T_1 by the following

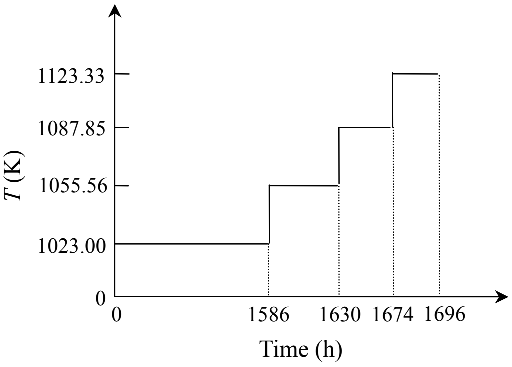

Fig.1 Applied stress models of step-stress tests

$$t_{T_1} = \begin{cases} t_i & (1\le i\le 3) \\ t_1^* + (t_i - t_1^*)\tau_{21} & (4\le i\le 6) \\ t_1^* + (t_2^* - t_1^*)\tau_{21} + (t_i - t_2^*)\tau_{31} & (7\le i\le 13) \\ t_1^* + (t_2^* - t_1^*)\tau_{21} & \\ \quad +(t_3^* - t_2^*)\tau_{31} + (t_i - t_3^*)\tau_{41} & (14\le i\le 20) \end{cases} \tag{15}$$

where t_k^* (k=1,2,3) represents the monitoring time in step k, and t_1^*=1586 h, t_2^*=1630 h, t_3^*=1674 h; t_i is the failure time of the sample i; τ_{21}, τ_{31}, τ_{41}, which can be calculated by Eq.(14), are respectively acceleration factors of T_2, T_3 and T_4. So the failure time caused by the other stresses can be expressed as follows

$$t_{T_2} = t_{T_1}/\tau_{21}, \quad t_{T_3} = t_{T_1}/\tau_{31}, \quad t_{T_4} = t_{T_1}/\tau_{41}, \tag{16}$$

Test data

The failure time of the constant-stress tests (T_1=1023.00 K, T_3=1087.85 K) and the step-stress test ($T_1\rightarrow T_2\rightarrow T_3\rightarrow T_4$) are respectively given in Table 1 and Table 2.

TEST DATA PROCESSING

The test data processing and calculations were achieved with the aid of the self-designed software because the life estimation was rather complex. The core source code of the software was programmed by Fortran, and the strong visual operating interface was developed by VB (Microsoft Visual Basic 6.0). This software has some advantages as follows: strong versatility, simple operation, high speed and precision

Table 1 Failure time in constant-stress tests at T_1 and T_3

No.	Failure time (h)	
	T_1	T_3
t_1	1509.00	213.33
t_2	1553.00	220.67
t_3	1591.50	231.67
t_4	1597.00	235.33
t_5	1602.50	239.00
t_6	1641.00	242.67
t_7	1657.50	246.33
t_8	1663.00	253.14
t_9	1668.50	256.29
t_{10}	1685.00	259.43
t_{11}	1729.00	262.57
t_{12}	1747.33	265.71
t_{13}	1754.67	268.86
t_{14}	1773.00	277.50
t_{15}	1789.50	283.00
t_{16}	1795.00	288.50
t_{17}	1800.50	299.50
t_{18}	1839.00	305.00
t_{19}	1883.00	310.50
t_{20}	2037.00	327.00

Table 2 Sample failure time in step-stress tests

No.	Failure time (h)			
	T_1	T_2	T_3	T_4
t_1	1569.50	–	–	–
t_2	1575.00	–	–	–
t_3	1580.50	–	–	–
t_4		1593.33	–	–
t_5		1600.67	–	–
t_6		1619.00	–	–
t_7			1637.33	–
t_8			1644.67	–
t_9			1655.67	–
t_{10}			1659.33	–
t_{11}			1663.00	–
t_{12}			1666.67	–
t_{13}			1670.33	–
t_{14}				1676.75
t_{15}				1679.50
t_{16}				1682.25
t_{17}				1685.00
t_{18}				1687.75
t_{19}				1690.50
t_{20}				1693.25

in calculating, expedient application in engineering.

Data processing of the constant-stress accelerated life test

The constant-stress test data (shown in Table 1) were processed by the predicted-life software, and the statistical curves fitted by LSM are plotted in Fig.2 showing that the relationship between x and y is basically linear. The determination coefficients, the slope coefficients and the intercepts of the fitting lines (T_1, T_3) are respectively given as follows: R_1^2=0.9074, R_3^2=0.9459, a_1=15.54, a_3=9.81, b_1=−116.23, b_3=−55.18. From Eq.(13), one can get: m_1=15.54, η_1=1772.59 h, m_3=9.81, η_3=277.59 h.

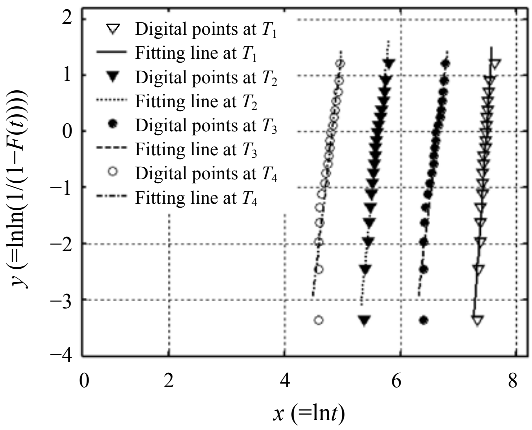

Fig.2 Statistical curves of constant and step stress data

Accelerated life equation

Substituting η_1=1772.59 h, T_1=1023.00 K and η_3=277.59 h, T_3=1087.85 K into Eq.(4), one can get: α=−23.62, β=31817, so the accelerated life equation can be written as

$$\ln\eta=-23.62+31817/T \quad (17)$$

Data processing of the step-stress accelerated life test

The failure time of the step-stress test can be converted into the failure time of the stress levels T_2 and T_4 (Table 3) by combining Eqs.(14)~(17).

The test data in Table 3 were processed by the same method, with the corresponding fitting lines shown in Fig.2. The calculated parameters are: R_2^2=0.9073, R_4^2=0.9073, a_2=8.76, a_4=8.76, b_2=

Table 3 Failure time in step-stress tests at T_2 and T_4

No.	Failure time (h)	
	T_2	T_4
t_1	601.34	97.58
t_2	603.44	97.93
t_3	605.55	98.27
t_4	614.99	99.80
t_5	622.33	100.99
t_6	640.66	103.97
t_7	669.59	108.66
t_8	687.55	111.58
t_9	714.46	115.94
t_{10}	723.41	117.40
t_{11}	732.39	118.85
t_{12}	741.37	120.31
t_{13}	750.25	121.75
t_{14}	776.25	125.97
t_{15}	793.20	128.72
t_{16}	810.14	131.47
t_{17}	827.09	134.22
t_{18}	844.04	136.97
t_{19}	860.98	139.72
t_{20}	877.93	142.47

−58.18, b_4=−42.25, m_2=8.76, η_2=756.42 h, m_4=8.76, η_4=124.21 h.

Correction of the acceleration parameter

The above data η_i, T_i (i=1,2,3,4) were inputted into Eq.(4) to calculate the modified acceleration parameters by LSM as follows: α=−22.78, β=30975. So the modified accelerated life equation was re-written as

$$\ln\eta=-22.78+30975/T \quad (18)$$

The accelerated life characteristic pattern for each stress level is shown in Fig.3. The determination coefficient of the fitting line is R^2=0.9972, which highly approaches to 1, showing that the VFD accelerated parameter is well expressed by β=30975 calculated in this paper. Furthermore, based the statistical data m_i (i=1,2,3,4) and Eq.(3), the estimated value of the shape parameter is m=10.72.

Kolmogorov-Smirnov test

Greater significance level ($\bar{\alpha}=0.2$) was selected due to limited samples. Inputting the failure time at each stress level into the self-designed software yielded output: $\bar{\alpha}_1=0.9690$, $\bar{\alpha}_2=0.9580$, $\bar{\alpha}_3=0.9721$, and $\bar{\alpha}_4=0.9580$. It shows that all temperature stress levels passed the K-S test successfully, so it is verified that the VFD life follows Weibull distribution.

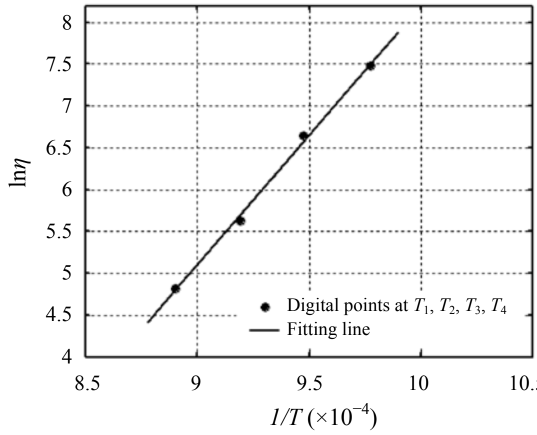

Fig.3 Life characteristic pattern

ESTIMATION OF THE VFD LIFE

When the VFD life pattern follows Weibull distribution, the average life μ_i and reliable life $t_R^{(i)}$ at T_i can be respectively expressed as follows:

$$\mu_i=\eta_i\Gamma(1+1/m) \quad (19)$$

$$t_R^{(i)}=\eta_i(\ln(1/\bar{R}))^{1/m} \quad (20)$$

In which $\Gamma(\cdot)$ is the gamma function; $\bar{R}$ is the given reliability ($\bar{R}$=0.9 in most instances).

Based on Eqs.(14) and (19), the accelerated life factor and the average life at T_i (i=1,2,3,4) were respectively calculated as follows: τ_1=25.69, τ_2=65.36, τ_3=156.18, τ_4=383.89, μ_1=1730.26 h, μ_2=679.96 h, μ_3=284.58 h, μ_4=115.78 h. So the average life of VFD at the normal working stress T_0 can be expressed as

$$\mu_0=\tau_i\mu_i \quad (21)$$

The average life μ_0 at T_0 is 44446 h (=$\mu_1\tau_1$=$\mu_2\tau_2$=$\mu_3\tau_3$=$\mu_4\tau_4$) and the reliable life $t_{\bar{R}=0.9}$ got by the same method is 37762 h. It shows that the average life and reliable life calculated by each accelerated life factor and each average life at T_i are the same because the relationship between $1/T$ and $\ln\eta$ is linear [Eq.(18)] under the condition of changeless failure mechanism.

Therefore, the average life and the reliable life of VFD at the normal working stress T_0 can be estimated by the accelerated life test at the maximum stress after the key accelerated life parameter β=30975 is accurately obtained. So the VFD life can possibly be estimated in a short time (1000 h).

CONCLUSION

From the above statistical analyses of the constant-step stress life test data, it can be obviously concluded that: (1) The VFD life pattern follows Weibull distribution; (2) The determination coefficient of the accelerated life line for four stress levels is R^2=0.9972, which highly approaches to 1, so it is verified that the VFD accelerated model satisfies the linear Arrhenius equation; (3) The accurately calculated key parameter used to predict VFD life enables estimation of VFD life short time (1000 h), so that the test time and financial resources needed will be greatly reduced; (4) Successfully self-designed predicted life software makes it easy to achieve complex statistical analyses of accelerated life test data; (5) The average life and the reliable life calculated accurately in this paper can serve as guidelines for VFD manufacturers and users.

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