Accelerated life method and assessment for storage vacuum electronic device

H. Yuan,\textsuperscript{a,b} J. Feng\textsuperscript{c} and X. Sun\textsuperscript{a,1}

\textsuperscript{a}Research Center for Electronic Device and System Reliability, Southeast University, Nanjing 210096, China
\textsuperscript{b}Information College, Huaibei Normal University, Huaibei 235000, China
\textsuperscript{c}Beijing Vacuum Electronics Research Institute, Beijing 100015, China

E-mail: xhsun@seu.edu.cn

Abstract: We proposed an accelerated life testing method for the storage vacuum electronic devices (SVED) based on pressurization according to the relationship between gas inflow rate and pressure. And then a storage life assessment model was presented, using the cathode current to evaluate the SVED performance. Consequently, a test platform was established to verify the ALT method by storing three SVEDs in air for 10y and at 4.5 atm within its pressure limit for 5m. The results showed that, when pressurization, the cathode current dropped faster than when stored in air. And the expected storage life of the three SVEDs decreased from 10.4y, 15.5y and 31.4y respectively when stored in air to 2.6y, 3.9y and 10.0y respectively when stored at 4.5 atm. Also, leak plays a more important role than permeation in determining the storage life of the SVED.

Keywords: Manufacturing; Detector design and construction technologies and materials

\textsuperscript{1}Corresponding author.
1 Introduction

Vacuum electronic devices (VED), as critical components of accelerator system [1, 2] and satellite communication system [3, 4], have often been stored for long periods before use as a backup. Therefore, storage life (SL) is a key factor affecting the reliability of these systems. The storage vacuum electronic devices (SVED) expected storage life (ESL) over a period of decades, is much longer than what laboratory testing would allow. Thus, accelerated life test (ALT) is a method of obtaining information about ESL within experimental time limits [5].

As is known to all, most of SVED breakdown is due to the failure of cathode, so we can accelerate the cathode failure to obtain the life of SVED within a short period. Mita presented that cathodes have two life-limiting factors: the degradation of surface coating and the reduction of impregnant. Then, he proposed an accelerated life testing for working cathodes on the basis of temperature. Heating a cathode to 1100°C served to verify this method, and the results showed that the cathode has a useful life of 105 h [5]. And Zhang set dual-layer porous tungsten dispenser cathode temperatures at 980°C, 1020°C, 1060°C, and 1100°C separately to test working life and obtained a cathode life of 1.9×105h [6]. In the report [7], an accelerated lift testing is presented for M-type dispenser cathode operating over two years, however the cathode life is not obtained yet and the testing is continuing. As mentioned above, the cathode working life can be obtained within a short period by ALT at high temperatures, although the need remains for an ALT method for the cathode in storage. The main failure mechanism of a cathode in a SVED is cathode poisoning caused by residual gas from desorption, virtual leaks, leaks, and permeation [8]. The virtual leaks and desorption have no effect on the cathode in long storage because they finish within a short time. Thus, the main gas source is attributable to leaks and permeation [9, 10]. High temperatures can not only accelerate the leak rate and the permeation rate but can also increase the amount of gas released from the material and the cathode [11]. Therefore, the high temperature is unsuitable for accelerating the SVED SL because it is difficult to establish the relationship between the temperature and the SL. This paper presents an accelerated testing method for the SVED on the basis of high pressure because the high pressure can increase the leak rate and the permeation rate without other influences.
The remaining part of the paper is organized as follows. Section 2 proposes an accelerated life testing method for SVEDs on the basis of an analysis of the relationship between high pressure and cathode current. Section 3 presents an accelerated test and analyzes the results. Conclusions are presented in section 4.

2 Methodology

As mentioned above, most of the residual gas comes from permeation and leak. The gas inflow rate $q_p$ through permeation can be expressed as follows [12]:

$$q_p = \frac{M e^{-b/T} \left( (P_h)^n - (P_l)^n \right)}{d}$$  \hspace{1cm} (2.1)

where $M$ and $b$ are the constants related to the gas-metal system, which can be obtained by experiment; $d$ is the thickness of the metal; $T$ is the temperature; $P_l$ and $P_h$ are the low pressure and the high pressure of gas at both sides of the metal; and $n$ is 1 when gas dissolves as molecules, which is 0.5 when gas dissolves as atoms. It has been proved that hydrogen in air has the highest permeation rate; thus, we focused on hydrogen permeation; and $n$ is 0.5 for hydrogen permeation. When $P_h \gg P_l$, $P_l$ can be ignored; therefore, $q_p \propto \sqrt{P_h}$.

The gas inflow rate through leak $q_l$ can be expressed as follows [13]:

$$q_l = R_L (P_h - P_l)$$  \hspace{1cm} (2.2)

where $R_L$ is a constant related to the leak. When $P_h \gg P_l$, $P_l$ can be ignored; thus, $q_l \propto P_h$

Therefore, the total gas inflow rate $q$ is the sum of $q_p$ and $q_l$ as expressed in

$$q = a_1 P_h + a_2 \sqrt{P_h}$$  \hspace{1cm} (2.3)

where $a_1$ and $a_2$ are the constants related to the sealing performance of SVED. Consequently, it is obvious that the $q$ will rise as the $P_h$ rises according to Formula (2.3). Thus, we can accelerate the failure of SVED by raising the pressure outside of the SVED. We assume that the initial residual gas content in SVED is $Q_0$; thus the residual gas content $Q$ can be expressed as follows:

$$Q = \int q dt + Q_0$$  \hspace{1cm} (2.4)

Therefore, we can obtain the relationship between the residual gas content and the pressure outside of SVED, which can be expressed as follows:

$$Q = \int \left( a_1 P_h + a_2 \sqrt{P_h} \right) dt + Q_0$$  \hspace{1cm} (2.5)

Next, we analyze the relationship between $P_h$ and SVED SL. We assume that the SVED SL comes to an end once the cathode current decreases to the threshold value. According to the Wagener’s article [14], the cathode current $I$ decreases when the residual gas content rises. Therefore, their relationship can be assumed as

$$I = A + B \ln Q$$  \hspace{1cm} (2.6)

where $A$ and $B$ are the constants obtained by the experiment.
Therefore, the relationship between $I$ and $P_h$ can be expressed as (2.7), according to (2.5) and (2.6):

$$I = A + B \ln \left( \int \left( a_1 P_h + a_2 \sqrt{P_h} \right) dt + Q_0 \right) + \varepsilon (t) \tag{2.7}$$

where $\varepsilon(t)$ is the test noise consistent with normal distribution.

We assume that the SVED current failure threshold is a fraction ($a$) of the initial value; thus the SVED ESL $\zeta$ can satisfy the relationship

$$a I_0 = A + B \ln \left( \int \xi \left( a_1 P_h + a_2 \sqrt{P_h} \right) dt + Q_0 \right) + \varepsilon (t) \tag{2.8}$$

Assuming that the $P_h$ does not change and that the $\varepsilon(t)$ is ignored, we can express $\zeta$ as follow [15]

$$\xi = \left( e^{\frac{a I_0 - A}{B}} - Q_0 \right) / \left( a_1 P_h + a_2 \sqrt{P_h} \right) \tag{2.9}$$

Thus, we analyze the permeation or leak effect on SVED life expectancy. We assume that $a_2 = 0$ or $a_1 = 0$ when only one factor is working. To simplify the analysis, we set $a I_0 = 0.5$; $A = 1$; $B = 1$; and $Q_0 = 0$. The relationship between $\zeta$ and $P_h$ is shown in figure 1. As we can see from figure 1, $\zeta$ decreases when the $P_h$ increases. An increase in $a_1$ or $a_2$ will also result in the degradation of $\zeta$. Leaking plays a major role at a relatively high pressure; however, permeation has a greater effect on $\zeta$ at a relatively low pressure.

![Figure 1. Effect of permeation and leak on the ESL. The ESL decreases when the pressure rises, and the values of $a_1$ and $a_2$ determine the ESL degradation rate.](image)

The value of the parameter can be obtained by testing. We achieve the decrease rate of cathode current by taking the derivative of (2.7) with respect to $t$.

$$\frac{dI}{dt} = \frac{a_1 P_h + a_2 \sqrt{P_h}}{Q} \tag{2.10}$$

The decrease rate of the cathode current depends on $Q$ and $P_h$. Thus, we can increase the cathode current decrease rate by increasing $P_h$. Hence, the values of $a_1$ and $a_2$ can be obtained by the step stress accelerated life test.
Presumably, the different $P_h\{P_1, P_2, \ldots, P_n\}$ is applied to the SVED in the period $\{[t_{s_1}, t_{e_1}], [t_{s_2}, t_{e_2}] \ldots [t_{s_m}, t_{e_m}]\}$; where $t_{s_n}$ is start time and $t_{e_n}$ is end time. The value of $I$ at a different time is $\{\{t_1, I_1\}, \{t_2, I_2\} \ldots \{t_m, I_m\}\}$. Therefore, we can determine the relationship between $I$ and $P_h$.

$$I_m = A + B \ln \left( \sum_{g=1}^{k} \left( a_1 P_{g} + a_2 \sqrt{P_{g}} \right) (t_{e_g} - t_{s_g}) + \left( a_1 P_{k+1} + a_2 \sqrt{P_{k+1}} \right) (t_m - t_{s(k+1)}) + Q_0 \right) + \epsilon(t)$$

where $t_m \in [t_{s(k+1)}, t_{e(k+1)}], t_m \in [t_{s(k+1)}, t_{e(k+1)}]$. Thus, we can obtain the values of $A$, $B$, $Q_0$, $a_1$, and $a_2$ by the least squares method.

3 Experiment

Figure 2. The function of scheme was consisted with five parts: hardware control, data acquisition, data storage, data processing and data display.

According to the accelerated method, a test scheme was proposed as shown in figure 2, which could maintain the high pressure outside of the SVED and assess its storage life according to its cathode current reduction. It could be divided into five parts, each of which contained several sub-functions, and the line represented the data stream.

To realize the function, the hardware design was shown in figure 3, which was consisted with three modules. The sealed storage module contained a pressure vessel to store the SVED. And the pressure measure/control module was used to maintain a constant pressure in the pressure vessel. The last module was the SVED performance test module with function of testing the SVED high frequency performance.

The test platform was established as shown in figure 4. It could monitor the temperature and pressure in the vessel, which had an acquisition frequency of 1 k/s; a temperature measurement error of 0.5°C; and a pressure measurement error of 300 Pa. Also, the test platform could work continuously for more than 4 months and could maintain the pressure at the set value within ±1000 Pa. The temperature could be controlled within ±5°C by air-conditioning in the laboratory.
Figure 3. The hardware of test platform design. It was consisted with three parts: sealed storage module, sealed vessel measure/control module and SVED performance test module.

Figure 4. (a) The sealed storage module and pressure measure/control module. (b) The monitoring computer was used to store and process the data of SVED.

4 Result and assessment

We performed the test on three SVEDs. The test procedure is as follows: firstly the SVEDs were tested when produced; secondly they were stored in the air for a period of time; thirdly the ALTs were performed on the test platform at 4.5 atm pressure for about 5 months; at last, the ALTs stopped and the SVEDs were stored in the air again. During each storage period, the SEVDs were tested twice. The experimental time of the three SVEDs is listed in table 1.
Table 1. The experimental time of the three SVEDs.

| No. | Produce time | Start time of ALT | End time of ALT | End time of Test |
|-----|--------------|-------------------|-----------------|-----------------|
| 1   | 2008/10/29   | 2015/9/15         | 2016/2/18       | 2019/2/20       |
| 2   | 2009/4/21    | 2016/2/25         | 2016/7/24       | 2019/2/20       |
| 3   | 2009/5/23    | 2016/8/10         | 2017/1/17       | 2019/2/20       |

Figure 5. Test result of the SVED cathode currents. The cathode currents dropped faster when at 4.5 atm than when stored in air.

The test results are given in figure 5. We fit the formula (2.11) to the test results and get the values of $a_1, a_2, A, B, Q_0$, based on which we obtained the cathode current degradation curve.

As shown in figure 5, the cathode currents decreased faster after pressurization than the decrease rate when the SVED is stored in air. Thus, it was proved that pressurization can accelerate the SVED ELF. Comparing the cathode current fitting curves of the three SVEDs, the current of the No. 2 SVED has the slowest decrease rate due to its good sealing; however the current of the No. 3 SVED has the fastest decrease rate. Assuming that the SVED fails when its cathode current decreases by 15%, the No. 3 SVED has a SL of 3359d (about 9.2y).

Assuming that this SVED was stored under pressure as soon as it was produced, the relationship between its ESL and pressure is shown in the figure 6 according to the values of values of $a_1, a_2, A, B, Q_0$. As shown in figure 6 the ESLs of the three SVEDs are 10.4y, 15.5y and 31.4y respectively when stored in air, however they decreases to 2.6y, 3.9y and 10.0y respectively when stored at 4.5 atm.

According to the values of $a_1, a_2$, we find that the main gas source of the No. 1&3 SVEDs were leaks since $a_1P_h \gg a_2\sqrt{P_h}$. And the rates of leak and permeation of the No. 3 SVED are close when it is stored in the air. As shown in figure 5, the No. 3 SVED has a longer SL due to its lower decrease rate of cathode current. So leak plays a more important role than permeation in determining the SL of the SVED.
Figure 6. Relationship between ESL and gas pressure. The ESLs of the three SVEDs are 10.4y, 15.5y and 31.4y respectively when stored in air, however they decrease to 2.6y, 3.9y and 10.0y respectively when stored at 4.5 atm.

5 Conclusion

We propose an accelerated life testing method for SVED on the basis of pressurization after analysing the relationship between the descent rate of the SVED cathode current and the gas pressure outside of the SVED. After which, a SVED ESL assessment model is established. On the basis of this method, we presented an accelerated life test platform and conducted accelerated life tests to three SVED, which were stored in air for 10y and at 4.5 atm for 5m. The results showed that, after pressurization, the cathode current dropped faster than the current decreased rate when stored in air, and the ESL decreased from 10.4y, 15.5y and 31.4y respectively when stored in air to 2.6y, 3.9y and 10.0y respectively when stored at 4.5 atm. Therefore, it was proved that pressurization could accelerate the SVED SL. Also, leak plays a more important role than permeation in determining the SL of the SVED.

Acknowledgments

This work was supported in part by the National key Laboratory of Science and Technology on Vacuum Electronics of China [Grant numbers 1508097]; National Major Scientific Research Plan of China (973) [Grant numbers 2013CB933600]; the Anhui University Natural Science Research Fund [Grant numbers KJ2016A647].

References

[1] I.A. Guzilov, BAC method of increasing the efficiency in klystrons, in 2014 Tenth International Vacuum Electron Sources Conference (IVESC), IEEE (2014).

[2] A.Y. Baikov, C. Marrelli and I. Syratchev, Toward high-power klystrons with RF power conversion efficiency on the order of 90%, IEEE Trans. Electron Devices 62 (2015) 3406.

[3] E. Cianca, T. Rossi, A. Yahalom, Y. Pinhasi, J. Farserotu and C. Sacchi, EHF for satellite communications: The new broadband frontier, Proc. IEEE 99 (2011) 1858.
[4] M. De Sanctis, E. Cianca, T. Rossi, C. Sacchi, L. Mucchi and R. Prasad, Waveform design solutions for EHF broadband satellite communications, *IEEE Commun. Mag.* 53 (2015) 18.

[5] F. Pascual, *Accelerated Life Test Planning With Independent Weibull Competing Risks*, *IEEE Trans. Rel.* 57 (2008) 435.

[6] N. Mita, An accelerated life test method for highly reliable on-board TWT’s with a coated impregnated cathode, *IEEE Trans. Electron Devices* 41 (1994) 1297.

[7] M. Zhang, Y. Liu, S. Yu, Y. Wang and H. Zhang, Life Test Studies on Dispenser Cathode With Dual-Layer Porous Tungsten, *IEEE Trans. Electron Devices* 61 (2014) 2983.

[8] O.M. Sabev and T.J. Grant, M-type dispenser cathode accelerated life testing within a pierce gun configuration, in 2018 IEEE International Vacuum Electronics Conference (IVEC), IEEE (2018).

[9] A.S. Gilmour, *Principles of Klystrons, Traveling Wave Tubes, Magnetrons, Cross-Field Amplifiers, and Gyrotrons*, Artech House, Incorporated (2011).

[10] L.G. Harus, M. Cai, K. Kawashima and T. Kagawa, Determination of temperature recovery time in differential-pressure-based air leak detector, *Measur. Sci. Tech.* 17 (2006) 411.

[11] O.W. Richardson, J. Nicol and T. Parnell, The diffusion of hydrogen through hot platinum, *Phil. Mag.* 8 (1904) 1.

[12] H. Yuan, J. Zhang, J. Ouyang, J. Zhou, X. Sheng and X. Sun, Mixture gas permeation model for stored VED, in 2015 IEEE International Vacuum Electronics Conference (IVEC), IEEE (2015).

[13] C.J. Smithells and C.E. Ransley, The diffusion of gases through metals, *Proc. Roy. Soc. Lond.* A 150 (1935) 172.

[14] C.D. Ehrlich, A note on flow rate and leak rate units, *J. Vac. Sci. Tech.* A 4 (1986) 2384.

[15] S. Wagener, Reactions between Oxide Cathodes and Gases at Very Low Pressures, *Proc. Phys. Soc.* B 67 (1954) 369.

[16] H. Yuan, J. Zhang, C. Shen, N. Bai, H. Fan, X. Zhao and X. Sun, Accelerated life test method for storage vacuum electron device based on pressurization, in 2017 Eighteenth International Vacuum Electronics Conference (IVEC), IEEE (2017).