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Determination of the optimal burn-in time and cost using an environmental stress approach: a case study in switch mode rectifier

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Abstract

Stress burn-in is an effective burn-in means of screening out the infant mortality components of a system which are conducted under an extremely stressful environment. While investigating stresses, screening burn-in by thermal stress, voltage stress, or mechanical shock stress, most related studies failed to develop an effective method to determine the optimal burn-in time and burn-in cost for a practical operation. Therefore, this study presents an effective procedure that adopts robust design techniques and the accelerated stress test to determine the optimal burn-in time and burn-in cost. A case study of the production of switch mode rectifier demonstrates the proposed procedure's effectiveness. Moreover, the results show that the proposed procedure generalizes well, and can screen out the early failure from material and manufacturing process. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Stress burn-in; Accelerated stress test; Accelerated factor; Burn-in; Switch mode rectifier

1. Introduction

Burn-in, an extensively used method to screen out defects before a product is shipped to the customer, consumes much time and energy during production. To solve this problem, environmental stress screening (ESS) can be applied to eliminate failures before appearing in the field, which are typically observed during the product life. Owing to their emphasis on reducing early field failures, ESS and burn-in are occasionally confused in literature. Reddy and Dietrich [1] stated that they differ mainly in that burn-in is normally conducted under ambient conditions, while ESS is generally conducted under accelerated conditions. ESS conditions are often more severe than normal operating conditions and may occasionally differ from the operational environment. Pohl and Dietrich [2] described that ESS is more economically viable than burn-in owing to its ability to precipitate defects in a much shorter time period. Despite their differences, ESS and burn-in processes can be modeled similarly.

Burn-in has received considerable attention. Park [3] investigated life distribution to determine whether burn-in increases the mean residual life. Weiss and Dishon [4], and Whitbeck and Leemis [5] considered that relationship between component and system burn-in maximize the mean residual life. Stewart and Johnson [6] developed a cost model to determine the optimal burn-in time and replacement policy. Nguyen and Murthy [7] as well as Genadis [8] derived the optimal burn-in time for products sold under warranty. Kuo [9] considered a cost model for systems using burn-in times of the components as the decision variable. Perlstein and Littlefield [10] adopted the assumption of a mixed exponential distribution to develop screening strategies for a system of components by superpositioning the individual components renewal processes. Their model assumes that all components are replaced with new ones upon failure. Chien and Kuo [11] considered the multiple-stage burn-in strategies for electronic components and, later, proposed a nonparametric approach to estimate the optimal system burn-in time [12]. Hui and Lu [13] used accelerated burn-in to calculate the optimal burn-in cost. Importantly, burn-in focuses mainly on maximizing the mean residual life and minimizing the expected total costs.

Reddy and Dietrich [1] developed a two-level ESS model by exploiting the weaknesses of Perlstein's models. A mixed exponential distribution was used in the component and unit level at burn-in process. In the minimum repair policy, components are replaced upon failure and are modeled using renewal theory. Pohl and Dietrich [14] developed a three-level model and investigated the possibility that ESS may reduce the useful life of the screened

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population. In their study, a mixed exponential distribution was used to model component times-to-failure and mixed Weibull distributions were used to model component the times-to-failure for board and system level conditions. Using ESS, Yan and English [15] constructed an integrated cost model and determined the optimal burn-in time. Lu and Hui [16] investigated the feasibility of using two-stage burn-in procedure to enhance the outgoing product quality. The first stage involves a high stress level burn-in to screen out material defects, while the second stage involves a low stress level burn-in to detect manufacturing defects. Pohl and Dietric [2] extended the results of an earlier study by using phase-type distribution to model component and connection lifetimes. Their work also applied many screening strategies to several lifetime distributions, and used numerical examples to illustrate the effect of various model parameters to determine the optimal stress screening strategy.

Pertinent literature often assumes that the failure pattern follows a specific distribution and the burn-in process is implemented under approximately the same environment as that of the early operating life of the product. These assumptions do not provide an effective means of determining the optimal burn-in time and burn-in cost for practical operations. Therefore, this study presents an effective procedure to determine the optimum time and cost for burn-in based on the ESS approach. The proposed procedure is implemented in a rectifier manufacturing process.

Rectifiers play an important role in a telecommunications power system by converting AC power input into DC power output for wireless and wireline network applications. A rectifier must be highly reliable in a telecommunications network, thereby necessitating that burn-in be completed before shipping the rectifier to the customer. Previously, the burn-in condition and time were normally determined by an experienced rectifier engineer. However, doing so did not always overcome material failure, poor workmanship or weakness of design, as well as large consumption of time and energy. Under a variant working environment, this study determines the accelerated factor function. Combining this function and the times-to-failure of historical data allows us to obtain an optimal burn-in time and cost via the proposed procedure.

2. Background information

2.1. Burn-in

Burn-in is widely recognized as an effective means of screening out early failures. Jensen and Petersen [17] described burn-in as a rapidly changing technology and production method used to effectively respond to an increasing awareness of reliability. Most manufacturers must adopt reliability screening to minimize early failures in the field, thus minimizing guarantee and service expenditures. Yan and English [15] defined burn-in as a subset of ESS that screens out infant failure by combining appropriate electrical and thermal environments in a short time span. Kuo et al. [18] defined burn-in as an effective means of weeding out the infant mortality failure by applying a stress level higher than normal, to accelerate the deterioration of electronic devices. In the burn-in process, a product (also termed as a system) may contain subsystems and components. Burn-in tests are also extensively applied to higher assembly levels such as PBAs (printed board assemblies) or complete systems. Many IC makers arrange burn-in between two final test stages, referred to herein as the pre- and post-burn-in tests. In practice, four types of burn-in test are during burn-in, static burn-in, dynamic burn-in and stress burn-in. Test during burn-in, in which an electronic test is conducted after a long burn-in process, is frequently used for DRAM and SRAM processes. Static burn-in applies stresses to the samples at either a fixed level or in an elevated pattern. Dynamic burn-in is exercised on the samples by stressing them to simulate operating environments. Conducted under an extremely stressful environment, stress burn-in is always more effective than dynamic and static burn-in for defects resulting from corrosion or contamination. This method is highly promising for the IC industry. However, according to our results, for switch mode rectifiers used to supply stable power to telecommunication systems, stress burn-in can save more time and energy. Finally, the performance and failure rate are calculated when all samples have completed the burn-in process.

2.2. Part stress analysis

Part stress analysis, a reliability prediction method, can be performed when most of the design is completed and a detailed list of parts (including part stresses) are available. The quality engineering department can also adopt this method during later design phases to evaluate reliability trade-off vs. part selection and stress. In parts analysis processing, the loading of each component in a system is critical. This loading determines the failure rate and mean time between failures of each component. This analysis is typically performed in a chamber under various temperatures, voltage stresses and functional tests. Each condition is an experimental treatment, and the loading of stress is measured by using individual parameter characteristics of each component. After evaluation, an engineer normally uses this data to either redesign the system or change to another component to satisfy the specification requirements. If redesign is not an option, purchasing a higher grade material may be another means of preventing the defect from causing a system failure.

2.3. Environmental stress screening

Two types of defects are patent and latent ones. While functional testing or inspection can detect patent defects, latent defects cannot be detected until they are transformed into patent defects. The final test may be unable to detect latent defects, thus giving the product a very short lifetime. Kececioglu and Sun [19] described ESS in which all products are subjected to one or more stresses, e.g. thermal cycling, electrical stress, and vibration, in order to force latent defects to surface as early failures. ESS accelerates the aging of latent defects by applying excessive stresses without shortening their useful life. Consider the expense of defects to both the manufacturer and customer. ESS yields the economic benefits of a higher quality and lower cost product, such as lower shop repairs, fewer warranty claims and field repairs, as well as customer loyalty.

3. Determination of burn-in time and cost

Herein, the determination of burn-in time and cost is divided into two main phases: (1) determine the optimum value of accelerated factor, and (2) optimize the burn-in time and cost. A detailed procedure is described as follows.

3.1. Determine the optimal value of accelerated factor

This phase attempts to provide an effectively designed experiment to determine the function of accelerated factor. Under this function, an optimum accelerated factor can be obtained for the stress burn-in process. Orthogonal arrays are used to design an experiment in this process. This flexibility accommodates diverse situations and can be easily executed in practice. This phase comprises of the following steps:

Step 1. Identify the quality characteristic to be observed.
Step 2. Identify the control factors and their alternate levels.
Step 3. Design the matrix experiment.
Step 4. Conduct the matrix experiment.
Step 5. Analyze the data to obtain the function of accelerated factor.
Step 6. Obtain the optimum average accelerated factor under various dwell times of a burn-in cycle.

Herein, an attempt was initially made to identify the quality characteristic for estimating the function of accelerated factor. Kececioglu and Sun [19] defined the accelerated factor as the ratio of the failure rate at the accelerated condition to that at the operating condition. Therefore, the quality characteristic can be identified as the ratio of failure rate.

After the quality characteristic was identified, response and control factors were determined for the experiment. The response can be expressed by the failure rate for each trial. Each trial was processed by the type I censoring test of burn-in. The type I censoring test, an estimation approach, tests the samples at chosen points; the experiment terminates at a pre-specified time. Also, in the power system industry, the control factors are temperature, input voltage and output loading of current. Owing to that the alternate levels of control factors are selected from upper, central and lower limits of specification, an $L_9(3^4)$ orthogonal array can be used for the experiment in this phase. When the experiment was conducted, the function of accelerated factor can be estimated by the model fitting of regression.

Fig. 1 shows the two worst burn-in conditions, which were considered in a stress burn-in process. On the time scale, input voltage and output loading of current are

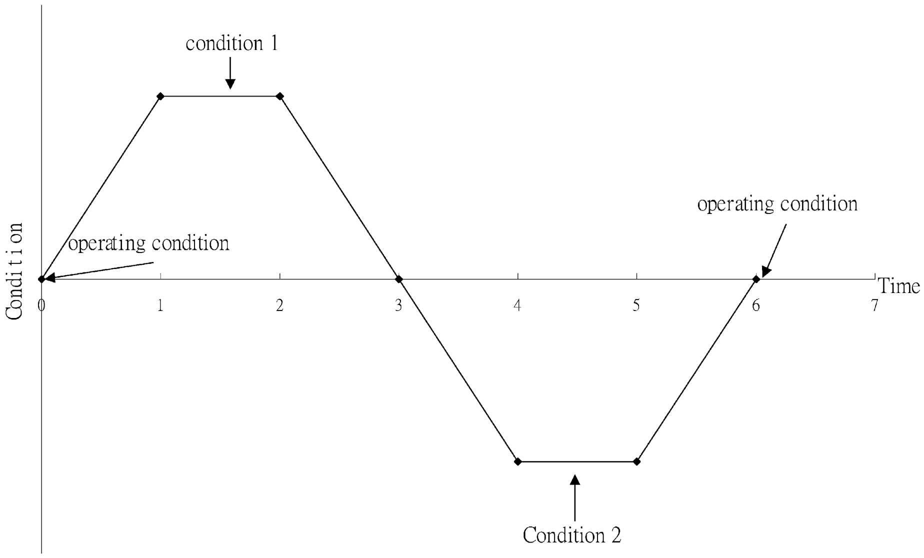

Fig. 1. A typical stresses cycle in burn-in.

changed at time 0, t_2 and t_5, heating occurs in the intervals $(0, t_1)$ and (t_5, t_6), and cooling occurs during (t_2, t_4). The interval (t_1, t_2) and (t_4, t_5) are two dwell times of worst conditions. By the accelerated factor function, the average accelerated factors of time scale can be calculated and yields.

$$A^*_{\mathrm{AF}} = \frac{\left(\int_0^{T_{\mathrm{f}}} A^*_{\mathrm{F}t}\,\mathrm{d}t\right)}{T_{\mathrm{c}}} \tag{1}$$

where T_{f} is the fixed burn-in time interval; T_{c} the cycle time of a burn-in cycle; $A^*_{\mathrm{F}t}$ is the accelerated factor at time t.

The higher the value of average accelerated factor implies a higher efficiency of screen latent defect. Since the different dwell times lead to different cycle times and average accelerated factors of burn-in, the optimum average accelerated factor can be found through the analysis of dwell time.

3.2. Optimize the burn-in time and cost

If the failure rates and mean lives at operational stress S^*_{o} and at accelerated stress S^*_{a} are given by $\lambda(S^*_{\mathrm{o}})$, $\lambda(S^*_{\mathrm{a}})$, $L(S^*_{\mathrm{o}})$ and $L(S^*_{\mathrm{a}})$, the acceleration factor, $A_{\mathrm{F}}(S^*_{\mathrm{o}}, S^*_{\mathrm{a}})$, can be defined as the ratio of the mean life at the operating stress to that at the accelerated stress, or

$$A_{\mathrm{F}}(S^*_{\mathrm{o}}, S^*_{\mathrm{a}}) = A^*_{\mathrm{F}} = \frac{L(S^*_{\mathrm{o}})}{L(S^*_{\mathrm{a}})} = \frac{\lambda(S^*_{\mathrm{a}})}{\lambda(S^*_{\mathrm{o}})} \tag{2}$$

According to Eq. (2), the times-to-failure of accelerated stress burn-in is linear with the operating condition of burn-in. Therefore, the optimum burn-in time of accelerated stress can be represented as:

$$T^*_{\mathrm{sb}} = \frac{T^*_{\mathrm{b}}}{A^*_{\mathrm{F}}} \tag{3}$$

where T^*_{b} is the optimum burn-in time under operating condition.

In addition, T^*_{b} can be found from the cost model of burn-in. Herein, we make the same assumptions about the cost of the burn-in procedure as in Ref. [20]. Namely, the cost is additive and has the following elements:

C_0: the manufacturing cost per unit without burn-in;
C_1: the fixed setup cost of burn-in per unit;
C_2: the cost per unit time of burn-in per unit;
C_3: the shop repair or replacement cost per failure;
C_4: the extra repair or replacement cost per failure during the warranty period.

Now, if the burn-in time is T_{b}, from the above assumptions, the cost function of burn-in is given as:

$$h(T_{\mathrm{b}}) = C_0 + C_1 + C_2 T_{\mathrm{b}} + C_3 \int_0^{T_{\mathrm{b}}} r(t)\mathrm{d}t + C_4 \int_{T_{\mathrm{b}}}^{wt} s(t)\mathrm{d}t \tag{4}$$

where $r(t)$ and $s(t)$ are the failure rate at shop and after shipment of the warranty period. If the failure rate of latent defect P of a product can be found in advance, Eq. (4) can be rewritten as:

$$h(T_{\mathrm{b}}) = C_0 + C_1 + C_2 T_{\mathrm{b}} + (C_3 - C_4) \int_0^{T_{\mathrm{b}}} r(t)\mathrm{d}t + PC_4 \tag{5}$$

Also, from Eq. (5), if the probability density function $f(x)$ of time-to-failure of latent defect can be obtained in advance. Therefore, Eq. (5) can be rewritten as:

$$h(T_{\mathrm{b}}) = C_0 + C_1 + C_2 T_{\mathrm{b}} + P\left((C_3 - C_4) \int_0^{T_{\mathrm{b}}} f(t)\mathrm{d}t + C_4\right) \tag{6}$$

The optimum burn-in time and cost of operating condition can be obtained from Eq. (6). Under optimum average accelerated stress, the optimum burn-in time and cost of accelerated stress can be obtained by Eq. (3).

This phase comprises of the following steps:

Step 7. Obtain the average failure rate and the probability density function of latent defects by using the historical data.
Step 8. Calculate the optimum burn-in time and cost of operating condition by using Eq. (6).
Step 9. Calculate the optimum burn-in time and cost for accelerated stress condition by using Eq. (3).

4. A case study

4.1. The problem

The telecommunications industry has rapidly expanded in recent years. Both wireless and wireline telecommunications networks must satisfy customer requirements. The advanced power system of Delta Corporation can achieve these complex network tasks reliably and economically. Designed to provide the ultimate in reliability and flexibility for wireless and wireline applications, the power system incorporating ESR-3000 switch mode rectifier is a plug-in module rated at 50 A at −48 V DC or 100 A at +24 V DC. Its compactness and lightweight ensure easy installation and maintenance. Fig. 2 depicts the structure of a rectifier system, and its operating environments are summarized as

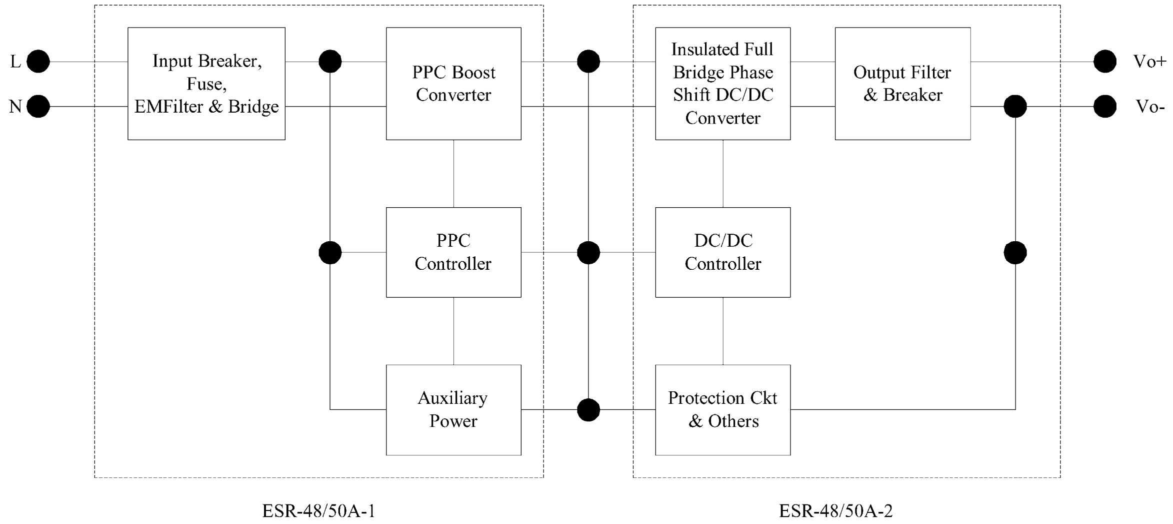

Fig. 2. A rectifier diagram.

follows:

1. Input voltage: 220 V AC 20% single phase
2. Input frequency: 47–63 Hz
3. Operating temperature: 0–50 °C
4. Humidity: 10–90%

Correcting an external failure is very costly. As widely assume, burn-in is the most effective means of screening out early product failure before shipment. Following MIL-STD-217F, the burn-in operating environmental parameters of the ES-3000 rectifier can be separated into three factors: input voltage, temperature and output loading. Previously, static burn-in was used for the burn-in process. Since static burn-in is operated in an elevated condition and did not simulate the real worst operation, some potential defects may be absconded in the burn-in process. This study proposes a procedure to increase the burn-in efficiency. The settings for the stress burn-in operation might decrease the failure rate and cost more than that by the static burn-in procedure.

4.2. Implementation

In the stress burn-in process, the levels of control factors can be selected from upper, central and lower limits of specification, and are listed in Table 1. Through the part stress analysis of MIL-STD-217F and engineer's experience, $A_3B_1C_3$ and $A_3B_3C_3$ were selected to simulate the real worst operation of a product, and the operational time lasts more than 0.5 h.

After the burn-in condition was determined, type I censoring test approach was used on an $L_9(3^4)$ orthogonal array to conduct the failure rate of each trial. The test was

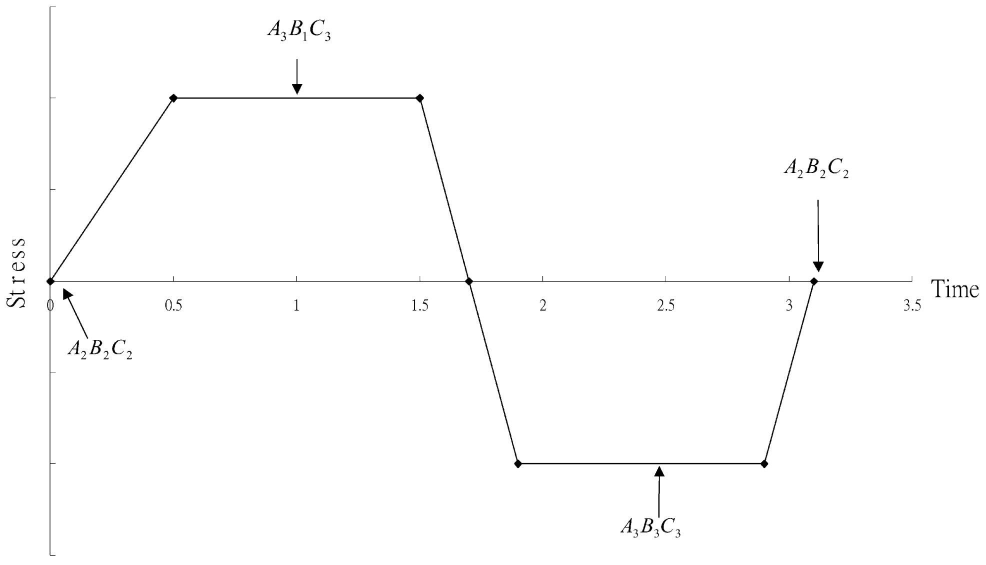

Fig. 3. The dwell time of one cycle.

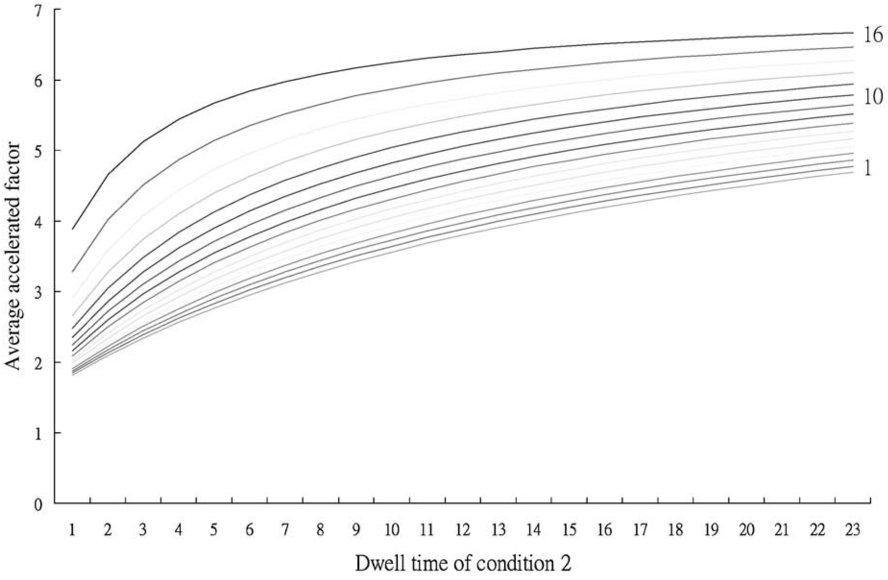

Fig. 4. The accelerated factor of dwell time.

terminated at 24 h. Based on the engineer's experience, the dwell time of each condition was initially setting 1 h. Owing to the limitations of the equipment, the average heating rate is 0.8 °C min^{-1} and the cooling rate is 1 °C $^{-1}$. Fig. 3 shows the burn-in process. In this burn-in process, eight cycles of condition were processed and 300 samples were used in each trial of $L_9(3^4)$. The second to last column of Table 2 lists the failure rates of each trial. Based on the failure rate of operating condition (i.e. the last trial of Table 2), the accelerated factor of each trial was transferred and listed in the last column of Table 2. Accordingly, the accelerated factor can be fitted as regression model and yields

$$A_F(T, V, C) = 61.863422 + 0.203595T - 0.59578V + 0.303736C + 0.005244T^2 - 0.002015TV + 0.001468V^2 - 0.002806TC - 0.00065VC - 0.000674C^2 \quad (7)$$

where T, V and C are the temperature, input voltage and output loading of current, respectively. Since the different dwell times lead to different average accelerated factor, Fig. 4 presents the trend of accelerated factor for two

Table 1
Control factor and their levels

Factor	Levels		
	1	2	3
Input voltage (*A*)	264 V	220 V	176 V
Output loading (*B*)	50 A	25 A	0 A
Temperature (*C*)	50 °C	25 °C	15 °C

Table 2
Failure rate by experiment

Trials	Factors			Failure rate	Accelerated factor
	Input voltage (V)	Output loading (A)	Temperature (°C)		
1	176	0	15	1	1
2	220	25	15	2	2
3	264	50	15	6	6
4	176	25	25	4	4
5	220	50	25	2	2
6	264	0	25	2	2
7	176	50	50	8	8
8	220	50	0	3	3
9	264	50	25	3	3
10	220	25	25	1	1

Table 3
The times-to-failure of operating condition

Time (h)	Quantity
1	80
2	2
3	5
4	79
5	117
6	119
7	106
8	71
9	35
10	18
11	10
12	7
13	5
14	4
15	3
16	2
17	2
18	1
20	1
23	1

different dwell times, indicating that the accelerated factor increases as the dwell time of condition (1) increases. Consequently, the optimum average accelerated factor can be calculated from Eq. (1), and the value is 6.77.

After the optimum average accelerated factor was obtained, the optimum burn-in time of operating condition must be determined. Table 3 lists the times-to-failure data of 14,300 samples that resulted from operating condition. By the probability plot with 95% confidence limits, Table 4 lists the R^2 value of several distributions. The R^2 value is a measure of how well the data forms a straight line. An R^2 value is 1.0, indicating a perfect straight line. This same table reveals that the exponential distribution can be used as the distribution of data in Table 3. Moreover, the mean of latent defects can be obtained by the data fitting which is 5.125. Table 5 listed the elements of cost. By the record of historical data, the average failure rate of latent defect is 0.05. From above datum, Eq. (6) can be represented as:

Table 4
The R^2 of distributions

Distribution	R^2
Exponential	0.996
Lognormal	0.8606
Weibull	0.8412
Normal	0.7172

Table 5
Elements of cost

Elements	Cost
C_0	1283NT\$/U
C_1	145NT\$/U
C_2	35NT\$/H,U
C_3	1400NT\$/U
C_4	70,000NT\$/U

$$h(T_b) = 4928 + 35T_b - 3430\int_0^{T_b} \frac{e^{T_b/5.125}}{5.125}\,dT_b \tag{8}$$

The optimum burn-in time and cost were calculated as US\$15.123 and 71.19. The failed unit is often more than 100 times the cost of catching the failure before it leaves the

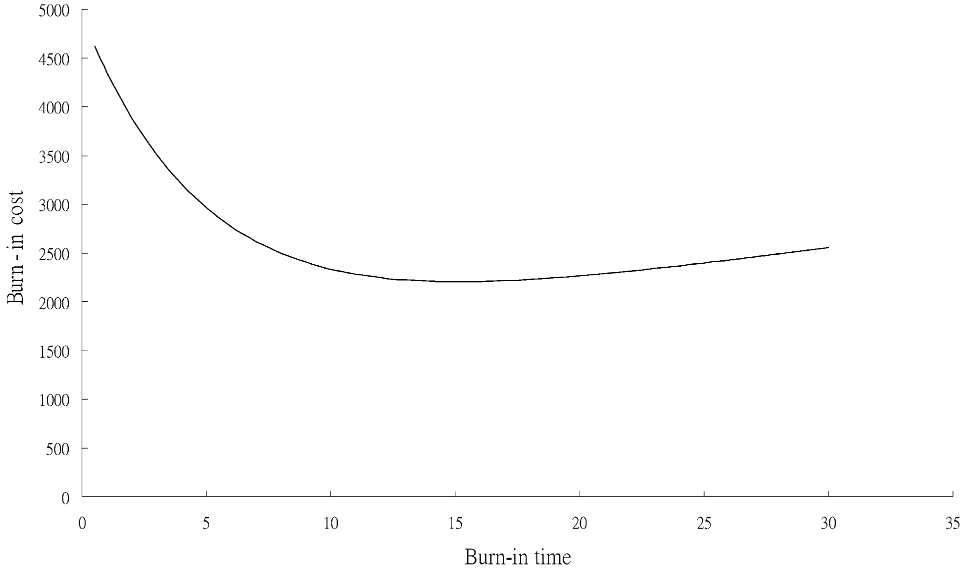

Fig. 5. Burn-in time vs. burn-in cost.

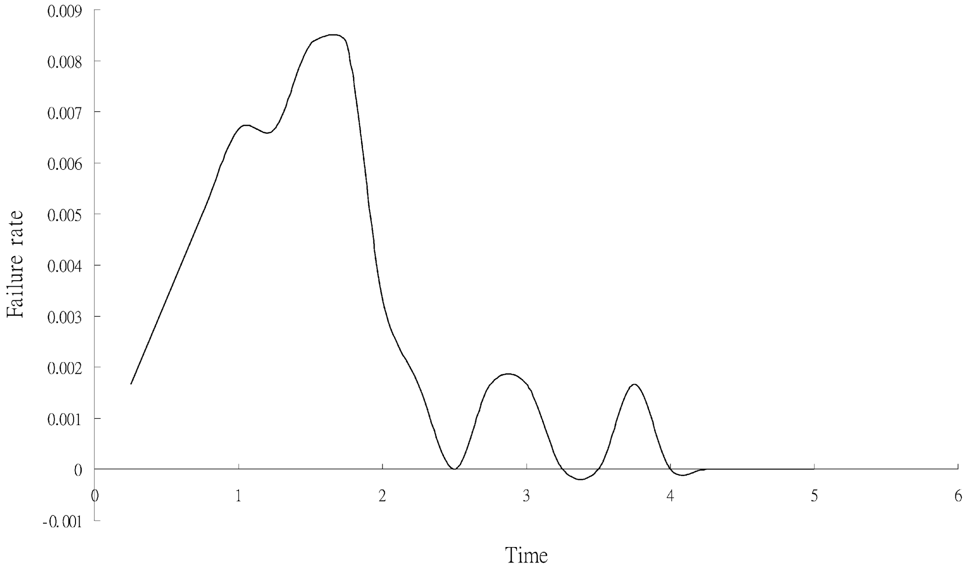

Fig. 6. Failure rate vs. burn-in time for accelerated stress condition.

factory [2], i.e. the warranty cost are much larger than shop repair cost. Table 6 summarizes the change of warranty cost. Under the minimum cost constraint, a larger warranty cost results in larger burn-in times. When the warranty cost is US$2258, Fig. 5 indicates that the minimum burn-in cost occurred at 15.123 h.

After the optimum burn-in time of operating condition was determined, the optimum burn-in time of accelerated stress can be obtained by Eq. (3) in which the value is 2.234 h.

4.3. Confirmation

After optimum burn-in time was implemented, 600 samples were verified by 5 h of burn-in process. Table 7 lists these times-to-failure data and Fig. 6 plots the curve of data fitting. The mean life of latent defects is 1.25, and the optimum burn-in cost can be calculated from Eq. (8) and yields US$69.35. The cost was less than the cost of operating condition. Moreover, according to Fig. 6, all defects can be eliminated at the optimum burn-in time point, thus demonstrating the effectiveness of the proposed approach.

Table 6
Warranty cost vs. optimum burn-in time

Warranty cost (US$)	Optimum burn-in time (h)
161.3	0.0175
322.5	4.481
645.2	8.434
967.7	10.6392
1290.3	12.176
1612.9	13.357
1935.5	14.316
2258.1	15.123
2580.6	15.820
2903.2	16.430
3225.8	16.982
6451.6	20.571
12,903.2	24.143
22,580.6	27.017

5. Conclusions

Environmental Screening Stress and burn-in are two effective means of screening latent defects in the electronics

Table 7
The times-to-failure of accelerated stress condition

Time (h)	Quantity
0.25	1
0.5	2
0.75	3
1	4
1.25	4
1.5	5
1.75	5
2	2
2.25	1
2.5	0
2.75	1
3	1
3.25	0
3.5	0
3.75	0
4	0
4.25	0
4.5	0
4.75	0
5	0

industry. Combining these characteristics of ESS and burn-in enables stress burn-in to eliminate the defect of latent. Manufacturers have focused on determining an effective stress burn-in time and cost for quite some time. Although many burn-in models have been developed, none have been practical. Engineers have had difficulty in determining the optimal burn-in time and cost for an electronic product, which is time consuming and costly. This study presents an effective approach to determine optimal burn-in time and cost. The proposed approach can effectively screen out latent defects before a product is shipped to the customer. A case study involving the production of rectifier demonstrates that the proposed procedure yields a lower cost and failure rate than ambient condition of burn-in process.

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