Understanding the Technology

Guidance for accelerated testing and reliability —For electrical and electronic parts and equipment—

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Resources are continually being poured into efforts to improve the reliability of electrical and electronic parts and equipment. This has lead to the production of a large number of highly reliable products, and brought about a sharp decline in failure rates. Concretely evaluating product reliability requires extremely long periods of time of environmental testing, specifically in the area of reliability testing. These time constraints have created a need for accelerated testing that can produce effective results in shorter periods of time. However, accelerated testing cannot be achieved by merely ratcheting up the stress to shorten testing times, and this type of testing is not applicable to every situation. Accelerated testing, just like other forms of reliability testing, is a reliable test method supported by scientific logic.

In this report, we would like to present the logic behind accelerated testing in an easily understandable way, from the standpoint of environmental testing used in the fields of electricity and electronics.

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1. Introduction

The details of environmental testing differ according to the type of product, and no one test method can serve for all products. We could go so far as to say that each individual product requires its own test procedure. Within the category of reliability testing, environmental testing normally focuses on determining whether a product can fully display and maintain its established functions within the marketplace environment of actual use after the product has been shipped from the factory. This testing is done from the standpoint of technology directly related to the product. However, even the same types of products face a variety of environments in the marketplace, including how the individual product may be used. Because products meet such conditions, each type of environmental test has its own significance. However, accelerated testing is not created by merely increasing the stress in a rush for results. Such methods will simply create destruction testing. Because of this, we must thoroughly understand the principles of accelerated testing, carefully construct the logic involved, and create a method in which no contradictions arise in the testing procedure.

2. Definitions, prerequisites, and fundamentals

According to "JIS (Japanese Industrial Standard) Z 8115 Glossary of terms used in reliability", accelerated testing refers to "a test in which the applied stress level is chosen to exceed that stated in the reference conditions in order to shorten the time required to observe the stress response of the item." In general, the more severe the conditions in relation to standard conditions, the more quickly it is possible to complete the test. However, it would be premature to conclude that we have proven the excellence of a product simply because it has endured an accelerated test. A product that has successfully endured extremely severe conditions may fail in a relatively short time under the same type of stress conditions that are considered extremely mild. We must create a test plan for all methods of use and surrounding environments that can be imagined, and we must carry out complete pre-test studies and check for misconceptions in logic, and make sure we haven't missed anything.

To start with, there is always a cause for each type of product failure. Unless there has been severe misuse, such failures do not merely appear out of the blue. Seen from a qualitative standpoint, the failure of electrical and electronic products, and electronic equipment in particular, begins when changes are experienced in the physical and chemical characteristics of the materials used in their production. Such changes can be caused by an intrusion from the external environment, or from internal factors, or from a combination of both internal and external factors. These physical and chemical reactions are affected by the surrounding environment (heat, in particular), speeding the reaction, and the product functions are weakened are weakened or completely stopped in the course of achieving equilibrium in that reaction. Therefore, accelerated testing consists of speeding up this physical and chemical process with suitable ambient environments, causing malfunctions to appear.

Accelerated testing characteristically entails knowing in advance the results of testing when deciding to run the tests, because one must establish what is being accelerated in relation to what, and clearly establish the items that serve as the basis for acceleration. Essentially, accelerated testing is not a means for ferreting out new modes of failure, but rather serves as a time-saving means of confirming phenomena that have already been identified. Therefore, major premises have already been proposed concerning the factors involved in failure and the mechanism leading to failure. Only when expected results are obtained do the conclusions form accelerated testing. Then, by recording the test preparations and accumulating the data, it finally becomes possible to apply the procedures to similar products. However, there are no accelerated tests that can be applied indiscriminately to all products and failure modes. For example, if the relation between the failure mode and the acceleration mechanism is not known and we just expose a new product to severe conditions and cause the product to fail, the only result will be that we have destroyed the product. We will not be able to obtain any scientifically valid data at all from such testing. We must remember that accelerated testing, as one form of reliability testing, is a very specific technical method.

To sum up, accelerated testing consists of, "accelerating the mechanisms causing product failure by using conditions that are more severe than standard conditions, and saving testing time by utilizing the systematic nature existing between the standard conditions and the accelerated conditions in the identical mode of failure." In other words, the absolute prerequisites to accelerated testing are:

(1) Having the same product failure mode, and
(2) Having a systematic relationship between standard conditions and accelerated conditions.

Care must also be taken in the following matters when performing accelerated testing.

(1) The test must be based on the main points whose results have been predicted by thoroughly examining the problems.
(2) The test conditions must be constructed on the basis of thoroughly grasping the usage conditions and the ambient environment of the product.
(3) When special prerequisites exist, they must be dealt with, but one should always try to gather universal data that can be applied in the future.

The most important condition of all is to clarify exactly the purpose for running the test. In other words:

(1) The test presumes a correlation with conditions in the field. (Conditions are within the product ratings, and the test aims at forecasting or reproducing failures that occur in the field.)
(2) The test attempts to detect the characteristic weaknesses of the product. (With the aim of collecting data to discover and improve product weaknesses)

(3) The test simply attempts to confirm product durability. (Durability is confirmed outside the product rating.)

Details and procedures will vary, depending on the purpose of the test, and different types of test and measurement equipment will be used.

3. Accelerated testing and the physical chemistry of product failure

The physical chemistry of product failure in electrical and electronic equipment can be broadly grouped into approximately 30 categories, or more specifically classified into about 70 categories. The mechanisms leading to failure have mostly been elucidated. Therefore, the method of planning accelerated testing or analyzing product failure quite often consists of selecting the appropriate mechanism leading to predicted failure from among these categories, and then verifying the pre-selected or pre-constructed failure model.

First of all, to capture the general concept of failure occurrence, the stress-strength model is briefly checked, and then great emphasis is placed on the chemical kinetics model, which is extremely easy to understand for accelerated testing.

3-1 Stress-strength model

This model explains the process leading to failure through the relationship between the characteristic durability of the product and the stress from the ambient environment. (Failure occurs in the areas in which deterioration of durability and distribution of stress overlap.)

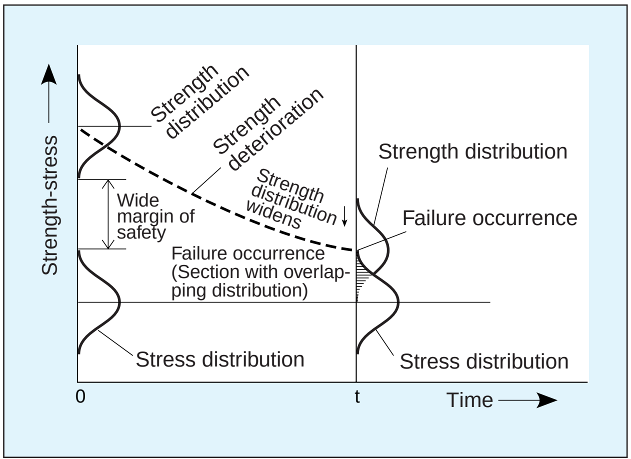

Fig. 1 Stress-strength model

3-2 Chemical kinetics model

This model is based on the chemical reactions between the molecules of matter within a solid, and utilizes the principle that the existence of background heat strongly influences the initiation and the progress of the reaction. For example, when hydrogen and oxygen react to form water, the higher the temperature, the greater the speed of the chemical reaction.

The Arrhenius model is the model that most directly expresses the thermal transition. In 1899, S.T. Arrhenius proposed the formula

$$K = \Lambda\,[\exp(-B/T)] \qquad (3.1)$$

Where T represents temperature (absolute temperature) and K represents the speed of the chemical reaction. This formula shows strong conformity to test results.

Formula (3.1) can also be written in the following way.

$$K = \Lambda\,[\exp(-E/RT)] \qquad (3.2)$$

Here, Λ and E represent individual constants for the reaction conditions. Λ is called the frequency factor, and E is called the apparent activation energy. R is the Boltzmann constant, and by writing this another way, it can be done in the same manner as the Maxwell-Boltzmann distribution, which specifies the energy distribution of the gas molecules. When the chemical reaction is primary, Λ contains the $[\text{time}]^{-1}$ dimension, so it is called the frequency factor. The fact that E is positive in this formula means that rising temperature increases the speed of the chemical reaction, and the greater the value of E, the greater the speed of the chemical reaction.

As the temperature of a gas rises, the motion velocity increases in the molecules that make up the gas. However, the gas contains a mixture of fast-moving and slow-moving molecules, and if we posit that the velocity distribution conforms to the negative exponential distribution in relation to ($1/T$), then in particular the activated molecules abounding in energy are what is actually contributing to the reaction, and the proportion of activated molecules increases markedly along with rising temperature. It has been proposed that the chemical reaction between two gases can only be contributed to by molecules with relative motion energy that exceeds activation energy level E. Therefore, in isothermal reactions in this type of molecular collision between two gases, the explanation of formula (3.1) applies to the proportion of $\exp(-E/RT)$, which is the proportion of activated molecules with energy above a certain energy limit value. However, because this theory cannot be properly applied to more complex reactions in which numerous molecules participate, in 1935 H. Eyring and E.H. Eyring proposed the absolute reaction theory that was developed from this approach.

This approach holds that activation energy is the main factor in reaction velocity, and that this can be separated into activation energy and activation entropy. When T represents temperature stress and S represents other stress, reaction velocity K becomes

$$K = \Lambda\,[\exp(-B/T)]S^{\alpha} \qquad (3.3)$$

This is known as the Eyring formula. This formula is frequently used in the field of electrical and electronic equipment. However, no theory has yet been established that can account for all chemical reactions. Here, α becomes the constant.

3-3 Applying chemical kinetics

Let's try to adapt these formulas to the field of electrical and electronic equipment reliability. Using the aforementioned stress-strength model, we can conceptually grasp the process in which physical changes resulting from stress such as temperature and voltage reduce durability and lead to failure. Can chemical kinetics be applied to explain this type of phenomenon?

If we express the level of stress applied to a product as x and the level of resulting deterioration as y, and if we regard y as a function of x, then we can express the following relationship.

$$y = \phi(x)$$

When there are multiple sources of stress, we must regard x as a vector, but to simplify matters, we can make it scalar.

Deterioration with age dy/dt signify reaction velocity, so we can express this as

$$\frac{dy}{dt} = K \qquad (3.4)$$

Here, when K is a constant, if we integrate formula (3.4), we get $y = Kt$. Now, if we set L as the time in which deterioration level y reaches product proof stress limit r, then the $y = Kt$ relationship yields the relationship

$$L = r/K \qquad (3.5)$$

Next, if we substitute formula (3.3) for this formula, we get

$$L = [(r/\Lambda)\exp(B/T)]S^{-\alpha} \qquad (3.6)$$

At this point, we can think of the product being operated. If we have the following two instances,

(1) Stress voltage is V_1, operating temperature is T_1 and the corresponding life is L_1, and the failure rate is λ_1

(2) Stress voltage is V_2, operating temperature is T_2 and the corresponding life is L_2, and the failure rate is λ_2

Using formula (3.6), we can show both relationships as

$$L_2 = L_1 \exp[B(1/T_2 - 1/T_1)] \cdot \left(\frac{V_2}{V_1}\right)^{-\alpha} \qquad (3.7)$$

If we attempt to express this as a failure rate, the mean life L and the failure rate λ of the electrical and electronic equipment have an inverse function relationship, and so the above formula becomes

$$\lambda_2 = \lambda_1 \exp[-B(1/T_2 - 1/T_1)] \cdot \left(\frac{V_2}{V_1}\right)^{\alpha} \qquad (3.8)$$

In the above formula, $V_2/V_1 = S$ is called the stress ratio.

When $\alpha = 0$ in formula (3.7), this becomes the Arrhenius formula, and is often adapted to temperature-dependent deterioration phenomena, and is useful for establishing the acceleration factor when performing accelerated testing.

In other words, formula (3.7) can be rewritten in the following way.

$$\begin{aligned} L_2 &= L_1 \exp[B(1/T_2 - 1/T_1)] \\ &= L_1 \exp[E/R(1/T_2 - 1/T_1)] \end{aligned} \qquad (3.9)$$

In other words, the rate of acceleration (the acceleration factor) can be found with the following formula.

$$Ac = \frac{L_2}{L_1} = \exp\left[\frac{E}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)\right]$$

$$\text{or} \quad \ln\frac{L_2}{L_1} = \left[\frac{E}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)\right] \qquad (3.10)$$

The Arrehnius model is widely applied to reliability testing and failure analysis of electrical and electronic equipment, especially to semiconductor devices. That is to say, semiconductor devices are manufactured using physical and chemical changes in the surface layers of material, and rather than having a structure of complete crystallization or solidification, they are combined in an amorphous state. Because of this, the changes that appear tend to be chemical rather than physical changes, and so chemical theory is considered easier to apply.

4. The relationship between accelerated testing and predicting product life

At this point, we would like to take up a very simple example and examine it using numerical values.

From the standpoint of environmental conditions, we shall set the following theme. "What levels of acceleration are possible if instead of using a TH (Temperature and Humidity) test with test conditions of 85°C and 85 percent RH, we substitute a HAST (Highly Accelerated Temperature and Humidity Stress Test) with test conditions of 120 to 140°C and 85 percent RH? Also, using those results, to what level of reliability can we predict product life in the field?"

As a precondition, these are temperature and humidity tests, and in detailed analysis the water vapor pressure differential is required as an environmental condition. However, to simplify the explanation, let's say the relative humidity is proportional to the temperature, and utilize the common value and just do away with the humidity parameters. (There has yet to be a theory established proving the humidity relationship. Perhaps water vapor pressure corresponds to the amount of intruding water vapor. Water vapor and water are physical matter, and so this activity level is thought to correspond to the temperature.)

First of all, let's look at the first of the two formulas in formula (3.10).

$$Ac = \frac{L_2}{L_1} = \exp\left[\frac{E}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)\right]$$

If we say that $R = 8.615 \times 10^{-5}$ (eV/K), the above formula becomes the following.

$$Ac = \exp\left\{1.16 \times 10^4 \times E \times \left(\frac{1}{273 + T_{85}} - \frac{1}{273 + T_{HAST}}\right)\right\} \tag{3.11}$$

If we insert the various temperatures into this formula and do the calculations, we obtain the acceleration factors in Table 1 depending on the different values for E.

Table 1 Acceleration factors for TH tests in HAST

E (eV)		0.6	0.8	1.0	1.2	1.5
HAST	110°C	3.56	5.43	8.29	12.7	23.9
	120°C	5.65	10.1	17.9	31.9	75.8
	130°C	8.77	18.1	37.3	76.6	228
	140°C	13.3	31.6	74.8	177	647

Note: The values of E, the activation energy, are values obtained from typical failure modes of semiconductor devices, but please regard these numerical values as strictly hypothetical.

Next, from the results of HAST (130°C and 85 percent RH), let's try to predict the corresponding product life for a product submitted to the test, and let's say that the product will be used in Japan in a typical Japanese summer environment of 35°C and 85 percent RH. Let's take the lower limit for the value of E as 0.8 and the upper limit as 1.0.

Predicted life when $E = 0.8$

$$L_{E=0.8} = \exp\left\{1.16 \times 10^4 \times 0.8 \times \left(\frac{1}{273 + 35} - \frac{1}{273 + 130}\right)\right\}$$

=1268.512 ⟶ approximately 1200 times

Predicted life when $E = 1.0$

$$L_{E=1.0} = \exp\left\{1.16 \times 10^4 \times 1.0 \times \left(\frac{1}{273 + 35} - \frac{1}{273 + 130}\right)\right\}$$

=7570.39 ⟶ approximately 7500 times

Therefore, if we perform a 48-hour test using the above test conditions, and we say that failure did not occur, the product life in the field would be:

For $E = 0.8$: 48×1200 = 57,600 hours = 6.5 equivalent years

For $E = 1.0$: 48×7500 = 360,000 hours = 41.0 equivalent years

5. Constructing accelerated tests

5-1 The acceleration factor

When we discuss accelerated testing, our immediate greatest concern is the acceleration factor.

By the way, we are often told, "We would like to perform humidity endurance testing for a certain product, but at what level should we estimate the acceleration factor, and what test conditions should we use?" Well, there is no acceleration test that corresponds unconditionally even to any one product, and moreover, there is no acceleration factor that can be applied unconditionally with no preconditions at all. The related references and research papers contain notations of acceleration factors as test results for specific products, and for those of you who are considering testing this may look like something you just "gotta have", but wait just a minute. Previously, we introduced the matter of "preconditions". Do those references and research papers include the details of those "preconditions"? Unfortunately, in most cases those preconditions simply don't exist, and the details of the course and conditions of the test have been omitted. As these are not completely hypothetical discussions, they should serve as a reference, but they are, after all, other people's data, and you'll have to decide for yourself whether you can rely on them in your own circumstances.

There are three variables (E, T_1, and T_2) in formula (3.10), given earlier for finding the extremely simple acceleration factor. We have nothing to say at this point about T_1 and T_2, but E is crucial. It is the value for activation energy, and as we saw in the previous example, even a slight change in this value can yield a prediction for product life that is about six times longer. Therefore, the actual value of E must be found at all costs from the experimental data itself.

Well, how should we go about finding the value of E?

5-2 Constructing conditions for an acceleration test (1)

First of all, rather than indulge in excessive explanations, let's try to solve the following example.

Question

Preliminary testing of a certain product found that the MTTF (mean time to failure) was 310 hours at 150°C, 1000 hours at 125°C, and 4000 hours at 100°C. Let's hypothesize that the failure mechanism for this product does not change at temperatures between 75 and 150°C, and answer the following questions.

(1) Find the activation energy, then find the MTTF at 75°C.

(2) Indicate whether a test should be run to find how many hours MTTF will be at 125°C to prove that MTTF is 5000 hours at 75°C.

Answers

(1)

a) First of all, arrange the preconditions as follows.

L_{150} = 310-hour life at 150°C

L_{125} = 1000-hour life at 125°C

L_{100} = 4000-hour life at 100°C

b) Next, using the second of the two formulas in (3.10), change the formula to find *E*.

$$\ln\frac{L_2}{L_1} = \left[\frac{E}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)\right]$$

$$\rightarrow E = \frac{R(\ln L_{100} / L_{150})}{\left[\frac{1}{T_{100}} - \frac{1}{T_{150}}\right]} \tag{3.11}$$

If we substitute the actual values in formula (3.11), we get

$$E = \frac{8.615 \times 10^{-5}(1n\ 4000/310)}{\frac{1}{273+100} - \frac{1}{273+150}}$$

$$= 0.68(eV) \text{ ... the activation energy}$$

c) Since we have found the activation energy, let's see what sort of ratio exists between L_{100} (T = 100°C) and L_{75} (T = 75°C).

$$\ln\frac{L_{75}}{L_{100}} = \frac{0.68}{8.615 \times 10^{-5}}\left(\frac{1}{273+75} - \frac{1}{273+100}\right)$$

$$= 1.523$$

$\therefore L_{75}/L_{100}$ = exp 1.523=4.59 (the acceleration level between L_{75} and L_{100})

Since the MTTF is 4000 hours when T = 100°C, we can find the MTTF when T = 75°C by calculating 4000(hr) × 4.59 = 18,360(hr).

(2)

Using the MTTF for T = 75°C found above in part (1), find the acceleration factor between L_{75} and L_{125}.

Ac = L_{75}/L_{125} = 18,360hr/1,000hr = 18.36

Therefore, to prove that MTTF is 5000 hours at temperature conditions of 75°C, the conditions at 125°C would be 5000(hr)/18.36 = 272.33(hr). In other words, a test of approximately 272 hours would be required.

(When solving this sort of problem, in addition to methods such as the above relying entirely upon using formulas to calculate the answers, one can also use the Arrehnius plot using semi-logarithmic paper. Due to space limitations we cannot deal with that method in this report.)

5-3 Constructing an acceleration test (2)

From the example in section 5-2, we have seen an overview of how to construct an acceleration test. Namely,

(1) Since product tolerances for the ambient environment are set in the product planning and design stage, pretesting should be done, and just as in this example, test conditions should be separated into several stages to find the MTTF.

(2) In an attempt to shorten testing time, these pretests are begun from temperatures thought to be at the upper limits of product heat endurance. However, you have a small number of specimens and you are collecting a wide variety of technical data in the course leading up to product failure, then you should start from low temperatures. In the example, acceleration testing was constructed for tests at low temperatures, but if the product has a high temperature tolerance, then high temperatures can be used to find test times.

(3) Perform failure analysis for products that fail at each stage, and analyze the mechanism leading to failure. Since obtaining identical failure modes is a precondition for accelerated testing conditions, it is extremely important to check analysis work and results. (At this time, it is also important to analyze products that did not lead to failure. A comparison of good products with failed products can be a conclusive factor in determining product quality, and can also be a basis for improvement measures.)

(4) As you can see, the conditions for accelerated testing are determined at the stage of pretesting and analyzing the pretest results. More time is required for constructing an accelerated test than for carrying out the test. When there are no systematic relations, there can be no accelerated testing.

(5) The following two methods are used to reveal acceleration. In the example, we used method number 1 below to calculate acceleration.

1. One method is to use proportionate time and attain an equivalent cumulative failure rate to compare accelerated testing and tests run at standard conditions.

$$\textbf{Degree of acceleration} = \frac{\textbf{Time required at standard conditions}}{\textbf{Time required at accelerated conditions}}$$

2. Another method is to use proportionate time for the failure rate at a specific time to compare accelerated testing and tests run at standard conditions.

$$\textbf{Degree of acceleration} = \frac{\textbf{Failure rate at accelerated conditions}}{\textbf{Failure rate at standard conditions}}$$

In general, the first method is more widely used.

6. Conclusion

When considering accelerated testing from the standpoint of the reliability of an individual product, the preceding examples show that it can be relatively dangerous to assume that you can just use the same test conditions that another company has used. In particular, when applying the chemical kinetics model, the key to success is the value of *E*, the activation energy, and this value can be assumed to vary with different products. Even among products with the same types of functions, there will be slight variance among different manufacturers in raw materials, design details, and manufacturing methods. This "slight variance" can have a considerable impact on the value of *E*.

If you should feel that, "It's the same type of product, and seen from the current level of technology, there should be very little difference from our company in materials, design details, and manufacturing methods," we must concede the possibility of opening reference literature or other research papers and utilizing the values of *E* given there. However, it will not be possible to ascertain whether these values are actually applicable to your company's product. You should keep in mind that the reliability testing results and the predicted life calculated using these values may be lacking in accuracy.

Up to this point we have been discussing individual accelerated tests, but actually it is possible to predict the failure rate without relying on testing, though this is limited to electronic parts. This can be done by using such procedures as MIL-HDBK-217F Reliability prediction of electronic equipment, and the Bellcore TR332 ISS05 Reliability prediction procedure. The former, being "MIL" naturally is used by the US military for electronic parts, but since it is based on field data, it has a high level of precision, and is very useful as a reference. However, it requires some modification for application to civilian parts. The latter is based on MIL-HDBK-217, and consists of purchasing specifications establishing an independent evaluation method.

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