

Accelerated Degradation Test under Multiple Environmental Stresses and Reliability Estimation for Circular Electrical Connectors

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Abstract

The circular electrical connector is widely used in aviation, aerospace and military system applications. Under such working or reserving conditions, contact failure is the most prevalent failure mechanism of electrical connectors. But only a few tests especially multiple stresses tests and physics of failure (PoF) modeling study are conducted on this type of electrical connectors. This paper addresses some concerns related to the last application of modeling, estimation of electrical connectors' reliability. A combined laboratory accelerated degradation testing (ADT) and PoF modeling approach to estimating connector reliability will be proposed.

Firstly, the basic approach and mathematics of reliability estimation based on degradation data are proposed and summarized. The contact resistance is selected as degradation index, and an application-specific failure criterion for contact resistance degradation is also determined. Secondly, random vibration and current stress are selected as acceleration factors that affecting the contact life of electrical connectors. And an appropriate multiple stresses ADT scheme is derived. The PoF model for electrical connectors under multiple stresses yielded the generalized Eyring relationship. According to the system reliability model for multi-position connectors, connectors' life follows Weibull distribution, which is derived from extreme-value distribution theory. Through ADT and data statistical analysis yielded the estimated value of reliability character of MIL-C-38999 I series electrical connectors under the action of vibration and current stresses. Finally, scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) surface analysis are performed to determine the failure phenomena after exposure to environmental conditions.

Key words: Electrical connector, reliability estimation, accelerated degradation test, physics of failure

1. INTRODUCTION

An electrical connector is an important type of electro-mechanical devices which provides a separable connection between two elements of an electronic system without unacceptable signal distortion or power loss [1]. They are usually made up of two main parts, plug and socket. Each part includes: contact, shell, insulator and etc. Contact finish (plating) provides protection for the base metal (copper alloy usually) of a connector against corrosion, diffusion, wear, and help to establish and maintain a stable and reliable contact resistance of the contact interface. The reliability of contact is the main and direct contributor to electrical connector reliability [2].

The circular electrical connectors are widely used in aviation, aerospace and military system applications. Under such working or reserving conditions, contact failure is the most prevalent failure mechanism of electrical connectors. There are three types of failure (degradation) mechanisms: corrosion, wear and stress relaxation (loss of normal force) [3][4]. Among these, corrosion and

wear is related with contact finish and its physics. And stress relaxation is related with contact materials selection and design. These degradation mechanisms can all lead to connector failure, directly or indirectly, through increased contact resistance.

The reliability estimation of the circular electrical connectors is important and necessary for customer satisfaction, vendor selection, design improvement and etc. Some efforts have been conducted in this area. In military standard MIL-HDBK-217, the failure rate of connector can be calculated using failure rate models and adjustment factors based on historical field data or unspecified laboratory data [5]. But the use of such models and databases are strongly opposed by some researchers due to its limiting and misleading [3][6]. R. S. Mroczkowski conducted a study on modeling of connector degradation mechanism. And an approach to transmitting connector degradation to reliability is proposed based on extreme-value estimation with failure test data [3][4]. This effort has been published in British

Standard BS-IEC-61586 1997 “Estimation of the reliability of electrical connectors” [7]. But this study did not consider the effecting of different stress type and interaction between different degradation mechanisms. J. Wu has studied the fretting corrosion degradation mechanism for lead-free alloy plated contacts [8]. But this study did not given a specific reliability estimation model.

With appropriate design and manufacture quality control, these connectors can usually experience a long life and have a high reliability in field operation. However, due to time- and cost-restriction, no one willing to spent large amount of money and time to conduct the life testing. Even the accelerated life test (ALT) can not help much also, for that connector failure can not be highly accelerated in the lab condition without introducing any new failure modes. While accelerated degradation test (ADT) provides a way to estimate its life or reliability cost- and time- effectively [9]. Having time tracking on degradation index within relatively short test duration, the reliability under normal operation conditions can be estimated through ADT data, even without any failures.

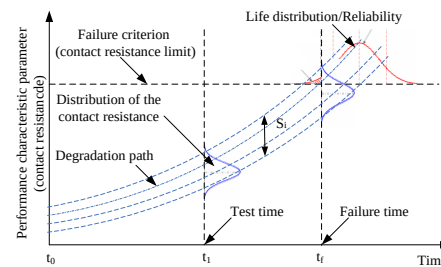
This paper addresses some concerns related to the last application of modeling, estimation of circular electrical connectors’ reliability. A combined connector laboratory ADT and physics of failure (PoF) modeling approach to estimating connector reliability will be proposed. The process and mathematics of reliability estimation based on degradation data are summarized firstly. A multiple stresses ADT with different accelerated stress level on circular electrical connectors are conducted in the laboratory to estimate the connector reliability. The contact resistance is selected as degradation index, which turns out to be one of the most reliable indices for time tracking on connector contact failure. A time- and stress- to degradation model is constructed based on the physics of failure (PoF) models and test observations. The contact resistance degradation induced life distribution (uncertainty) is described by a two-parameter Weibull distribution Maximum likelihood estimation is employed to analyze test data. The reliability of the connectors can be estimated through the obtained degradation distribution model.

2. RELIABILITY ESTIMATION BASED ON DEGRADATION DATA

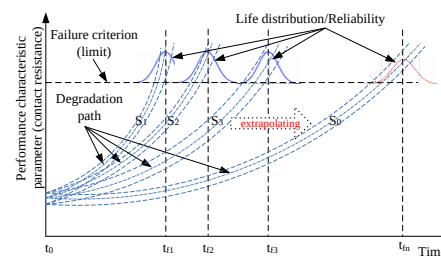
Generally, during the process of storage, shipping or operation, some product performance (parameters) would change over the life cycle time. When they reaches a certain level (threshold/failure criterion), a failure occurs (see fig. 1). This type of failure is defined as degradation failure, such as electrical performance declining of parts and devices, wear of mechanical component, aging of insulated material, corrosion of metal material and

etc. Some certain performance or characteristic parameters can be selected as degradation index that denote the product performance degradation. The performance degradation is a stochastic process and the degradation index would change over the operation time, usually monotonic increasing or decreasing. This point reflects the nonreversibility of degradation process. The degradation index value directly denotes the reliability of products. The degradation index data obtained from test title as degradation data.

The corrosion contact failure of electrical connector is a typical degradation process. The contact resistance can be selected as degradation index based on engineering experience and past research findings. But the degradation rats at normal operation condition are usually so slow that appreciable degradation might not be observed during a short period of test time. An increased stress is applied to accelerate the process of degradation. With the knowledge of physics of corrosion failure, the random vibration, current stress and temperature are all good candidate for acceleration stress.



(a) Degradation paths, distribution of the performance characteristic and life distribution under certain stress level



(b) Extrapolating from accelerated stress conditions to normal operational stress

Fig. 1 Reliability estimation based on degradation data

Fig. 1 illustrates the basic idea and process for reliability estimation based on degradation data. Assumed that the stress level in electrical connector ADT is $S_1, S_2, \dots, S_q$, and they are all larger than normal operational stress S_0 . Under a certain stress level S_i , the contact resistance R is measured at time point t_{ij} for the k_i test sample. A series of measurement of degradation data can be obtained, expressed as

$$\{R_{S_i}(k_i, t_{ij}); t_{ij}, S_i\} (i=1 \dots q, j=1 \dots m, k=1 \dots n)$$

Due to the uncertainty of manufacture process

and environmental conditions, the dispersion exists in measured degradation data. In general, the Weibull and lognormal distributions serve well for performance degradation data, because both can be applied to various failure modes [10]. A two-parameter Weibull distribution is selected for the contact resistance degradation induced life distribution.

$$F(R; t, S) = 1 - e^{-\left(\frac{R}{\eta}\right)^\beta} \quad (1)$$

Where, R is the contact resistance, t is measure time point during the test, S is the accelerated stress level, $F(R; t, S)$ is the cumulative distribution function (CDF) at t time point under S stress level, β and η are shape and scale parameters of the Weibull distribution.

Generally, the trending of above distribution parameter can be used to describing the degradation tending and they may be the function of test time and accelerated stress level, depressed as $\beta(t, S)$ and $\eta(t, S)$. The both function can be determined based on the physical theories of degradation failure and the observations of the contact resistance degradation test data. Under the assumption of invariant degradation failure mechanism, the shape parameter β is a constant. While the scale parameter η reflects the relationship between life and stress. In general, Arrhenius model, Eyring model and inverse power model can be selected as the life-stress relationship for different failure mechanism [9].

Chemical reaction rate or performance parameters degradation under temperature stress and other types of stresses has been commonly expressed by the Eyring relation as follows [11]:

$$dM / dt = A(kT / h)e^{-E / kT} e^{f(S)(C + D / kT)} \quad (2)$$

Where, M is parameter used to denote performance, dM / dt is performance degradation rate (chemical reaction rate), A, C, D is undetermined constants, $f(S)$ is a function of the applied stress in addition to temperature, h is Planck constant, T is absolute temperature of the active element, E is activation energy, k is Boltzman's constant.

Particularly for electronic connector, the scale parameter in formula (1) directly denotes the contact resistance degradation. Under assumption of constant temperature, equation (2) can be reduced to the following power formal function related with test time and stress level [9][12]:

$$\eta(t, S) = a \cdot S^b \cdot t^c \quad (3)$$

When put formula (3) into (1), the contact resistance degradation distribution model can be expressed as follows:

$$F(R; t, S) = 1 - e^{-\left(\frac{R}{a \cdot S^b \cdot t^c}\right)^\beta} \quad (4)$$

Where, β, a, b, c are the model parameters need to be estimated from ADT data.

Formula (4) is a statistical-physical function, the model parameters can be estimated by fitting the test observation data to it. To make full use of the degradation data, all observations are fitted to the degradation distribution model simultaneously. The maximum likelihood estimation (MLE) method is utilized to estimate the unknown model parameters. The likelihood function is constructed as follows:

$$L(\beta, a, b, c) =$$

$$c \cdot \prod_{k=1}^n \prod_{i=1}^q \prod_{j=1}^m \frac{\beta}{(a \cdot S_i^b \cdot t_{ij}^c)^\beta} \cdot R(k_i, t_{ij})^{\beta-1} \cdot e^{-\left(\frac{R(k_i, t_{ij})}{a \cdot S_i^b \cdot t_{ij}^c}\right)^\beta} \quad (5)$$

Put all of the measurements $\{R_{s_i}(k_i, t_{ij}); t_{ij}, S_i\}$ into equation (5), and by solving the ML equations of

$\partial L / \partial \beta = 0, \partial L / \partial a = 0, \partial L / \partial b = 0, \partial L / \partial c = 0$, the estimator $\hat{\beta}, \hat{a}, \hat{b}, \hat{c}$ of β, a, b, c is obtained. Thus, the contact resistance degradation distribution may be expressed as shown below:

$$F(R; t, S) = 1 - e^{-\left(\frac{R}{\hat{a} \cdot S^{\hat{b}} \cdot t^{\hat{c}}}\right)^{\hat{\beta}}} \quad (6)$$

Further, having tacking the degradation path for a while, the reliability or life distribution can then be estimated by extrapolating the degradation trend to its threshold. For a given operating time and loading condition, the reliability of a connector is the probability of its contact resistance R larger than the threshold level R_0 , the connector reliability function at time t is reduced to the CDF of the contact resistance distribution:

$$R(t, S) = \Pr(R < R_0; t, S) = 1 - e^{-\left(\frac{R_0}{\hat{a} \cdot S^{\hat{b}} \cdot t^{\hat{c}}}\right)^{\hat{\beta}}} \quad (7)$$

3. TEST SETUP

A certain type of MIL-C-38999 I series circular electrical connectors that is widely used in aviation, aerospace and military system is selected. This type of connector contains 12 pair of contact and each contact contains 4 pair of 16# (contact size/diameter) and 8 pair of 20# contact pin and socket. The specification for this test sample as Table 1 [12][13].

Contact resistance measurement is the critical part in this test study. A contact resistance auto tester (or milliohm meter) designed on the principle of four wire measurement is introduced in this test [8][14]. The initial contact resistance of test samples is measured, and the resistance scope is 1.30mΩ~1.34mΩ which is within the operating specification requirement. Moreover, scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS/EDX) surface analysis are performed to verify the consistency of contact

plating surface quality. The inspection results show that the main chemical element of random sample's plating surface is gold and gold series composition and the plating surface meet the requirement of testing. The chemical composition analysis results can provide the reference for test failure sample physical analysis (see section 5).

Table 1 The basic information for test sample

Structure and materials	Contact and wire interface	Crimping and removable
	Contact	Copper alloy
	Contact plating /thickness	Au/0.05mils
	Contact size /diameter	16#: Φ 1.60mm 20#: Φ 1.00mm
Mechanical	Random vibration	frequency 100~1000Hz density of power $5g^2/Hz$
Electrical	Current rating	16#: 13 A 20#: 7.5 A
	Contact resistance /failure criterion	16#: $\leq 2.5 m\Omega$ 20#: $\leq 5 m\Omega$
Environmental	Operation temperature	-65°C~175°C (B class)
	Relative humidity	98% at 40°C

According to the specification of the test connector, three level (i.e. power spectral density $5g^2/Hz$, $4g^2/Hz$ and $3g^2/Hz$) random vibration stresses are selected within the affordable stress limit. These stress level are larger than normal operating condition for the purpose of accelerated degradation or failure. Simultaneously, the current are also selected as accelerated stress that simulates the real operational condition for the comparison purpose. Furthermore, under each level random vibration, the samples are setting in two different directions, one for horizontal, and another for vertical (contact pair axis versus vibration axis). Thus, under a certain stress level, there are four whole connector samples, and each connector contains 8 pair of contact, and one contact is defined as a sample unit. The details of the test setup and test conditions are shown in Table 2.

Table 2 The matrix for test conditions

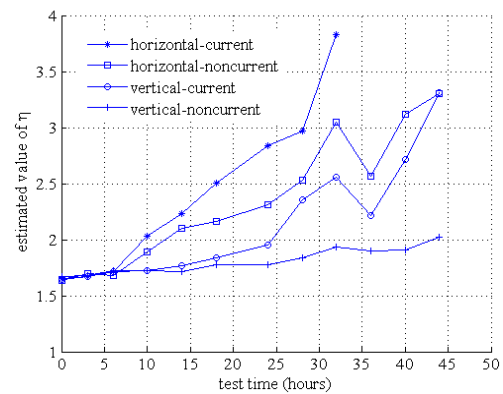
Current rating	Setting direction Contact pair axis vs. vibration	Sample No. / Random vibration Stress level		
		5 (g^2/Hz)	4 (g^2/Hz)	3 (g^2/Hz)
7.5A	Horizontal	1#	5#	9#
	Vertical	2#	6#	10#
—	Horizontal	3#	7#	11#
	Vertical	4#	8#	12#

4. TEST RESULTS AND RELIABILITY ESTIMATION

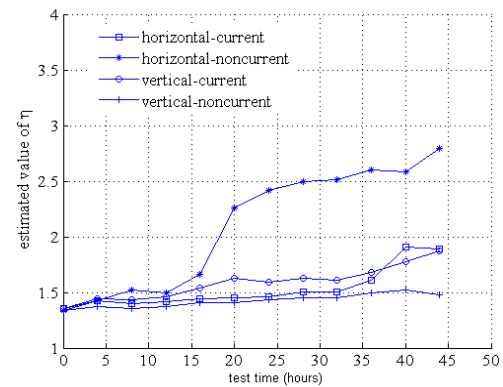
The failure of connector is real-time monitored during the test. For case of loading current stress, an open circuit implies failure has occurred. For the case of no loading current stress, wink break time

tester is utilized to monitor the failure of contact. The contact resistance is measured and recorded periodically over the test time. For different stress level, the interval may be 3, 4, or 6 hours.

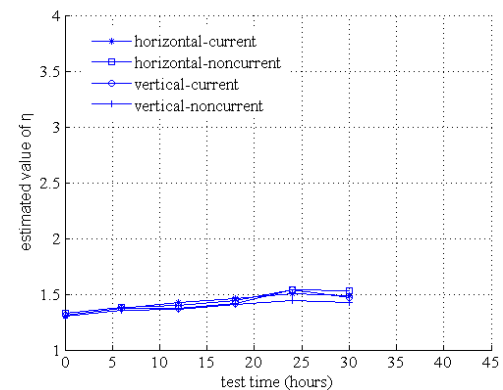
With the test observations and the above presented two parameters Weibull distribution model, a series of estimator β and η are estimated using MLE methods. And $\hat{\beta}$ is approximate constant and value is $\hat{\beta} \approx 33.7657$. However, $\hat{\eta}$ is variable related with different time and stress level. Fig.2 shows the trending of $\hat{\eta}$ over test time at different vibration level.



(a) $5g^2/Hz$



(b) $4g^2/Hz$



(c) $3g^2/Hz$

Fig. 2 Estimator of η variation with test time

The estimator of η directly denote the contact resistance degradation trending. From this

figure, we can see that contact resistance degradation trending tend to decreasing with the decreasing of stress level. The connector setting direction has a big influence on degradation rates. The difference of degradation rates under different test conditions is reduced with the decreasing stress level. Among all of the four types of test conditions, the connector's contact resistance degradation is most serious under the test condition of horizontal setting direction with loading current stress. This finding can be explained by the principle of the fretting corrosion mechanism in electric contact [15][16]. During the next section, the analysis is mainly conducted for this case of test condition. The contact resistance degradation distribution variation over time is shown in Fig. 3:

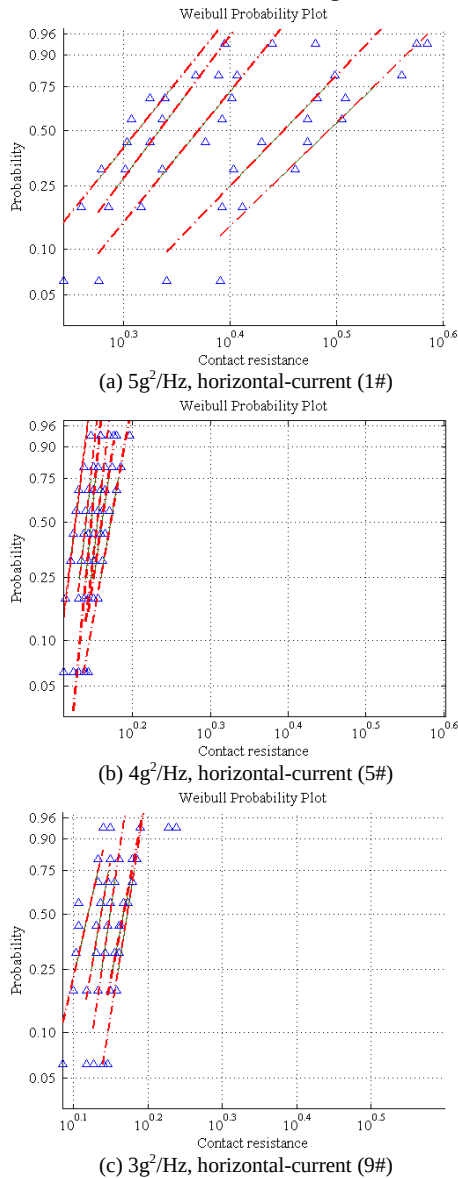


Fig. 3 contact resistance distribution with test time under different vibration level

Fig. 3 is Weibull distribution plotting with MLE approach. Farther, with the data of estimator η at different time point and stress level, the

model parameters a, b, c are all estimated. Then the connector contact resistance degradation distribution model is introduced as

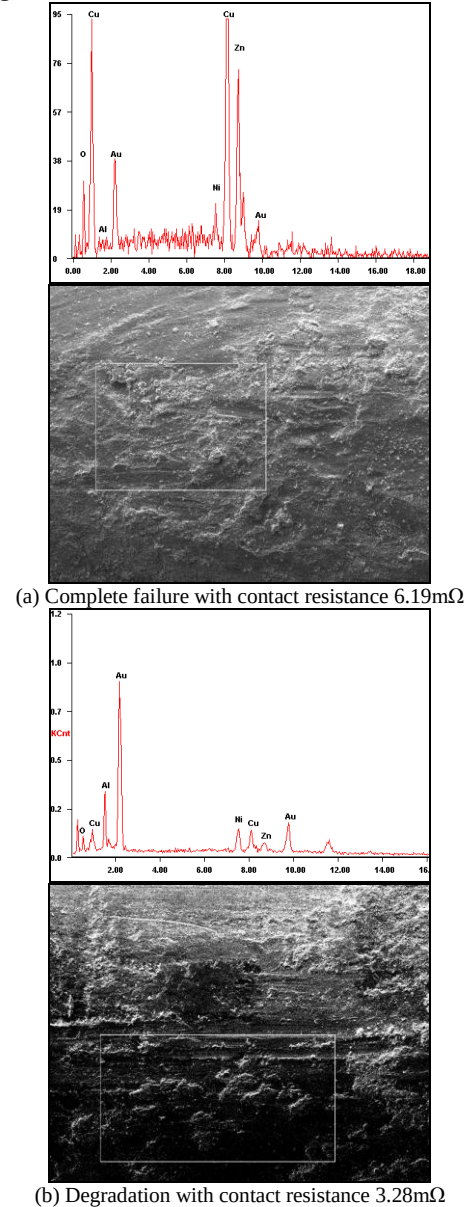
$$F(R; t, S) = 1 - e^{-\left(\frac{R}{0.068 \cdot S^{2.054} \cdot t^{0.149}}\right)^{33.7657}} \quad (8)$$

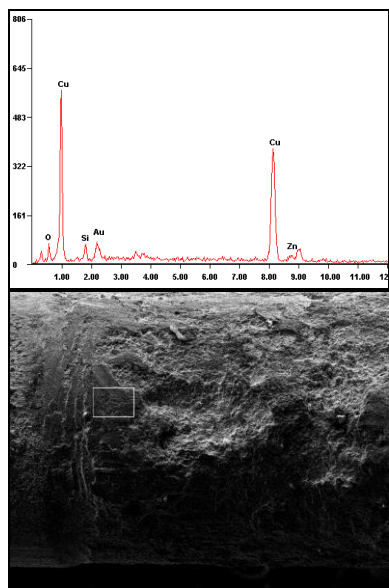
According to the connector specification, the contact resistance threshold is 5 mΩ. Finally, the reliability function for this type of circular electrical connector is as follows:

$$R(t, S) = 1 - e^{-\left(\frac{5}{0.068 \cdot S^{2.054} \cdot t^{0.149}}\right)^{33.7657}} \quad (9)$$

5. PHYSICAL ANALYSIS AND DISCUSSION

The SEM and EDS analysis are performed on the complete failed and degradation connector sample after ADT for comparison and verification purpose. The typical contact surface micro-morphology for three states (premature failure, fully failure and degradation) is shown in Fig. 4:





(c) Can't work normally due to severe surface wear

Fig. 4 Results for SEM and EDS analysis

Fig. 4(a) shows the contact surface of a complete failure sample. A large amount of black copper oxide (high content of Cu and O elements) deposits on the surface. And a mass of "black pockmark" exist on surface. The mainly component of this pockmark is proved to be gold and copper elements. According to Bryant's study, the pockmark is introduced by felt transmitting and fretting corrosion [17]. Besides, the grid shape of scratching, mass of plating exfoliating and delaminating phenomena are incidental.

Fig. 4(b) shows the contact surface of a degradation sample. There is still a little of black copper oxide accumulated on the surface. And chemical component analysis shows that the Zn, Ni element appears which all are the component of base copper alloy and composite plating of electric contact. This phenomenon indicates a middle stage of contact degradation.

Fig. 4(c) shows the contact surface of an early failure sample. This connector cannot complete full insertion due to the heavily surface wear. The chemical composition analysis shows that only a small amount of gold series elements exist on the surface and the base copper is exposed cause by wearing.

6. CONCLUSION

A multiple stresses ADT is conducted on a typical circular electrical connector. A statistical-physical degradation distribution model is employed to summarize the ADT results and a reliability model is formed to estimate the reliability at normal operation condition. We come to conclusion as follows:

- The life-stress relationship (PoF) model and the life distribution model are combined to establish the degradation distribution model, which can be used to estimate the circular electrical connector with ADT data fitting and

estimation. For other type of connector or other product with degradation failure features, the estimation methods and models are also applicable, but the model parameters must be re-estimated with corresponding ADT degradation data;

- Under random vibration condition, the fretting corrosion mechanism is the main contributor to connector degradation failure. The setting direction of connector (i.e. random vibration axis direction) has a significant influence on the contact degradation rates. The test results denote that the most severe degradation occurs in horizontal direction. The current stress has a little influence on the degradation rates which especially would speed up the degradation under higher accelerated stress level.

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