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Estimating Product Field Life Under Multi-Stress Environments in HALT and HASS

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ABSTRACT

The estimated field life of a product is determined by subjecting the product to accelerated testing at various stages, including the engineering, development, and production stages. Accelerated testing involves subjecting a large base of sample products to thermal shock, humidity, dust, or other tests to accelerate aging. After accelerated testing, at the time of mass production, the product is subjected to HALT/HASS as a form of ongoing reliability testing. HALT and HASS apply multiple stressors at different intensity combinations but cannot produce field-life estimates. This disclosure leverages HALT-HASS by using Arrhenius and modified-Eyring modeling to estimate acceleration factor and field life. The techniques enable testing and screening of products with lower test duration. Further, the number of samples needed for testing is lower. Use of the techniques can reduce product returns (also known as return merchandise authorizations, or RMAs), improve reliability, lower costs, and shorten test-turnaround time.

KEYWORDS

- Highly Accelerated Life Testing
- Highly Accelerated Stress Screening
- Field life
- Reliability engineering
- Acceleration factor
- Arrhenius model
- Boltzmann's constant
- Cold step
- Eyring model
- Hot step
- Thermal cycle step
- Vibration step
- Multi-stress testing
- Weibull distribution

BACKGROUND

The estimated field life of a product is determined by subjecting the product to accelerated testing at various stages, including the engineering, development, and production stages. Accelerated testing involves subjecting a large base of sample products to thermal shock, humidity, dust, or other tests to accelerate corrosion at a fixed temperature. Accelerated testing results in an acceleration factor that enables estimation of the field life of the product. For example, if a testing chamber had such conditions that it accelerated aging by a factor of 200 and the product survived the testing chamber for four hours, then the estimated field life of the product is 200×4=800 hours.

The acceleration factor (AF) can be calculated by the Arrhenius model, e.g.,

$$AF = exp\left[\frac{\Delta H}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right],$$

where

k is Boltzmann's constant (8.617×10^{-5} eV/K),

T is temperature measured in Kelvin, and

ΔH is the activation energy, which varies by failure mechanism (activation energies for some failure mechanisms are shown in Table 1).

The Arrhenius model is suitable only for one stressor (accelerating factor) at a time. For example, it predicts the AF for a hot step or for a cold step, but not for a hot-cold combined cycle, nor for a cycle that simultaneously includes vibration, humidity, and dust.

Failure mechanism	Accelerating factors	Activation energy (eV)
Dielectric breakdown	Electric field, temperature	0.2-1.0
Corrosion	Humidity, temperature, voltage	0.3-1.1
Electromigration	Temperature, current density	0.5-1.2
Au-Al intermetallic growth	Temperature	1.0-1.05
Hot carrier injection	Electric field, temperature	-1.0
Slow charge trapping	Electric field, temperature	1.3
Mile ionic contamination	Temperature	1.0-1.05

Table 1: Activation energies for various failure mechanisms

After accelerated testing, at the time of mass production (MP), the product is subjected to HALT (highly accelerated life testing) and HASS (highly accelerated stress screening) as a form of ongoing reliability testing. HALT and HASS apply multiple stress parameters, e.g., temperature, vibration, etc. at different intensity combinations. Compared to pre-MP accelerated testing, HALT/HASS have condensed timelines, e.g., the device is not tested for performance or functionality at the end of every hot (or cold or vibrational) cycle; rather, such testing is performed only at the end of multiple such cycles. HALT/HASS can thus be performed more frequently; even so, HALT/HASS cannot produce acceleration factors or field-life estimates.

Obtaining a quantifiable equivalent to product field life from HALT/HASS has been a long-sought goal of reliability engineers. However, thus far, effective techniques to obtain field life from HALT/HASS do not exist. The few attempts (e.g., [1], [2]) to evaluate field life under HALT/HASS are generally unscalable, not robust, or require large numbers of product samples to obtain usable data.

DESCRIPTION

This disclosure describes techniques to obtain an acceleration factor and field life from HALT and HASS using the Arrhenius model and a modified-Eyring model. In contrast to conventional acceleration factor (and field life) estimation, which uses a separate pre-MP test phase with a separate base of product samples, the described techniques leverage HALT-HASS, which have condensed timelines and can be done more frequently, to estimate AF and field life. In contrast to pure Arrhenius modeling, which can only handle one stressor at a time, the described techniques combine the multiple stress factors applied during HALT/HASS cycles into a scalable cumulative process to obtain field life estimates. The techniques enable testing and screening of products with lower test duration. Further, the number of samples needed for testing is lower. Use of the techniques can reduce product returns (also known as return merchandise authorizations, or RMAs), improve reliability, lower costs, and shorten test-turnaround time.

Per the techniques, a modified-Eyring model unites multiple stressors as follows.

$$AF_2 = AF_1 \times exp\left[\frac{\Delta H}{kT}\left(B + \frac{C}{T}\right) \times S_1\right],$$

where

AF_1 is the result of the aforementioned Arrhenius model at the target temperature;

k is Boltzmann's constant (8.617×10^{-5} eV/K);

T is the target temperature measured in Kelvin;

ΔH is the activation energy (which can be set, e.g., to 0.7 eV);

B is set to a suitable value indicative of temperature interaction with respect to the other stresses, e.g., B=0 if there is no interaction;

C is set to a suitable value indicative of temperature interaction effect with respect to the other stresses, e.g., C=1 if there is no interaction to address;

S is an additional stress introduction, e.g., vibration in units of Grms.

In contrast to conventional Eyring models, which only calculate the total time to degradation (and hence are unsuitable for the estimation of AF), the described modified-Eyring model obtains an estimate of AF under multiple simultaneous stressors. Prior attempts to model field life had been stymied by the inability to estimate acceleration factors at sub-zero or negative temperatures. Since AFs increase near-equivalently at positive as well as negative temperatures, the acceleration factor in Kelvin isn't deducted as negative for a cold cycle; rather, it is added on as if the current temperature has increased.

HALT modeling

A small number of product samples (e.g., between 3 and 20) are subjected to accelerated aging via HALT, which comprises multiple cycles, e.g., a cold cycle, a hot cycle, a thermal-shock (alternating heat and cold) cycle, a vibration cycle, a combined cycle (vibration and thermal), etc. The acceleration factor from each cycle is computed based either on the Arrhenius model or on the modified-Eyring model, and a total acceleration factor is determined. The duration of survival of all samples (e.g., the time up to the failure of the first sample) in the testing chamber is determined. Weibull statistics and the computed acceleration factor are used to determine the field life (also known as mission time) with an associated confidence level.

Computation of acceleration factor

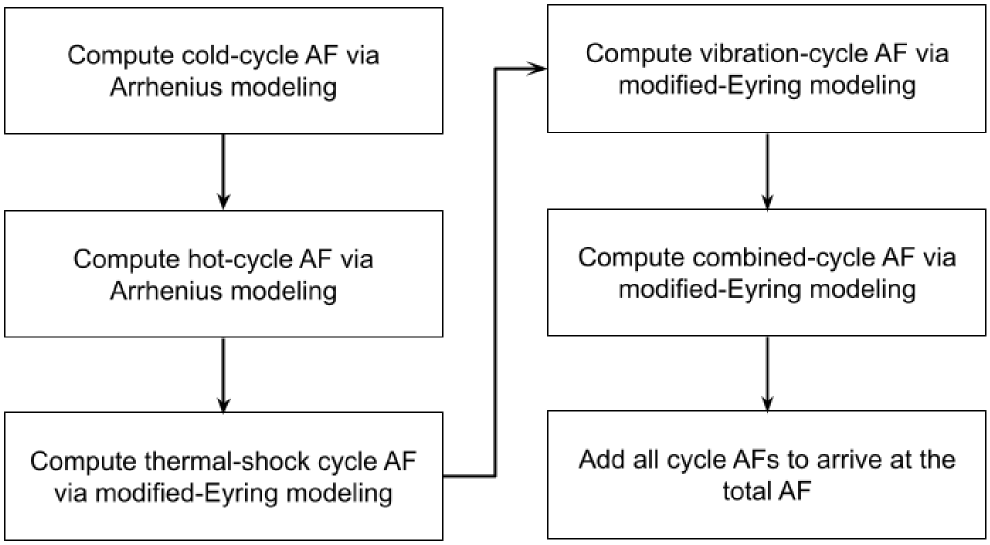

Fig. 1: Computing the acceleration factor from a HALT procedure

Fig. 1 illustrates computing the acceleration factor from a HALT procedure. The AFs from component cycles (cold, hot, thermal-shock, vibration, combined) are computed and added to arrive at the total AF. As explained before, Arrhenius modeling applies to single-stressor cycles like the cold cycle or the hot cycle. Modified-Eyring is applied to multi-stressor cycles like thermal shock, vibration, combined-cycle, etc. In what follows, the computation of AFs for component cycles will be illustrated.

AF for the cold cycle

Temperature	Time	Acceleration Factor	Cold cycle AF
25 °C	60 min	1	
10 °C	60 min	0.236	
0 °C	60 min	0.092	
−10 °C	60 min	2.420	
−20 °C	60 min	5.544	

Temperature	Time	Acceleration Factor	Cold cycle AF
−30 °C	60 min	12.071	
−40 °C	60 min	25.101	
−45 °C	60 min	50.047	
			96.511

Table 2: Acceleration factor computation for the cold cycle

Acceleration factor computation for the cold cycle is illustrated in the example of Table 2. In this example, the temperature of the product samples is reduced from 25°C in steps, the samples spending 60 minutes at each new (lower) temperature, until the first sample fails (at −45°C, in this example). The AF for each temperature plateau is computed using the Arrhenius model. The cold-cycle AF is computed by adding the AFs at each temperature plateau.

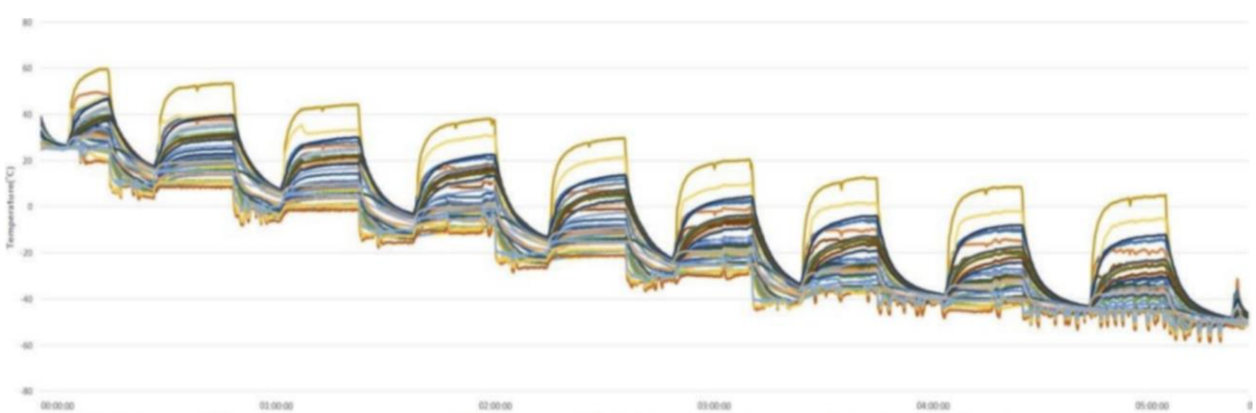

Fig. 2: Temperature versus time for the cold cycle, measured at various components within the product sample

Fig. 2 illustrates the temperature versus time graph for the cold cycle, measured at various components within the product sample. The temperature trend at each component is clearly downwards with a sixty-minute plateau at each temperature step. The difference in temperatures between components arises from the fact that some components (e.g., CPUs) generate heat while others (e.g., heat sinks, fans) dissipate heat.

AF for the hot cycle

Temperature	Time	Acceleration Factor	Hot-cycle AF
25 °C	60 min	1	
35 °C	60 min	2.420	
45 °C	60 min	5.544	
55 °C	60 min	12.071	
65 °C	60 min	25.101	
70 °C	60 min	35.622	
			81.758

Table 3: Acceleration factor computation for the hot cycle

The acceleration factor computation for the hot cycle is illustrated in the example of Table 3. In this example, the temperature of the product samples is increased from 25°C in steps, the samples spending 60 minutes at each new (higher) temperature, until the first sample fails (at 70°C, in this example). The AF for each temperature plateau is computed using the Arrhenius model. The hot-cycle AF cycle is computed by adding the AFs at each temperature plateau.

AF for the thermal-shock cycle

Temperature	Time	Acceleration Factor	Thermal-shock AF
−35 °C	60 min	17.503	
60 °C	60 min	17.503	
−35 °C	60 min	17.503	
60 °C	60 min	17.503	
−35 °C	60 min	17.503	
60 °C	60 min	17.503	
−35 °C	60 min	17.503	
60 °C	60 min	17.503	
−35 °C	60 min	17.503	
60 °C	60 min	17.503	
			175.03

Table 4: Acceleration factor computation for the thermal-shock cycle

The acceleration factor computation for the thermal shock cycle is illustrated in the example of Table 4. In this example, the temperature of the product samples alternates between −35°C and 60°C, the samples spending 60 minutes at each temperature plateau, until the first sample fails (after five cycles, in this example). The AF for each temperature plateau, computed using the modified-Eyring formula, is identical due to its dependence on the temperature difference (which is constant, at 95°C) between the upper and lower limits of the thermal shock. The thermal-shock AF is computed by adding the AFs at each temperature plateau.

<u>*AF for the vibration cycle*</u>

Temperature	Vibration	Time	Acceleration Factor	Vibration AF
40 °C	0 Grms	60 min	3.688 = $exp\left[\frac{0.7}{8.617\times10^{-5}}\times\left(\frac{1}{298.15}-\frac{1}{313.15}\right)\right]\times exp\left[\frac{0.7}{313.15\times8.617\times10^{-5}}\times\left(\frac{1}{313.15}\right)\times0\right]$	
40 °C	5 Grms	60 min	5.580	
40 °C	10 Grms	60 min	8.444	
40 °C	15 Grms	60 min	12.777	
40 °C	20 Grms	60 min	19.334	
40 °C	25 Grms	60 min	29.256	
40 °C	30 Grms	60 min	44.269	
40 °C	35 Grms	60 min	66.986	
40 °C	40 Grms	60 min	101.360	
40 °C	45 Grms	60 min	153.374	
40 °C	50 Grms	60 min	232.079	
				677.147

Table 5: Acceleration factor computation for the vibration cycle

The acceleration factor computation for the vibration cycle is illustrated via the example of Table 5. In this example, the temperature of the product samples is maintained at 40 °C (a value chosen to account for the self-heat created by active components that pushes the product temperature above room temperature of 27 °C), while vibration is increased from 0 Grms in steps of 5 Grms, the samples spending 60 minutes at each vibration plateau, until the first sample fails (at 50 Grms, in this example). The AF for each vibration plateau is computed using the modified-

Eyring formula, an example computation being illustrated in the first row of Table 5. The vibration-cycle AF is computed by adding the AFs at each temperature plateau.

AF for the combined cycle

Temperature	Vibration	Time	Acceleration Factor	Combined-cycle AF
−35 °C	8 Grms	60 min	31.436	
60 °C	8 Grms	60 min	31.436	
−35 °C	16 Grms	60 min	56.458	
60 °C	16 Grms	60 min	56.458	
−35 °C	24 Grms	60 min	101.396	
60 °C	24 Grms	60 min	101.396	
−35 °C	32 Grms	60 min	182.102	
60 °C	32 Grms	60 min	182.102	
−35 °C	40 Grms	60 min	327.047	
60 °C	40 Grms	60 min	327.047	
				1396.878

Table 6: Acceleration factor computation for the combined cycle

The acceleration factor computation for the combined cycle is illustrated via the example of Table 6. In this example, the temperature of the product samples is alternates between −35°C and 60°C while vibration is increased from 8 Grms in steps of 8 Grms, the samples spending 60 minutes at each temperature-vibration plateau, until the first sample fails (at 40 Grms, in this example). The AF for each temperature-vibration plateau is computed using the modified-Eyring formula. The combined-cycle AF is computed by adding the AFs at each temperature-vibration plateau.

Total AF

Cycle	**Cycle acceleration factor**
Cold	96.511
Hot	81.758
Thermal shock	175.030
Vibration	677.147
Combined	1396.878
Total acceleration factor	**2427.324**

Table 7: The total AF is the sum of the AFs of the individual cycles

As illustrated in Table 7, the total acceleration factor is computed by adding the AFs for the individual cycles (Tables 2-6). Since the period of each stress is 60 minutes (one hour), the field life, which is acceleration factor multiplied by test-time, equals 2427.324×1 hour = 2427 hours or 101 days.

Confidence level

The parametric binomial reliability demonstration test (Weibull distribution) can be used to obtain a confidence that a certain fraction of products will survive the length of time indicated by the HALT procedure. For example, when 2 sessions of HALT are performed with 3 units undergoing the same stress tests (to give a total of 2×3 = 6 samples), the confidence intervals are computed as in Table 8.

Parameter	**Value**
Reliability requirement at mission time	60%
Weibull shape parameter (**β**, can be chosen as indicator for first-year mortality and test time)	0.5

Parameter	Value
Sample size	6
Mission time (hours)	8,760 (1 year)
Confidence level	80%
Required test time	2,415

Table 8: Computing confidence level

Per Table 8, there is an 80% confidence that if 60% of the units pass 2,415 hours of testing, then 76.5% of the units will meet a mission time of 8,760 hours or 1 year of operation.

HASS modeling

Effective modeling for HASS testing with the acceleration matrix enables scalable and cost-effective techniques to adjust test-cycle time according to target field-life reliability, as illustrated by the example below.

Example

Question: The product is targeted to have less than 5% mortality rate after 3 years (26,280 hours) of normal usage. Estimate the time required to complete a HASS cycle using data from the HALT session of Table 9 below.

Temperature	Vibration	Time for each step
−35°C	40 Grms	60 min
60°C	40 Grms	60 min

Table 9: Program of stressors for a HALT session

<u>Answer</u>: Applying the modified-Eyring formula, the acceleration factor for each step of the HALT session is found to be 327.047. Applying the Weibull distribution with parameters as in Table 10,the required test time without acceleration is obtained as 64,683 hours.

Parameter	Value
Number of allowable test failures	0
Reliability requirement at mission time	95%
Weibull shape parameter (**β**)	0.5
Sample size	20
Mission time (hours)	26,280 hours (3 years)
Confidence level	80%
Required test time	**64,683 hours**

Table 10: Computing the required test time to achieve the given confidence level

From the Weibull distribution, the reliability requirement of 95.0% at a mission time of 26,280 hours is equivalent to a reliability of 92.2681% at a test time of 64,683 hours. Testing 20 items for 64,683 hours with zero failures demonstrates a reliability of 95.0% for a 26,280-hour mission at an 80% confidence level. Without acceleration, the test time of 64,683 hours (7 years 8 months) actually exceeds the product mission time (3 years).

With an acceleration factor of 327.047 (Table 9), the estimated time to complete the HASS cycle of Table 9 is 64683 ÷ 327.047 ≅198 hours or 8.25 days.

In this manner, HALT/HASS can be leveraged to provide scalable and cost-effective techniques to determine in the development stage product field life under normal usage conditions. The techniques can be combined with other techniques of product-life estimation and/or modeling processes to obtain a best fit.

CONCLUSION

This disclosure leverages HALT-HASS by using Arrhenius and modified-Eyring modeling to estimate acceleration factor and field life. The techniques enable testing and screening of products with lower test duration. Further, the number of samples needed for testing is lower. Use of the techniques can reduce product returns (also known as return merchandise authorizations, or RMAs), improve reliability, lower costs, and shorten test-turnaround time.

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