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Can HALT and HAST Replace Some U.S. MIL-STD-331 Climatic Tests for Electronic Fuzes?

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Project Background

- Electronic fuze including safe, arm, and fire functions and inline detonator.
- Fuze uses plastic encapsulated microcircuits (PEM).
- Potentially long storage period prior to operation.
- Non-repairable item.
- Conventional, U.S. Army weapon system application.
- Overall, the fuze design appeared to meet MIL-STD-1316E safety requirements.

Project Background

- During a review of the fuze qualification test plan, it was implied that MIL-STD-331 climatic tests C1 (temp./humidity) and C6 (extreme temp.) could be omitted from qualification test program by virtue of Highly Accelerated Life Test (HALT) performed during development.
  - *Is this a valid claim?*
- In order to evaluate this claim, we'd like to have some quantitative means of comparison, e.g., an acceleration factor.

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Research Approach

- Literature Review (no resources for test program)
  - Accelerated test principles, including HALT.
  - MIL-STD-331 and fuze safety evaluation guides.
  - Arrhenius equation and its use in reliability prediction.
  - Failure mechanisms.
- Expert elicitation.
- Calculate and evaluate acceleration factors.
- Try to draw some conclusions.
- Repeat as necessary.

MIL-STD-331B Test C1

- Temperature and Humidity Test
- 28 day test (two 14-day cycles)
- Bare fuzes alternately exposed to +71 ºC/95%RH and –54 ºC with additional "storage periods" at –62 ºC. Each temp. extreme is applied for 8 hours with transition through ambient of 1 hour.
- Fuze is off during temperature conditioning and allowed to return to ambient for operational checkout.
- Fuze must be safe to handle, transport, and operate afterwards.
- Rationale is that moisture accelerates failure mechanisms, e.g., corrosion, delamination, etc.

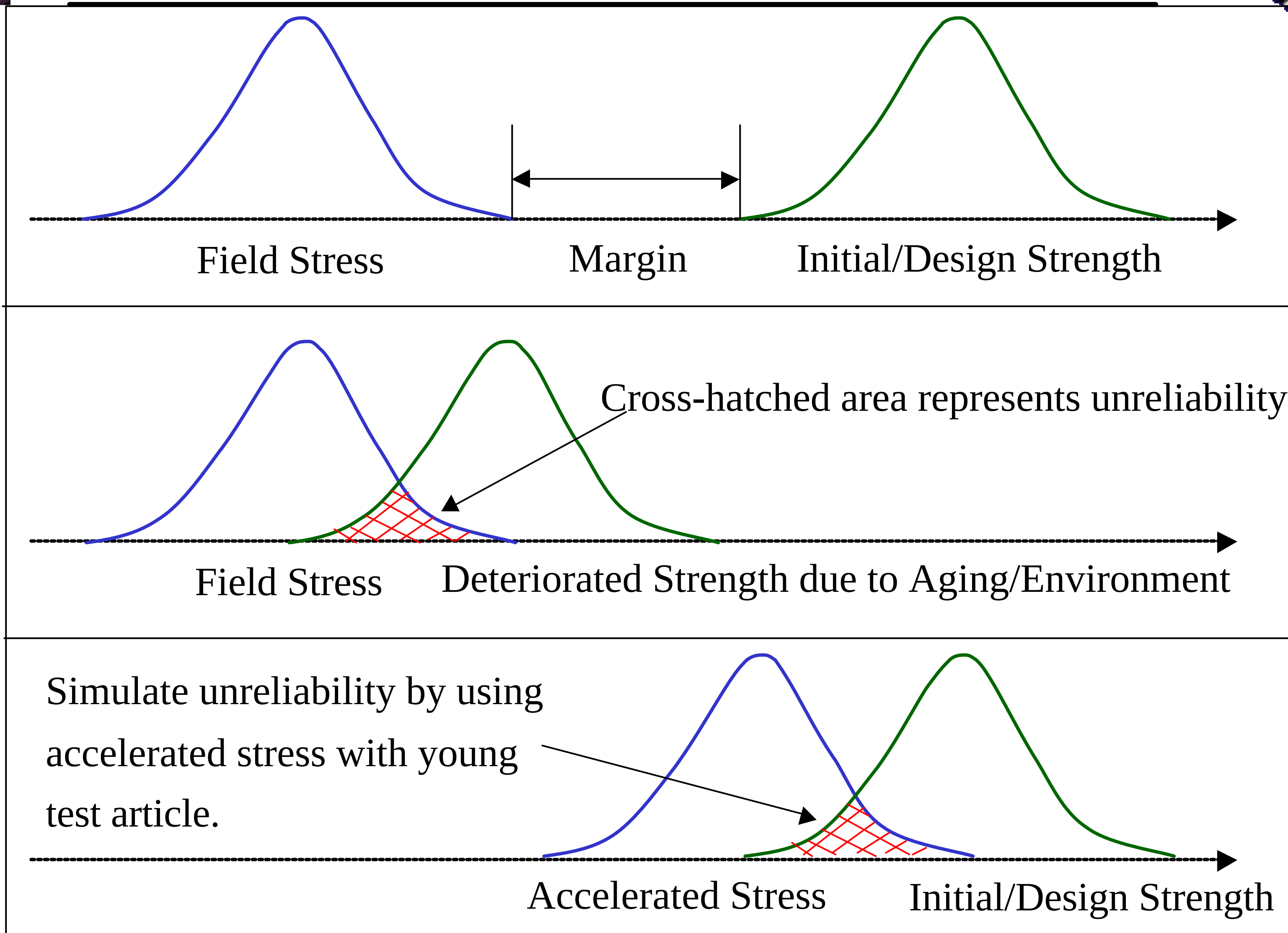
MIL-STD-331B Test C6

- Extreme Temperature (hot and cold)
- Bare fuzes alternately exposed to +71 ºC and –54 ºC. Each temp. extreme is applied for 28 days.
- Fuze is off during temperature conditioning and allowed to return to ambient for operational checkout.
- Fuze must be safe to handle, transport, and operate afterwards.
- Rationale is that time required for certain failure modes to manifest, e.g., permanent embrittlement of plastics.
- Can choose hot only, cold only, or both hot and cold.

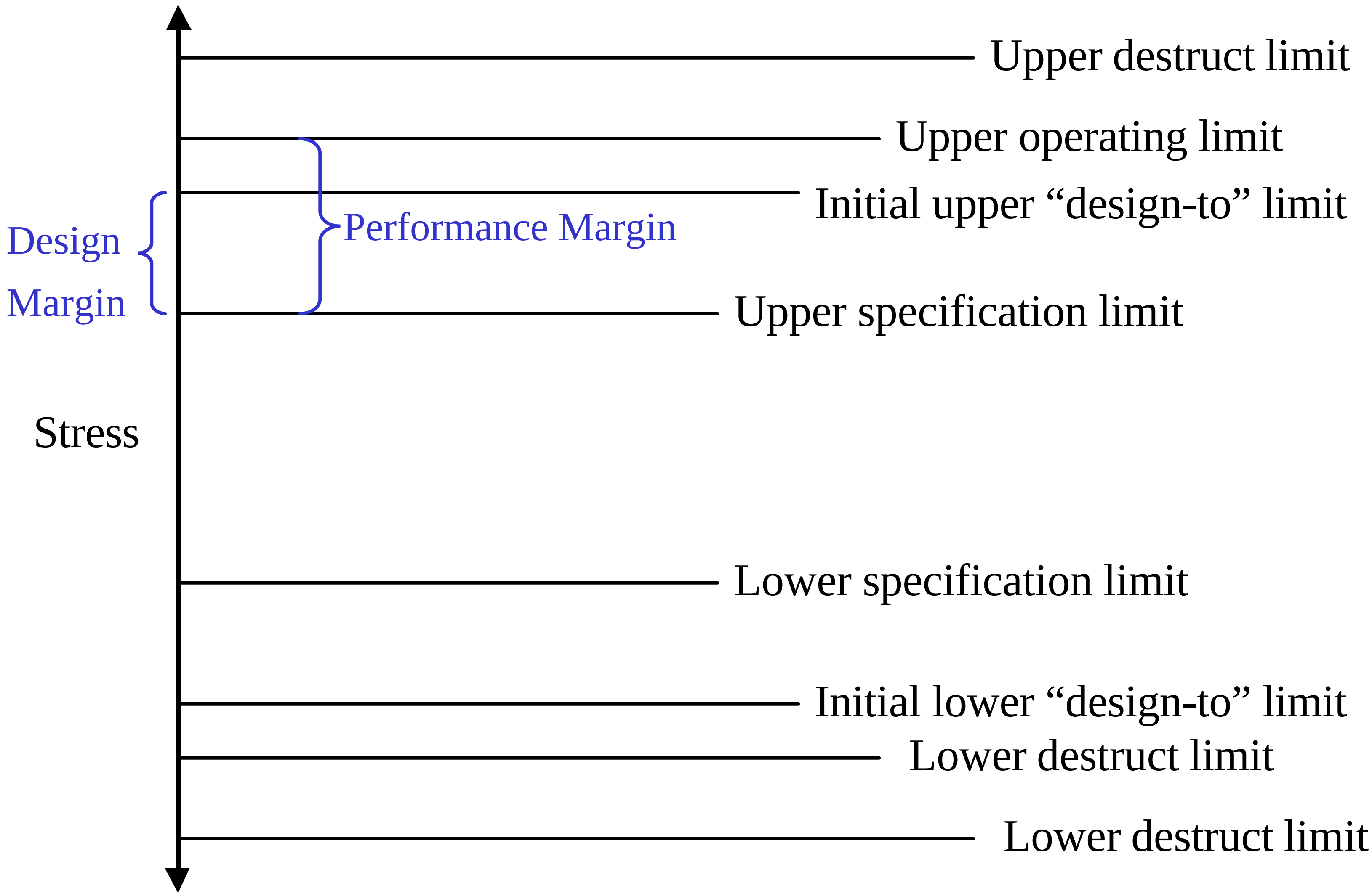
Highly Accelerated Life Test

- HALT: Term coined by Dr. Gregg K. Hobbs
- Lots of ways to do this.
- Stimulate normal-use failure modes by subjecting the test article to multiple high-level stresses simultaneously.
- This is a design-improvement test method, not a qualification test method.
- Root-causes of failures must be identified and corrected to form a stronger, robust product.
- Find operating and destruct limits.

Highly Accelerated Life Test



Highly Accelerated Life Test



Highly Accelerated Life Test

- Example high temperature step-stress: ambient to 130 ºC in 10 ºC increments.
- Example low temperature step-stress: ambient to –70 ºC in 10 ºC increments.
- Rapid transition between temperature steps.
- Dwell only long enough for temperature in device-under-test to stabilize plus any additional time to verify device is functioning properly.
- Can include multi-axis (simultaneous) vibration, typical levels applied in steps up to 35 Grms.
- Can also include humidity and electrical stresses.

Additional Testing Decided

- Fuze designers added high and low temperature storage tests, but only tested for a few days.
- Also added "Sequential Life Test", which included increasing periods of thermal cycling alternated with unbiased Highly Accelerated Stress Test (HAST).
- Tested circuit cards as well as complete housed fuze.

Highly Accelerated Stress Test

- HAST is a temperature and humidity test.
- 85 ºC/85% relative humidity (for assembly-level).
  - 130 ºC usually used for individual components.
- "Unbiased" means the device isn't operational during the test.
- Not to be confused with HASS (Highly Accelerated Stress Screening) which is a production quality assurance/burn-in technique and is a superset of traditional Environmental Stress Screening (ESS) techniques.
- See EIA/JEDEC Test Method A110-B (JESD-A110-B)

Arrhenius Equation

- One of the traditional models that came to mind is the Arrhenius equation, which models reaction rate (presumably of failure mechanisms, e.g., corrosion) vs. absolute temperature.
  - *Could this be used for our purposes?*
  - *If so, what are the corresponding acceleration factors?*
  - *If not, why not?*

Arrhenius Equation

$$R = A \cdot \exp\left[-\frac{E_a}{k}\left(\frac{1}{T}\right)\right]$$

where

R = reaction rate

A = an empirically-determined constant

exp = natural (base *e*) antilog function

E_a = activation energy, in electron-volts (eV)

k = Boltzmann’s constant = 8.617E-5 eV/K

T = temperature, in kelvin (K)

Acceleration Factor

$$AF = \frac{R_{stress}}{R_{use}} = \frac{A \cdot \exp\left[-\frac{E_a}{k}\left(\frac{1}{T_{stress}}\right)\right]}{A \cdot \exp\left[-\frac{E_a}{k}\left(\frac{1}{T_{use}}\right)\right]} = \exp\left[\frac{E_a}{k}\left(\frac{1}{T_{use}} - \frac{1}{T_{stress}}\right)\right]$$

where

AF = Acceleration Factor

R_{stress} = Reaction rate at accelerated temperature

R_{use} = Normal reaction rate

T_{stress} = Temperature in accelerated environment

T_{use} = Temperature in normal use environment

Some Calculations

- Assume activation energy of 0.7 eV, HALT thermal-stress test performed for 20 minutes at 120 ºC, and a normal-use temperature of 27 ºC.
- The acceleration factor and equivalent test time are given by the following:

$$AF = \exp\left[\frac{E_a}{k}\left(\frac{1}{T_{use}} - \frac{1}{T_{stress}}\right)\right]$$

$$= \exp\left[\frac{0.7}{(8.617)(10^{-5})}\left(\frac{1}{300} - \frac{1}{393}\right)\right]$$

$$\approx 607 \rightarrow (607)(20\text{ minutes}) \approx 202\text{ hours}$$

Some Calculations

- Repeat the calculation assuming a normal-use temperature of 71 ºC.
- The acceleration factor and equivalent test time are given by the following:

$$AF = \exp\left[\frac{E_a}{k}\left(\frac{1}{T_{use}} - \frac{1}{T_{stress}}\right)\right]$$

$$= \exp\left[\frac{0.7}{(8.617)(10^{-5})}\left(\frac{1}{344} - \frac{1}{393}\right)\right]$$

$$\approx 19 \rightarrow (19)(20 \text{ minutes}) \approx 6.3 \text{ hours}$$

Some Calculations

- Now do the calculation with normal-use temperature of 27 ºC, HALT at 120 ºC for 20 minutes, and activation energy of 1.0 eV.
- The acceleration factor and equivalent test time are given by the following:

$$AF = \exp\left[\frac{E_a}{k}\left(\frac{1}{T_{use}} - \frac{1}{T_{stress}}\right)\right]$$

$$= \exp\left[\frac{1.0}{(8.617)(10^{-5})}\left(\frac{1}{300} - \frac{1}{393}\right)\right]$$

$$\approx 9453 \rightarrow (9453)(20 \text{ minutes}) \approx 3151 \text{ hours}$$

Some Calculations - Summary

Activation Energy	Field Use Temperature	Accelerated Temperature	Acceleration Factor	Equivalent Field Use Time*
0.7 eV	27 ºC	120 ºC	607	202 hours
0.7 eV	71 ºC	120 ºC	19	6.3 hours
1.0 eV	27 ºC	120 ºC	9453	3151 hours

- Model is sensitive to difference in temperatures, activation energies.

* Relative to 20 minutes of HALT (temperature stress only).

Observations on Arrhenius Equation

- Sensitive to activation energy.
  - May be impractical to determine dominant activation energy for multi-component system.
  - Values can vary, typically in range of 0.3 to 1.5 eV.
- Sensitive to definition of normal/field use temperature.
- How to handle effect of dormancy of device under test?
  - Fuze is off during MIL-STD-331 C1 and C6 tests.
  - Fuze is operating during HALT (biased).
    - Biasing can accelerate some failure mechanisms, e.g., corrosion. Requires caution as other failure mechanisms might be masked.

Observations on Arrhenius Equation

- Most thermal failure modes are much more dependent on rate of temperature change (dT/dt), total min/max temperature encountered (ΔT), or temperature gradient (∇T or dT/dx).
  - Wire flex fatigue, dependent on ΔT.
  - Package stress corrosion, dependent on dT/dt.
  - Electromigration, dependent on ∇T.
- Many absolute thermal failure mechanisms have been minimized in off-the-shelf components, e.g., reduction of chloride residues in PEM.
- Alternate multi-stimulus models exist.

Observations on Arrhenius Equation

- Literature seems to fall into two categories:
  - Those who believe "Arrhenius is erroneous" and should be discarded. Generally they show data that supports non-correlation of failures with absolute temperature.
    - Majority position in much of the recent literature.
  - Those who haven't heard that yet and make no effort to disprove it. Generally they show data that supports correlation of failures with absolute temperature!
    - May be special cases, e.g., simple/homogeneous components.

Observations on HALT

- HALT represents the trend in quality management of making latent failures patent (detectable) and eliminating them vs. performing operational “in-spec” tests.
  - Test to failure, not just test to conformance.
- Must understand the physics of the failures to determine true root causes in order to effect corrective action.
- Sometimes failure modes have different mechanisms for field vs. accelerated test conditions.
  - Example: A vibration-induced failure in the field may be precipitated by temperature during HALT.

Observations on HALT

- HALT doesn’t allow you to calculate MTTF or other traditional reliability prediction metrics.
- HALT is a very good thing, but doesn’t necessarily replace classical qualification tests.
  - Has to be done correctly.
  - Requires adequate coverage to detect failures.
  - Requires root-cause capability to identify failure mechanisms.
  - Requires management buy-in on up-front expenses.
  - Professional training/consulting is required.

Recommendations

- Recommend HALT as a design-improvement process.
- MIL-STD-331 C1 (T&H) test might be replaced by HAST if the test duration is sufficient.
  - Some of the literature is recommending a higher temperature 130 ºC/85% RH to achieve test-to-failure.
    - Higher temperature may be more appropriate for component-level testing.
  - Have to be careful since glass-transition temp. of PEM encapsulant may decrease with humidity.
  - JEDEC standard JESD-A110-B (HAST) doesn't include temperature cycling. MIL-STD-331 C1 does.

Recommendations

- Keep MIL-STD-331 C6 tests to verify absence of time-dependent failures, unless a quantitative acceleration relationship is found.
    - Extreme cold storage in particular.

Next Steps

- Authors are still working on a definitive answer.
  - Continuing research into useful acceleration models and understanding of failure mechanisms.
  - Continuing review of industry best practices to see where justified improvements exist over MIL-STDs.
  - Keeping an open mind, but vendors should be prepared to support claims of advantages of non-traditional techniques.
  - *Constructive feedback from audience is desired!*

Further Reading

- “Accelerated Reliability Engineering: HALT and HASS”, by Gregg K. Hobbs.
- EIA/JEDEC Standard Test Method A110-B (JESD-A110-B), Highly Accelerated Stress Test (HAST).
- “Electronic Failure Analysis Handbook”, by Perry L. Martin.
- “Evaluation Engineering” (trade magazine).
- “Failure Modes and Mechanisms in Electronic Packages”, by Puligandla Viswanadham and Pratap Singh.
- “HALT, HAST, and HASA Explained”, by Harry W. Maclean.
- MIL-STD-1316, Safety Criteria for Fuze Design.
- MIL-STD-331, Environmental Tests for Fuze and Fuze Components.

Further Reading (cont'd)

- MIL-HDBK-338, Electronic Reliability Design Handbook.
- MIL-STD-810, Test Method Standard for Environmental Engineering and Laboratory Tests.
- "Practical Reliability Engineering", by Patrick D.T. O'Connor.
- "Proceedings of the Institute of Environmental Sciences"
- "Quality and Reliability Engineering International" (journal).
- "Reliable Application of Plastic Encapsulated Microcircuits", Reliability Analysis Center.
- U.S. DoD SD-18, "Part Requirement and Application Guide"
- "Test Engineering", by Patrick D.T. O'Connor.
- http://www.electronics-cooling.com
- http://www.weibull.com

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