Comparing the Effectiveness of Stress-based Reliability Qualification Stress Conditions

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Abstract: The accelerated stress regimens used to characterize failure rates in reliability qualification procedures mimic various environmental aspects of the products' usage conditions. A simple figure of merit—percent of usage conditions simulated—was devised to compare how well the simulated environment applied during reliability qualification corresponds to the application environment. Automotive and telecom standards were used as reference procedures, adding necessary assumptions to complete acceleration factor calculations. Assumptions and calculations to arrive at the figure of merit for high temperature operating life, temperature humidity bias, and temperature cycling stresses are presented. A wide range is observed in the figure of merit, implying the standardized stresses used may overstress or understress the component.

Keywords: Reliability Testing, Accelerated Testing, Component Testing, Temperature, Humidity, Operating Cycle

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Table of Contents

List of Tables

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1 EXECUTIVE SUMMARY

The accelerated stress regimens used to characterize failure rates mimic various environmental aspects of products' usage conditions. As such, accelerated stress test conditions can be viewed as a simulation of the usage environment. A simple figure of merit was devised to compare how well the simulated environment corresponds with the application environment. A wide range was observed in the figure of merit, implying that standardized stresses used may overstress or understress the component.

2 PURPOSE

The purpose of this report is to present calculations and conclusions about how well some commonly used accelerated stress conditions simulate their corresponding use conditions.

3 COMPARING THE SIMULATION ENVIRONMENT TO THE USE ENVIRONMENT

To achieve a qualification in a reasonable amount of time, accelerated stress test conditions are selected to simulate the usage environment. The criteria for selection hinge on a number of variables, including defect types, activation energies, acceleration factors, and the amount of risk to be taken. As stress conditions are selected, two aspects of risk need consideration:

1. Applying stress conditions that are unrealistically demanding and therefore creating inappropriate failures.
2. Being "too easy" in selecting the stress conditions and not applying enough stress to adequately simulate use conditions, therefore not producing failures related to those conditions.

3.1 Metric for Comparison

To compare and understand this two-sided risk, a metric called *percent of use conditions simulated* (PUCS) was devised to compare various stress conditions. PUCS is a figure of merit for comparing application usage condition to the stress condition used in a reliability qualification. In theory, a qualification stress condition that closely simulates the application use condition would have a PUCS of 100%. Correspondingly, values above and below 100% indicate more or less stress relative to the application environment.

3.2 Comparison Procedure Summary

A comparison study was performed to analyze the stress conditions described in two widely used qualification procedures.[1,2] First, the procedures were examined to understand what they considered expected use conditions (Table 1 and Table 2) and stress conditions (Table 3 and Table 4). Then, commonly recognized industry acceptable activation energies or exponents were

[1] *Stress Test Qualification for Integrated Circuits, AEC - Q100 - Rev F, July 18, 2003,* Automotive Electronics Council, Component Technical Committee.

[2] *Generic Requirements for Assuring the Reliability of Components Used in Telecommunications Equipment, Document Number GR-357-CORE,* Telcordia Technologies.

used to calculate acceleration factors.[3] Three representative stress conditions were analyzed in detail: high temperature operating life (HTOL), biased temperature and humidity (THB), and temperature cycling. In this step, the acceleration factors were calculated and used to convert the stress conditions to equivalent hours (or cycles) in the specified use environment. To formulate comparative PUCS values, assumptions for application lifetimes, activation energies, or other required variables were made based on typical industry applications. For each stress, a numeric value of the PUCS was calculated, by dividing the simulated hours (or temperature cycles) by operating or expected lifetime hours (or temperature cycles).

4 COMPARISON AND ANALYSIS

4.1 Example Operating Conditions

The first step is to define the operating environments (i.e., the application or use conditions environments). Table 1 and Table 2 summarize the expected usage conditions. Information in these tables is drawn from the industry standards and from the authors' assumptions about the market usage. There are significant differences in lifetime and operating conditions for the automotive and telecommunications markets. For automotive uses, the operating expectations include an operating temperature range (ΔT) of 190°C (-40°C to 150°C), while for telecom a worst-case ΔT is 86°C (-40°C to 46°C). Market usage assumptions for automotive are a) an application life of 10–15 years, b) actual operating (on) time of less than 1 year, and c) over 27,000 on/off cycles (5 per day). The telecom standard indicates an application use condition of a 25-year life with 100% on time.

Table 1 Example Automotive Use Conditions

Application	Under-hood			Passenger Compartment	Passenger Compartment
Usage Category	0	1	2	3	4
T_{use} Min (°C)	-40	-40	-40	-40	0
T_{use} Max (°C)	150	125	105	85	70
Expected Life*	10–15 years*				
On/Off Cycles*	5 per day*				
RH%*	75% (mean)*				

* Assumed variables and values.

[3] *Failure Mechanisms and Models for Semiconductor Devices, JEP122B, August 2003,* JEDEC Solid State Technology Association.

Table 2 Example Telecom Use Conditions

Application	Enclosed Building: Normal	Enclosed Building: (Short term <96 consecutive hrs or <15 days/yr)	Uncontrolled Environment
Operating Temp. Range	5–40ºC	5–50ºC	-40 to 46ºC
Operating Mean T_a	23°C	28°C	≤ 65°C inside equip housing
Expected Life	219,000 hrs	9,000 hrs (included in 219K hrs)	219,000 hrs
On/Off Cycles	0		
RH% Range (mean 50%)	5–85%	5–90%	5–95%

4.2 Example Stress Conditions

The stress conditions described in the procedures are summarized in Table 3 and Table 4. The automotive procedure offers some alternatives including HTOL durations, a choice between highly accelerated stress testing (HAST) or THB, and various temperature cycling conditions. The telecom stress examples (Table 4) do not offer as many choices.

Table 3 Example Automotive Reliability Stress Conditions

Stress	Option	0	1	2	3	4
T_{stress} HTOL 408 hrs	Use Either	175ºC	150ºC	125ºC	105ºC	90
T_{stress} HTOL 1000 hrs		150ºC	125ºC	105ºC	85ºC	70ºC
THB 1K hrs	Use Either	85ºC/85% RH				
HAST 96 hrs		130ºC/85% RH				
Temp Cycle Min/Max ºC 500 cycle	Use Either	-65/175	65/150	-50/150	-50/125	-10/105
Temp Cycle Min/Max ºC 1000 cycle		-50/175	-50/150	-50/125	-50/105	-10/90

Table 4 Example Telecom Reliability Stress Conditions

Stress	Option	Enclosed Bldg. (including short-term assessments)	Uncontrolled Environment
T_{stress} HTOL 1000 hrs	Required	125ºC	
THB 1000 hrs	Use Either	85ºC/85% RH	
HAST 100 hrs		120ºC/85% RH	
Temperature Cycle	Required	-55ºC to 125ºC 500 cycles`	-55ºC to 125ºC 1000 cycles

4.3 HTOL

Table 5 estimates the PUCS of an HTOL stress based on the automotive standard. Applying activation energies of 0.5 eV to 0.9 eV (0.7eV being the most widely applied to known failure mechanisms) with durations of 408 hours and stress temperatures ranging from 85ºC to 175ºC, the stresses have PUCS ranging from a low of 11% to a high of 27% of the expected 8200-hour operating life.

Table 6 shows the assumptions and analysis of HTOL stress conditions for the telecommunications segment. Using the same activation energies as the automotive example and selecting a stress temperature/duration of 125ºC/1000 hours, a performance of 3.3% PUCS is predicted (7,151 simulated hours of the 219,000 hour operating life).

Table 5 PUCS of HTOL Automotive Stress

	Use Condition		0	1	2	3	4	0,1,2,3 or 4
Based on Example Procedures	T_{stress}		175°C	150°C	125°C	105°C	90°C	As shown at left
	Stress Duration		408 hrs					1000 hrs
	T_{use} max		150°C	125°C	105°C	85°C	70°C	Same as stress temp
Assumptions and Calculated Values	Operating Life Time		5,500–8,200 hrs					
	Acceleration Factors	Ea = 0.7 eV	2.9	3.3	2.9	3.3	2.7	1
		Ea = 0.5 eV	2.1	2.4	2.2	2.4	2.0	1
		Ea = 0.9 eV	4.0	4.7	4.0	4.7	3.6	1
	Hours Simulated at T_{use} max		1,191	1,363	1,201	1,355	1,100	1000
% of Use Conditions Simulated (PUCS)	E_a = 0.7 eV		15–21%	17–25%	15–22%	17–25%	13–20%	12–18%
	E_a = 0.5 eV		11–16%	12–18%	11–16%	12–17%	10–25%	11–15%
	E_a = 0.9 eV		20–29%	24–35%	20–30%	23–35%	18–27%	20–26%

Note: (AF = Exp [(-E_a/K)*{1/(T_{stress}+273)-1/(T_{use}+273}]). Also, $T_{j\ use}$ =$T_{a\ use}$ is assumed.

Table 6 PUCS of HTOL Telecom Stress

	Use Condition	Enclosed Bldg	Enclosed Bldg. (Short Term)	Uncontrolled Environment
Based on Example Procedures	Operating Life Time (hrs)	219,000	9,000	219,000
	T_{stress}	175°C	150°C	125°C
	Stress Duration (hrs)	1000		
	T_{use} Max	40°C	50°C	65°C
Assumptions and Calculated Values	$T_{junction}$	90°C	100°C	110°C
	Acceleration Factor for E_a = 0.7 eV	7.2	3.9	2.2
	Hours Simulated at T_{max}	7,151	3,962	2,223
% of Use Conditions Simulated (PUCS)		3.3%	44%	1.0%

Note: (AF = Exp [(-E_a/K)*{1/(T_{stress}+273)-1/(T_{use}+273}]).

4.4 THB Comparison

PUCS calculations for THB stress are addressed in Table 7. The 85% relative humidity (RH)/85ºC stress conditions and highly accelerated stress test (HAST) applying 85% RH and 130ºC (automotive) or 120ºC (telecom) were selected for the evaluation. Assumptions include 0.7 eV activation energy, use condition temperatures ranging from 23°C to 30°C, an RH exponent of 2.7, and a voltage acceleration of 1.0. For automotive, the stress time equates to 104,049 hours use: a PUCS of 1,269% when compared to the actual operating lifetime of 8,200 hours. The telecom PUCS of 221% indicates a stress that is about 2.2X the expected life 219,000 hours.

Table 7 THB and HAST Stress (Automotive and Telecom)

	Use Condition	Typical Automotive	Typical Automotive	Typical Telecom	Typical Telecom
Based on Example Procedures	Stress RH%/T_{stress}	85/85	85/130	85/85	85/120
	Stress Duration (hrs)	1000	96	1000	100
	Use condition RH%	75*		50	
	T_{use} (°C)	30*		23	
Assumptions and Calculated Values	Operating Lifetime (hrs)	8,200*		219,000	
	Activation Energy (E_a [eV])	0.7			
	Voltage Acceleration (V stress + V use)	1			
	RH Acceleration Factor	1.4		4.2	
	RH Exponent (For Al corrosion)	2.7			
	Total Acceleration Factor ($AF_{temp} \times AF_{RH} \times AF_{voltage}$)	86	1082	487	3667
	Hours Simulated	86,000	104,049	484,901	366,000
% of Use Conditions Simulated (PUCS)		1049%	1269%	221%	167%

* Assumed values.

Note: $(AF = (RH_{stress}/RH_{use})^N$ where N varies strongly with failure mechanism.

4.5 Temperature Cycling

Table 8 and Table 9 address temperature cycling. As shown in Table 8, stress temperature deltas for the automotive industry range from 240°C (-65 to 175°C) to 115°C (-10 to 105°C). These ranges depend on the expected application temperature range, which spans -40 to 150°C. Stress duration options are 500 and 1000 cycles. A Coffin-Manson exponent of 4 was used in the calculations as it is worst-case (except for solder fatigue).

As shown in Table 9, the temperature cycle stress for telecommunications more than validates the use condition since this application is expected to remain in a power-on state for most of its operating life. Thus, it will experience few, if any, temperature cycles. The stress temperature delta is 180°C (-55 to 125°C) over 500 and 1000 cycles. Use temperatures are expected to span a 35°C range (5 to 40°C) in a controlled environment and an 86°C range (-40 to 46°C) in an uncontrolled environment. Reliable operation for over 349,000 cycles is predicted for the controlled environment and >19,000 cycles for the uncontrolled environment. Even though central office equipment is expected to run without shutdown, two on/off cycles per day were assumed. Using this assumption, the stress is predicted to represent 19X the expected life in the controlled environment and be approximately equal to the expected life in the uncontrolled environment.

Table 8 Automotive Temperature Cycle Stress

	Use Condition		0	1	2	3	4
Based on Example Procedures	T_{stress} (°C, Min/Max)	If 500 cycles	-65/175	-65/150	-50/150	-50/125	-10/105
		If 1000 cycles	-50/175	-50/150	-50/125	-50/105	-10/90
	T_{use} (°C, Min/Max)		-40/150	-40/125	-40/105	-40/85	0/70
	T_{max} (°C)		150	125	105	85	70
Based on Example Procedures	Operating Cycles (Life time)		27,375				
	Coffin-Manson Exponent		4	4	4	4	4
	Acceleration Factors	If 500 cycles	2.5	2.9	3.6	3.8	7.3
		If 1000 cycles	2.0	2.2	2.1	2.4	4.2
	# of Cycles Simulated	If 500 cycles	1273	1441	1810	1921	3642
		If 1000 cycles	1967	2159	2122	2364	4165
% of Use Conditions Simulated (PUCS)	If 500 cycles stress		5%	6%	7%	9%	13%
	If 1000 cycle stress		7%	8%	8%	9%	15%

Note: (AF = $(\Delta T_{stress}/\Delta T_{Use})^{\text{Coffin-Manson Exponent}}$). The C-M exponent varies strongly with failure mechanism.

Table 9 Typical Telecom Temperature Cycle Stress

	Use Condition	Enclosed Bldg	Uncontrolled Environment
Based on Example Procedures	Operating Lifetime cycles (assumes 2 cycles/day)	18,250	18,250
	T_{stress}, °C Min/Max	-55/125	-55/125
	T_{use}, °C Min/Max	+5/40	-40/46
	Stress Duration (Cycles)	500	1000
Assumptions and Calculated Values	Coffin-Manson Exponent	4	4
	Acceleration Factors	700	19.2
	Number of Cycles Simulated	350,000	19,000
% of Use Conditions Simulated (PUCS)		1,916%	105%

Note: (AF = $(\Delta t_{stress}/\Delta t_{use})^{\text{Coffin-Manson Exponent}}$). The C-M exponent varies strongly with failure mechanism.

5 SUMMARY AND DISCUSSION

The results in Table 10 suggest that these stress-based methodologies do not apply stresses corresponding to expected use conditions. The HTOL stress in these examples effectively validates reliable performance for only the early life of the device, not its entire operating life. Additionally, to pass some stress regimens, a considerable reliability margin must be available. The data in Table 10 also imply that applying similar reliability requirements to differing applications results in both over- and underestimation of the actual reliability needed.

Table 10 Summary of PUCS

	High Temp Operating Life	Temperature/Humidity	Temperature Cycle
Automotive	11–26%	1049–1269%	5–15%
Telecommunications	1–44%	167–221%	105–1916%

While a 100% PUCS value can serve as a logical starting point, discerning the optimal target for PUCS is probably not as simple as setting each stress condition to get a 100% PUCS value. No quantitative analysis has been made to relate how much the risk changes when moving from 100% PUCS to (for example) 200% or 25%. Possible future work could attempt to refine the PUCS value by analysis to determine factors making the dominant and secondary effects; this could lead to methods of making a data-driven decision about what is a meaningful increment of PUCS and its associated incremental change in risk.

6 CONCLUSION

To ensure the best match of performance and reliability, the qualifying activity must be flexible in its approach to validating reliability. A critical driver is the application conditions the product will experience over its life. Just as future processes and products are being targeted for specific markets and reliability needs, qualification procedures must also target market needs. Qualification procedures should have appropriate procedures to quantify risk and be rooted in accurate reflections of the use conditions they simulate. Tradeoffs among reliability, performance and other factors will continue to be evaluated as technologies follow Moore’s Law.

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