OPTIMIZING RELIABILITY QUALIFICATIONS OF BALANCED ARMATURES: USE OF ACCELERATED TEST CONDITIONS

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ABSTRACT

Reliability qualification is a vital aspect of balanced armature driver product development which verifies that the transducers meet performance requirements and warranty expectations. Knowles Electronics has traditionally utilized the Highly Accelerated Life Test (HALT) reliability test in the qualification process of balanced armatures. However, this test involves a long duration of exposure in the temperature and humidity chamber. This concern prompted the exploration of a solution to hasten the qualification process, thereby reducing time and resources.

In this paper, an alternate test method was developed for HALT which is specifically tailored for balanced armature drivers. The method utilizes the Arrhenius and Eyring reliability models which involves introducing accelerated temperature and humidity conditions while simultaneously reducing the exposure duration within the chamber. Corresponding experimentation has been conducted to validate the ability to anticipate the typical failure mechanisms that should be detectable by HALT.

With the introduction of the efficient and effective alternate test method, the concern about the lengthy duration of conventional HALT is addressed thereby enabling a more streamlined product and process qualification.

1.0 INTRODUCTION

1.1 Background of the Study

Balanced Armature (BA)[1] drivers are transducers that convert electronic signals into acoustical sound waves. The signal conversion involves vibrating a reed balanced between two magnets. The motion of the reed is translated to a diaphragm which results in the production of sound waves.

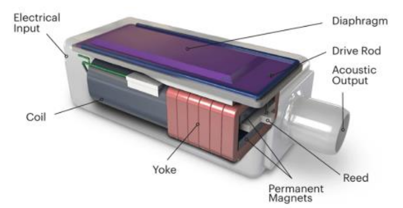


Fig. 1. Balanced Armature Construction

The Highly Accelerated Life Test (HALT) is a reliability test used during product or process qualification of these balanced armature (BA) drivers.

HALT intends to simulate failures of the components of balanced armature drivers when exposed to an elevated temperature of 63°C, a relative humidity of 95%, and with +9 dB drive at motor resonance. HALT has a corresponding test duration of 1008 hours (6 weeks).

The environmental conditions and test duration to which the balanced armature drivers are subjected can be extrapolated to establish equivalent “accelerated” conditions but still capture the intended failure mechanisms of the conventional test conditions used by Knowles Electronics. It is worth noting that there are no existing industry standards specific to the reliability testing of balanced armatures.

1.2 Statement of the Problem

The 1008-hour duration of HALT test is the longest leadtime among all the reliability tests performed at Knowles. Figure 2 provides a comparison of the reliability tests on the test duration. The long duration of HALT testing poses a challenge when it comes to releasing New Product Introduction (NPI) projects or qualifying product/process changes for parts that are already in mass production.

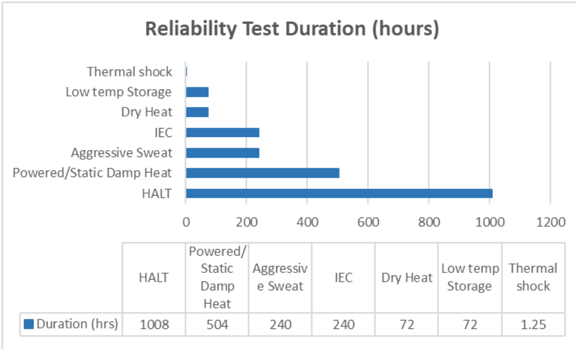


Fig 2. Reliability Test Duration Comparison

1.3 Objective of the Study

The paper aims to propose an alternative reliability test method to the current Highly Accelerated Life Test (HALT) conditions of 63°C temperature and 95% relative humidity, with the aim of reducing the test duration of 1008 hours. This reduction in test duration will improve the project timeline for New Product Introductions (NPIs) or qualifying product/process changes.

2.0 REVIEW OF RELATED WORK

Two reliability models were reviewed for potential applicability in this study: the Arrhenius Model and the Eyring Model. These models are commonly used in life prediction modeling in the semiconductor industry. This prompted the researchers to adopt and apply a similar approach to balanced armature drivers used in the medical technology and specialty audio industry.

2.1 Arrhenius Model for Temperature Acceleration

The Arrhenius model[2] as shown in Figure 3 was used for this study since the involved test condition utilized elevated temperature levels. This increased temperature testing can be used to cause failures to occur earlier than what would be observed in the field thus enabling earlier detection and correction.

$$A_f = e^{\left\{\frac{E_a}{K_B}\left(\frac{1}{T_u}-\frac{1}{T_t}\right)\right\}}$$

Where:
Af = Acceleration factor
E_a = Activation energy
K_B = Boltzmann Constant (8.62E-05 eV/K)
T_u = Use temperature in Kelvin
T_t = Accelerated test temperature in Kelvin

Fig 3. Arrhenius Model for Temperature Acceleration Factor Formula

2.2 Eyring Equation for Humidity Acceleration

H. Eyring introduced the Eyring equation[3] in chemical kinetics to describe changes in the rate of a chemical reaction against temperature. The model as shown in Figure 4 is versatile and therefore applicable in the field of Reliability Engineering. In this paper, the Eyring equation was used to model the effect of humidity as a stress on the reliability of the component.

$$A_f = \left(\frac{RHt}{RHu}\right) e^{\left\{\frac{E_a}{K_B}\left(\frac{1}{RH_u}-\frac{1}{RH_t}\right)\right\}}$$

Where:
Af = Acceleration factor
E_a = Activation energy
K_B = Boltzmann Constant (8.62E-05 eV/K)
RH_u = Use relative humidity
RH_t = Accelerated test relative humidity

Fig 4. Eyring Model for Humidity Acceleration Factor Formula

3.0 METHODOLOGY

This study utilized the PDCA (Plan-Do-Check-Act) approach to systematically analyze reliability conditions, design the necessary evaluation, and conduct validation activities.

3.1 PDCA – Plan-Do Phase

3.1.1 Review of Product Limit Capability

The existing reliability test conditions for balanced armature (BA) drivers at Knowles were established based on the known material limit characteristics of the components, particularly the diaphragm. The diaphragm is a key component of BA drivers and plays a crucial role in delivering the intended electroacoustic output.

Based on the datasheet, the diaphragm of the balanced armature has a maximum temperature specification of 65°C. Exceeding this temperature limit may impact the form of the diaphragm which would then reduce the ability to functionally operate.

3.1.1 Designing Step Stress Test Experiments

To reduce the 1008-hour test duration of the HALT conditions while maintaining reliability, the Step Stress Test method was utilized. This method involves testing the products at higher than typical levels of stress to induce early failures.

Step Stress Test involves testing the balanced armatures at levels that go beyond the specification limits reflected in the datasheet, up to the destruct limits of the product. By subjecting the products to higher stress levels, the occurrence of failures is accelerated and potential vulnerabilities are anticipated earlier in the testing process (refer to Figure 5).

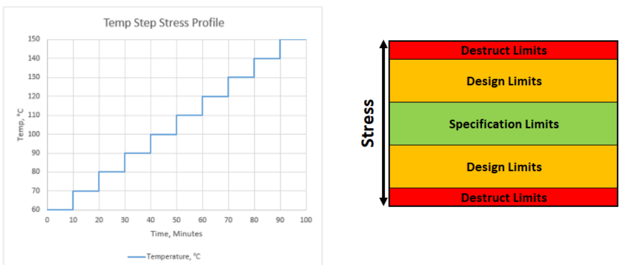


Fig 5. Temperature Step Stress Test Profile

In designing the Step Stress Test experiments, different temperatures were selected within the equipment chamber capability as shown in Figure 6. These temperatures were chosen based on their ability to induce stress on the products while still within the operational limits of the chamber. Additionally, two humidity levels between 50% and 95% were also comprehended. The selection of humidity conditions considered the existing use stress condition of 50% RH and ensures that the humidity does not exceed the maximum limit of the chamber.

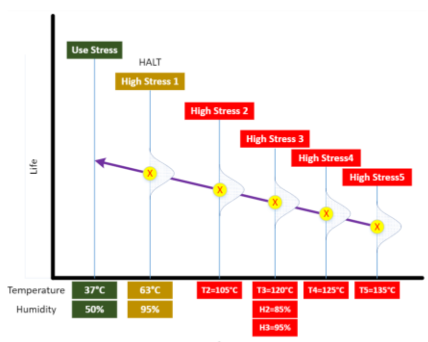


Fig 6. Step Stress Test Experiment Points

Test-to-fail was performed on ten samples for each of the selected temperature and humidity conditions outlined in the test matrix in Figure 7. The acceptance criteria derived from conventional conditions were adapted for assessing Sensitivity Shift and Total Harmonic Distortion (THD) parameters.

The duration for the samples to either fail or survive was then recorded. This data was subsequently utilized in the corresponding analysis.

Temp	Humidity		
	Ambient	85%	95%
63°C			✓
105°C	✓		
110°C			✓
115°C			
120°C	✓	✓	✓
125°C	✓		
130°C			
135°C	✓		
140°C	✓		

Criteria			
	Max Limits		
Sens Shift @500Hz	3	-3	dB
Sens Shift @1000Hz	3	-3	dB
Sens Shift @Peak1	3	-3	dB
THD1	5		%
THD2	5		%
THD3	10		%
THD4	10		%

Fig 7. Temperature and Humidity Test Matrix and Acceptance Criteria

4.0 RESULTS AND DISCUSSION

4.1 PDCA – Check Phase

4.1.1 Mean Life Analysis

The data from the Step Stress Test evaluation showed that some balanced armature drivers survived with a temperature of 125°C and ambient relative humidity, which is equivalent to a mean life of 373 hours.

However, when subjected to a temperature of 135°C with the same relative humidity, none of the units survived. This translates to an equivalent mean life of only 32 hours as shown in Figure 8.

Test Data - Temperature Only

125°C/Amb RH (I-22-0327)		
#	Hrs	S/F
1	600	S
2	336	F
3	504	F
4	600	S
5	360	F
6	120	F
7	336	F
8	120	F
9	192	F
10	600	S
Distribution	Lognormal	
Mean life	373	Hrs
	16	Days
Test Status	Completed	

135°C/Amb RH (I-22-0025)		
#	Hrs	S/F
1	30	F
2	18	F
3	18	F
4	18	F
5	18	F
6	30	F
7	70	F
8	35	F
9	71	F
10	30	F
Distribution	Lognormal	
Mean life	32	Hrs
	1	Days
Test Status	Completed	

Fig 8. Temperature Data Results

Decapsulation conducted on the failures showed deformed diaphragm film which is an expected failure mechanism of balanced armature drivers subjected to higher levels of temperature (see Figure 9) since the film is the most fragile part of the BA drivers.

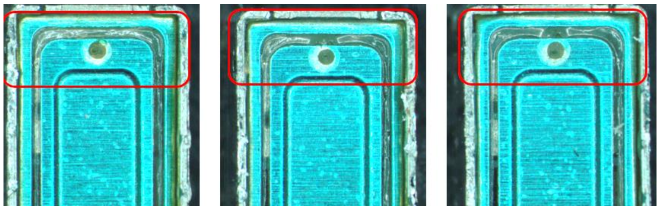


Fig 9. Decapsulation Result after Elevated Temperature Exposure

Subjecting to elevated humidity impacted the performance of the balanced armature drivers. At 85% relative humidity, partial failures were observed, with a mean life of 68.6 hours. However, when the relative humidity was increased to 95%, all 10 units experienced failures, with a mean life of 30.5 hours as reflected in Figure 10. In both cases, the parts were subjected to a temperature of 120°C.

Test Data - Temperature & Humidity

120°C/95% RH (I-23-0039)		
#	Hrs	S/F
1	17	F
2	17	F
3	17	F
4	109	F
5	17	F
6	17	F
7	5	F
8	5	F
9	92	F
10	5	F

Distribution:	Lognormal	
Mean Life:	30.5	Hrs
	1	Days
Test Status	Completed	

120°C/85% RH (I-23-0060)		
#	Hrs	S/F
1	24	F
2	24	F
3	131	S
4	24	F
5	113	F
6	113	F
7	19	F
8	41	S
9	22	F
10		

Distribution:	Lognormal	
Mean Life:	68.56	Hrs
	3	Days
Test Status	Completed	

Fig 10. Temperature and Humidity Data Results

The units that failed the temperature-humidity experiment were found to have ripped diaphragm film and deformed diaphragm film as shown in Figure 11.

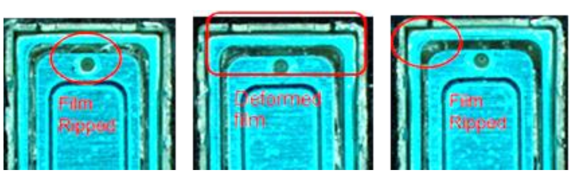


Fig 11. Decapsulation Result – Temperature-Humidity Sample

4.1.2 Temperature Data Analysis Using Arrhenius Model

The Arrhenius model, referenced in Section 2.1 of this paper, was used in the analysis of temperature data. This model considers changes in reliability when the temperature increases to establish a quantifiable relationship.

The time and temperature results obtained (shown in Figure 12) were analyzed using the Arrhenius model and Maximum Likelihood Estimation Method (MLE) in the life data analysis software.

A best-fit distribution analysis was also conducted, revealing that the data follows a lognormal distribution, as evidenced by the largest likelihood (LK) function value of -213.63, shown in Figure 13.

Raw Data

	Item Number	State F or S	Time to F or S (hr)	Temperature (K)
135°C	1	F	30	408.15
	2	F	18	408.15
	3	F	18	408.15
	4	F	18	408.15
	5	F	18	408.15
	6	F	30	408.15
	7	F	70	408.15
	8	F	35	408.15
	9	F	71	408.15
	10	F	30	408.15
125°C	11	S	600	398.15
	12	F	336	398.15
	13	F	504	398.15
	14	S	600	398.15
	15	F	360	398.15
	16	F	120	398.15
	17	F	336	398.15
	18	F	120	398.15
	19	F	192	398.15
	20	S	600	398.15
120°C	21	F	480	393.15
	22	F	360	393.15
	23	S	672	393.15
	24	S	672	393.15
	25	S	672	393.15
	26	F	192	393.15
	27	F	24	393.15
	28	F	624	393.15
	29	S	672	393.15
	30	F	216	393.15
105°C	31	F	1632	378.15
	32	F	1368	378.15
	33	F	1080	378.15
	34	F	768	378.15
	35	S	1800	378.15
	36	F	1440	378.15
	37	F	1296	378.15
	38	F	792	378.15
	39	S	1800	378.15
	40	F	1440	378.15

Fig 12. Time and Temperature Results

Distribution	Ranking
Weibull	2
Exponential	3
Lognormal	1
Weibull	
Beta	1.158264365
B	17784.16229
C	1.118758E-17
LK Value	-216.4129703
Exponential	
B	18219.74934
C	3.692491E-18
LK Value	-216.8865385
Lognormal	
Log-Std	0.990279508
B	18902.99688
C	4.308967E-19
LK Value	-213.6307268

Fig 13. Best Fit Distribution Results

The calculated activation energy (Ea) using the Arrhenius model was determined to be 1.62. The summary of results can be seen in Figure 14.

Quick Results Report	
Parameters	
Model	Arrhenius
Distribution	Lognormal
Analysis	MLE
Log-Std	0.99028
B (K)	18902.99688
C (hr)	4.308967E-19
Ea (eV)	**1.628944**
Mean (hr)	18.6595
LK Value	-213.630727
Fail \ Susp	31 \ 9

Fig 14. Activation Energy Result (T)

4.1.3 Humidity Data Analysis Using Eyring Model

Similar to the approach in the temperature data analysis using the Arrhenius model, the activation energy (Ea) was calculated using the Eyring equation that was tackled in Section 2.2 of the paper, concerning the relationship between relative humidity and reliability.

The Eyring model and Maximum Likelihood Estimation Method (MLE) were used for analysis and the obtained time, temperature, and humidity results (as shown in Figure 15) were processed using the life data analysis software. The best-fit distribution analysis in Figure 16 revealed that the data also followed a lognormal distribution, as it had the largest Likelihood (LK) function value of -78.86.

Raw Data				
	Item Number	State F or S	Time to F or S (hr)	Humidity (RH)
120°C 95%RH	1	F	17	0.95
	2	F	17	0.95
	3	F	17	0.95
	4	F	109	0.95
	5	F	17	0.95
	6	F	17	0.95
	7	F	5	0.95
	8	F	5	0.95
	9	F	92	0.95
	10	F	5	0.95
120°C 85%RH	11	F	24	0.85
	12	F	24	0.85
	13	S	131	0.85
	14	F	24	0.85
	15	F	113	0.85
	16	F	113	0.85
	17	F	19	0.85
	18	S	41	0.85
	19	F	22	0.85

Fig 15. Time, Temperature, and Humidity Results

Distribution	Ranking
Weibull	2
Exponential	3
Lognormal	1
Weibull	
Beta	1.010760267
A	3.178710872
B	6.211025781
LK Value	-81.076764
Exponential	
A	3.231791514
B	6.255772222
LK Value	-81.07846781
Lognormal	
Log-Std	0.988453164
A	5.352715888
B	7.716065571
LK Value	-78.85765365

Fig 16. Best Fit Distribution Results

The analysis resulted in a calculated activation energy (Ea) of 0.00065 (see Figure 17).

Quick Results Report	
Parameters	
Model	Eyring
Distribution	Lognormal
Analysis	MLE
Log-Std	0.988453
A	5.352716
B (RH)	7.716066
Ea (eV)	**0.000665**
Mean (hr)	10.772562
LK Value	-78.857654
Fail \ Susp	17 \ 2

Fig 17. Activation Energy Result (RH)

4.1.4 Life Calculation

The life calculation made certain assumptions about the customers' usage conditions, including a temperature of 37°C and a relative humidity of 50%. Figure 18 shows the activation energy (Ea) values for the conventional Highly Accelerated Life Test (HALT) conditions, derived from the Arrhenius and Eyring models, as 1.6 and 0.00065 respectively. These values were also included as input parameters in the analysis.

4.1.4.1 Life Calculation: 63°C / 95% RH

Calculation Assumptions		
Use Temperature:	37	°C
Use Humidity:	50	%
Activation Energy, Ea:	1.6	eV
Humidity Constant:	0.000665	

Test Conditions		
Test Temperature:	63	°C
Test Humidity:	95	%
Test Voltage:		
Test Duration:	1,000	Hours
Test Sample Size:	32	
Total Device Hours:	32,000	Hours
Desired No of Failures:	0	

Fig 18. Life Calculation Input Parameters (conventional test condition)

The guaranteed life of balanced armatures, when subjected to conventional HALT conditions of 63°C / 95% RH at 1008 hours was calculated to be at **~12 years** (see Figure 19). This calculation is based on 93% reliability and a 90% confidence level.

Acceleration Factor (Af)
Af = 102.61

$$Af = \left(\frac{RHu}{RHt}\right)^{-n} e^{\left[\frac{Ea}{k}\left[\frac{1}{Tu} - \frac{1}{Tt}\right]\right]}$$

Equivalent Device Hours @ Use Temp using Af	
3,283,648	Device Hours @ Use Temp

MTBF @ Use Temp		
MTBF (mL1) =	1,426,061	Hours
Frate =	7.01232E-07	Failures/Hour
FIT =	701.23	

$$Ta = \frac{MTBF\left[X^2 \alpha ; 2r + 2\right]}{2}$$

Specific Life Calculation		
Reliability =	93.0	%
CL =	90	%
Calc Life =	11.8	Years

$$R(T) = e^{-\left[\frac{T}{MTBF}\right]}$$

Fig 19. Calculated Life (conventional test condition)

4.1.4.1 Equivalent Temperature and Relative Humidity Determination

Using the same calculation assumptions as in conventional conditions (63°C / 95% RH), the accelerated temperature and relative humidity conditions were extrapolated to be 75°C / 85% RH at 168 hours (refer to Figure 20).

Test Conditions		
Test Temperature:	75	°C
Test Humidity:	85	%
Test Voltage:		
Test Duration:	168	Hours
Test Sample Size:	32	
Total Device Hours:	5,376	Hours
Desired No of Failures:	0	

Fig 20. Life Calculation Input Parameters (accelerated test condition)

The guaranteed life span was calculated at ~13 years which is at par with the conventional one at ~12 years as reflected in Figure 21.

Acceleration Factor (Af)
Af = 688.70

$$Af = \left(\frac{RHu}{RHt}\right)^{-n} e^{\left[\frac{Ea}{k}\left[\frac{1}{Tu} - \frac{1}{Tt}\right]\right]}$$

Equivalent Device Hours @ Use Temp using Af
3,702,455 Device Hours @ Use Temp

MTBF @ Use Temp		
MTBF (mL1) =	1,607,945	Hours
Frate =	6.21912E-07	Failures/Hour
FIT =	621.91	

$$Ta = \frac{MTBF\left[X^2 \alpha ;\, 2r+2\right]}{2}$$

Specific Life Calculation		
Reliability =	93.0	%
CL =	90	%
Calc Life =	13.3	Years

$$R(T) = e^{-\left[\frac{T}{MTBF}\right]}$$

Fig 21. Calculated Life (accelerated test condition)

4.1.5 Validation of Accelerated Conditions

To validate the performance under accelerated conditions, 9 part numbers representing various balanced armature families were subjected to both conventional (63°C / 95% RH) and accelerated conditions (75°C / 85% RH).

Three rounds of validation activities with corresponding weekly read-outs for 6 weeks were performed to ensure the consistency of the evaluation results. The results are summarized in Figure 22.

Part Number	63 °C /95% RH (Conventional)				75 °C / 85% RH (Accelerated)			
	1W (168 hr)	2W (336 hr)	4W (672 hr)	6W (1008 hr)	1W (168 hr)	2W (336 hr)	4W (672 hr)	6W (1008 hr)
A	FAIL	PASS	PASS	PASS	FAIL	PASS	PASS	PASS
B	FAIL	FAIL	PASS	PASS	FAIL	FAIL	PASS	PASS
C	PASS	FAIL	PASS	PASS	FAIL	PASS	PASS	PASS
D	PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
E	PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
F	PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
G	PASS	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
H	FAIL	PASS	PASS	PASS	FAIL	PASS	PASS	PASS
I	PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS

Fig 22. Validation Results of Both Conventional and Accelerated Conditions

Failures were observed in 4 out of the 9 part numbers that were subjected to both conventional and accelerated conditions. For these 4 part numbers, failures that were encountered within the 1008 hours (6 weeks) duration using the conventional conditions also manifested as similar rejections as early as 168 hours (1 week) when subjected to accelerated conditions.

Failure analysis was done on failures from both conventional and accelerated conditions which revealed detached drive rod and deformed diaphragm film failure mechanisms. Representative images from the failure analysis conducted can be seen in Figure 23.

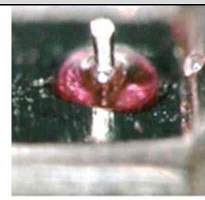
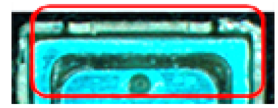
Detached Drive Rod	Deformed Diaphragm Film
	

Fig 23. Decapsulation Results (Conventional vs Accelerated Conditions)– Detached Drive Rod and Deformed Diaphragm Film

The results from the validation runs demonstrate that the accelerated conditions can substitute for the existing conventional conditions.

4.1 PDCA – Act Phase

With the favorable results of the evaluations, the accelerated test conditions of 75°C / 85% RH at 168 hours have been standardized and implemented at Knowles Electronics to be used during NPIs and product/process qualification. For each project, a corresponding 83% reduction in test lead time was attained as a result of a reduction from 1008 hours (6 weeks) to 168 hours (1 week).

Moreover, the new HALT test conditions were also applied to the Ongoing Reliability Testing (ORT) for parts that have already been released to mass-production.

5.0 CONCLUSION

From the study conducted, it is concluded that accelerated test conditions when subjecting balanced armature drivers to a Highly Accelerated Life Test (HALT) can be derived based on the Arrhenius and Eyring models. It is also concluded that these accelerated conditions (75°C / 85% RH at 168 hours) can guarantee the same life spans as that of conventional life testing (63°C / 95% RH) and equally expose the vulnerabilities of the products during accelerated life testing.

6.0 RECOMMENDATIONS

It is recommended to adopt accelerated test conditions during NPI and product/process qualification using HALT. However, it is also recommended to continue conventional testing for 3 months in parallel as part of safe launch activities on selected part numbers to further validate the change in reliability testing. Once the safe launch activities have been completed, there is projected to be a 70% increase in temperature and humidity chamber availability.

7.0 ACKNOWLEDGMENT

The authors would like to thank the Reliability team of Knowles Electronics Philippines and its management team and those who were involved in the project, especially to Sr. Staff Reliability Engineer Hernando Azarcon and Quality Manager Ray Pendor who through their guidance made the execution and completion of this optimization project possible resulting in the success of accelerated life test implementation.

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9.0 ABOUT THE AUTHORS

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10.0 APPENDIX

Not Applicable.