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Designing for Reliability with a System Life Estimator

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From big machines to small handheld equipment, all typically come with varying warranty timelines based on estimations. If this number is overestimated or underestimated, it can incur millions of dollars in losses to manufacturers. That's why it's important to look at the lifetime system estimation as a bottom-up process. The efficiency in this approach results in a robust method to formulate the top-down design flow of a system that can operate reliably over the required duration. The design method can guide a system designer at every design step to make the right decisions regarding electrical component choice as per the ratings, electromechanical component choices, such as crystal oscillators, component placement, trace thickness, copper imbalance, and operating conditions.

Contents

Introduction

Just as shelf stable foods with long life spans require expiration dates, electronics require a well understood lifespan that can be represented by metrics such as time to failure (TTF).

Bottlenecks in Life Estimation of PCBs

Electronics, like human beings, are vulnerable during their infancy and old age. During infancy, manufacturing defects can lead to sudden failures and near the end, failures are driven by wear and tear. The bathtub function in Figure 1 shows this variability in failure rate over duration of usage.

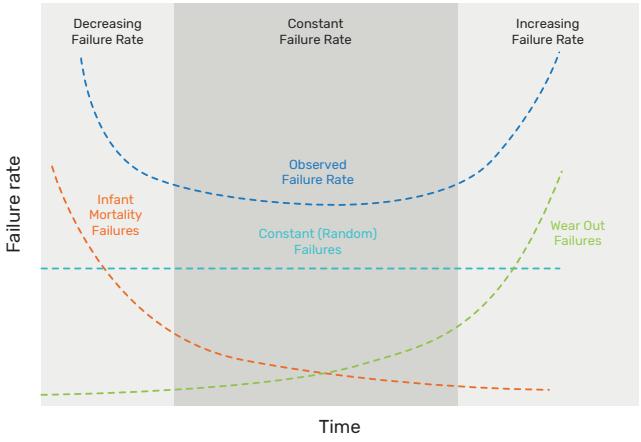

Figure 1: Bathtub Curve

An accurate estimation of lifetime of a system requires:

- Modeling the decreasing failure rate during the early stages of usage and an increasing failure rate during the late stages
- Large number of samples
- Inefficiently long duration of testing
- Prediction of all the possible ways that the system can fail or the failure modes
- Modeling the occurrence probability for all failure modes, such as open, short, and variation of parameters
- The above bottlenecks or challenges have led to the development of approximate methods to estimate system life. Three methods, which are not mutually exclusive, can estimate a system's lifetime.
  - The first, most basic approach is to calculate MTTF as an average of historical TTF recordings from field data. The data collected suffers from inherent inaccuracies, such as informal and inconsistent user reporting, varied operation environments, unreported mishandlings, etc.
  - The second method is where the system is tested in a controlled environment. The emulated environment is carefully crafted as per reliability testing standards such as MIL-HDBK-781A [1] to replicate a real usage scenario and trigger the failure modes that consumers may encounter. The system is then tested with regular inspections for visible failures—using a camera, structural failures—using an infrared imaging device and electrical failures, probes, multi-channel scopes, multimeters, and stray radiation detecting equipment. The testing environment largely depends on the nature of the system and its application environment.
  - The third method uses statistical estimations based on mathematical models for various failure modes. The inferences from historical data and lab tests are used in the estimations as well, which renders the methods as not mutually exclusive. Various standards can be used for performing life testing in labs and for estimations.

Standards for Estimation

During the early 1940s, the US Department of Defense (DoD) formulated the very first reliability standards as the MIL-SPEC, MIL-HDBK, MIL-PRF, MIL-DTL, and MIL-STD. Some other standards were developed, such as FIDES [2], owned by Thales Group, which is mainly concerned with avionics, SR-332, owned by Ericsson, which focuses on communications equipment, and SN-29500, owned by Siemens, which addresses reliability estimation pertaining to the communications and military domains.

The various entities in an electromechanical system have a list of contributing factors for a failure mechanism. These failure mechanisms have been modeled with various levels of approximations by standard formulating bodies across the globe. The failure mechanisms that a device follows can be narrowed down to a select few:

- Shorting of terminals
- Open between terminals
- Variation in electrical parameters leading to loss of functionality

All the standards have some scope that defines their applicability. The table below shows the scope of MIL-HDBK-217F [3] and FIDES.

Limitations of MIL-HDBK-217F	Limitations of FIDES-2009
Continuous operation is assumed. No handling of mission profiles.	Mission profiles are defined for the annual cycle. (Constraint removed in FIDES-2022)
Operating temperature cannot be lower than zero. Components should not be operating beyond their Absolute Maximum Ratings (AMR)	Operating temperature range $-55°C < T_{ambient} < 125°C$ $\Delta T_{cycling} < 180°C$ $T_{max\text{-}cycling} < 125°C$ Thermal Transition rate ≤ 20°C per minute
Thin-film and Thick-film passives are excluded from analysis due to their low failure rates.	Thermistors are excluded from the analysis.

Table 1: Comparison of MIL-HDBK-217F and FIDES-2009 limitations [2,3]

Accelerated Life Test (ALT)

A commercial PCB under normal operating conditions can operate for years depending on the usage, mission profile, or other parameters. If the life is to be verified in a laboratory environment that can emulate the operating conditions, the test time required would be years. This can result in very high costs and unacceptable delays in time-to-market. To mitigate this, PCBs undergo Accelerated Life Tests, where they are placed in environments that can accelerate aging and result in quicker albeit controlled failures.

The acceleration factor governed by the Arrhenius model can be obtained as shown below:

$$AF_{Arr} = e^{\left[\frac{Ea}{Kb}\left(\frac{1}{T_0} - \frac{1}{T}\right)\right]} \quad (1)$$

$$TTF = AF_{Arr} \times ATTF \quad (2)$$

Ea is the activation energy for a failure mode in ev, $T0$ is real operating temperature, T is the ALT temperature, kB is the Boltzmann's constant (8.617×10^{-5} $ev \cdot K^{-1}$), $ATTF$ is the time to failure obtained in ALT and TTF is time-to-failure under real operating conditions.

The acceleration factor can then be used to find the TTF and Expected Life (TTF-1) under normal operating conditions. The above equations can be easily applied in cases of ALT performed for a single device. When a collection of components is under test or a PCB is tested, the activation energy is a weighted average number or an effective value that proves to be another challenge in performing ALT for a system.

Sampling Process

Manufacturers and reliability assessment laboratories perform life testing, where a few samples (n) of the PCB are simultaneously subjected to varied operating conditions, such as thermal cycling, unstable power supply, vibrations, humidity, etc., to check robustness. The number of samples to be tested depends on

- Lot size (N)
- Acceptable quality level (AQL)
- Number of failures or defects (F)

In this test, we employed c = 0 (c is the acceptance number) sampling plan, where a lot is rejected if one or more defects are found in the sample.

	Index values (associated AQLs)								
	0.15	0.25	0.4	0.65	1	2.5	4.0	6.5	10.0
Lot Size	Sample Size								
2-8	*	*	*	*	*	5	3	2	2
9-15	*	*	*	*	13	5	3	2	2
16-25	*	*	*	20	13	5	3	3	2
26-50	*	*	32	20	13	5	5	5	3
51-90	80	50	32	20	13	7	6	5	4

Source: American Society for Quality – ANSI Z1.4 Standard

*Inspect 100 percent

Table 2: Sampling Plan for c = 0 [4]

The producer's risk is the probability of rejecting a lot whose true quality meets or exceeds the required quality level or acceptable quality level (AQL). In this experiment, the lot size falls under the 26-50 category and a sample size of 4 can have an AQL ≈ 8%, as highlighted in the table above.

	Probability of Acceptance											
Sample Size	0.10	0.25	0.50	0.625	0.6875	0.7188	0.7265	0.7344	0.75	0.9	0.95	0.99
3	52.50	36.30	20.20	14.59	11.78	10.37	10.02	9.67	8.97	3.39	1.67	0.33
4	43.95	29.75	16.30	11.74	9.46	8.32	8.03	7.75	7.18	2.70	1.34	0.27
5	35.40	23.20	12.40	8.89	7.14	6.26	6.04	5.82	5.38	2.00	1.00	0.20
8	23.20	14.80	7.72	5.52	4.41	3.86	3.72	3.59	3.31	1.25	0.62	0.12
13	14.20	8.91	4.59	3.26	2.59	2.25	2.17	2.09	1.92	0.76	0.38	0.07
20	8.73	5.42	2.82	2.04	1.64	1.45	1.40	1.35	1.25	0.50	0.25	0.05

AQL values in red were obtained by interpolation and appended.

Table 3: AQL values corresponding to varying sample sizes and probability of acceptance for a lot size of 26-50 [4]

Using the AQL value of 8% in the table above, the probability of acceptance is 0.7265 for a sample size of 4. The confidence number that can be allotted to this exercise is 72.65%.

Statistical Estimation

The ALTs can broadly be of two types: time-terminated or failure-terminated. A time-terminated test has a pre-determined test duration, irrespective of the count of failures observed, the test is terminated after time T as opposed to failure-terminated test, where a specific number of failures (F ≤ n) are required to declare the completion of test.

The probability distribution function of Time-To-Failure can be modeled using

- Non-parametric approach
  - When the information is limited
- Parametric approach
  - When the underlying distribution of TTF is assumed to be Exponential or Weibull or log-normal, etc.

In this computation, the exponential distribution (4) is assumed, where the failure rate is constant over the complete lifetime. The reliability of a system at time t is given by the equation (5).

$$f(t) = \lambda e^{-\lambda_0 t} \tag{4}$$

$$R(t) = e^{-\lambda_0 t} \tag{5}$$

If the Weibull Distribution is followed, the reliability function depends on the shape parameter, β, as shown.

$$R(t) = e^{-(\frac{t_0}{\theta})^{\beta}} \tag{6}$$

Mean Time Between Failures or MTBF is the mean value or expected value of random variable, Time-To-Failure.

$$\text{MTBF} = \text{E}\{\text{Time to failure...}\} \tag{7}$$

The MTBF estimate for a time terminated test with F failures will be bounded by the limits obtained from (8) and the bounds are dependent on the producer's risk parameter, α. The degree of freedom (DoF) depends on the number of failures and the type of test. For a time terminated test, the DoFs used are 2F+2 for the lower-bound and 2F for the upper-bound.

$$\text{Pr}\left[\frac{2T}{\chi^2_{(1-\alpha/2),2F+2}} \leq \text{MTBF} \leq \frac{2T}{\chi^2_{\alpha/2,2F}}\right] = 1 - \alpha \tag{8}$$

$$e^{-\lambda_U t_0} \leq R(t_0) \leq e^{-\lambda_L t_0} \tag{9}$$

The MTBF estimate for a time terminated test with zero failures is bounded on the lower side.

$$\text{Pr}\left[\frac{2T}{\chi^2_{(1-\alpha),2F+1}} \leq \text{MTBF} \leq \infty\right] = 1 - \alpha \tag{10}$$

$$e^{-\lambda_U t_0} \leq R(t_0) \leq 1 \tag{11}$$

The Confidence number, C can be understood as

- The probability that the probability of survival or reliability lies within the above limits.
- The probability that the MTBF of a system lies between the MTBF bounds.

As per the success run theorem, reliability for a non-parametric estimation is,

$$R_0 = (1 - C)^{1/n} \tag{12}$$

For Weibull distribution,

$$R_0 = (1 - C)^{1/n} = e^{-(\frac{t_0}{\theta})^{\beta}} \tag{13}$$

For exponential distribution,

$$R_0 = (1 - C)^{1/n} = e^{-\lambda_0 t_0} \tag{14}$$

Validation Exercise

The schematic of the board used in this validation exercise is shown below with its layout.

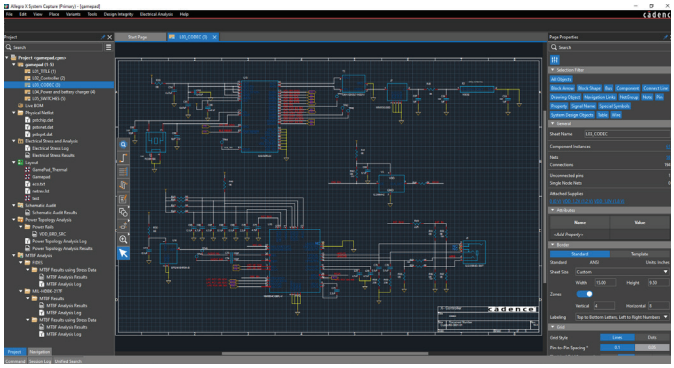

Figure 2 : Schematic representation of PCB under test

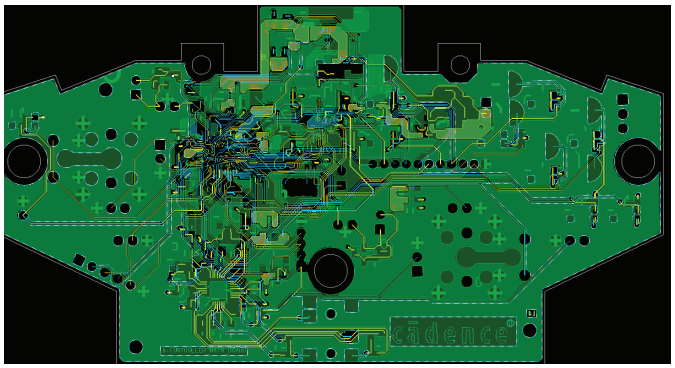

Figure 3: Snapshot of the PCB layout under test

Validation with calculators in market

In this exercise, the design netlist and electrical parameter values were used to estimate PCB life as per the MIL-HDBK-217F standard with ground benign as the choice of environment. The values obtained were close. Minor variations were observed due to

- different level of tool configurability
- different defaults assumed

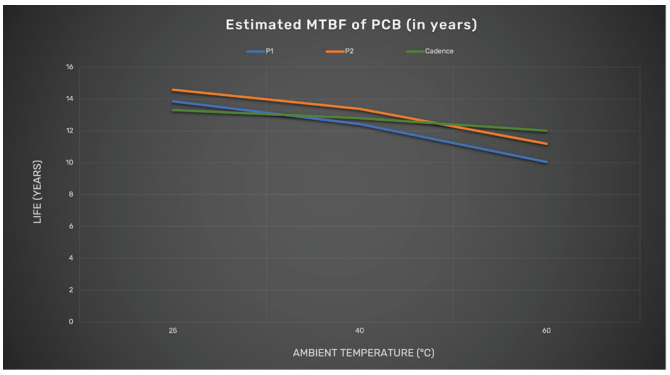

Figure 4: Comparison of MTBF obtained from Cadence Allegro® X System Capture against tool1 (P1) and tool2 (P2) at 25°C

Laboratory Validation

Designers placed the board samples in the thermal chamber in a non-operating state followed by the state where the system is powered by providing voltages and monitoring the test points. The samples were subjected to a varying thermal profile, as shown in the following figure:

Figure 5: Temperature profile employed for ALT

Figure 6: Four samples placed inside thermal chamber

Figure 7: Thermal chamber used for ALT

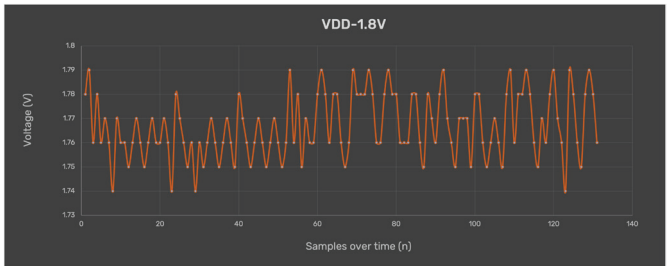

Figure 8: Voltage variation observed on VDD-1.8V net over operation time at T=75°C

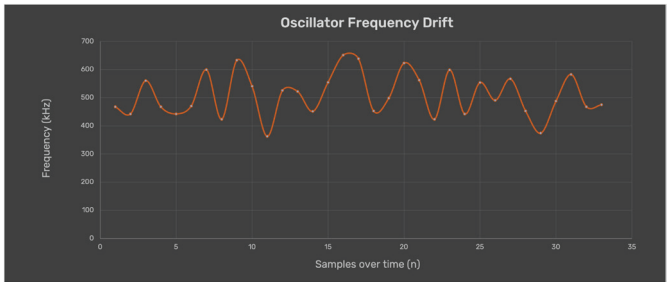

Figure 9: On-board oscillator frequency drift observed over operation time at T=75°C

Number of boards	4
Lot size	30
Number of failures	0
Test Time (hours)	1681
Total Accumulated Time (hours)	6724
Test Category	Type I Right Censoring (Time Terminated)

Table 4: Specifications of the performed experimental validation

Observations

The board did not fail after 1,681 hours with varied temperature and operation state. We can say that the MTBF of the system is 6,724 hours, and the total accumulated test time (6,724 hours) can be used for T (in equations 10 and 11) to calculate the MTBF bounds. The non-occurrence of a failure makes the statistical bound on MTBF unilateral. Only the lower bound can be estimated in this case, whereas the upper bound can be roughly assumed to be infinite due to added uncertainty on the future state of devices and PCB.

If we assume a failure in the next hour and use the test duration as 1,682 (in equation 8 and 9) with one failure, the bounds become bilateral. The MTBF bounds can be computed as shown in the following table:

	One Failure	No failure	One Failure	No Failure	One Failure	No Failure
	Confidence = 72.65%		*Confidence = 95%*		*Confidence = 98.3%*	
Lower MTBF (hours)	1925.6	5186.4	1206.8	2244.5	985.2	1650.2
Upper MTBF (hours)	45726	∞	265770.7	∞	787814.8	∞
Lower Reliability (at t_0 = T) (%)	3.04	27.3	0.38	5	0.11	1.7
Upper Reliability (at t_0 = T) (%)	86.3	100	97.5	100	99	100
Estimated Value (FIDES)	50808					
Estimated Value (MIL-217F)	16644					

Table 5: Obtained MTBF limits for different confidence numbers and corresponding reliability bounds

Now, using the equations (8-11 and 14), the reliability bounds over time can be plotted corresponding to the Upper MTBF bound, Lower MTBF bound, MIL-217F estimate, and FIDES estimate. As the boards did not fail over the accumulated time of 6,724 hours, the single-sided bounds were used in the plots below, where 100% reliability is shown corresponding to the upper MTBF bound of infinity (10-11).

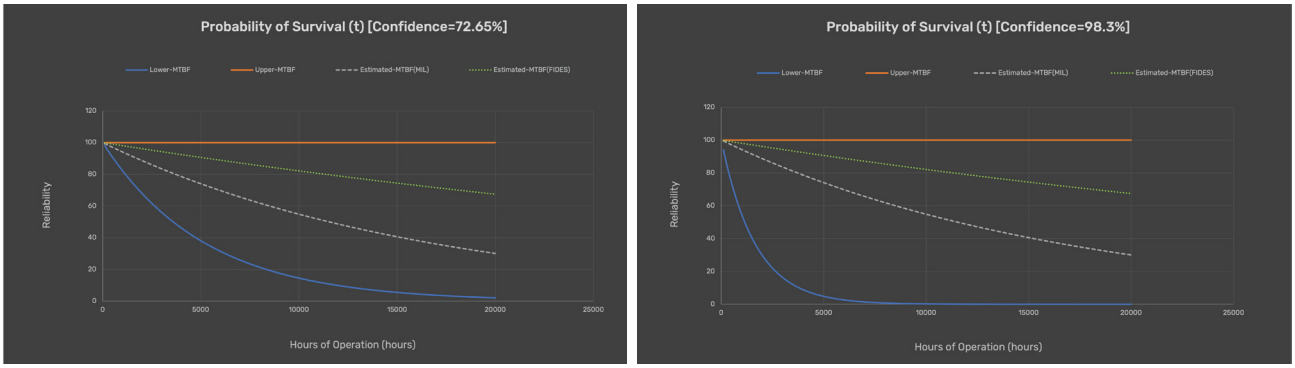

Figure 10: Probability of survival for upper bound and lower bound on MTBF (Zero failure case)

Similar plots for the case when assuming single failure are as follows:

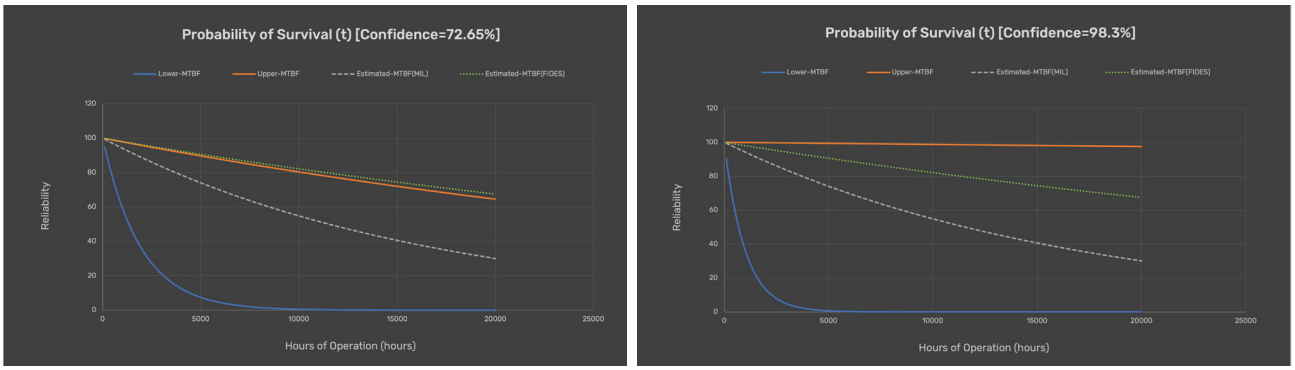

Figure 11: Probability of survival for upper bound and lower bound on MTBF (Single failure case)

The above plots show that over the duration of usage, the variation of reliability or probability of survival according to the estimates from the tool lies within the reliability bounds corresponding to the MTBF bounds from the laboratory validation.

So, the probability that the real MTBF number would lie between the bounds is given by the confidence number, which is 72.65% according to the current sampling plan.

Estimation Methodology in Allegro X System Capture

The tool performs the estimation based on design netlist to account for components and their connectivity, design parameters like voltage nets, default MTBF parameters that are suggested by the employed standard, library parameters for device ratings and characteristics, and electrical stress simulation results that indicate the real stress conditions.

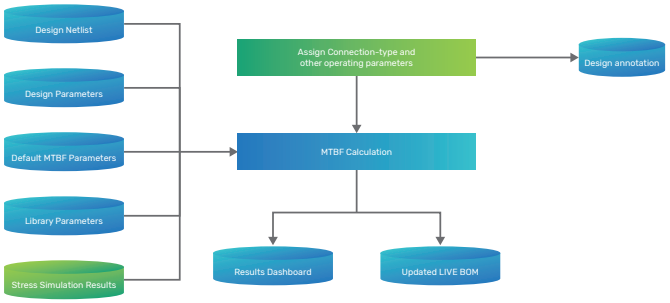

Figure 12: Estimation methodology

The system's designed schematic is first analyzed using CPSadence piceimulator to get an estimate of the electrical performance. Cadence's patented technology [5] enables the tool to split the entire schematic into small sub-circuits and simulate using stimuli that are set in the schematic design environment. Allegro® X System Capture creates the subcircuits as shown in the figure below.

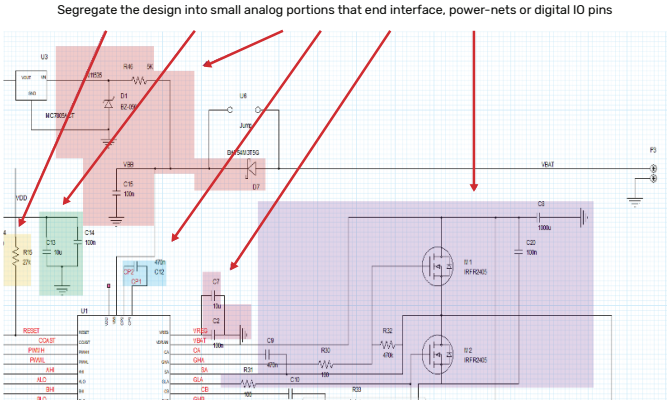

Figure 13: A pictorial representation of subcircuit creation employed by electrical overstress analysis tool in Allegro X System Capture.

Calculate the stress using the estimated current, voltage, and power numbers along with the rated values. These numbers provide MTBF estimations for almost all the standards.

For the life estimation according to the FIDES standard, the mission profile is created as shown in table below. The calendar hours define the duration, and ambient temperature is the starting temperature for thermal cycling of each phase. Electrical overstress analysis data is used in estimation only for the phases where the Operating Phase is "On." If the system is enclosed in a package, the protection level is to be set to hermetic, otherwise, it is non-hermetic. The details about other parameters such as environment pollution, application pollution, and application factor can be found in the FIDES standard document.

Phase Title	Calendar Hours	Operating Phase	Ambient Temperature	Relative Humidity	Delta Temp	Annual Cycles	Cycle Duration	Max Temp Cycling
Storage1	960	Off	25	40	50	1	240	75
Storage2	3168	Off	25	40	5	1	792	30
Operating1	960	On	25	30	50	1	240	75
Storage3	1536	Off	25	40	5	1	384	30
Operating2	96	On	25	30	75	1	25	100

Stress Random Vibration	Saline Pollution	Environmental Pollution	Application Pollution	Protection Level	Application Factor
0.01	Low	Moderate	Moderate	Non-Hermetic	7.4
0.01	Low	Moderate	Moderate	Non-Hermetic	8
2	Low	Moderate	High	Non-Hermetic	7.4
0.01	Low	Moderate	Moderate	Non-Hermetic	8
2	Low	Moderate	High	Non-Hermetic	7.4

Table 6: Mission profile created in Allegro X System Capture as per the lab validation phases employed

Cadence developed the MTBF estimation to model the entire mission profile. They performed the estimation according to the supported MIL-HDBK-217F and FIDES-2009 standards. The dashboard display below shows the results.

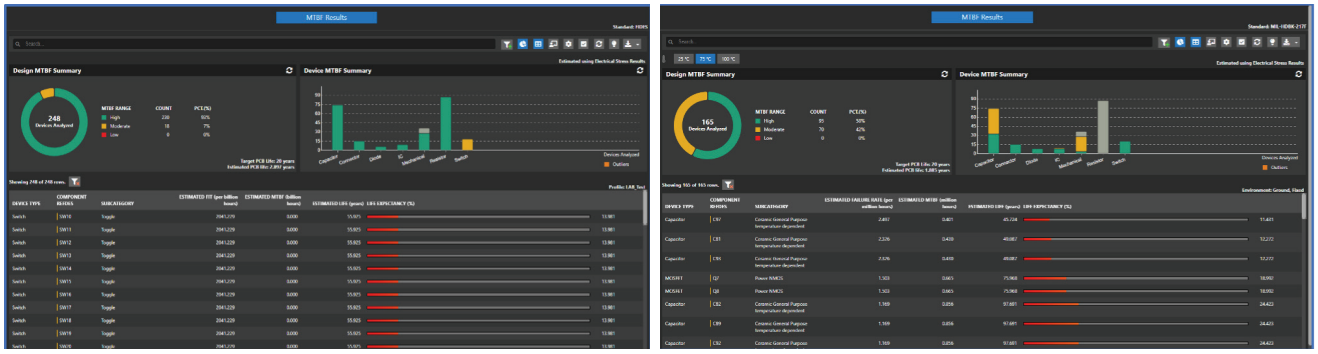

Figure 14: MTBF Estimation results for FIDES and MIL-217F

	FIDES-2009	MIL-HDBK-217F
PCB Life	5.8 years (50808 hours)	1.9 years at 75°C (16644 hours)
Number of Components	248	165 Thin Film resistors were ignored from the computation

Table 7: Estimation output

The MIL-217F standard evaluation is performed by setting the environment as ground benign with ambient temperature set as 75°C. Only one ambient temperature is used here because this is the phase that decides the overall failure rate.

$$\text{Failure rate} = \frac{t_1 * f_1(75℃) + t_2 * f_2(100℃)}{t_1 + t_2} \approx f_2(75℃) \text{ , as } t_1 + t_2 \approx t_1 \quad (15)$$

Design for Reliability

The following best practices and analyses should be utilized to increase design reliability:

- Choice of components should be such that the operating voltage, current, power and temperature do not exceed the absolute maximum ratings. The stress analysis capabilities provided by Cadence Design Systems in System Capture can ensure that these conditions are met.
- The integrated thermal analysis can help regulate the thermal stress. Excessive temperatures can lead to electromigration and warpage, leading to structural failures.
- The design audit within System Capture uses predefined and custom electrical and design rules to flag violations and increase product reliability.
- The MTBF estimation tool integrated in System Capture can guide the designer to take corrective measures early in the design cycle and increase the reliability of the designed system.

Conclusion

Reliability is paramount for electromechanical systems employed in critical applications such as military, aviation, medical, and telecommunications. It can be ensured only when each design step is performed as per the guidelines established in standards such as MIL-HDBK-217F, FIDES, Telcordia or ISO 26262. This is a tough task for designers as there can be at least three ways each component on a board can fail. The Cadence MTBF estimator can aid designers by automating this estimation and reducing the time to analyze design reliability.

References

1. MIL-HDBK-781A, MILITARY HANDBOOK: Reliability Test Methods, Plans, and Environments for Engineering, Development Qualification, and Production
2. UTEC 80811: 2011 - Reliability Methodology for Electronic Systems - FIDES Guide 2009 Issue A, Association Francaise de Normalisation, 2011.
3. MIL-HDBK-217F(NOTICE 2), MILITARY HANDBOOK: Reliability Prediction of Electronic Equipment
4. Nicholas L. Squeglia, Zero Acceptance Number Sampling Plans, Sixth Edition, American Society for Quality, 2023.
5. Kukal et al, " System and method for computing electrical over-stress of devices associated with an electronic design," US10997332B1, May 4, 2021.