SHELF LIFE EVALUATION METHOD FOR ELECTRONIC AND OTHER COMPONENTS USING A PHYSICS-OF-FAILURE (POF) APPROACH

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Abstract: Shelf lives are not well understood in the electronics industry. Despite the existence of recommended shelf lives for some units from standards or manufacturers' documents, many electronic parts are stored well beyond their recommended shelf lives for different reasons. In many cases, 'expired' parts are found to work fine after many years of extended storage, which gives extra motivation for parties along the supply chain, typically part user companies, to extend storage of their parts and to evaluate the 'actual shelf lives' of their components. The combination of motivations to extend shelf life, inadequacies in recommended shelf lives, and the lack of knowledge and guidelines to shelf life determination often results in arbitrary storage periods and conditions of electronic components in the industry.

In this article, common pitfalls of recommended shelf lives are identified. Then, a physics of failure (PoF) approach to evaluate shelf lives overcoming such pitfalls is proposed. The philosophy we introduce in this approach applies to most storage-induced effects for electronic parts and the approach is described with an electrolytic capacitor in this article.

Key words: Shelf life; Storage

Introduction: There are always motivations and attempts in extending storage period of parts in the electronics industry. One of the reasons is stocking life-time buy parts to minimize the impact of part obsolescence. Responding to the modification of parts through generations due to technology advances and compliances with new restrictions, many companies attempt to minimize the impact of part obsolescence for their future products by purchasing and storing additional parts. Depending on the company's role in the supply chain, this situation often applies to sub-assemblies and even final assemblies. Another reason for part and sub-assembly storage is for customer support with fast response to maintenance needs. Some equipment suppliers store spare parts and sub-assemblies at customer locations to improve system availability and in those cases, the immediate out of storage usability is of prime concern.

Although recommended shelf lives for some parts are specified in standards or manufacturers' documents, some of them are considered to be over-generalized to part types and in some cases, too conservative. In many cases, electronic components are found to work fine long after they are "expired" [1][2]. This collective experience from the industry motivates some companies to extend storage periods of their components. While in other cases, the suggestion of unlimited shelf lives under certain conditions from manufacturers raises doubts from the industry despite the appeal. The combination of motivations to extend shelf life, inadequacies in recommended shelf lives, and the lack of knowledge and guidelines to shelf life determination often results in arbitrary storage periods of electronic parts in the industry.

In this article, common pitfalls of recommended shelf lives are identified. Then, a physics of failure (PoF) approach to evaluate shelf lives overcoming such pitfalls is proposed. Compared to the typical procedure of model-based use life estimation, a fundamental difference in use life and shelf life necessitates additional steps in addition to identifying of the most critical degradation mechanism and applying models. This includes an analysis of the most critical storage-induced effect's impact on usability or reliability of the unit after storage, and the definition of acceptance criteria after storage. The philosophy we introduce in this approach applies to most storage-induced effects for electronic parts and systems and the approach is demonstrated with electrolytic capacitor in this article.

Common Pitfalls of Shelf Life: The definition for shelf life is not uniformly understood or accepted in the electronic industry. Numerical values of shelf life are often provided by part manufacturers and some part user companies may have developed guidelines of storage conditions and shelf lives for different parts. Some examples of shelf life interpretation by electronic component manufacturers and electronic component user companies are listed below. These two parties in the supply chain often refer shelf life to two different timeframes which are "from manufacture to shipment" and "from manufacture to use" respectively while using the same terminology. In addition, these interpretations are ambiguous if one is looking to directly adopt the shelf life numbers given in these documents. For example, recipients for shipments are not specified by most component manufacturers listed below while most electronic components go through multiple transportations in along the supply chain.

Example of shelf life interpretation from electronics component manufacturers:

- Fujitsu [3]: Period from product manufacture to shipment to customers
- NXP [4]: The time between assembly date code of the device and date of shipment
- Texas Instrument [5]: The amount of time from the product was manufactured to the time it is delivered by TI or a TI authorized distributor
- EPCOS [6]: A specified time for which a capacitor can be stored "voltage-free"

Shelf Life Interpretation from an Electronic Component Part User Company:

- GE Power Electronics [7]: The time within which an electronic component or mechanical piece part can be stored, at a given ambient condition, is usable without testing, evaluation or special conditioning.

Apart from the ambiguous timeframe regarding shelf lives, numerical shelf life values are often found to correspond only to one presumed degradation mechanism. These degradation mechanisms are often related to solderability or moisture sensitivity. In the shelf life interpretation example by EPCOS [6], the degradation mechanism being addressed is the thinning of dielectric oxide layer of the capacitor. Yet, if application of reforming voltage can be managed during the course of storage, the stated shelf life would not apply and will depend on other competing degradation mechanisms. Any variations in materials of a part, changes in storage conditions, or different procedures taken during and after storage can invalidate recommended shelf lives of a part.

Difference between Shelf Life and Use Life Estimation: The main difference between shelf life and use life lies in the life cycle phases they represent. Use life is usually assumed to be the final phase of a unit's life cycle. Therefore, after identifying the most critical degradation mechanism, use life is often determined by a PoF, or an empirical model under a certain operating condition until failure of the device, which is defined by predetermined failure criteria, i.e. functionality or parametric failure of the device. In the case of shelf life estimation, storage is not the final phase of a unit's life cycle. Therefore, subsequent procedures and life cycle stresses should be taken into account for the most critical storage-induced effect during storage be selected to ensure the desired usability or reliability of the part after storage. A more generalized term "storage-induced effects" is adopted from this section because some of the "effects" that may take place during storage do not resemble the general interpretation of "degradation"- the loss of relevant properties of the unit which proceeds gradually due to exposure to a certain condition. For example, moisture absorption of a plastic packaged component is not considered a degradation mechanism. However, it is considered to be one of the most critical "storage-induced effect" because it can induce delamination or pop-corning during solder reflow.

Physics of Failure Shelf Life Evaluation Approach: In this study, a shelf life estimation approach is developed and the simple philosophy involved is described in this section. In addition to conventional Failure Mode, Mechanism and Effect Analysis (FMMEA)[8], which is typical for model-based use life estimation, the difference between use life and shelf life necessitates the need for two extra steps in shelf life estimation. The steps takes into account the impacts of storage-induced effects when the most critical storage-induced effect is selected for modeling, and defines an acceptance criteria depending on the impact. A flowchart depicting the shelf life estimation approach is shown in Figure 1.

The left branch of the flowchart is a typical model-based use life estimation procedure. It begins with an FMMEA which requires input information such as materials being used in the part, and environmental conditions under which the life of the part is being estimated. Then, the most critical degradation or failure mechanism has to be identified, this determination is often made based on feedback from field failures of similar products, literature review, or risk and criticality analysis. With the most critical mechanism identified and a failure criteria defined, a model can be applied to predict useful life. For shelf life estimation, a parallel branch is added for determination of the most critical storage-induced effect. This is to take into account the effects' impacts on subsequent procedures or life cycle stresses of the part. Key steps in the approach are discussed in detail in the following sections. This approach can be applied to typical storage-induced effects in electronic parts.

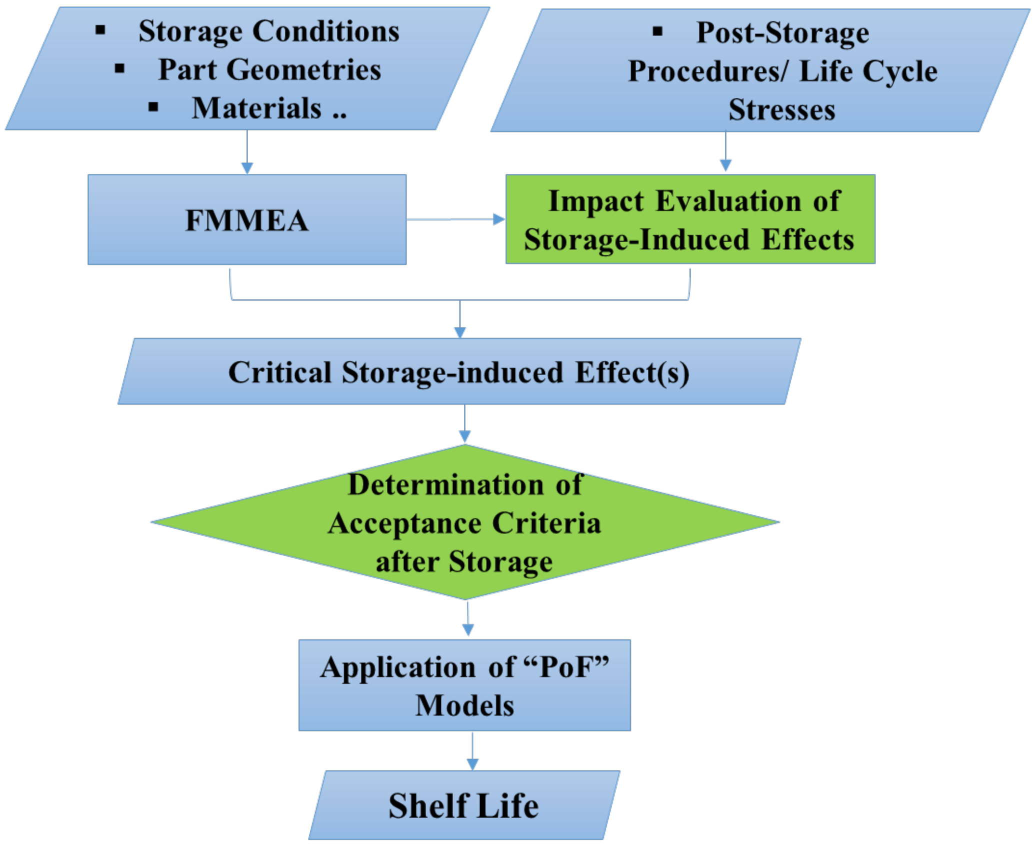

Figure 1. Physics of Failure Shelf Life Estimation Approach

Identify the Most Critical Storage-Induced Effect: As a first step, storage-induced effects during storage have to be identified. As the most common and effective way to identify storage induced effects in electronic parts and systems, FMMEA is adopted for this purpose. FMMEA results depend on the amount of information input. For an accurate and comprehensive study, detail environmental condition, material composition and dimensions are necessary. For material composition, instead of performing individual materials analysis, material declaration management forms IPC-1752A for most electronic parts can be acquired from their distributors or manufacturers. After possible degradation mechanisms are listed in FMMEA, calculation of Risk Priority Number (RPN) [9] can be carried out to identify critical degradation mechanisms out of the list. For the same part, the most critical storage-induced effect can differ depending on the post-storage procedures or use conditions. For example, solderability is a major concern for storage of loose leaded components. However, if the part is already soldered onto an assembly, then the most critical storage-induced effect will shift from lead oxidation to other storage-induced effects. Therefore, an extra step to evaluate impacts of different storage-induced effects is necessary for the selection of the most critical one to be modeled.

Impacts of the Storage Induced Effects: Impacts of storage-induced effects include degradations and environmental effects that can affect reliability or usability of the stored device depending on subsequent life cycle stresses or procedures. For example, reflow, hand-solder and different use conditions. For electronic components, storage-induced effects can be grouped into three categories based on their impacts. Examples of common storage-induced effects under each category are included in Table 1.

> Category 1: Degradation mechanisms that affect reliability of a device by taking place in a continuous manner through use conditions.
>
> Category 2: Degradation mechanisms that can affect usability of the device after storage. These degradation mechanisms may or may not be reversible. This category of degradation mechanisms is critical when the degradation is or becomes irreversible or when reforming procedure cannot be performed.
>
> Category 3: Environmental effects that can initiate degradation mechanisms under storage or subsequent life cycle stresses.

Table 1. Examples of Storage Induced Effects under Each Category

<table>
<tr><th>Category 1</th><th>Category 2</th><th colspan="2">Category 3</th></tr>
<tr><th>Degradation Mechanism</th><th>Degradation Mechanism</th><th>Environmental Effect</th><th>Potential Failure Mechanism</th></tr>
<tr><td>• Electrolyte Evaporation in Electrolytic Capacitors
• Lubricant Evaporation in Greased Components</td><td>• Reduction in Solderability (e.g., Lead oxidation/ Corrosion)</td><td>• Moisture Absorption in Plastic Packaged Parts</td><td>• Cracking
• Delamination
• Pop-corning
• Corrosion
• Conductive filament formation</td></tr>
<tr><td>• Interconnect Fatigue</td><td rowspan="2">• Thinning of Dielectric in Electrolytic Capacitors</td><td>• Halogen Infiltration</td><td>• Corrosion</td></tr>
<tr><td>• Interconnect Aging (e.g., Excessive Intermetallic Formation, stress relaxation)</td><td>• Charge Build-Up</td><td>• Electrostatic Discharge</td></tr>
</table>

Determination of Acceptance Criteria: After the most critical storage-induced effect is identified, acceptance criteria of the part after storage has to be determined. Acceptance criteria (not failure criteria) is the criteria that should be satisfied for particular requirements or reliability goals after storage, while should be compatible with the metric being modeled for life estimation. The determination of acceptance criteria for each category of storage-induced effects is slightly different.

For Category 1, in which the degradation mechanisms take place in a continuous fashion through use conditions, the acceptance criteria should be determined based on expected use condition and required service time. Take electrolyte evaporation in electrolytic capacitors as an example, electrolyte evaporates at a slower rate during storage (assuming a controlled storage condition) and the evaporation gets faster as the capacitor is put into use condition due to the increase in internal temperature due to self-heating. Therefore, depending on the field condition and required service time, the amount of remaining electrolyte after storage for usage consumption will be the acceptance criteria for this degradation mechanism.

For Category 2, in which the degradation mechanisms can affect usability of the device after storage, acceptance criteria should be determined based on whether the mechanisms are reversible and if the “reworking process” can take place. In cases that the mechanisms are irreversible or is reversible but a ‘reworking process’ cannot be performed, the acceptance criteria should be determined based on the usability requirements of the part. An example can be a certain percentage loss of parametric measurements of the part. Although mechanisms that are reversible and ‘reworking process’ can be performed are rarely critical, the acceptance criteria can be the critical point before which the degradation mechanism becomes “unreworkable” or “irreparable. Take lead oxidation or corrosion as an example, the acceptance criteria can be the critical point before which the leads surfaces have degraded significantly that the required solderability cannot be restored using solder dipping.

For Category 3, in which the degradation mechanisms can initiate other failure mechanisms under life cycle stresses. Take moisture absorption in plastic packaged devices as an example, the absorbed moisture can induce delamination or pop-corning during reflow. Moisture can also lead to corrosion of wirebonds which results in permanent or intermittent failures of the device [10][11]. For this type of degradation mechanisms, acceptance criteria should be determined based on the critical accumulation of the effect for the potential failure mechanism to initiate.

After the acceptance criterion of a critical degradation mechanism is defined, physics of failure models or physics based models can be used for shelf life estimation.

Shelf Life Estimation of Electrolytic Capacitor:

In this study, an aluminum electrolytic capacitor is selected for demonstration of the proposed shelf life evaluation approach. As a first step, the materials declaration management form IPC-1752A was acquired from the manufacturer, which provided us materials information of the part. Based on the materials information and a normal warehouse environment, an FMMEA is performed to identify the possible storage induced effects as shown in Table 2. Electrolyte evaporation is considered to be the most critical storage induced effect here because it is one of the most reported degradation mechanism for this type of capacitors and it is not reversible.

Failure Sites	**Potential Failure Mode in Use**	**'Observable Effects' during Storage**	**Storage Induced Effects**	**Failure Cause**
Electrolyte [12][13]	• Parametric failure • Open	• Weight Loss • Decrease in capacitance • Increase in ESR	**Electrolyte evaporation**	Diffusion or leakage through seal
Electrolyte [13]	• Parametric failure • Open	• Decrease in capacitance	Electrolyte Deterioration	Chemical degradation
Aluminum Electrodes [13]	• Parametric failure • Open	• Increase in leakage current	Corrosion	Infiltration of halogen
Dielectric Oxide Layer [13][14]	• Seal rupture by high leakage current • Short	• Increase in leakage current	Reduction in thickness (recoverable)	Absence of applied voltage
Terminal	Increase in Contact Resistance	Increase in Contact Resistance	Oxidation/ Corrosion	Air contamination, moisture
	Short	Short	Tin whisker	Sn content

Table 2. FMMEA for Storage of Aluminum Electrolytic Capacitor

Gasperi has derived a physics of failure model for electrolyte evaporation for aluminum electrolytic capacitors [12]. In this model, rate of electrolyte loss is related to temperature and vapor pressure of the electrolyte as shown in Equation (1).

$$\frac{dV}{dt} = Kexp(\frac{-A}{T} + B) \qquad \text{Equation (1)}$$

$\frac{dV}{dt}$: Rate of Electrolyte Loss
K: Leak Rate Constant
A, B: Vapor Pressure Constants
T: Temperature (K)

Given that the rate of electrolyte loss is assumed to be independent of time in this model, with V_o as the original volume of the electrolyte in the electrolytic capacitor, and x% as the percentage loss of electrolyte as the **failure** criteria, rearranging Equation (1) and substituting V with $x\%V_o$ gives the relationship of time required to cause the certain loss of electrolyte as shown in Equation (2).

$$Time\ to\ Failure = \frac{x\%V_o}{Kexp\left(\frac{-A}{T}+B\right)} \qquad \text{Equation (2)}$$

The electrolyte used is ethylene glycol as indicated in IPC-1752A for the capacitor. The vapor pressure constants A and B for ethylene glycol were reported to be 7060 and 21.63 respectively in the Handbook of Chemistry and Physics in 1970 [15]. In Gasperi's study, K was determined from experiment and is found to be 0.00031unit/mmHg/100Hr. Failure criteria for electrolyte evaporation typically range from 30% to 40% electrolyte loss [12], [13]. Assuming the same leak rate constant for the capacitor and using 40% electrolyte loss as the failure criteria, capacitor life at different temperatures can be calculated separately with Equation (2). Like other model-based life estimations, the accuracy of the estimated life can be improved by running experiments to determine constants in the available models. This step is not performed in this study as it does not add value to the purpose of demonstrating the proposed shelf life estimation approach. Then, maximum shelf life of a capacitor (considering the required use conditions and service life) can be calculated using a version of "Miner's Rule" of damage accumulation as shown in Equation (3). Simulated results based on this calculation are shown in

Capacitor Temperature during Operation	60°C	65°C
Life at Use Condition	9.5 years	7 years
Application Time	6 years	6 years
Maximum Shelf Life at 25°C	42 years	16.4 years
Maximum Shelf Life at 30°C	28 years	11.1 years

.

$$\frac{Required\ Application\ Time}{Life\ at\ Use\ Condition} + \frac{Maximum\ Shelf\ Life}{Life\ at\ Storage\ Condition} = 1 \qquad \text{Equation (3)}$$

Table 3. Estimated Shelf Life of Electrolytic Capacitor under Different Use Conditions

Capacitor Temperature during Operation	60°C	65°C
Life at Use Condition	9.5 years	7 years
Application Time	6 years	6 years
Maximum Shelf Life at 25°C	42 years	16.4 years
Maximum Shelf Life at 30°C	28 years	11.1 years

Conclusions: In this article, common pitfalls of recommended shelf lives are identified. Then, a physics of failure (PoF) approach to evaluate shelf lives overcoming such pitfalls is proposed for electronic units. Compared to the typical procedure of model-based use life estimation, fundamental difference in use life and shelf life necessitates a modified procedure in addition to identification of the most critical degradation mechanism and application of models. This includes an analysis of the most critical storage-induced effect's impact on usability or reliability of the unit after storage, and the definition of acceptance criteria after storage. The philosophy we introduce in this approach applies to most storage-induced effects for electronic parts and systems and the approach is demonstrated with electrolytic capacitor in this article.

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