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Degradation analysis of several performance characteristics of capacitors under elevated thermal and electrical stress

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Capacitors are electronic components with a wide field of technical applications. Their functionality has to be assured throughout the intended product lifetime. While in operation, the performance characteristics of capacitors slowly degrade. Ultimately, one or more of these characteristics reaches a threshold at which they are considered failed. Thus, modeling degradation is a key factor in assessing capacitor reliability. While most existing studies addressing capacitor degradation consider long runtimes and few stressors, this paper considers test performed under different temperature, humidity, voltage and excitation frequency (and thus, the number of voltage pulses). To reproduce realistic operation, repeated charging and discharging under PWM excitation is considered. Superimposed stress via controlled operation above the partial discharge inception voltage is included, as this is rarely explored. In the performed tests, the degradation of several performance characteristics was repeatedly measured. Based on the data, different degradation models are developed and compared. The influence of the considered stress factors on the degradation is estimated and statistically assessed. Unlike existing studies, where fixed performance thresholds are used to reduce the data to soft failure times, this paper focuses on the load dependency of the degradation path itself to allow variable failure thresholds.

Keywords: Metallized film capacitor, degradation test, accelerated degradation testing, lifetime models, design of experiments, statistical evaluation.

1. Introduction

Metallized Film Capacitors (MFCs) are fundamental electronic components in many technical systems across various domains, such as computers, energy infrastructure, mobility solutions, and medical technology. As for all technical components, sudden loss of function (hard failures, e.g. due to external shocks) has to be prevented. Apart from that, the performance characteristics of capacitors slowly degrade while in operation, leading to so-called soft failures when one of these physical quantities reaches a predefined threshold. Often, a capacity of less than $80\ \%$ or an ESR (equivalent series resistance) of more than $200\ \%$ compared to the initial values are considered as failures. The times when these thresholds are first transgressed can be treated as failure times to be analyzed with classic reliability engineering methods (Bertsche and Dazer (2022); Nelson (1982)).

1.1. *State of research*

It is well known that the degradation rate depends on the stresses applied to the product (Meeker and Escobar (1998)). For electronic components and specifically for capacitors, temperature, humidity and voltage are commonly considered relevant stress factors. Most publications consider one or two, but rarely three or more stress factors. In tests under AC excitation, partial discharges (PDs) are sometimes included in the studies. An exponential influence of both temperature and voltage is usually assumed and often confirmed in good approximation (cf. IEC (2011)). Some relevant publications are listed in the following.

Cygan et al. (1989) studied the time to breakdown of polypropylene capacitors under electric and thermal load. They found that for DC excitation, the ageing due to electrical stress dominates the ageing due to thermal stress. They assessed that the voltage influence is better described by the inverse power law than by an exponential model.

Nagamani and Ganga (1992) exposed metallized polypropylene film capacitors (MPPFCs) to 1.25–1.9 times their rated AC voltage for up to 2200 h at 30 °C. They experienced a slightly degressive capacitance degradation in the beginning, which transitioned into a progressive degradation not before 200 h test time. Most capacitors under 1.25 times the rated voltage (PD-free) exhibited only a weak degressive capacitance degradation. The authors extracted soft failure times by defining several different capacitance loss thresholds from 10 to 50 % and performed a Weibull distribution analysis with them. Due to the different degradation curve shapes, they found different shape parameters depending on the capacitance threshold (although the authors assessed these difference to be small in the case of 30–50 % capacitance loss). The model parameters, estimated with the inverse power law for voltage influence, also differed depending on the chosen capacitance threshold. Regarding PDs, they found that continuous operation above the partial discharge inception voltage (PDIV) leads to additional ageing, making lifetime extrapolation to the rated voltage impermissible.

Nagamani and Moorching (1997) tested a large number of MPPFCs with 15–22 nF nominal capacitance under PD-inducing AC excitation of 10–60 V/µm. Their results confirm an increasing PD magnitude with increased field strength as well as drastically shorter lifetimes under higher voltage. They also find a log-log relationship between PD magnitude and characteristic life. Their results indicate different failure mechanisms, as the Weibull shape parameter is drastically different on one of the three load levels (unfortunately, the authors didn't provide exact values).

Umemura et al. (2003) studied the degradation of electric double-layer capacitors. They divided the observations into two regions on the time axis, where the second region shows progressive capacitance loss, beginning very roughly at 1000 hrs test duration. The results in Teuber et al. (2019), who tested electric double-layer capacitors without charge/discharge cycles for several thousands of hours, are similar. Their tested specimens show a linear or degressive capacitance degradation in the beginning, followed by a progressive degradation under higher load and possibly a second degressive phase when the capacitance already has degraded drastically.

Emersic et al. (2016) studied the effect of operation above the PDIV on printed circuit boards (PCBs). They applied a bipolar sinusoidal AC excitation voltage and found that there is only a narrow voltage range in which the PD-caused degradation is neither negligible nor leading to early breakdown. They found degradation in form of growing surface cracks and were able to show a nonlinear relationship with the coating thickness. They noticed that the PDIV changes inconsistently over the test duration, exhibiting changes from 25 % to 44 %. This was hypothesized to be the consequence of conductive substance accumulating on the PCB surface, leading to an inhomogeneous surface electric field.

Li et al. (2021) measured the capacitance of MPPFCs due to electrochemical corrosion on several combinations of humidity and temperature, both with and without electrical excitation according to the rated voltage of 305 V RMS. They conclude that for encapsulated capacitors, the combined influence of temperature and humidity alone leads to a negligible capacitance loss of roughly 1 % under reference conditions (85 °C, 85 %) over a test duration of over 1,200 h. They found reason to divide the capacitance degradation into four stages with separate degressive power models, except for the comparably short first stage, which is assumed linear. They also note that the temperature influence is higher in stage one than in the subsequent stages, while the humidity influence exponent does not change.

Yao et al. (2024) analyzed capacitance degradation of MFCs with 13 µF nominal capacitance, which were operated with 1.4–1.7 times their rated voltage. They observed a clear division in the results based on the applied voltage: while on the lower voltage levels, the degradation began linearly and then transitioned to a progressive course somewhere over 200 h, it was progressive from the beginning for the higher voltage levels. Furthermore, the Weibull shape of the failure times – defined by a 5 % capacitance loss – was 3.3 on the lower voltage levels and 1.65 on the high voltages levels, indicating different failure behaviour.

1.2. *Research gap*

Based on the presented literature sources, it was assessed that the following topics need to be addressed in more detail:

- a description of the degradation path as a function of the applied stresses, instead of using soft failure times to assess the stress influences;
- the application of statistical methods to compare different models for the stress influence, including interactions between stresses;
- the degradation under PWM excitation instead of AC excitation;
- an analysis of the influence of PDs on the degradation path by defining voltage levels below and above the PDIV.

This paper thus examines the degradation of MPPFCs for different combinations of temperature T, relative humidity H, PWM voltage U, and excitation frequency f, where both PD-free and PD-inducing voltage levels are included. The following steps are performed:

(a) capacitors are operated under clearly defined stress levels and are repeatedly measured;
(b) several degradation path models are fitted to the measurement data of each capacitor;
(c) it is statistically evaluated whether significant degradation is found;
(d) the estimated degradation path models are examined for their load parameter dependency.

The intended result are stress-dependent degradation path models, which allow to estimate the failure distribution for arbitrary end-of-life criteria.

2. Experimental setup

As test specimens, 53 MPPFCs with 10 nF nominal capacitance and 275 V rated AC voltage are used. They are placed in a climate chamber, where the defined temperature and humidity are held constant to prevent hysteresis effects on the capacitance. During the whole test, the capacitors are repeatedly charged and discharged with unipolar PWM excitation (50 % duty cycle). The test terminates after 158–164 h, which is comparatively short and thus lead to no failures.

Before, during and after the test, the capacitors are measured to assess their degradation state. Measurements are done every 33 h on average, except for the PDIV, which was measured only once in between start and end. Each measurement takes place outside the climate chamber under lab ambient temperature and humidity, which varied between 19 and 25 °C, and 36 and 55 %.

The PDIV is measured as repetitive PDIV according to IEC 60270 with a Si-IGBT half bridge circuit (phase-resolved with coupling capacitor, cf. IEC (2000)). Every PDIV measurement is repeated five times and then averaged. The mean standard deviation of these repetitions is 1.25 V. Like the measurement error of capacitance (1.20 pF) and resonance frequency (41.5 kHz), this is considered negligible.

As the available testing time and thus the number of possible parameter combinations is limited, not all parameters can be varied on more than two levels. As temperature has been considered most prominently in existing studies, this quantity is reduced to two levels, 20 °C and 90 °C. While this makes it impossible to discern between a linear and a non-linear temperature influence, it allows to properly assess the influence of all involved parameters and, if present, their interactions.

The tested load combinations are given in Table 1. The applied voltage is defined for each capacitor individually in relation to the initially measured PDIV,

$$U_{rel} = \frac{U}{\mathrm{PDIV}(t=0)}, \qquad (1)$$

to ensure PD-inducing or PD-free operation. The initial PDIV is found to be normally distributed with mean $\mu = 307.0$ V and standard deviation $\sigma = 15.9$ V. With a capacitor film thickness of 12 µm, this corresponds to an average field strength of 25.6 V/µm. Considering the measurement setup rise time of 80 ns, the resulting average slew rate for $U_{rel} = 1$ is 3.84 V/ns.

Table 1. Parameter combinations on which n capacitors have been tested.

n $[-]$	T $[^\circ\mathrm{C}]$	H $[\%]$	U_{rel} $[\mathrm{PDIV}(t=0)]$	f [kHz]
2	20	20	0.5	0.5
2	20	20	0.5	1.2
2	20	20	0.5	2
2	20	20	2.5	2
2	20	20	5	0.8
2	20	20	5	1.2
2	20	40	0.5	0.8
2	20	40	5	0.5
9	20	90	0.5	0.5
3	20	90	0.5	2
3	20	90	2.5	0.5
3	20	90	2.5	2
2	90	20	0.5	0.8
2	90	20	0.5	1.2
5	90	20	0.5	2
2	90	20	5	0.5
2	90	20	5	1.2
2	90	20	5	1.6
2	90	40	0.5	0.5
2	90	40	5	0.8

3. Measured degradation

As output quantities which characterize the degradation of the tested capacitors, the capacitance C at 1 kHz, the resonance frequency f_{Res} and the PDIV are chosen. The ESR has been measured as well, but changes insignificantly over the test duration and is thus not considered any further. Fig. 1 shows the raw data. The data is grouped by voltage levels, as this parameter has the highest influence. The following observations can be made:

- there is a clear voltage dependency of the degradation path for all considered quantities, especially for the highest and lowest voltage levels;
- capacitance and resonance frequency show strongly correlating curves;
- the degradation is rather degressive than linear;
- in the rare cases in which non-monotonous behaviour is found for capacitance or resonance frequency, it is of negligible magnitude; for the PDIV, however, it is strong for some capacitors;
- for maximum voltage only, the PDIV shows a systematic behaviour, which is an increase.

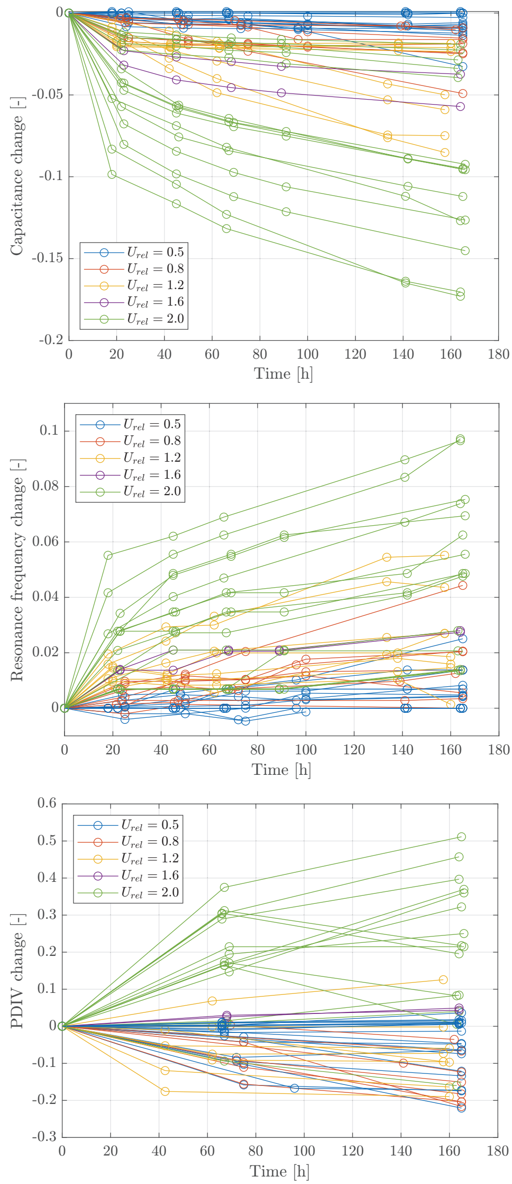

Fig. 1. Relative change of capacitance, resonance frequency, and PDIV, grouped by relative voltage.

In general, an influence of the voltage on the degradation is obvious, as was to be expected. Different degradation stages, which were found in several publications presented in Section 1, cannot be found. This is plausible considering the low test duration. For the same reason, the found degradation is low when the applied voltage is below the maximum. On the lowest voltage level $U_{rel} = 0.5$, several capacitors show completely constant values over the test duration. This applies to 8 units regarding the capacitance, 12 units regarding the resonance frequency, and to no unit regarding the PDIV. These capacitors cannot be included in the statistical evaluation.

4. Degradation path modeling

Based on the measurement data, empirical degradation path models are fitted to each capacitor via least squares estimation (LSE) and are statistically assessed. For all three outputs, a linear model

$$y(t) = a_1 + a_2 t \tag{2}$$

is considered. For capacitance and resonance frequency, the degressive power model

$$y(t) = a_1 + a_2 t^{a_3} \tag{3}$$

and the degressive exponential model

$$y(t) = a_1 + a_2 \exp(t/a_3) \tag{4}$$

with appropriate boundary conditions on the coefficients a_i are considered as well. All models are estimated from the recorded absolute values, so that a_1 resembles the production variance.

For the PDIV, no degressive models can be statistically evaluated, since with only three data points per capacitor, no error degree of freedom remains. As the indication for a degressive PDIV behaviour is much weaker than for the other two outputs, this is unproblematic.

To compare the goodness-of-fit, the variance explained by the models is calculated with an F test including all available capacitors (cf. Montgomery (2013), Rencher and Schaalje, 2008). The resulting adjusted R^2 and the share of capacitors with significant degradation are given in Table 2. Differences in the number of capacitors evaluated result from a few invalid measurements.

As nearly all of the capacitors showed a monotonous capacitance curve with initial drop, only 2 out of 46 have insignificant degradation. The resonance frequency development is slightly more noisy, so that 13 of 43 capacitors are found to have no significant degradation.

Table 2. Goodness-of-fit characteristics from an F test. n_{sign} is the number of capacitors where the chosen degradation path model is significant ($\alpha = 0.05$), R^2_{adj} is the adjusted R^2 using all capacitors.

Output	Path model	n	n_{sign}	R^2_{adj}
C	Linear	46	35	70 %
	Degr. (power)	46	44	99 %
	Degr. (exp.)	46	43	95 %
f_{Res}	Linear	44	30	72 %
	Degr. (power)	43	30	95 %
	Degr. (exp.)	43	29	91 %
PDIV	Linear	51	6	44 %

For both capacitance and resonance frequency, the degressive models are found to fit much better than the linear models. The degressive exponential model implies that a_1 is a limiting value, for which no clear evidence is found. Furthermore, R^2_{adj} is slightly lower for the degressive exponential models. Thus, the degressive power model is chosen for both capacitance and resonance frequency. The coefficient of correlation for the coefficients (a_1, a_2, a_3) between capacitance and resonance frequency is $(-0.72, -0.93, -0.72)$, confirming the interdependence between both quantities.

The degradation path models for the absolute capacitance are shown in Fig. 2, which graphically proves the high correlation between measurement and model. Due to their similarity, the models for the resonance frequency are not shown.

The results for the PDIV are worse, where only 6 capacitors are found to have significant degradation. This is caused by

(a) a relatively high scattering (several capacitors show non-monotonous jumps of 10–15 %);
(b) the inability of a linear model to fit the often degressive degradation paths.

For the reasons stated previously, no degressive modeling is possible for the PDIV, hence the linear models are the only available option. Regarding the comparably high scattering, choosing a simplified linear model is no disadvantage per se, as

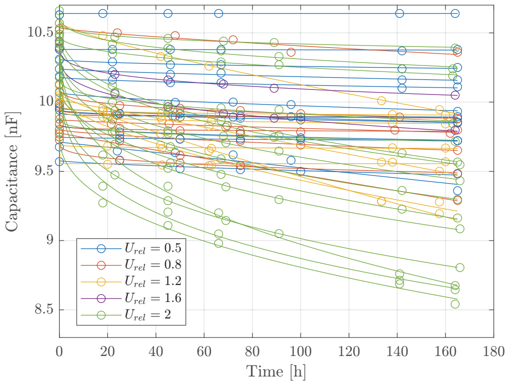

Fig. 2. Measured (circle) and modeled (line) absolute capacitance for 46 capacitors.

it prevents overfitting. As long as no extrapolation is performed, a linear approximation is considered permissible.

Although different models are used, there is a correlation between the slope coefficient a_2 for the PDIV and either capacitance (-0.64), or resonance frequency (0.64). This is mainly due to the systematically increasing PDIV for $U_{rel} = 2$. As less than half of the observed PDIV variance is explained by the degradation models, this quantity has to be handled with particular care.

5. Load dependency modeling

To assess the influence of the load parameters on the degradation process, models for the estimated degradation path coefficients as function of the load parameters are considered,

$$a_i = a_i(T, H, U, f)\,, \quad i = \{2, 3\}\,. \qquad (5)$$

For the initial values of each output, a_1, no such modeling is necessary, as they are found to be normally distributed without load dependency, which is the expected result.

To find the models in the sense of Eq. 5, LSE is applied together with a backward elimination algorithm. This algorithm starts by estimating a model containing all possible influences. Then, the most irrelevant insignificant input ($\alpha = 0.05$) is removed and the model is estimated anew. This process is iterated until only significant influences remain (except for a constant term, which is required in all models).

As possible influences, the load parameters defined in Eq. 5 are considered, including several transformations of them (x^2, $\sqrt{x}$, $\ln(x)$, $\exp(1/x)$). Transformations of the temperature are omitted, since it has been varied on only two levels. Terms for first level interdependencies are included for all load parameters (e.g., TU as interdependency between temperature and voltage). Terms for second level interdependencies are included when combined with Uf, due to the relevance of this quantity (see below).

As training data for the load dependency models, all estimated degradation path model coefficients are used – even those for capacitors where no significant degradation was found. This is justified by the following rationale: if the degradation speed is indeed load-dependent, capacitors under low load will have insignificant degradation, corresponding to failure at high runtimes. This information is of practical value and should thus be included in the load dependency models.

The evaluation shows that it can be beneficial to estimate models for only a subset of the data, where the boundaries are defined over U_{rel}. The most plausible resulting load models and their performance statistics are given in Table 3. The following observations can be made:

(a) an influence of the temperature T and the logarithm of the number of weighted voltage pulses, $\ln(Uf)$, is found in every model;
(b) identical models can be found for capacitance and resonance frequency;
(c) $a_2(C)$ and $a_2(f_{Res})$ are estimated with higher accuracy when limited to $U_{rel} \leq 1.2$;
(d) model residuals are normally distributed for all a_3 coefficients and a_2(PDIV);
(e) the PDIV model has a surprisingly high R^2_{adj}, considering its low systematic degradation.

The missing humidity influence is most likely explained by missing combination with high temperature. Occasionally occurring non-normal residuals are probably caused by the limited domain of the coefficients and are thus not considered critical. Due to their high accuracy and similarity, the models are assessed to be generally plausible.

Table 3. Load dependency models for the degradation path coefficients a_2, a_3. For each model, data from n capacitors has been used, which comply to the given restrictions on U_{rel}. p is the result of an Anderson-Darling test for normality of the model residuals.

Output	Influences	U_{rel}	n	$R^2_{adj}\,[\%]$	RMSE	p
$a_2(C)$	$T, TU^2, \ln(Uf), U\ln(Uf)$	$[0.5, 1.2]$	29	85.8	$2.32E$-2	0.00
$a_2(C)$	$T, TU^2, \ln(Uf), U\ln(Uf)$	$[0.5, 2.0]$	46	70.0	$5.67E$-2	0.16
$a_2(C)$	$U\ln(Uf)$	2.0	15	53.8	$8.24E$-2	0.21
$a_3(C)$	$f^2, T\ln(Uf), f\ln(Uf)$	$[0.5, 1.2]$	29	73.6	$1.75E$-1	0.93
$a_2(f_{Res})$	$T, TU^2, \ln(Uf), U\ln(Uf)$	$[0.5, 1.2]$	26	79.2	$1.90E$-2	0.67
$a_2(f_{Res})$	$T, TU^2, \ln(Uf), U\ln(Uf)$	$[0.5, 2.0]$	43	65.1	$4.02E$-2	0.01
$a_2(f_{Res})$	$U\ln(Uf)$	2.0	15	45.2	$6.21E$-2	0.26
$a_3(f_{Res})$	$f^2, T\ln(Uf), f\ln(Uf)$	$[0.8, 1.2]$	16	51.3	$2.51E$-1	0.80
a_2(PDIV)	$TU, U\ln(Uf), H$	$[0.5, 2.0]$	53	76.7	$1.57E$-1	0.66

The fact that the case $U_{rel} = 2$ cannot be described by most models or decreases their performance indicates that a different failure mechanism is at work there, supposedly due to the strong PD-inducing excitation. This effect could still be weak at $U_{rel} = 1.2$, explaining why these cases can be included in all models. In any case, further research is necessary to explain this behaviour.

For a_2 under the highest voltage level $U_{rel} = 2$, separate models are estimated, showing a significant effect of $U\ln(Uf)$ for both capacitance and resonance frequency. A weak temperature influence is also found, but it is insignificant and thus excluded from the model. For both outputs, when $U_{rel} = 2$, a_3 is lognormally distributed without load influence. With this information, degradation paths under maximum voltage can be simulated, as well. To be able to model all outputs on all voltage levels, $a_3(f_{Res})$ for $U_{rel} = 0.5$ has to be considered, too. It is found to mostly equal unity, indicating linear degradation behaviour. Thus, no further model is needed.

6. Lifetime estimation

To estimate the capacitor lifetime with the derived models, the load conditions have to be specified first. Then, the excitation voltage is calculated from the initial distribution of the PDIV. Subsequently, the systematic coefficients $a_{i,sys}$ are calculated from the load dependency models. To properly reproduce the model uncertainty, they are superimposed with (log)normal scattering defined by the model RMSE. With these sampled coefficients, synthetic degradation paths are calculated from Eq. 2 or Eq. 3. Soft failure times are obtained as the lifetime at which the predefined failure threshold for capacitance, resonance frequency or PDIV is reached. From these failure times, the failure distribution is estimated. Fig. 3 depicts a simple example with only a capacitance threshold.

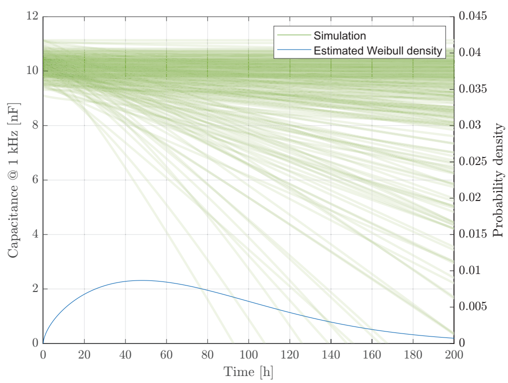

Fig. 3. Simulated degradation paths from the obtained models ($T = 20$ °C, $U_{rel} = 0.8$, $f = 5$ kHz). Considering 5 % capacitance loss as failure, a Weibull failure distribution has been estimated ($\eta = 85.6$ h, $\beta = 1.71$).

7. Summary & Conclusion

53 MPPFCs have been operated with unipolar PWM excitation under elevated load for 165 h, including PD-inducing excitation for some of the capacitors. The degradation of the capacitance,

the resonance frequency, and the PDIV has been monitored. It has been found that the first two are well described by degressive degradation models in the considered time frame. Due to the limited PDIV data, only linear models could be used here, which gave poorer results. Regarding the applied stresses, an influence of several load parameters has been found, most prominently temperature and the number of weighted voltage pulses. While both PD-free and PD-inducing operation could be modeled, further research is necessary to find a common model incorporating both cases.

It was shown that the obtained models can be used to create synthetic degradation paths and estimate a lifetime distribution for arbitrary end-of-life criteria. To be able to demonstrate specific lifetime targets, further tests with higher duration are required. Then, existing methods for the calculation of confidence bounds can be applied (cf. Meeker and Escobar (1998)).

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