

Life Prediction of Battery/Motor Decoupling Capacitor in Passenger Vehicle Electric Power Steering

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Summary

Motor-current causes decoupling capacitor heating in passenger vehicle electric power steering systems, which shortens capacitor life and can reduce vehicle power system reliability. A thermal model for an electrolytic decoupling capacitor (E-Cap) is presented using electrolyte loss rates to predict E-Cap life in this application. Events like parallel parking produce ripple currents three to five times higher than the E-Cap rating for 50 to 200 s and reduce E-Cap life and thus system life. E-Cap life is discussed in detail; predictions are made based on the root-cause of E-Cap failure and not on a generalized Arrhenius relationship.

Keywords: Power steering, energy storage, case-study, reliability, simulation

1. Introduction

Electrolytic capacitors (E-Caps) are used in motor/battery electrical power systems to decouple the battery from the motor. In this paper we discuss a typical motor/battery application – electric power steering (EPS). Motor current is controlled by high frequency (20 kHz to ~50 kHz) pulse width modulation which, if not decoupled from the battery, thermally stresses the battery and shortens its life. Ripple current, which is proportional to the motor current, is absorbed by the E-Cap and causes its temperature to rise. This impacts E-Cap life and thus influences EPS system reliability. In this paper we present a model that determines whether E-Cap life meets the 15-year passenger vehicle requirement. The capacitor-life model is based on the quantity of electrolyte lost due to its diffusion through package seals, which is a strong function of capacitor temperature and thus the ripple current level and its duration. The EPS circuit and control board are shown in Figure 1. A power MOSFET in the full bridge motor control circuit is used to switch current during power steering. Inductive energy (I^2L) stored in the coils of the power steering motor coil during operation is dissipated by the E-cap when the motor is switched off and this ripple current causes capacitor heating.

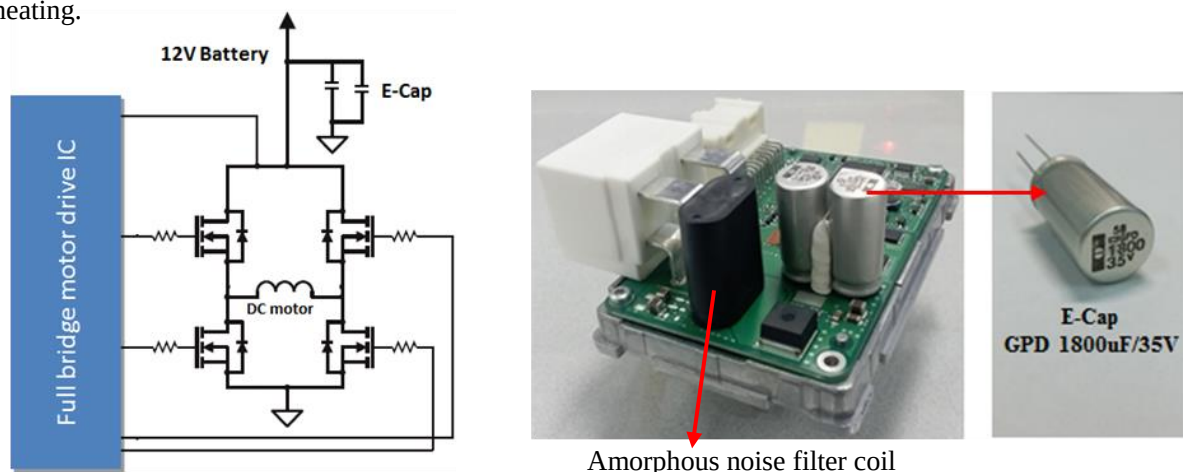


Figure 1. (left) Typical EPS Control circuit with DC brush motor. (middle) EPS control board. (right) Electrolytic capacitor.

2. Thermal model of the E-Cap

Here the E-Cap is a Nippon Chemi-Con electrolytic capacitor rated at 1800 μF , 35 V, 125°C, 3000 hr life. It reaches end of life, defined as 30 % capacitance loss and/or 300% dissipation factor increase, which occurs when total electrolyte loss reaches 247 mg. The thermal model for the capacitor is shown in Figure 2, where heat generated in the core of the capacitor passes to the capacitor case and then to the ambient environment in sequence through thermal resistances θ_{r1} and θ_{r2} with heat capacities θ_{c1} and θ_{c2} .

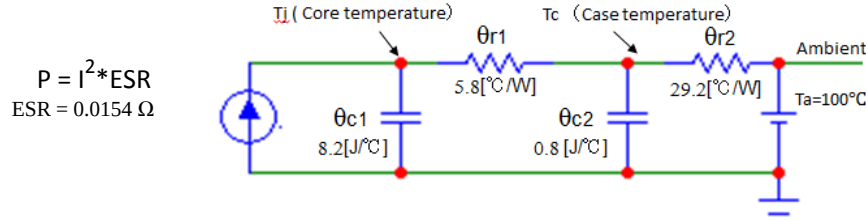


Figure 2. Thermal model for the E-Cap. [1, 2] This model was derived for an ambient temperature of 100°C. It has two response times.

The thermal model in Figure 2 was derived from the thermal transient response characteristics shown in Figure 3. The measured thermal resistance θ_r is $\Delta T / (I_{\text{rms}}^2 * \text{ESR}) = 35 \text{ } ^\circ\text{C/W}$. The measured thermal heat capacity is $\tau / \theta_r = 9 \text{ J/}^\circ\text{C}$. The heat capacity of the aluminium case, θ_{c2} , is 0.8 J/°C and the thermal resistance between the case and ambient, θ_{r2} , is 29.2 [°C/W]. This allows calculation of the heat capacity of the core and the thermal resistance between the core and case. $\theta_{c1} = 9 - 0.8 = 8.2 \text{ J/}^\circ\text{C}$ and $\theta_{r1} = 35 - 29.2 = 5.8 \text{ J/}^\circ\text{C}$.

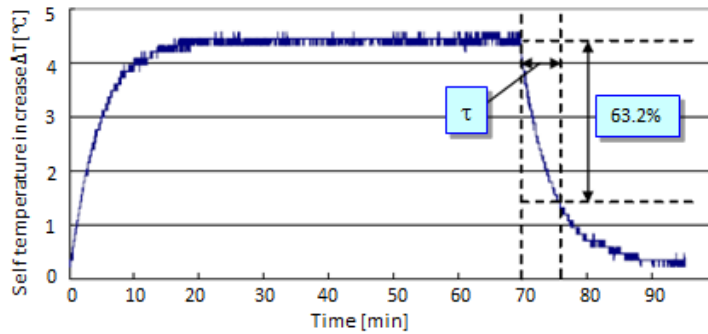


Figure 3. Thermal transient response of the 35 V 1800 μF capacitor with $I_{\text{rms}} = 3.0 \text{ A}$ applied at 100 kHz. This response was used to calculate θ_r and θ_c .

3. Electrolyte Diffusion

The rate of diffusion of electrolyte out of the package through seals is known for this particular capacitor. Figure 4 shows the electrolyte diffusion rates in both tabular and graphical form. The values for 85 °C, 105 °C, and 125 °C were measured; others were estimated as

$$W_s(T_a) = 4.4479\text{E-}6 * e^{7.9102\text{E-}2 * T_a} \quad \text{mg/hr for } T_a < 105^\circ\text{C} \quad (1)$$

$$W_s(T_a) = 5.6284\text{E-}7 * e^{5.4931\text{E-}2 * T_a} \quad \text{mg/hr for } T_a > 105^\circ\text{C} \quad (2)$$

where W_s is the diffusion rate and T_a is the ambient temperature shown in Figure 4.

Ambient Temperature, T_a	W_s [mg/h]
70°C	0.00113
80°C	0.00249
85°C	0.0037
90°C	0.0055
100°C	0.01212
105°C	0.018
125°C	0.054

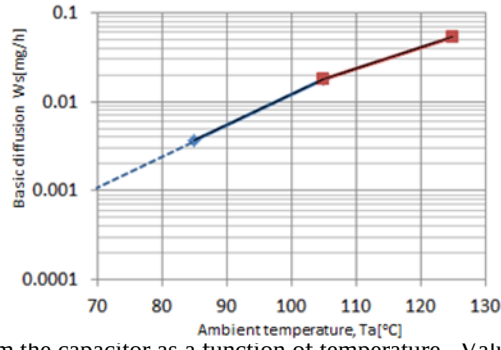


Figure 4. Electrolyte diffusion rates from the capacitor as a function of temperature. Values were measured at 85 °C, 105 °C, and 125 °C and calculated at other temperatures.

Electrolyte loss predicted by equations 1 and 2 was fit to one empirical equation with two parameters selected with $T_a = 100$ °C as the base case. This base case is considered to be the worst case ambient temperature for a power steering event during parking, which is outside in the summer with strong sunshine. Thus electrolyte loss as a function of temperature with self-heating due to ripple current is calculated as:

$$W_t(t) \text{ [mg/h]} = [W_s * K1^{(\Delta T(t)/K2)}] \quad (3)$$

where $W_t(t)$ is the electrolyte loss rate as a function of temperature, W_s is the electrolyte loss rate at $T_a=100$ °C = 0.01212 mg/h, $K1$ is an acceleration factor over the base case of $T_a = 100$ °C for a temperature increase of $K2 = 5$ °C. The data in Figure 5 where the points marked with the triangles, squares, and diamonds are measured points.

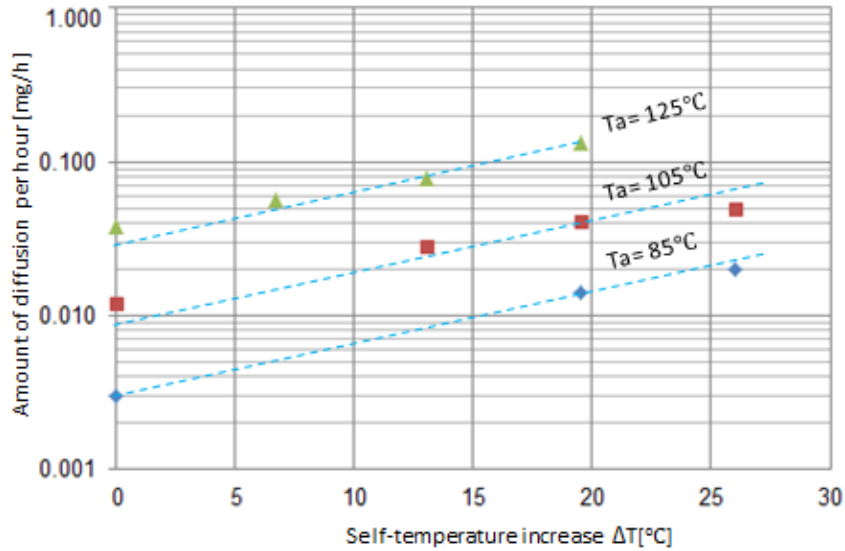


Figure 5. Measured electrolyte loss as a function of self-heating temperature increase ΔT .

When parameter $K2$ is set to 5°C, the acceleration factor $K1$ ranged from 1.3 to 1.5 (i. e., the diffusion rate increased by a factor of 1.3 to 1.5 for each 5°C increase in temperature). For purposes of predicting life here, $K1$ has been set to 1.6 to include a design margin. Thus equation 3 above is implemented as equation 4 including conversion of the electrolyte loss rate from hours to seconds:

$$W_t(t) \text{ [mg/sec]} = [0.1212 * 1.6^{(\Delta T(t)/5)}] / 3600 \quad (4)$$

The total electrolyte loss, $W(T)$, is calculated by integrating $W_t(t)$ over the time of the ripple current event:

$$W(T) \text{ [mg]} = \int_0^T W_t(t) dt \quad (5)$$

where T is the duration of the parking event in seconds.

Capacitor end of life (EOL) is reached when total electrolyte loss reaches 247 mg for the capacitor used here. Thus life, L, in seconds and years are calculated as:

$$L \text{ in seconds} = [W_o/W(T)] \quad (6)$$

$$L \text{ in years} = [W_o/W(T)] / (3600 \text{ sec/hour} * 24 \text{ hours/day} * 365 \text{ days/year}) \quad (7)$$

where W_o is the electrolyte loss at EOL and $W(T)$ is the electrolyte loss in a the period T (in seconds). The goal is $L > 15$ years, i.e. for the capacitor to have 15 year operational life. Capacitor life depends primarily on the duration and frequency of ripple current events and in particular to high current associated with parallel parking.

4. E-Cap Electrolyte Loss in Response to a High Current Event

$T_a=100^\circ\text{C}$ is considered to be the worst case ambient temperature (summer outside parking under strong sunshine). High-ripple current associated with parallel parking has a duration of 1180 sec with the current profile shown in Figure 6. This figure also shows the thermal response and electrolyte loss rate of the E-Cap during this high current parallel parking event. RMS ripple current is 10.3 A, which is approximately three times higher than E-Cap rated ripple current. Motor current decreases to 0.82 A at 180 seconds at which time the capacitor core temperature has risen by 25°C to 125°C . Total electrolyte loss is shown in Figure 7 with 0.0113 mg of electrolyte lost during the 1180 sec parking event.

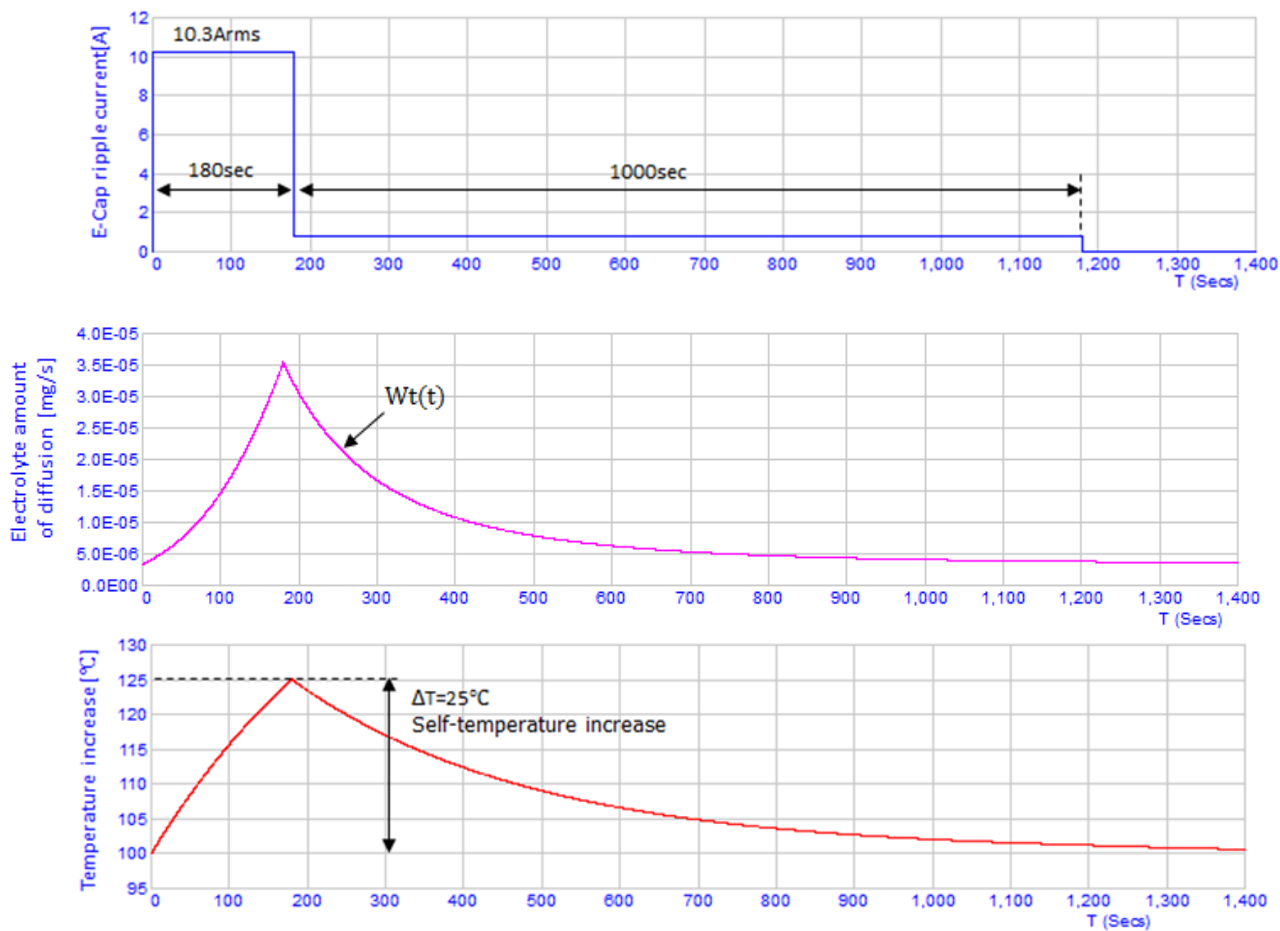


Figure 6. (upper) Ripple current profile of power steering parking event with durations of 180 sec and a period of 1180 sec. (middle) Electrolyte loss rate due to temperature rise associated with the parking event. (lower) Temperature rise in response to the ripple current shown above.

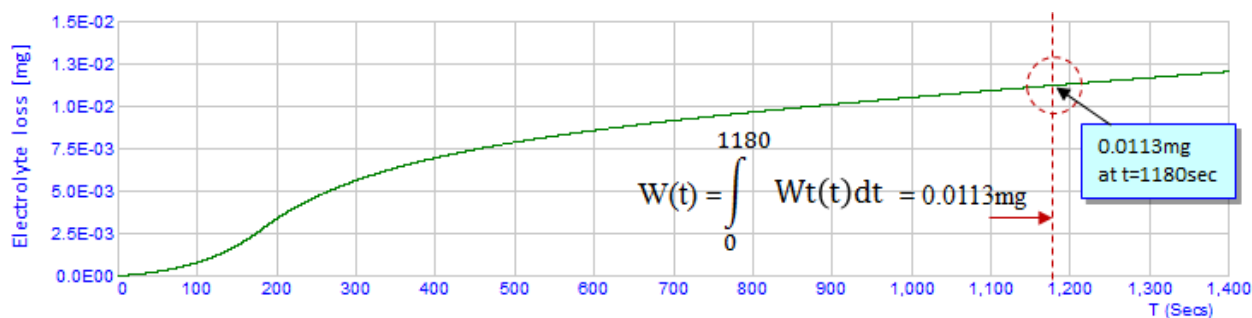


Figure 7. Electrolyte loss during the parallel parking event.

Electrolyte is also lost during normal EPS operation at the $T_a = 100^\circ\text{C}$ ambient temperature worst case scenario. However, the loss rate is small since it is a strong function of temperature: losses are $\sim$ ten-times higher at 125°C than at 100°C as shown in Figure 8. Thus loss during short-term parallel parking events, when the capacitor has been heated by the high ripple current, is most significant.

5. Life Analysis

Capacitor life prediction was made using the above analysis with comparisons to measurements of the capacitor dissipation factor, which is a function of the quantity of electrolyte lost from the capacitor. In this case the capacitor reaches EOL when the dissipation factor, $\tan \delta$, increases 300 % ($\tan \delta = 0.42$), which occurs when total electrolyte loss reaches 247 mg. Measurements were made for a capacitor held at $T_a = 125^\circ\text{C}$ ($W(T) = 0.0113\text{ mg}$ using the rated ripple current).

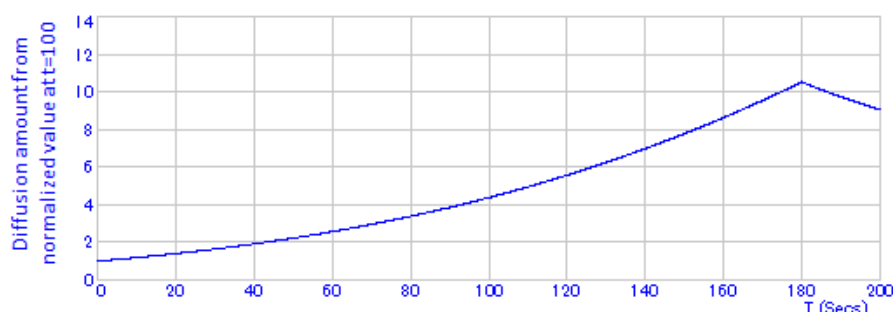


Figure 8. Electrolyte loss rate normalized to 1 for the loss rate at $T_a = 100^\circ\text{C}$. The loss rate at 125°C , the temperature reached 180 seconds into the parking event, is ten times greater than the 100°C value.

The simulated life prediction is compared to the measurements in Figure 9 and agrees very well. The simulation was conducted assuming ambient temperature $T_a = 100^\circ\text{C}$, and that electrolyte loss occurs from repeated parallel parking events, each one lasting 1180 s. Electrolyte loss in the 1180 second period was 0.0113 mg, which yields a loss of 247 mg after 7164 hours of this event.

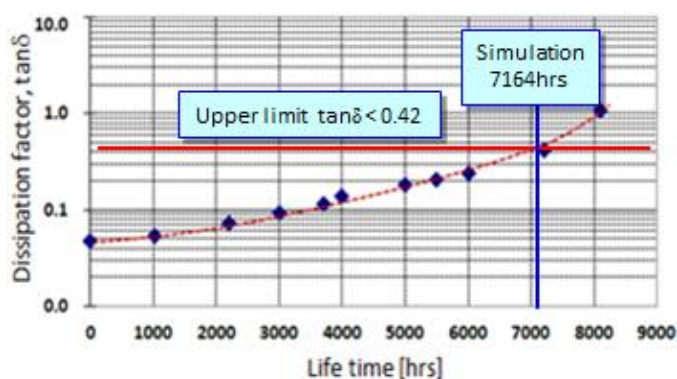


Figure 9. Comparison of measured and predicted capacitor life.

Thus the predicted life was calculated as 7,164 hrs.

- $L = [W_o/W(T)] * T / 3600 = [247\text{mg}/0.0113\text{mg}] * 1180\text{sec} / 3600\text{sec/hour} = 7164 \text{ hrs.}$
- If the parking event occurs twice each day, then $T = 1180\text{sec} \times 2 = 2360 \text{ sec.}$
Total number of hours is $2,360\text{sec} * 365\text{days} * 15\text{years} / 3600\text{sec} = 3540 \text{ hrs}$ for 15 years operation of vehicle.
- The predicted life L is two times greater than accumulated total number of hours during 15 years vehicle operation.

The prediction is that when the parallel parking event occurs two times a day for 15 years, the capacitor has effectively been aged for only 3540 hours, about half of its 7164 hour life at these conditions.

6. Life study based on the provided temperature profile

The electrolyte loss and life analysis described above is for constant ambient temperature $T_a=100^\circ\text{C}$ but in the real world the ambient temperature profile varies with the season and time of day as well as the geographic location, which directly impacts E-Cap life. The typical way to calculate the life under different ambient temperatures is to apply the Miner's Rule [3], which describes cumulative damage when different levels of stress are applied. For life predictions the rule is described as:

$$\frac{1}{L} = \sum_{n=1}^n \frac{R_n}{L_n} \quad (8)$$

Where L is predicted life, n is the number of stress temperature levels, L_n is the life at each temperature, and R_n is the ratio between the number of hours at each temperature vs the entire profile.

Figure 10 shows the temperature profile for Phoenix, Arizona, geographically the hottest state in the United States. [4] The high temperature profile is approximated by the temperature levels and durations shown in Table 1. When the vehicle is driven and parallel parked outside under direct sunshine in summer time, engine compartment temperature increases to $\sim \Delta T = 50^\circ\text{C}$ [5] over ambient within 300 sec and then gradually drops to $\Delta T=20^\circ\text{C}$ over ambient at 900 sec. We derive a worse-case scenario assuming the engine compartment temperature around the E-Cap is 50°C above the temperatures listed in Table 1. Table 2 shows a summary of the assumptions, calculated electrolyte loss, and calculated life at each of the temperature conditions. This provides the results to be used with Miner's Rule to determine E-Cap life for the variable temperature profile of Figure 10.

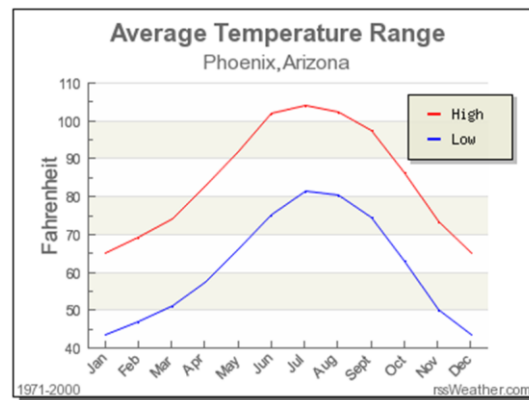


Figure 10. Average temperature distribution for YR 1971 to 2004

Table 1. Approximation of the monthly high temperatures of Figure 10. There are 3600 hours at 20°C , 2280 hours at 30°C , and 2880 hours at 40°C for a total of 8760 hours in the year.

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Highest [°C]	18.3	20.8	23.5	28.3	33.3	38.9	40.1	29.1	36.3	30.2	22.9	18.3
Rearrange[°C]	20			30			40			30	20	

Using Miner's Rule capacitor life is calculated as

$$L = 1 / \left(\frac{0.41}{77105} + \frac{0.26}{35048} + \frac{0.33}{15875} \right) = 29,830 \text{Hrs} \quad (9)$$

Note the analysis neglects electrolyte loss in the absence of ripple current, which is justified by the strong effect of temperature on the electrolyte loss rate. For example, electrolyte loss at 40 °C is 0.000105 mg/hour, over two orders of magnitude slower than the case described above. The loss rate is so small that the calculated lifetime for a capacitor at $T_a = 40$ °C is 268 years.

Table 2. Summary of the predicted electrolyte loss and E-Cap life at each in Table 1 for the Phoenix temperature profile shown in Figure 10.

Month	Jan-Mar Nov-Dec	Apr-May, Oct	Jun -Sept
Estimated number of hours	3600 hrs	2280 hrs	2880 hrs
Outside temperature	20 °C	30 °C	40 °C
T_a at Engine compartment + $\Delta T=50^\circ\text{C}$ (around E-Cap)	70 °C	80 °C	90 °C
E-Cap core temperature* ¹⁾ Self-temperature increase $\Delta T=25^\circ\text{C}$	95 °C	105 °C	115 °C
$W_s(T_a)^{*2)}$	0.00113 [mg/h]	0.00249 [mg/h]	0.0055 [mg/h]
$W(t)$ Amount of Loss electrolyte* ³⁾	0.00105 mg	0.00231 mg	0.0051 mg
Life at each temperature, $L_n^{*4)}$	77105 hrs	35048 hrs	15875 hrs
Ratio to total Hours $R_n^{*4)}$	0.41	0.26	0.33

*1) The current profile, see Figure 6. The self-heating temperature increase $\Delta T=25$ °C

*2) See Table 1 and Figure 4.

*3) The 1180 sec duration is 10.3 A for 180 sec and 0.82 A for 1000 sec.

*4) See equation (8).

7. Summary

- ❖ Using this E-Cap thermal model with electrolyte diffusion rate as a function of temperature and an EPS power profile allows E-Cap life prediction.
- ❖ Capacitor life is predicted based on the actual capacitor failure mechanism, i. e. electrolyte loss, rather than a general Arrhenius relationship.
- ❖ The simulation procedure with electrolyte diffusion at the high ripple current event like EPS application for the prediction of E-Cap life was shown.

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