Guidelines for Lifetime Specification of Power Supplies

An overview of an EPSMA publication and its contents

The EPSMA – who we are

- Brief history of the EPSMA
  - Formed 1995
  - Around 30 members

- Brief description of activities
  - Promotion of European power companies
  - Liaison with standards authorities
  - Generation of technical white papers

- More info at www.epsma.org

The subject - Specifying the lifetime of power converters

- Overview of the document
  - Lifetime terminology and formulae are clarified in relation to MTBF
  - Stress conditions that affect the lifetime of power converters are pointed out
  - Components which dominate limitation to lifetime are discussed
  - Conclusion: Key points are stated when specifying lifetime figures in datasheet to guide the end-user in decisions on the service life of their end-product
- Target audience are experts working in the field of
  - Product definition
  - Engineering
  - Application
  - Quality assurance

  of DC/DC, AC/DC, DC/AC power converters
- What you will learn from the document

  Comprehensive understanding for life expectancy with focus on lifetime-dominant components

Definition of MTBF

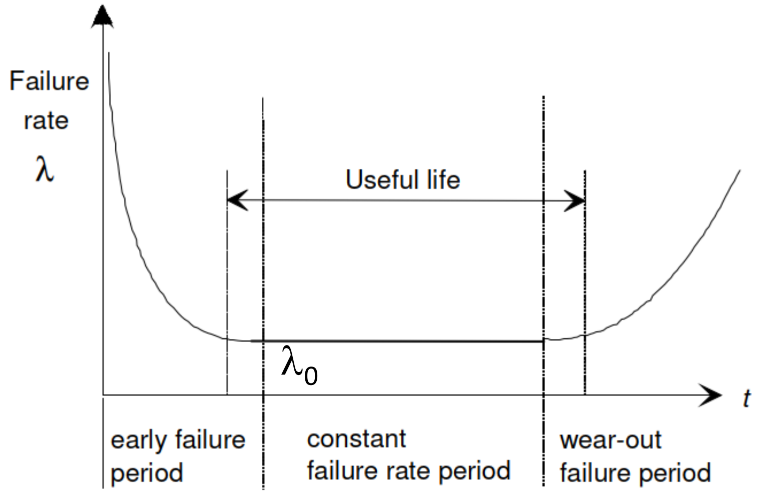
- Differentiation of lifetime versus reliability/MTBF
  - Lifetime: Time until an unacceptable increase of failures can be observed (wear out)
  - MTBF: A probability (risk) figure, of how likely an item is to fail within the lifetime period. A system of n power supplies increases the risk, hence reduces the overall MTBF by factor n.
- Definition of
  - MTTF: Meantime to failure. Probability time until first failure
  - MTBF: Meantime between failure. Probability time between failures considering also service/repair time during life cycle.
  - **failure or hazard rate** λ: statistical fails per hour

    1 **FIT** (Failures in 10^9 hours) = 10^9/MTBF

    What is a failure?
  - hard failure – unit stops operating
  - out of spec failure – parameters run out of min/max limits

Definition of Lifetime

- Period during valley λ_0 of the bathtub curve (useful life)



- End of life EOL can be defined by accumulated failures e.g. F=10% allows to calculate lifetime t_{EOL} by failure distribution function

$$F(t) = 1 - e^{-\lambda_0 t} \cong \lambda_0 t \quad \text{for } \lambda_0 t \ll 1$$

$$t_{EOL} = \frac{F(t_{EOL})}{\lambda_0} = F(t_{EOL}) \cdot MTBF$$

-> Difference between lifetime and MTBF needs to be understood

Example differences between life and failure rate

- Examples of extremes short life <-> high reliability
  - Rocket – Life expectancy approx. 5min, MTTF >1,000,000hrs due to extreme low Failure rate requirement (Human beings on board!)
  - Human Being – Life expectancy 75 years / MTBF approx. 800 years (hard to define EOL, death?)

Factors affecting Product Lifetime

- Lifetime dominated by weakest component. Not a matter of parts count!
- Condition factors
  - Electrical
    - High voltage transients on components, particularly MOVs, TVSs, insulation (Partial Discharge)
    - High electrical current -> losses, temperature rise
    - High operating voltage at power semiconductors
    - Switching cycles (turn on/off) on electro-mechanical parts, e-caps
  - Mechanical
    - Short-term shock
    - Long-term vibration
  - Environmental
    - Temperature -> described by Arrhenius law, most dominant, component aging
    - Humidity -> corrosion, insulation
    - Altitude -> impact on cooling -> temperature, cosmic radiation

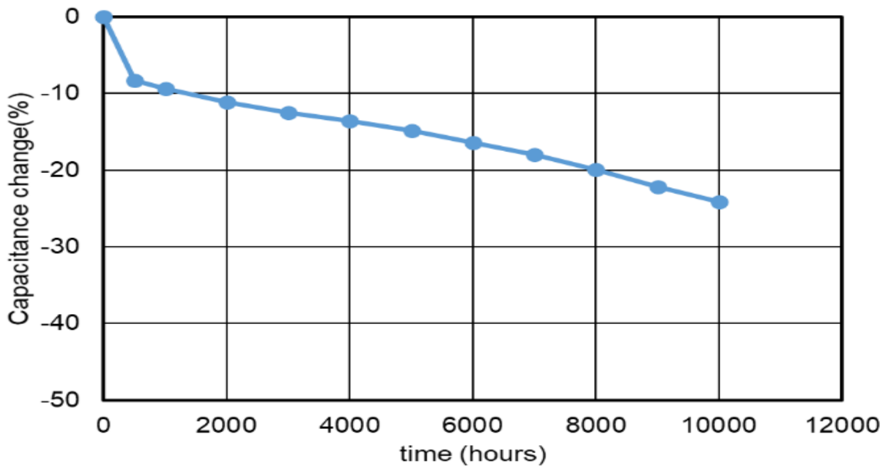
Lifetime prediction of key components

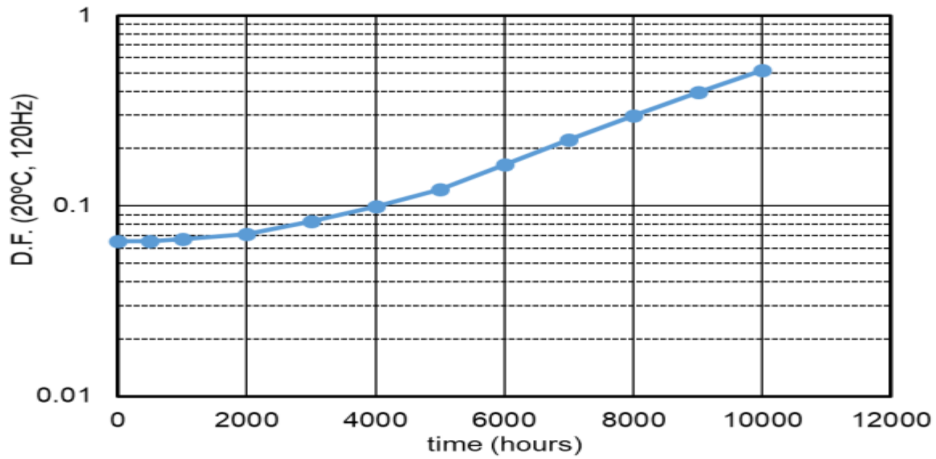
- List of components that dominate lifetime in a typical PSU
  - Electrolytic capacitors (wet, polymer, hybrid)
  - Fans
  - Optocouplers
  - Film capacitors
  - Semiconductors (power-, flash memories)
  - Rechargeable batteries
  - Film resistors
  - Electromechanical parts
  - Inductive Parts
  - Metal Oxide Varistors (MOVs)

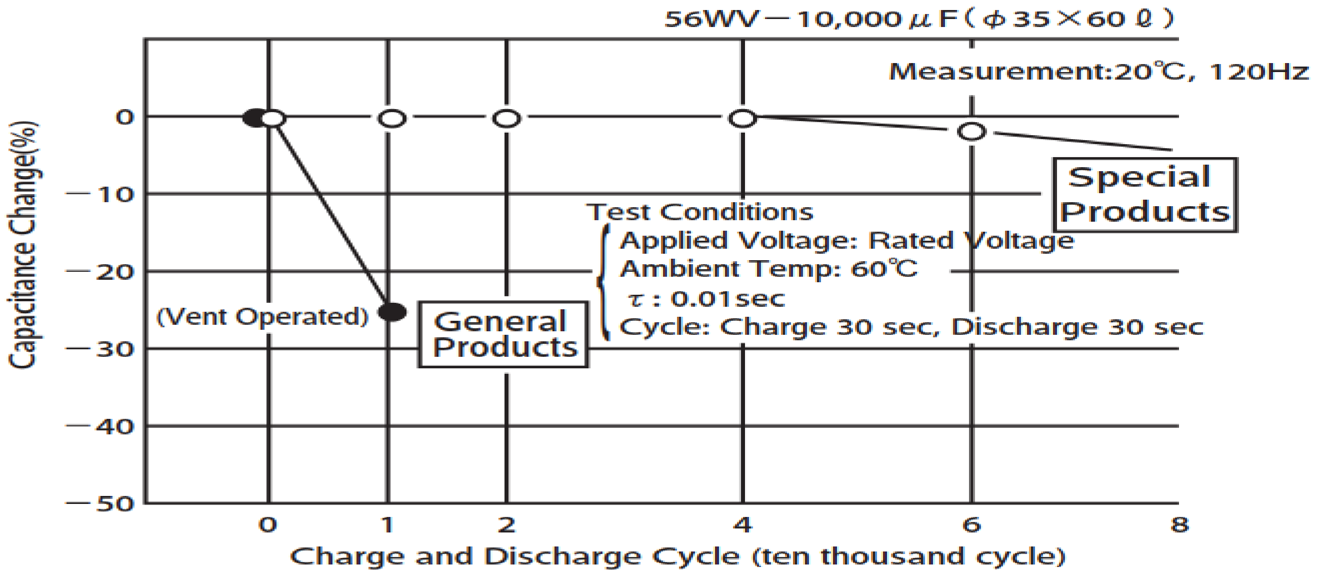
Aluminum Electrolytic capacitor lifetime

- Failure mechanism
  - Electrolyte evaporates and diffuses out through the rubber seal, leading to decrease of capacitance and increase of dissipation factor tanδ
  - Chemical reaction between Al-foil and electrolyte of wet e-caps during charge/discharge cycles extending the oxide range hence reducing capacitance
- Stressors
  - Charge/discharge cycles most dominant
  - Component ambient temperature
  - Ripple Current causing self heating
- Lifetime estimation
  - Manufacturer-specific formulas based on Arrhenius' law and self heating
  - Nowadays e-caps with load-life of 10kh can easily reach 100kh
  - Specified temperature range and max. life (15 years) to be considered

Aluminum Electrolytic capacitor lifetime







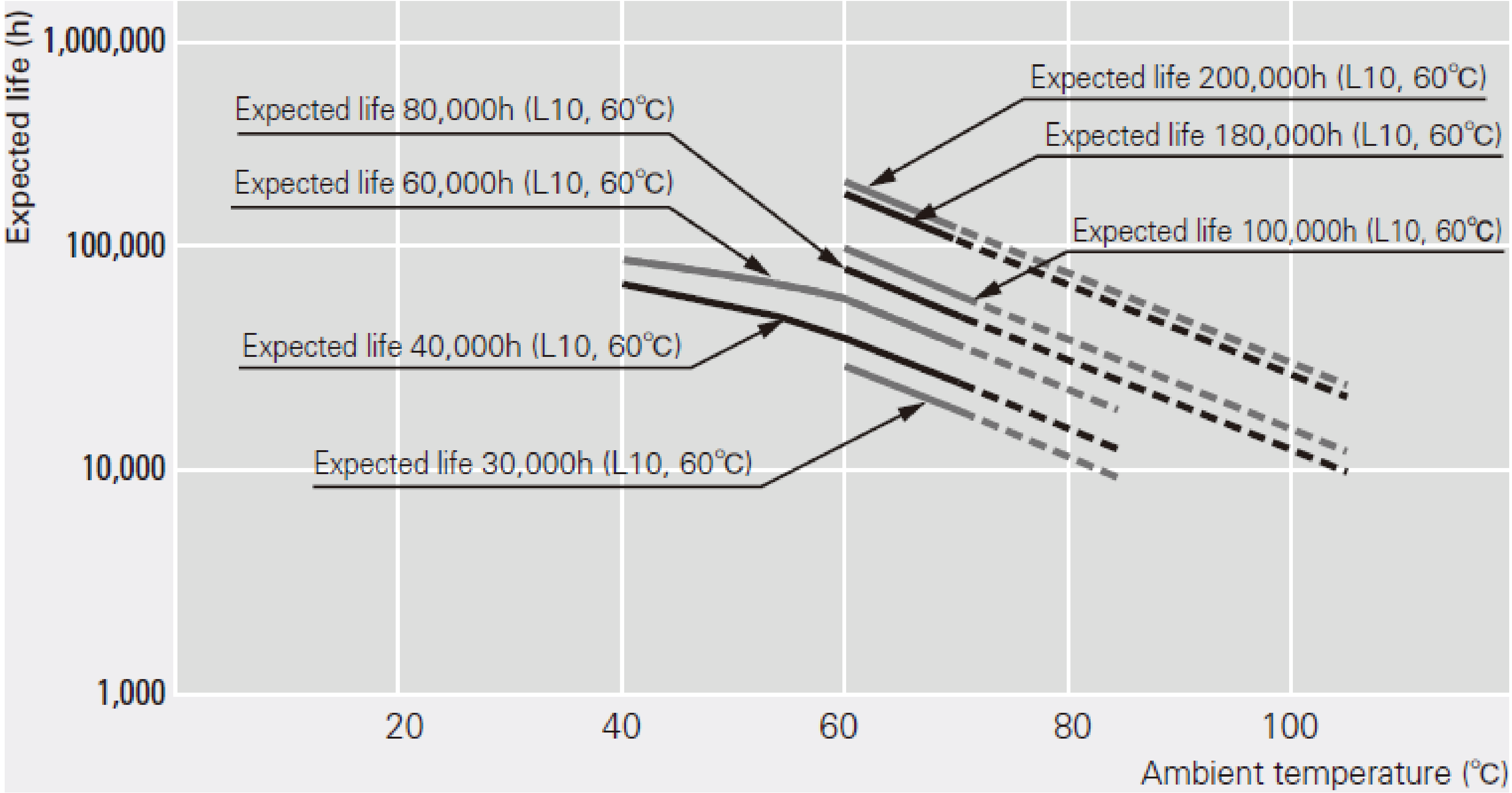
Film capacitor lifetime

- Failure mechanism
  - Deformation and damage of the dielectric foil reducing capacitance or and increasing leakage current
  - Corrosion of contacts and metallization worsens ESR
  - EOL reached when capacitance, ESR or insulation resistance deviates from specified tolerance of initial limit
- Stressors
  - Humidity -> corrosion, deformation of unsealed dielectric foil
  - Component ambient temperature
  - Ripple current -> self heating due to ESR
  - High ac voltage -> “Partial Discharge” in incapsulated air
  - Mechanical stress on contacts
- Lifetime estimation
  - Manufacturer specific calculations acc. IEC61709
  - Lifetime figures for polypropylene typically in the range of 200kh

Fan lifetime

- Failure mechanism
  - Bearing and associated grease or lubricant may gum
  - Control PCB and motor considered not lifetime dominant
  - EOL usually defined by L10 (failure 10%) reached by sudden stop or by reduced performance
    - fan speed -10% to -30% of nominal rpm
    - Increased noise levels > +3 dB of specification
    - Increased operating current, usually +10% to +20% of nominal value
- Stressors
  - Operating temperature -> most impact on grease and lubricant
  - Revolution count
  - Adjacent electromagnetic fields inducing current in the bearing -> self heating and corrosion
- Lifetime estimation
  - Lifetime of lubricant and bearing dominant
  - Standard IPC-9591, Arrhenius law basic
  - Figures for typical operating points available in datasheet. Long life types might reach 60,000 hours at T_{op}= 50°C.

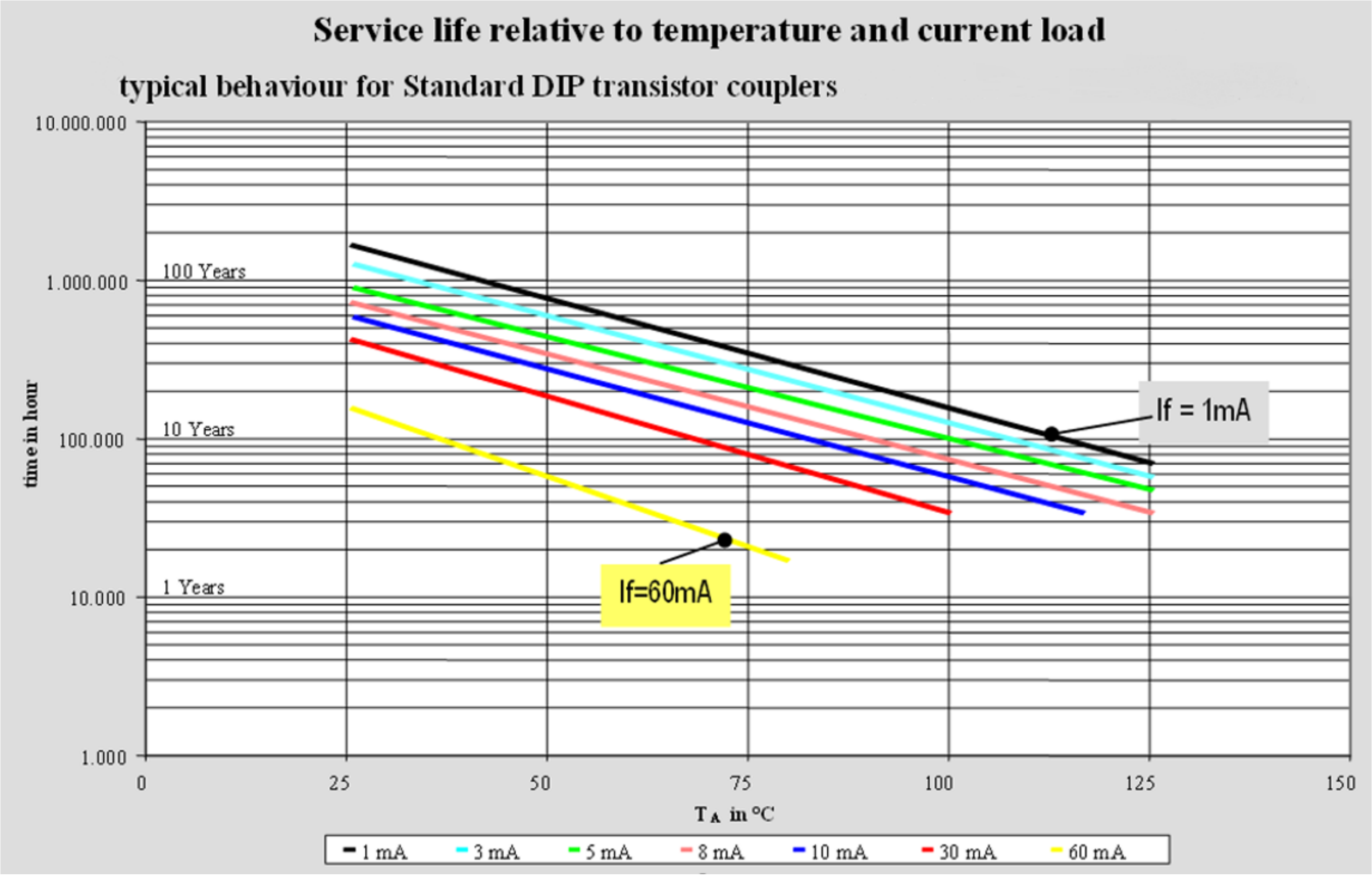
Fan lifetime



Optocoupler lifetime

- Failure mechanism
  - Degradation of light emitting radiation of the LED due to thermal stress to the crystal
  - Effect of aging – reducing current transfer ratio CTR = I_c/I_f
  - EOL if CTR degrades below 50% of its initial value.
- Stressors
  - Component ambient temperature
  - Self heating due to forward current I_f
- Lifetime estimation
  - Specified by graphs based on stressors
  - Typical lifetime 300kh

Optocoupler lifetime



Semiconductor lifetime (1)

- Failure mechanism
  - Power Semiconductor die (especially MOSFETs)
    - Dielectric breakthrough
    - Diffusion processes from package to die causing parametric drift
    - Channel degradation caused by hot carriers
    - Mechanical stress and electromigration
    - Cosmic Radiation
  - Packaging
    - Corrosion
    - Diffusion
    - Tin whisker growth
    - Delamination
  - Flash memories
    - Degrading oxide barrier of floating gate cells -> increased leakage current, reduced memory time

Semiconductor lifetime (2)

- Stressors
  - Chip temperature and temperature cycling
  - Altitude -> cosmic radiation
  - Operating blocking voltage in terms of cosmic radiation
  - Flash memory data retention degrades mainly by the number of cycles and temperature rise
  - Humidity
  - Mechanical stress
- Lifetime estimation
  - Arrhenius model for thermal acceleration of failure mechanisms
  - Eyring and Power Law models for voltage-accelerated failure mechanisms
  - Peck model for corrosion (humidity-induced failure mechanisms)
  - Coffin-Manson model for temperature cycling stress
  - Flash memory defined by data retention time for T_{amb} and program cycle count

Rechargeable battery lifetime

- Failure mechanism
  - Chemical pollution on electrode surfaces such as sulfides retards redox exchange to the electrolyte
  - EOL reached when capacity reaches -20% and resistance +200% of initial value
- Stressors
  - Battery Temperature
  - Charge Current
  - Discharge Current
  - Discharge Depth
- Lifetime estimation
  - Float service life (in standby mode) and cyclic service life (charge/discharge) to be distinguished
  - Charge/discharge cycles are more relevant than an operating life figure
    - Ni-Cd <1500 cylces
    - Li-Ion, Ni-MH <1000 cycles
    - Lead-Acid < 300 cycles

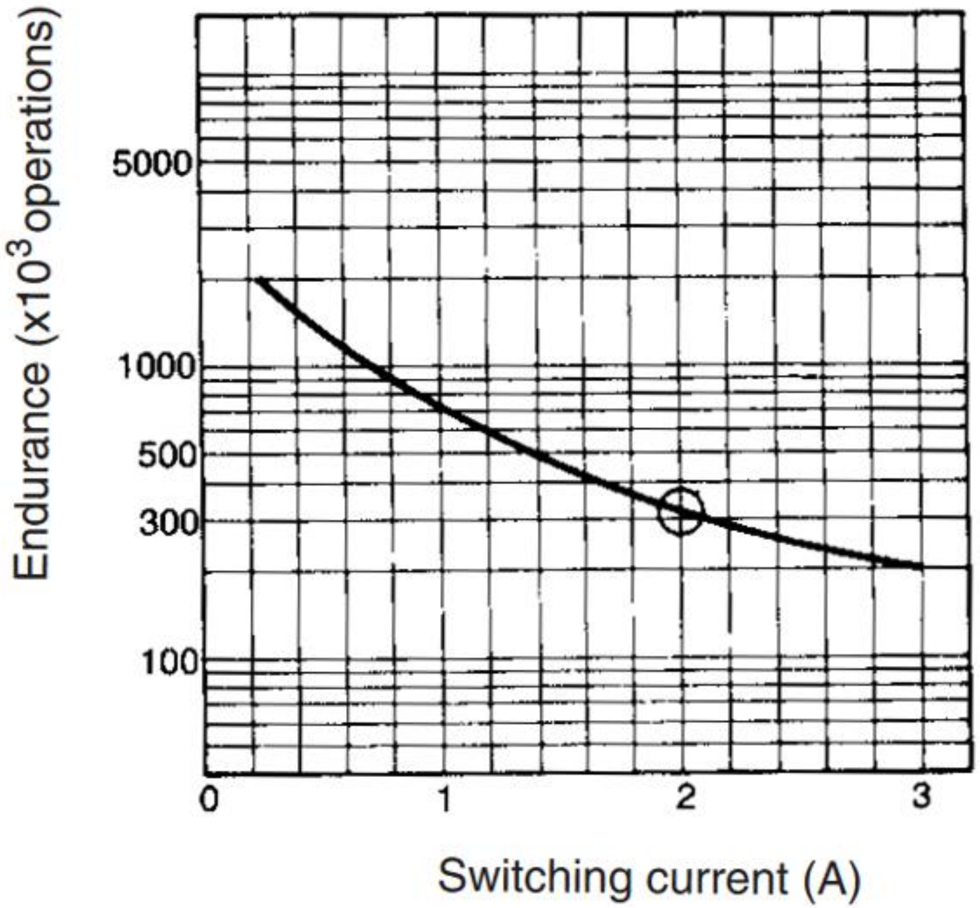
Thin film resistor lifetime

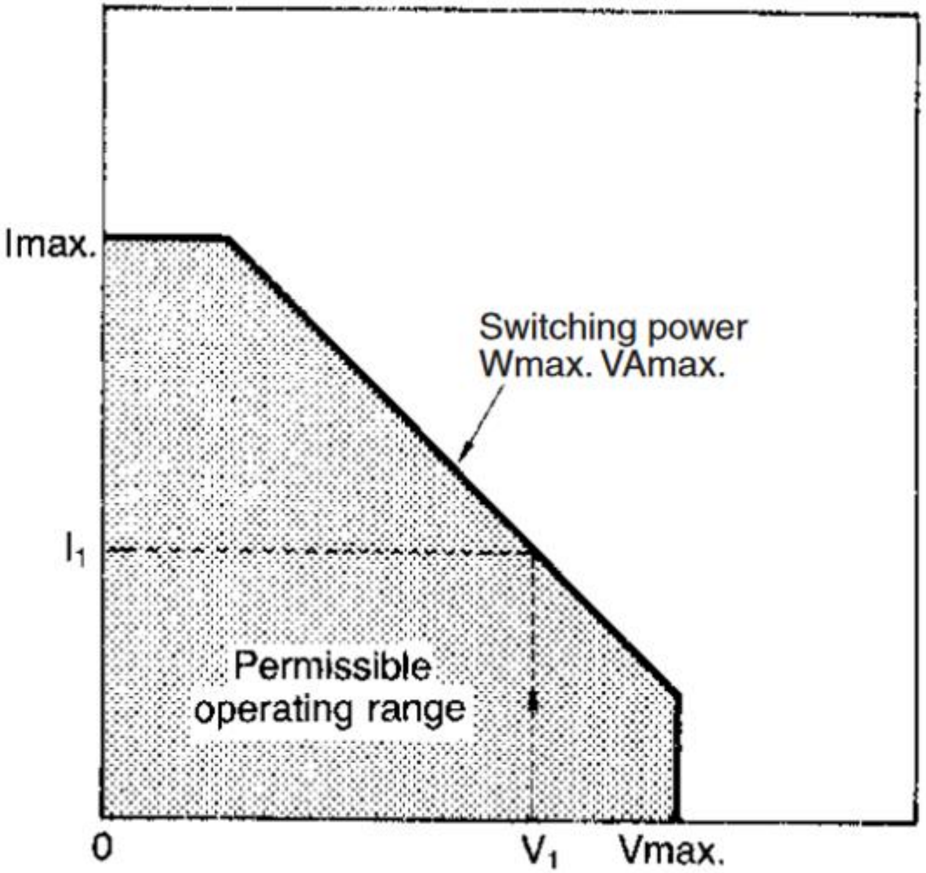
- Failure mechanism
  - Resistance variation due to
    - Aging of resistance material -> strongly dependent on technology
    - Termination effectiveness
  - Maximum acceptable drift to designer’s choice of the acceptable tolerance
- Stressors
  - Component ambient temperature T_{amb}
  - Dissipated power losses P_l
- Lifetime estimation
  - Manufacturer specific error formulas dependent on stressors are available
  - Reference drift for MELF 0,3% at 8000h, 125°C

Electromechanical parts lifetime

- Failure mechanism
  - Erosion of contacts during make or break dominant
  - Electric arcing during break will destroy part, especially DC supply
  - Electrical static on-endurance regarded >10 times greater -> negligible
  - Mechanical cycles (no-load operating cycles) also negligible
  - EOL reached when contact make or break fails. Failure rate R10=10% commonly defined
- Stressors
  - Switched current (break) and voltage (make) specified in a safe operating area (SOA)
  - Capacitive load cause high I^2t -> melting contacts
  - Component temperature
- Lifetime estimation
  - Endurance specified by operating cycles shown in graphs

Electromechanical parts lifetime





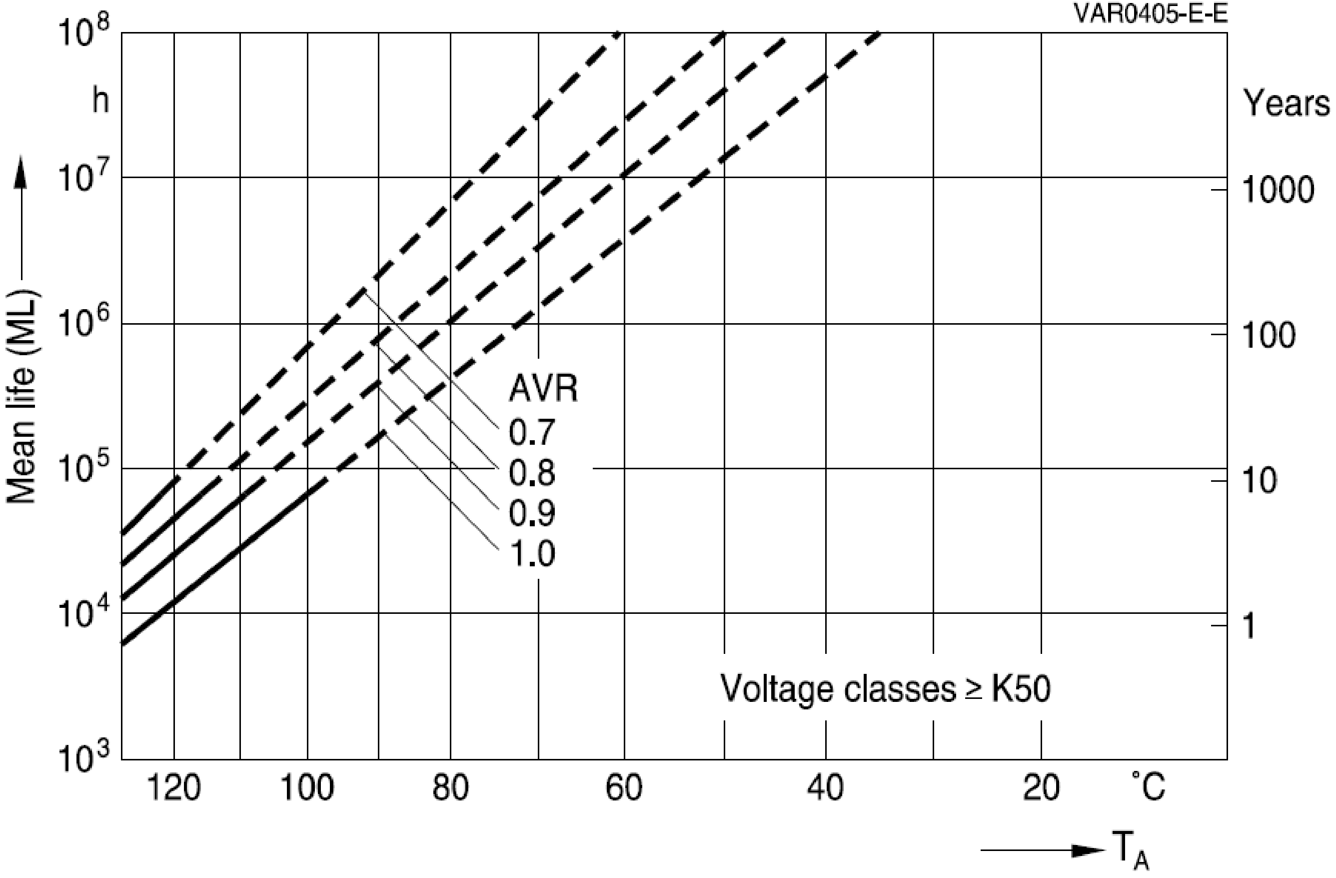
Inductive parts lifetime

- Failure mechanism
  - Thermal aging of iron powder cores due to insufficient heat-resistant organic binder e.g. epoxy -> increase in eddy current losses
  - Copper and insulation material are considered less dominant if operated within specified range
- Stressors
  - Iron powder core temperature
  - Core excitation frequency
- Lifetime estimation
  - Iron powder aging relevant beyond 100°C at AC >10kHz.
  - Manufacturer specific charts are given in datasheet e.g. Micrometals

MOV lifetime

- Failure mechanism
  - Damage to the oxide structure with every transient voltage causing a change (reduction) of the clamp voltage, hence increase bleeding current
  - Self-heating further increases bleeding current and accelerates aging.
  - EOL reached if clamp voltage -10% of initial value
- Stressors
  - Operating temperature T_{op}
  - Applied Voltage Ratio $AVR=V_{op}/V_{max}$
  - Absorbed energy
- Lifetime estimation
  - Max. pulse count dependent on pulse energy acc. derating curves
  - Lifetime by Arrhenius law (T_{op}, AVR)
  - Typical lifetime at T_{rate}, AVR=1 >100kh

MOV lifetime – steady state



Practical life time tests

- HALT during design process with focus on mechanical parts:
  - Shock/vibration
  - Thermal cycles
  - Beyond specified conditions to figure out vulnerable points in a reasonable time
  - No precise criteria for endurance
- HASS during manufacturing process:
  - Thermal and cycle operation series test close to specified limit
  - Goal: Unveil early state failures during phase 1 in order to reduce λ to bathtub level λ_0
  - After phase 1 statistical fit analysis with high unit population possible to derive λ_0
  - Lifetime acc. specified failure rate (e.g.L10) by $\boldsymbol{t_{EOL} = \frac{F(t_{EOL})}{\lambda_0} = F(t_{EOL}) \cdot MTBF}$

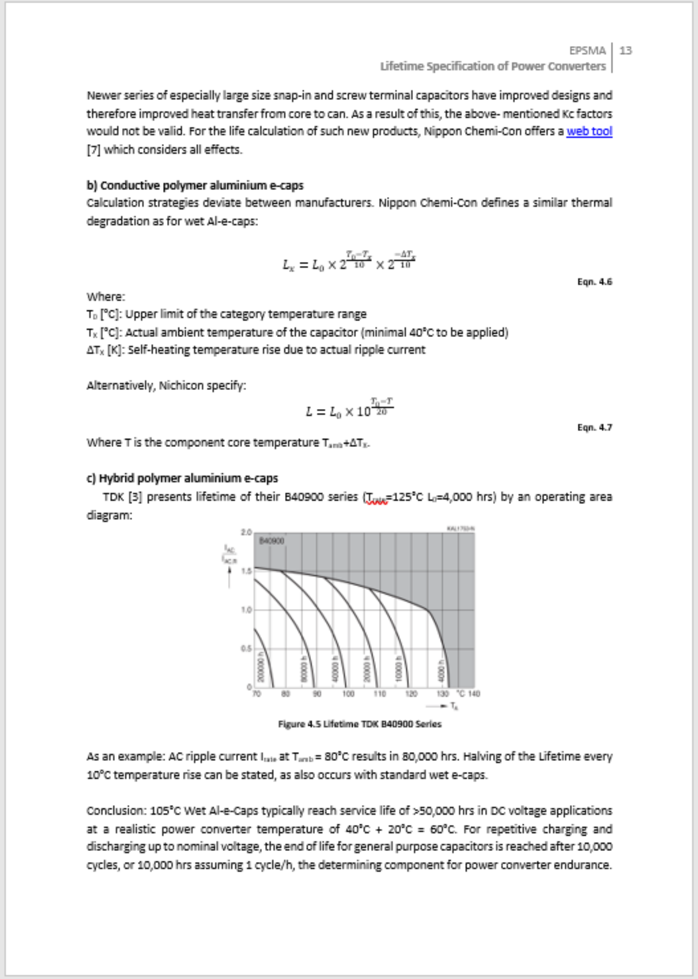
Recommended converter data sheet specification methods

- Factors to be included in power supply data sheet to indicate lifetime transparently under customer conditions
  - Operating ambient temperature
  - Electrical conditions like input/output voltage, load
  - Mounting position for convection cooled devices
  - Forced airflow for active cooling (fan)
  - Installation altitude and air pressure have distinctive impact on thermals
  - Max. on/off or voltage transient cycle specification, as mechanical contacts, MOVs, batteries are limited. What assumptions are made about servicing
  - Definition of adequate environmental conditions (humidity, pollution) in terms of corrosion
  - Limited component lifetime to max. shelf life to be considered (e.g. e-caps max. 15 years)
  - All unit comprising components to be considered , also fans. Otherwise state explicitly with lifetime figures!

Conclusions

- Lifetime and MTBF hours have been differentiated with reference to EPSMA publication *‘Guidelines to understanding reliability prediction’*
- Impacts of environmental and operating conditions on lifetime are stated with reference to EPSMA publication *’Lifetime prediction of power supplies’*
- The lifetime-dominant components of a power converter are pointed out
- A practical specification for transparent lifetime figures in datasheet is presented

The full document - sample pages



Newer series of especially large size snap-in and screw terminal capacitors have improved designs and therefore improved heat transfer from core to can. As a result of this, the above- mentioned Kc factors would not be valid. For the life calculation of such new products, Nippon Chemi-Con offers a web tool [7] which considers all effects.

b) Conductive polymer aluminium e-caps
Calculation strategies deviate between manufacturers. Nippon Chemi-Con defines a similar thermal degradation as for wet Al-e-caps:

$$L_x = L_0 \times 2^{\frac{T_0 - T_x}{10}} \times 2^{\frac{-\Delta T_x}{10}}$$

Eqn. 4.6

Where:
T_0 [°C]: Upper limit of the category temperature range
T_x [°C]: Actual ambient temperature of the capacitor (minimal 40°C to be applied)
ΔT_x [K]: Self-heating temperature rise due to actual ripple current

Alternatively, Nichicon specify:

$$L = L_0 \times 10^{\frac{T_0 - T}{20}}$$

Eqn. 4.7

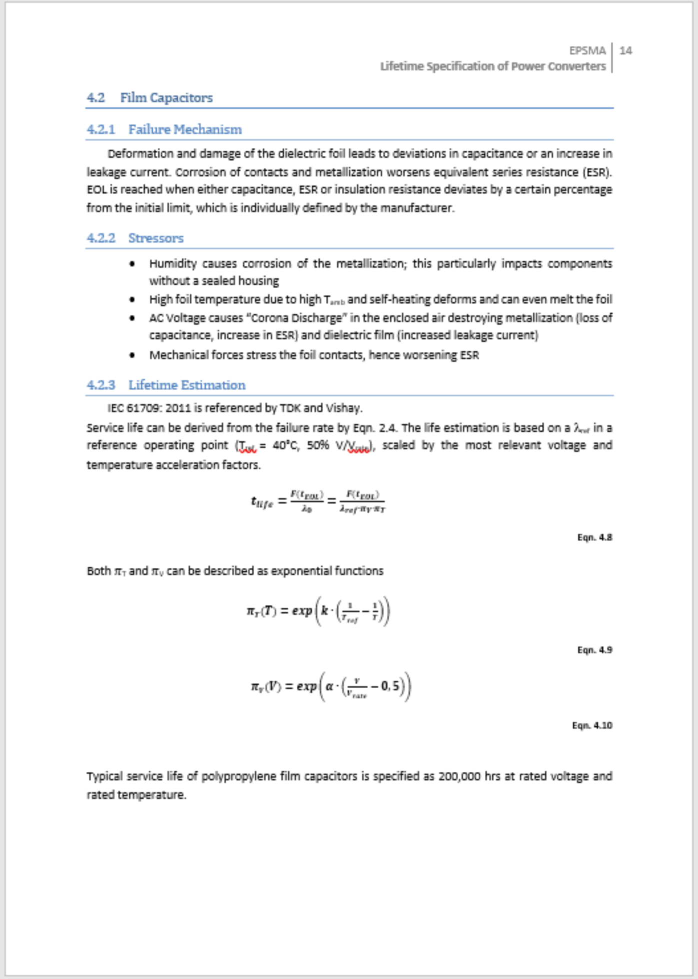
Where T is the component core temperature $T_{amb}+\Delta T_x$.

c) Hybrid polymer aluminium e-caps
TDK [3] presents lifetime of their B40900 series (T_{rate}=125°C L_0=4,000 hrs) by an operating area diagram:

Figure 4.5 Lifetime TDK B40900 Series

As an example: AC ripple current I_{rate} at T_{amb} = 80°C results in 80,000 hrs. Halving of the Lifetime every 10°C temperature rise can be stated, as also occurs with standard wet e-caps.

Conclusion: 105°C Wet Al-e-Caps typically reach service life of >50,000 hrs in DC voltage applications at a realistic power converter temperature of 40°C + 20°C = 60°C. For repetitive charging and discharging up to nominal voltage, the end of life for general purpose capacitors is reached after 10,000 cycles, or 10,000 hrs assuming 1 cycle/h, the determining component for power converter endurance.



4.2 Film Capacitors

4.2.1 Failure Mechanism

Deformation and damage of the dielectric foil leads to deviations in capacitance or an increase in leakage current. Corrosion of contacts and metallization worsens equivalent series resistance (ESR). EOL is reached when either capacitance, ESR or insulation resistance deviates by a certain percentage from the initial limit, which is individually defined by the manufacturer.

4.2.2 Stressors

- Humidity causes corrosion of the metallization; this particularly impacts components without a sealed housing
- High foil temperature due to high T_{amb} and self-heating deforms and can even melt the foil
- AC Voltage causes "Corona Discharge" in the enclosed air destroying metallization (loss of capacitance, increase in ESR) and dielectric film (increased leakage current)
- Mechanical forces stress the foil contacts, hence worsening ESR

4.2.3 Lifetime Estimation

IEC 61709: 2011 is referenced by TDK and Vishay.

Service life can be derived from the failure rate by Eqn. 2.4. The life estimation is based on a λ_{ref} in a reference operating point (T_{ref} = 40°C, 50% V/V_{rate}), scaled by the most relevant voltage and temperature acceleration factors.

$$t_{life} = \frac{F(t_{EOL})}{\lambda_0} = \frac{F(t_{EOL})}{\lambda_{ref} \cdot \pi_V \cdot \pi_T}$$

Eqn. 4.8

Both π_T and π_V can be described as exponential functions

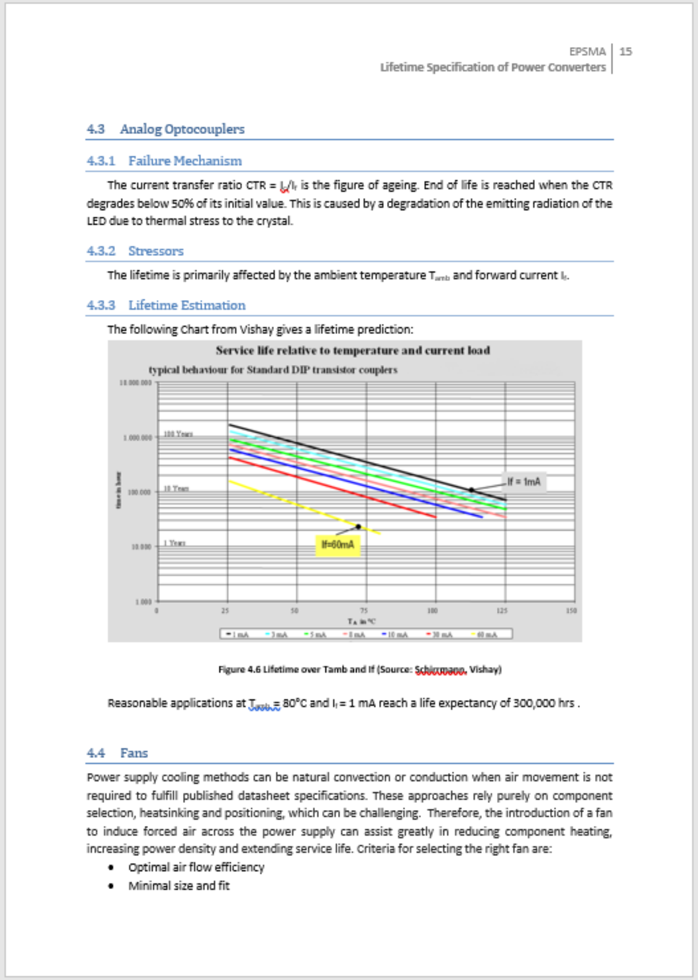
$$\pi_T(T) = exp\left(k \cdot \left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right)$$

Eqn. 4.9

$$\pi_V(V) = exp\left(\alpha \cdot \left(\frac{V}{V_{rate}} - 0,5\right)\right)$$

Eqn. 4.10

Typical service life of polypropylene film capacitors is specified as 200,000 hrs at rated voltage and rated temperature.



4.3 Analog Optocouplers

4.3.1 Failure Mechanism

The current transfer ratio CTR = I_c/I_f is the figure of ageing. End of life is reached when the CTR degrades below 50% of its initial value. This is caused by a degradation of the emitting radiation of the LED due to thermal stress to the crystal.

4.3.2 Stressors

The lifetime is primarily affected by the ambient temperature T_{amb} and forward current I_f.

4.3.3 Lifetime Estimation

The following Chart from Vishay gives a lifetime prediction:

Figure 4.6 Lifetime over Tamb and If (Source: Schirrmann, Vishay)

Reasonable applications at T_{amb} = 80°C and I_f = 1 mA reach a life expectancy of 300,000 hrs .

4.4 Fans

Power supply cooling methods can be natural convection or conduction when air movement is not required to fulfill published datasheet specifications. These approaches rely purely on component selection, heatsinking and positioning, which can be challenging. Therefore, the introduction of a fan to induce forced air across the power supply can assist greatly in reducing component heating, increasing power density and extending service life. Criteria for selecting the right fan are:

- Optimal air flow efficiency
- Minimal size and fit

Thank you !

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