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Capacitor Reliability Issues and Needs

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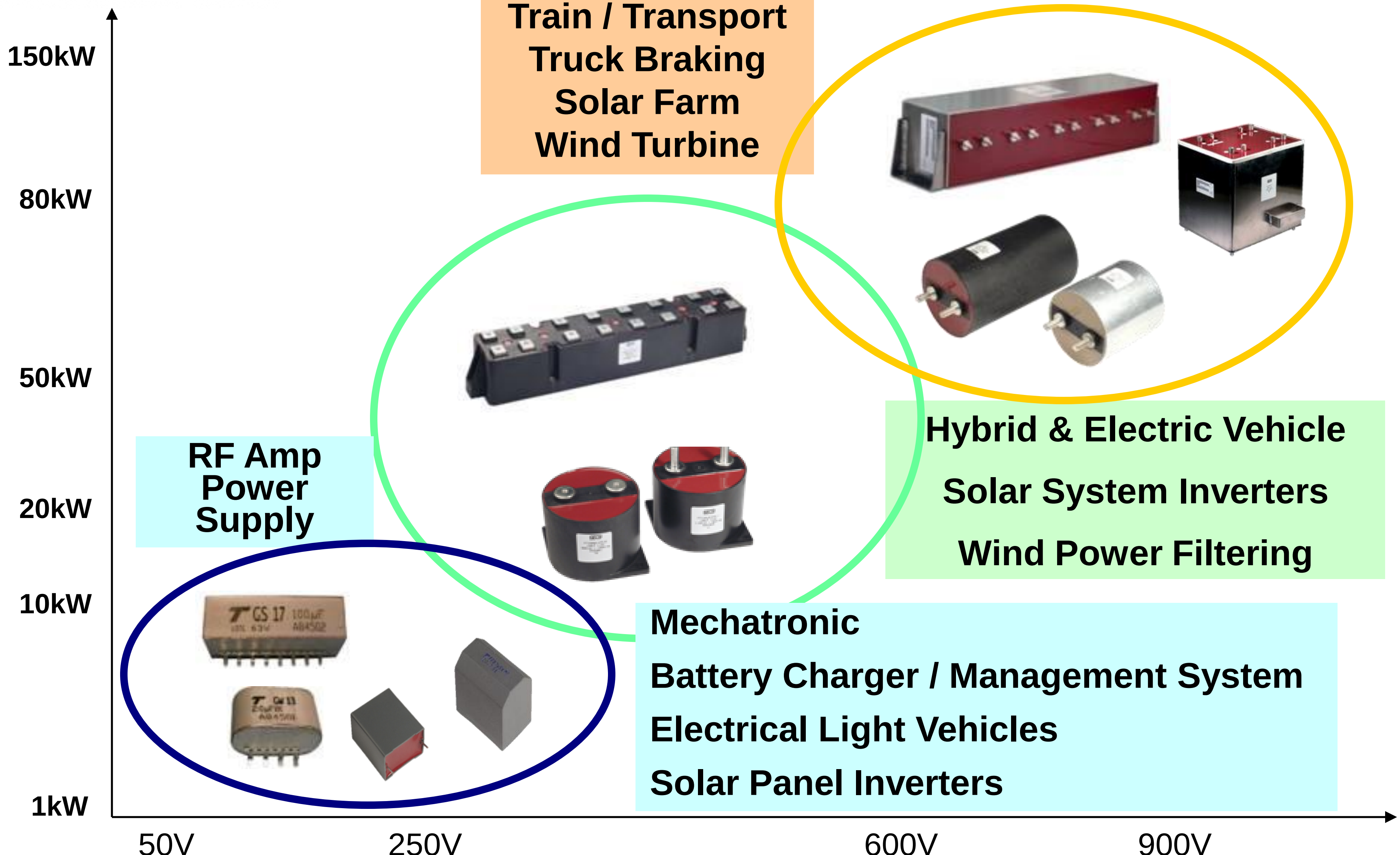
Outline

- Film Capacitor Design Considerations
- Film vs. Aluminum Failure Modes
- Film Dielectric Characteristics
- Failure Mitigation: Controlled Self-Healing
- Hot Spot Temperature Calculation
- Lifetime Expectancy

Inverter Applications



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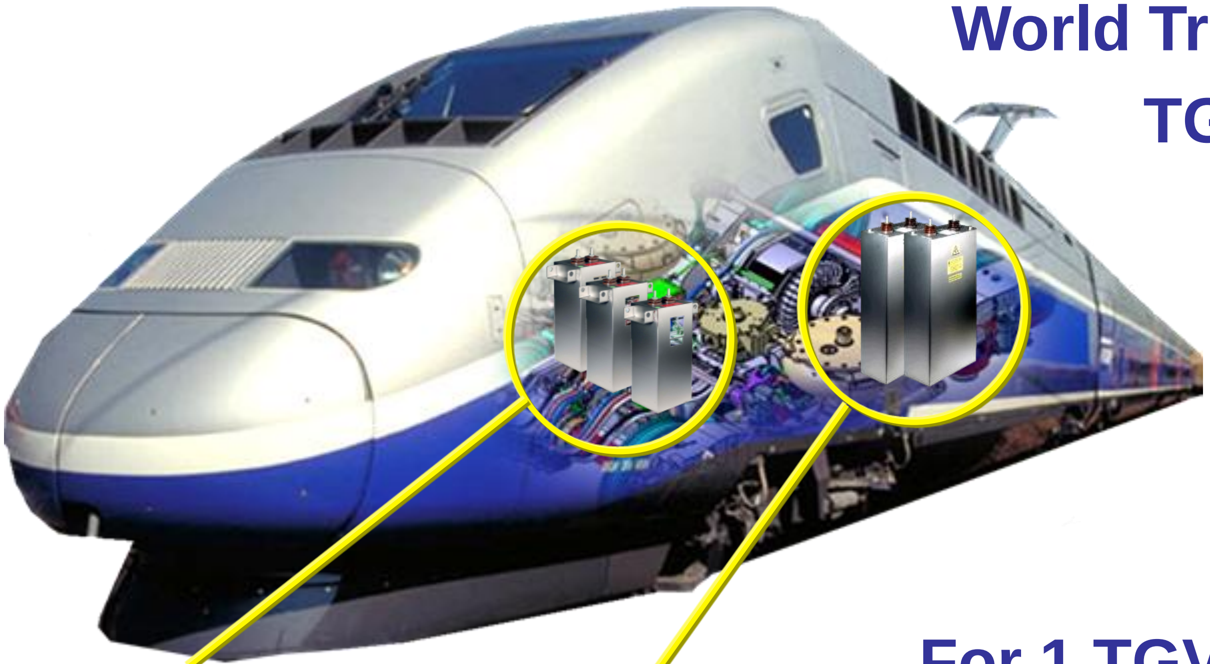
High Speed Trains



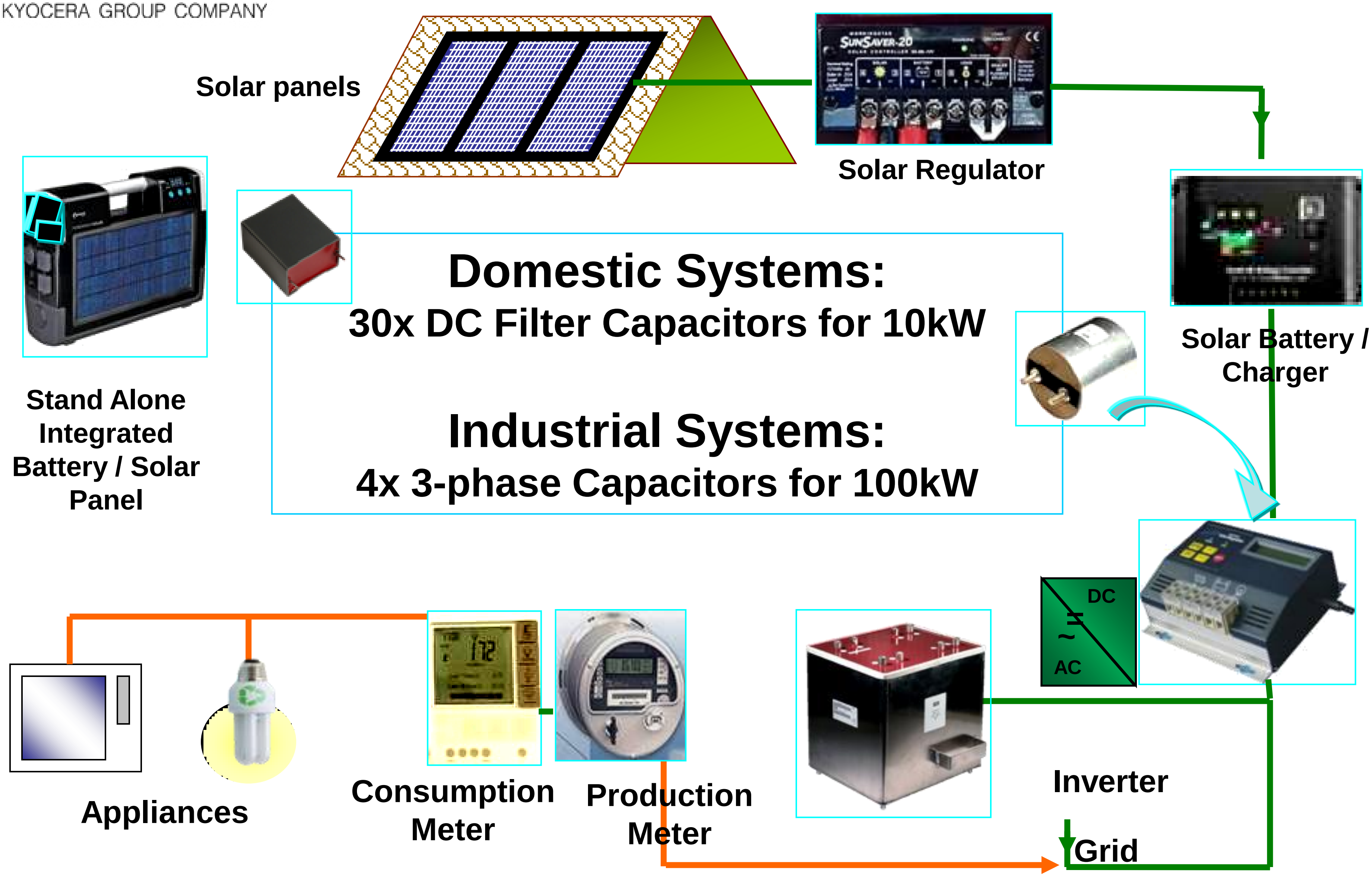
World Train Speed Record:
TGV 2007: 357mph

For 1 TGV Train:
48 x Capacitors = 3,640lbs

DC Link
Film Capacitor

Traction - Resonant
Filter Film Capacitor

Solar Energy



Film Technology for PV

Historically, solar power inverter systems used capacitors with application voltages ~ 500VDC, but today the trend is in 2 directions:

For domestic or small industrial applications, the trend is for microinverters within each panel to match system current when daisy chained to achieve >95% efficiency. Typical cap ratings are 10uF / 525V (FFB series).

For large-scale solar farms, high voltage systems are being developed for better conversion & transport efficiency. These have capacitance / voltage range of 1mF / 600VDC to 1350VDC (FFLI & FLFC series). Higher voltages reduce power loss in the inverter for the panel array.

Film capacitor technology offers significant advantages in these applications due to higher life expectancy, environmental performance and power handling capability.

Failure Mode / Mitigation Summary

Film	Al
Pinholes – self clearing, oil-filling for HV devices	Dielectric Breakdown – operate below critical voltage
Voltage Punch-through – segmented electrodes, controlled self-healing	Parametric changes (dielectric-electrolyte interaction)– material selection, derating
Aging of polymer (shrinkage) – film processing, mat'l development	Loss of Electrolyte – maintain temp below critical limit
	Gas Generation – operate below critical voltage, vent enclosure

Temperature and Voltage are Key Acceleration Factors

Film vs. Aluminum

- **Films fail open (no short circuit mode in application).**
- **Lower ESR & ESL - Higher Ripple Handling.**
  - **FFVS series ESR ~ 2.5 mΩ and cap 135uF / 1kV w/ 60Arms ripple**
  - **Comparable Al 30 mΩ, Cap 4.8 mF / 500V w/ 13 Arms ripple**
- **Higher surge voltage tolerance (2x vs. 1.2x)**
- **Films have environmentally friendly materials.**
  - **Dry film & non-toxic Oil Filled – No acid content.**
- **High Voltage film designs do not require serialization.**
  - **Serialization to achieve high voltage requires balancing resistors and subsequent increase in leakage current.**

Film Dielectric Characteristics

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Film characteristics	ε_r	tg δ_0	Tmax (°C)	Tmelt (°C)	Minimum Thick (µm)	Cost
Standard Polypropylene (PP)	2,2	1.5 *E-4	115	168	2,5	$
High Crystallinity Polypropylene	2,2	1.5 *E-4	125	173	2,8	$
Polyethylene Terephtalate (PET)	3,2	40*E-4	140	260	0,9	$
Polyethylene Naphtalate (PEN)	3,0	40*E-4	150	265	1,4	$$
Polyphenyle Sulfide (PPS)	2,9	5*E-4	170	285	1,2	$$$
Under Development (PXX)	3,0	5*E-4	150	260	2	$

Polypropylene – standard “workhorse” dielectric for power film caps

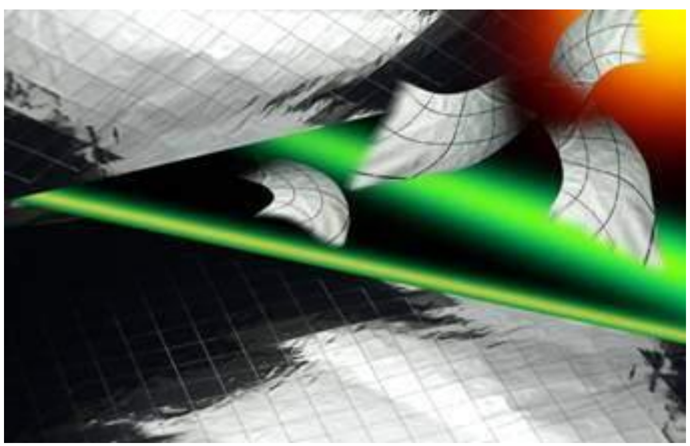
AVX Controlled Self-Healing

Controlled Self-Healing Technology

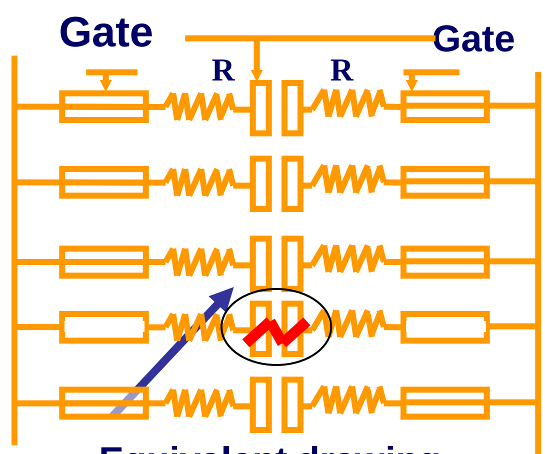
* More than 30 years of experience
* Invented by AVX TPC
* Soft end of lifetime → No short-circuit no avalanche effect
* Predictable lifetime → Capacitance decrease

All AVX Power Films use Segmented Metallization AS STANDARD

Mosaic design of segmentation



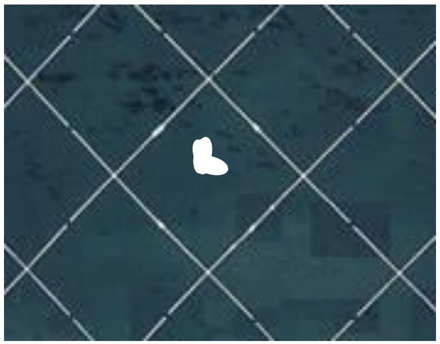
Elementary Capacitor

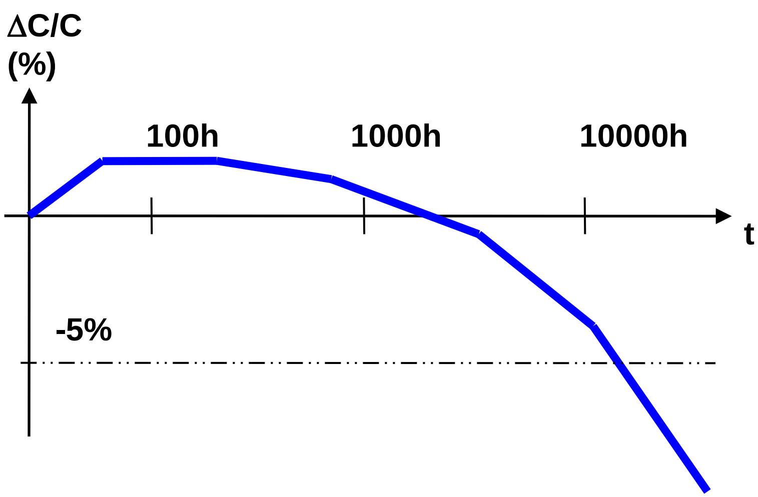


Equivalent drawing

Medium Voltage Power Technology
Controlled Self-Healing

Basic concept of segmented metallized film:

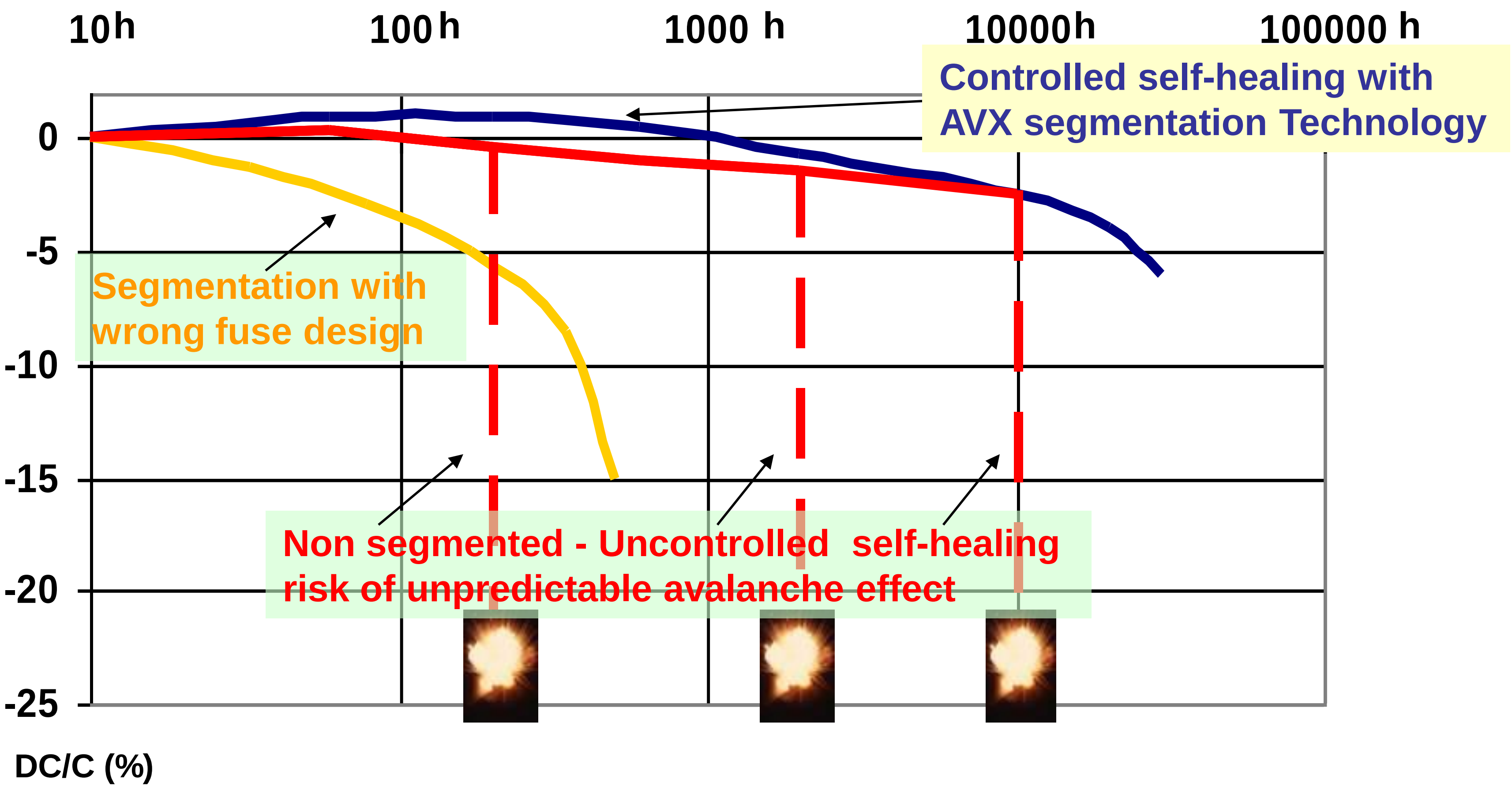




- ➔ The total capacitance is divided into elementary cells protected by fuse gates (several million).
- ➔ In the event of a weak point, only that cell will be removed by fuse activation.
- ➔ Capacitance decreases as a function of cell element fuse activation.
- ➔ No catastrophic failure (short circuit) results, only a decrease in bulk capacitance.
- ➔ Aging level (Delta cap) is predictable.

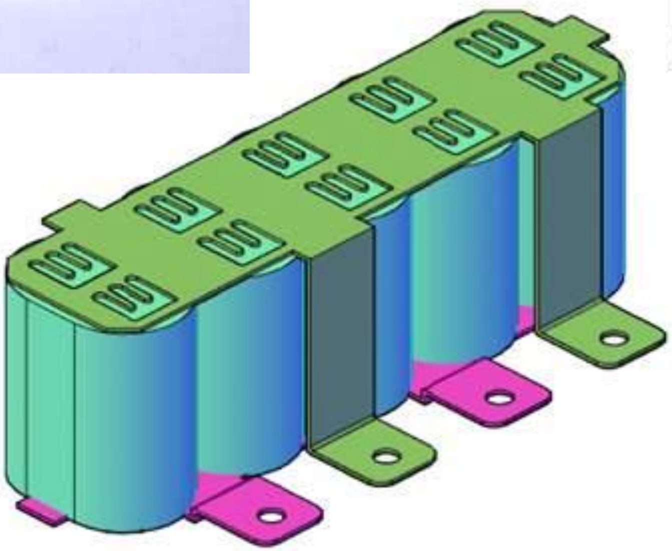
➔ Total Safety

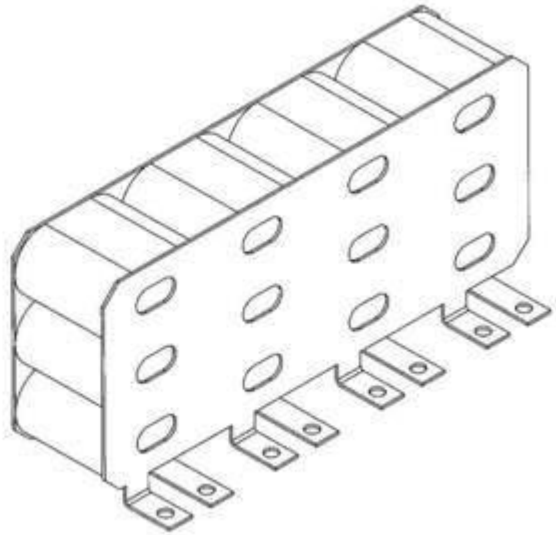
Controlled Self-Healing

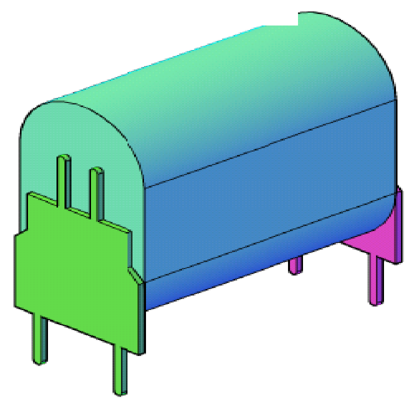


Inverter Capacitor Design - Module

Flattened Capacitor Element Array

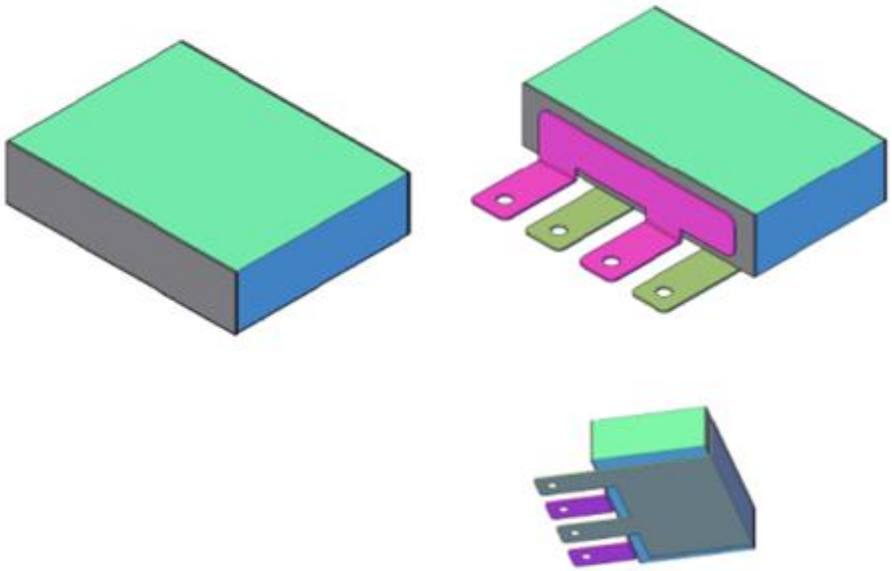




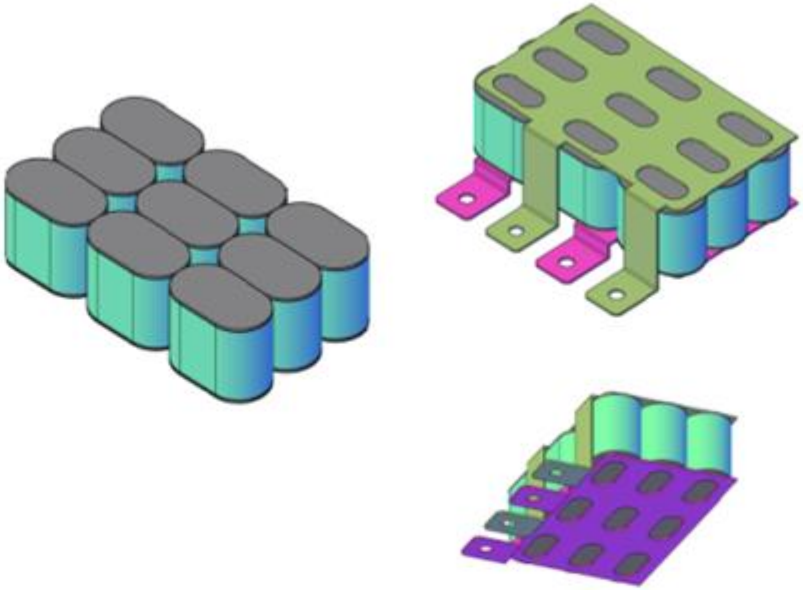


Design Comparison
Large Stacked vs Multiple Bricks

Large stacked design



Elementary bricks design



Ls = 20nH
ESR = 3mΩ

Ls = 13nH
ESR = 0.2mΩ

Elements of Design:

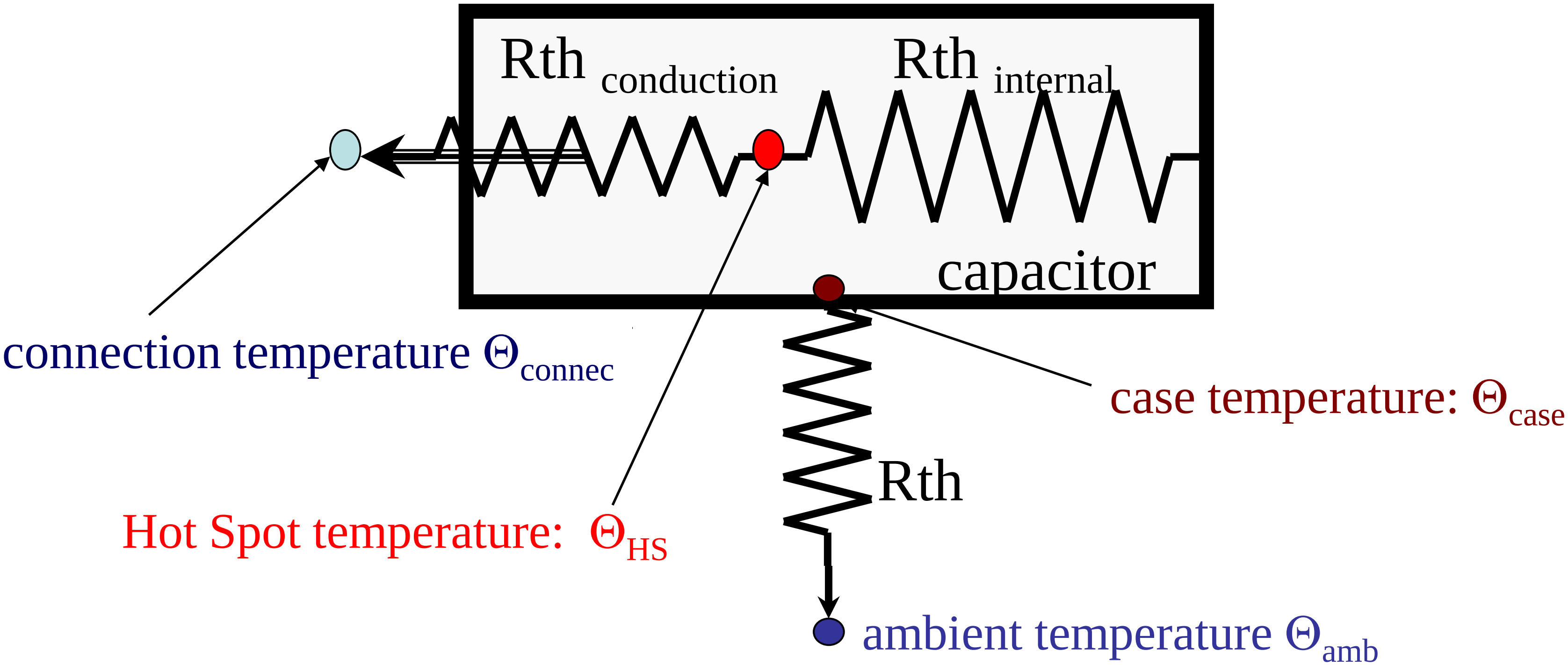
1. Identify "Mission Profile" – time spent at certain voltage & current levels over the operational lifetime.

2. Calculate Hot Spot Temperature for capacitor design for identified current / voltage duty cycle.

3. Calculate Fusing Activation of film segmentation design for Voltage & Current Profiles.

Hot Spot Temperature Calculation

Hot Spot temperature depends on environment temperature and cooling system



$$\Theta_{case} = \Theta_{amb} + P{*}Rth$$

P: capacitor power losses

$$\Theta_{HS} = \frac{\Theta_{case}{*}Rth_{\ conduction} + P{*}Rth_{\ internal}{*}Rth_{\ conduction} + \Theta_{connec}{*}Rth_{\ internal}}{Rth_{\ internal} + Rth_{\ conndiction}}$$

Hot Spot Temperature Calculation

$Rth_{internal}$: The internal design of the capacitor minimizes this in order to reduce as far as possible ΔΘ (Hot Spot / case) (Low ESR / Low ESL).

$Rth_{conduction}$: Some of the wattage generated by the capacitor will be conducted through internal connections and external bus bar. The important thing is to have the temperature gradient negative from cap to bus bar, or capacitor will be cooling bus bar.

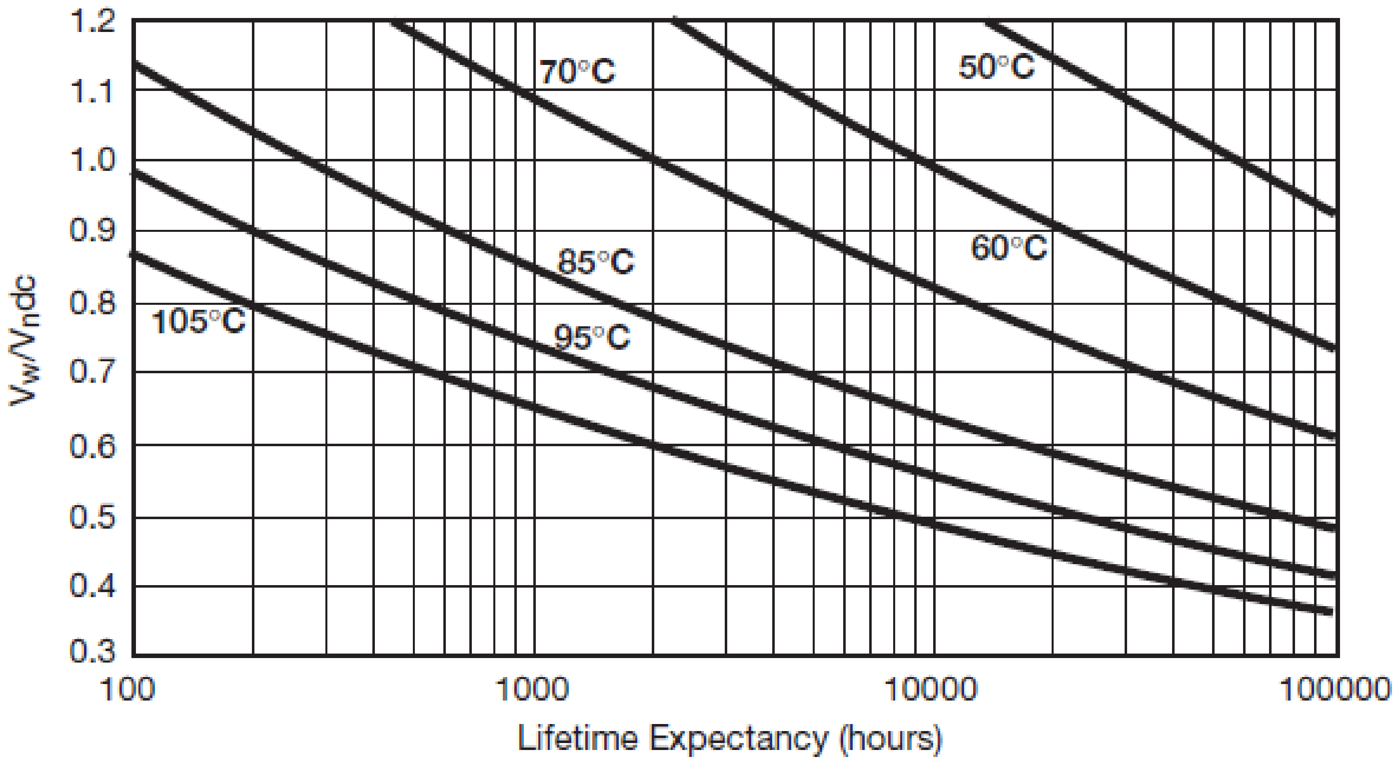
Rth (case to chassis): this element is the most important and depends on cooling system choice. Rth is the result of 2 parallel resistances:

- Natural convection (ambient temperature with air cooling)
- Forced cooling (cooling system)

☞ Hot Spot temperature will influence lifetime expectancy and reliability

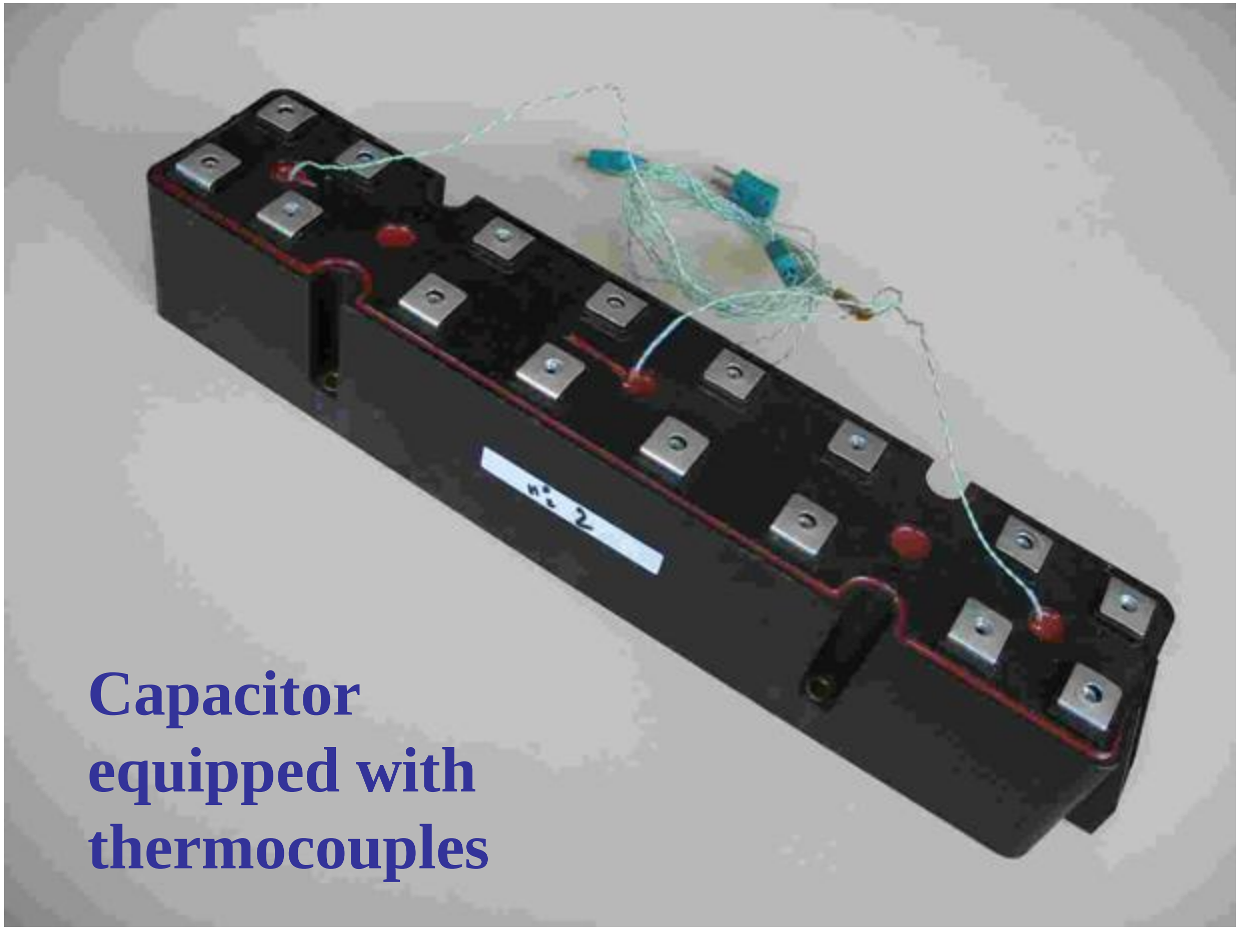
Lifetime & Hot Spot

LIFE TIME EXPECTANCY vs VOLTAGE & HOT SPOT TEMPERATURE



FFLC HEV Thermal Modeling

FFLC6-xxxx Capacitor characterization



Capacitor equipped with thermocouples

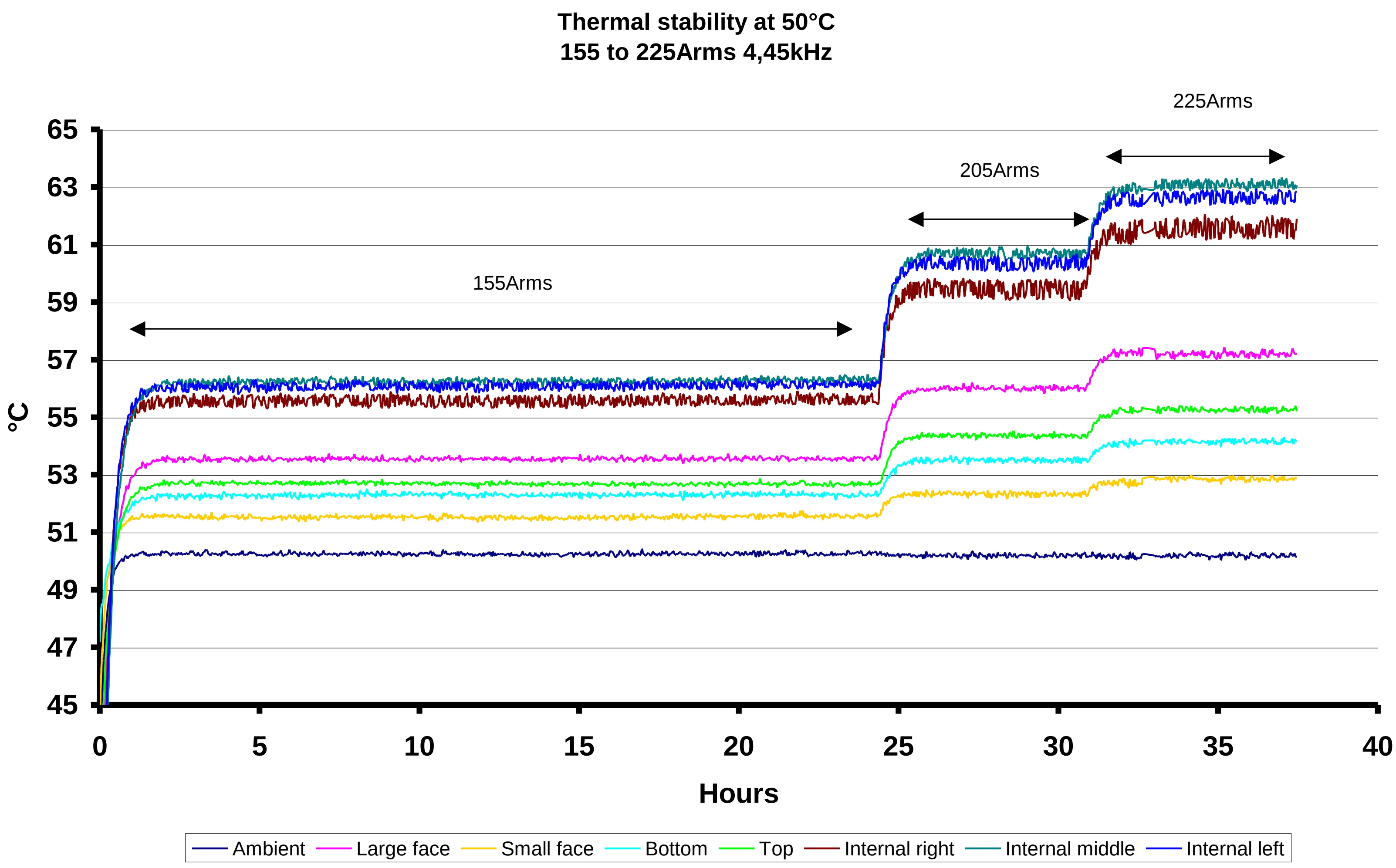
FFLC HEV Thermal Modeling

FFLC6-xxxx Capacitor characterization

Thermal stability test cabling

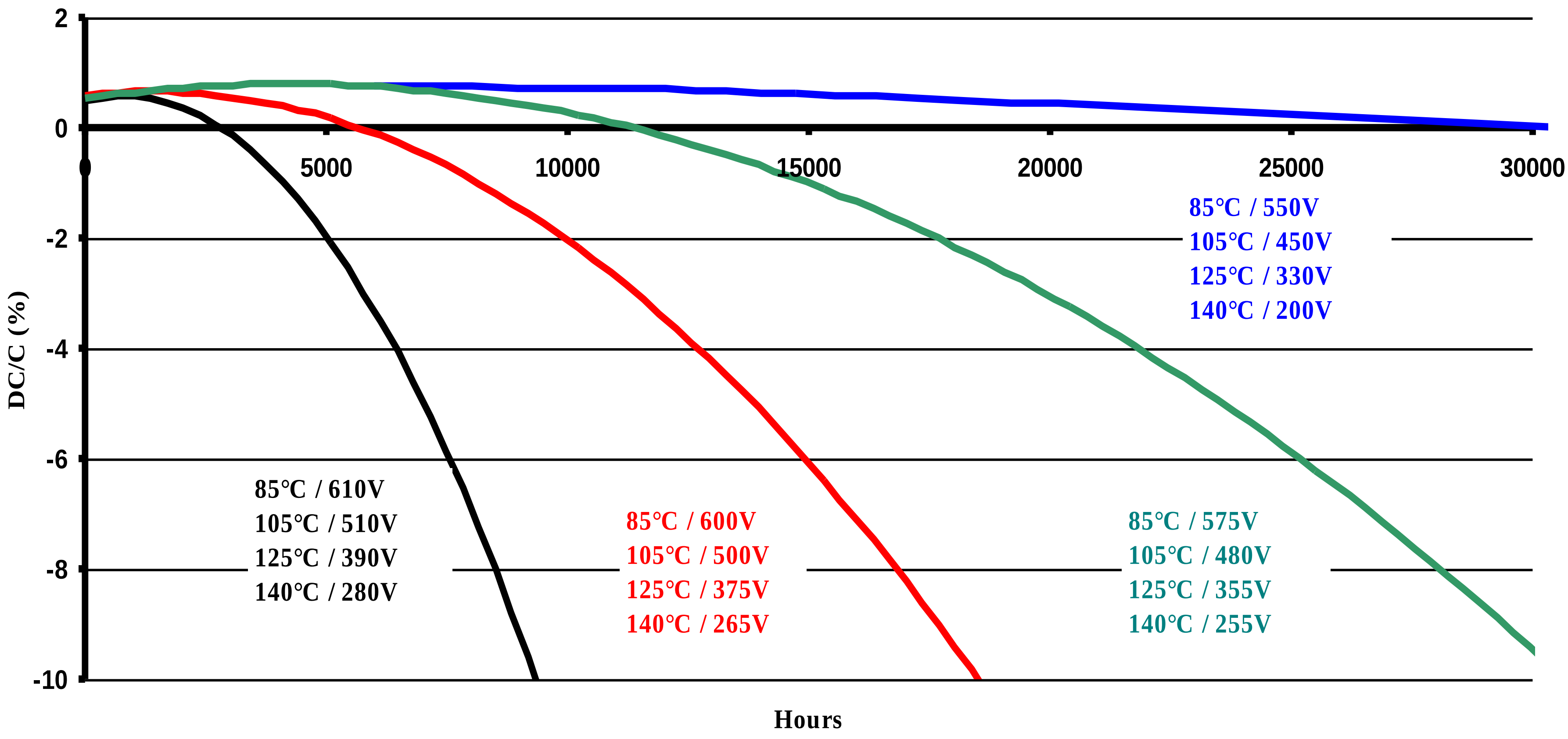
FFLC HEV Thermal Modeling

FFLC6-xxxx Capacitor characterization



Lifetime Expectancy Curves

Results of endurance tests: ΔC/C vs (Un, θ)



Application Voltage vs Hot Spot Temperature

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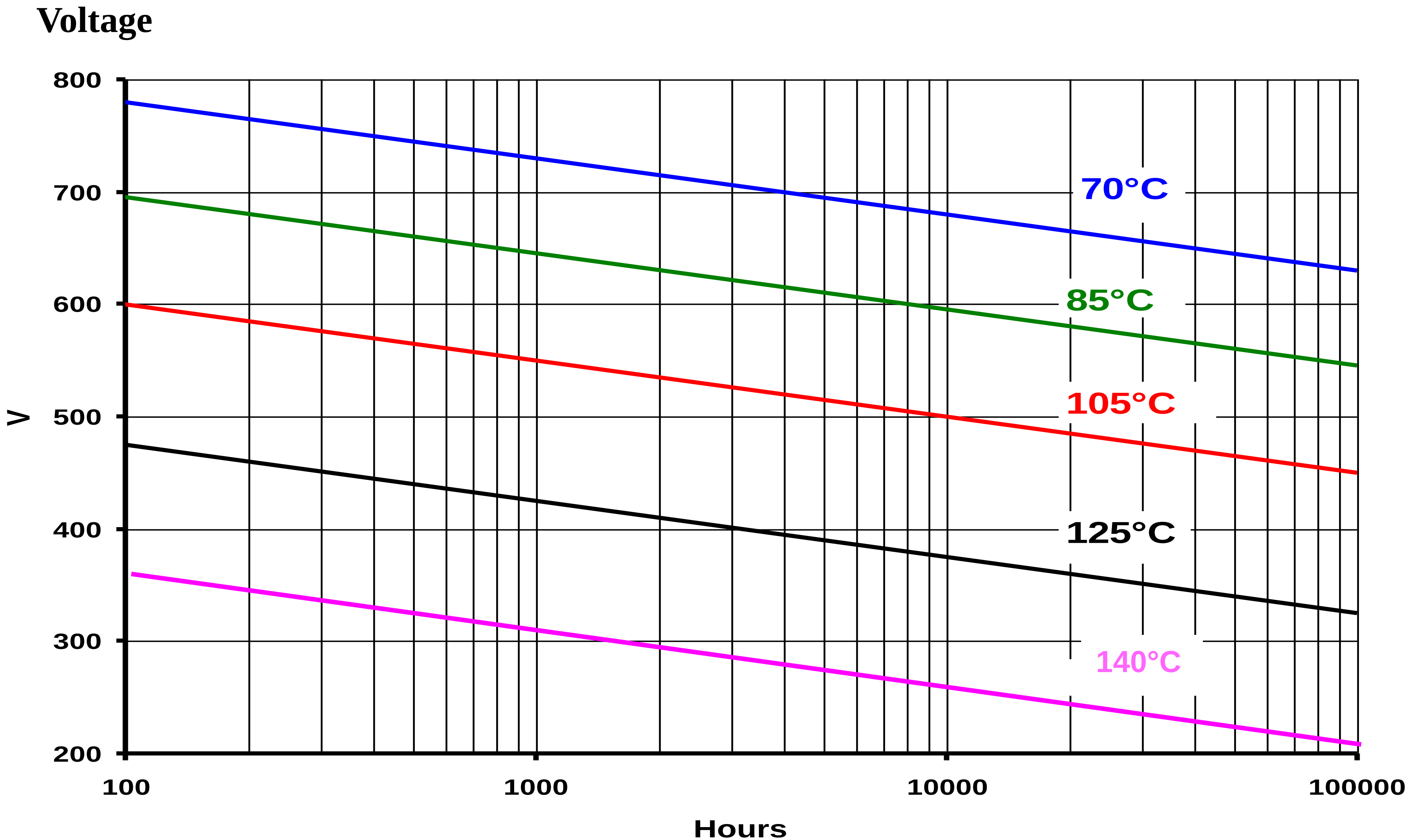

Lifetime : Mission Profile

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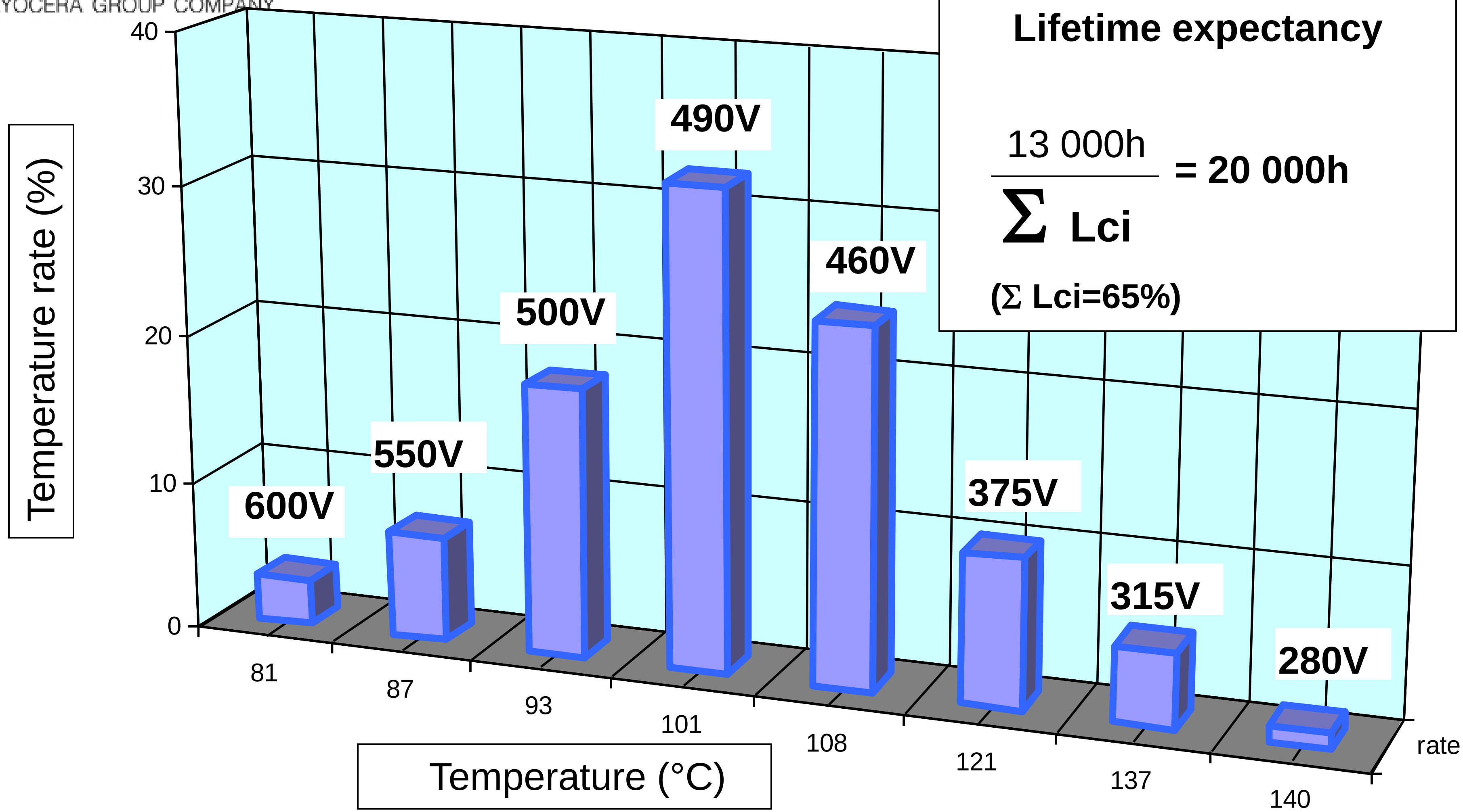
Mission profile Input data: I, ambient temp,voltage are given vs rate

rate	3%	7%	18%	32%	24%	10%	5%	1%
I (Arms)	50	190	250	220	200	150	120	100
Power (W)	5	8	12.5	9.7	8	4.5	3	2
Amb Temp.	76	79	83	92	100	116	134	138
$\Delta\theta$ (°C)	5	8	10	9	8	5	3	2
Hot Spot (°C)	81	87	93	101	108	121	137	140
Voltage (V)	600	550	500	490	460	375	315	280

For each rate, lifetime consumption is calculated vs voltage and Hot Spot temperature

Lifetime : Mission Profile



Lifetime expectancy

$$\frac{13\,000h}{\Sigma\ Lci} = 20\,000h$$

(Σ Lci=65%)

Lifetime consumption LC	2%	2%	6%	9%	8%	3%	32%	3%

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Design vs Mission Profile

Power Film Experience

✓ Number of parts shipped	$3.01x\ 10^{6}$
✓ Parts manufactured since	1979
✓ Average number of designs sold per year	450
✓ Voltage range	75V to 4.6kV
✓ Estimated cumulative working hours	$66.3\ x10^{9}$ hours
✓ Intrinsic catastrophic failure	ZERO

Summary

Film Technology is an ideal technology fit for Solar Inverters. Key advantages are:

- **Failsafe Operation - No short Circuit Failure Mode.**
- **Calculable Lifetime – ability to design for -2% cap loss over 100,000 hrs for most mission profiles.**
- **High Voltage / Low ES / Low ESL characteristics to Maximize Inverter Efficiency**
- **Mechanically Robust Design**