Reliability Run and Data Analysis of the Accelerated Ageing of Present and Future Electrolytic Capacitors Installed in the Protection Systems of Superconducting Magnets of the Large Hadron Collider at CERN

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Outline

- Introduction
- Ageing and measurements methods
- Knowledge after LHC runs 1 and 2
- Qualification of candidates for the new production
- Results
- Summary

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About the Heater Discharge Power Supplies (HDS)

- Quench event: a superconducting magnet loses superconductivity locally
- This condition would damage the magnet if not protected on time
- Response: the whole magnet is heated to distribute the load and thus reduce the stress peak
- The HDS are the units storing and releasing the energy into the heater strips

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About the Heater Discharge Power Supplies (HDS)

- In operation at LHC since its start in 2008 (LHC runs 1 and 2)
- Basic figures:
  - 6 caps per unit
  - ≈ 3 kJ
  - 900 V full charge voltage
- In the framework of the HiLumi LHC Project, new units are being developed and manufactured
- The current units accumulate significant working time, so lifetime knowledge is also needed

Motivation

- LHC: 36,000 caps for 6,000 HDS
- HL-LHC: 2160 caps for 360 HDS
- New caps needed for the new HL-LHC HDS to be installed during the next shutdown (Long Shutdown 3)
- Aluminium electrolytic capacitors:
  - Critical for reliability of protection systems
  - Replacement is costly at all levels

Samples for qualification

Requirements

- Capacitance: 4.7 mF (±20%)
- Rated voltage: 500 V (usage: 450 V)
- Minimum rated temperature: 85 °C
- Required operation time in HDS application: **20 years**
- Must handle occasional discharges ($\tau \approx$ 30 ms)

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Types of failures

Parametric failure

- Reduction of capacitance (-10%)
- ESR increase (2x initial value)
- Leakage current > limit (by manufacturer)

The decrease in C and increase in ESR are mostly related to the evaporation of electrolyte

Catastrophic failure

- Short circuit
- Open circuit
- Safety vent operation
- Breakage of capacitor housing

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Parameters that affect lifetime

- High temperature
- Large ripple currents
- Rapid charging cycles
- Vibrations
- Overvoltage
- Reverse Voltage

- In the HDS, the capacitors don't work under any of these stress conditions

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Previous works

- We need a method to estimate lifetime over 20 years in use condition, but in shorter time: accelerated ageing
- First iteration: collaboration with *Laboratoire Ampère*, Université Claude Bernard Lyon 1:
    1. **Frédéric Perisse, Pascal Venet, Gérard Rojat.** *Reliability determination of aluminium electrolytic capacitors by the mean of various methods. Application to the protection system of the LHC.* Microelectronics Reliability, 2004, 44(9-11), pp.1757-1762. DOI: 10.1016/j.microrel.2004.07.108. HAL: hal-00140548.1
    2. **Frédéric Perisse.** *Etude et analyse des modes de défaillances des condensateurs électrolytiques a l'aluminium et des thyristors, appliquées au système de protection du LHC (Large Hadron Collider).* Sciences de l'ingénieur [Physics]. Université Claude Bernard - Lyon I, 2003.

1. https://hal.science/hal-00140548v1/document
2. https://theses.hal.science/tel-00268354

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Accelerated ageing: Arrhenius law

The degradation of an electrolytic capacitor is essentially caused by its chemical reactions. As all chemical reactions, they follow Arrhenius law:

$$k = E\,e^{-\frac{E_a}{k_B T}} \rightarrow \frac{k_2}{k_1} = e^{\frac{E_a}{k_B}\frac{T_2 - T_1}{T_2 T_1}} \rightarrow \begin{cases} k\text{: rate constant of the reaction} \\ \text{T: absolute temperature [K]} \\ \text{Ea: activation energy [eV]} \\ k_B\text{: Boltzmann constant [eV K}^{-1}\text{]} \end{cases}$$

We use other measurable parameters as a proxy for *k*, and study the ratio at two temperatures to obtain *Ea*. For reference:

$$E_a = 0.4\ eV \rightarrow \frac{t_{25\,°C}}{t_{85\,°C}} = 14$$ (1 h @ 85 ºC = 14 h @ 25 ºC)

Ageing at 2 temps → Difference in evolution → Estimation of Ea → Estimation of equivalent aged time

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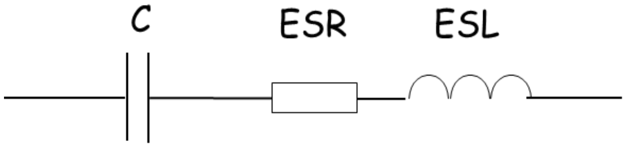
Accelerated ageing: procedure (simplified)

- Capacitors charged at rated voltage
- Units from the same batch aged at two high temperatures, so that we can obtain the Activation Energy
- Measurements every ~1000 h
- Weekly measurements of leakage current and visual inspection

Measurements

- Weight → evaporation of electrolyte
- AC capacitance (C_{AC})
- AC equivalent series resistance (ESR)
- DC capacitance (C_{DC})
- Leakage current (I_{leak})
- Measurements done at 25 °C



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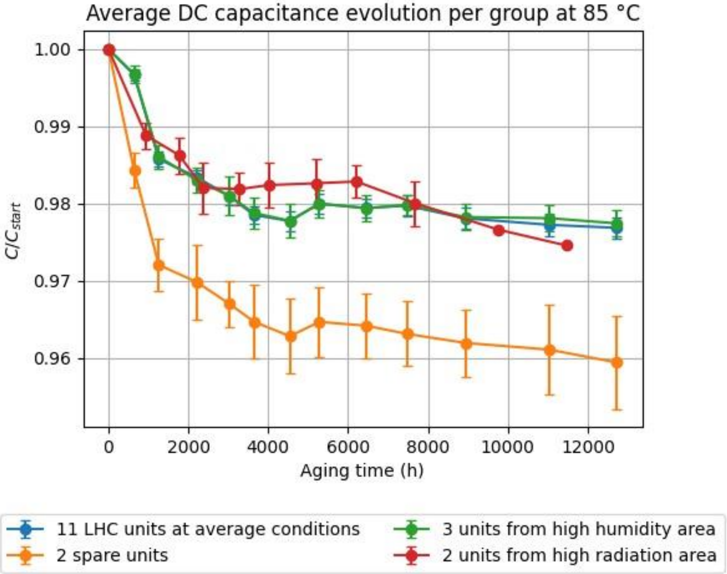
Sample size

- 18 units aged at 85 ºC + 18 units aged at 70 ºC
- Statistically, with 2x18 units without any failures we can expect a reliability > 98% with 90% confidence ([1])
- Different working conditions.
  - Standard “average” conditions
  - High humidity areas
  - High radiation areas
  - Spares

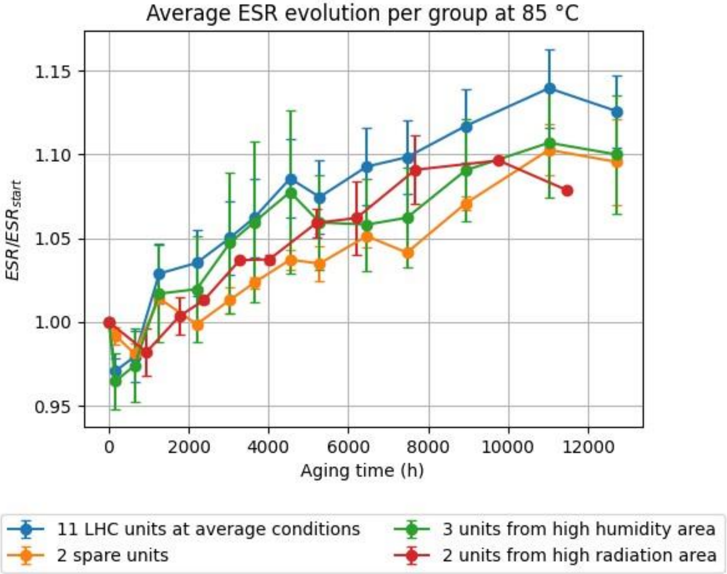
(1) **Stephen N. Luko.** *Attribute Reliability and the Success Run: A Review.* 1997 SAE International Off-Highway and Powerplant Congress and Exposition. September 1997. DOI: 10.4271/972753.

Evolution of the main parameters

DC capacitance:

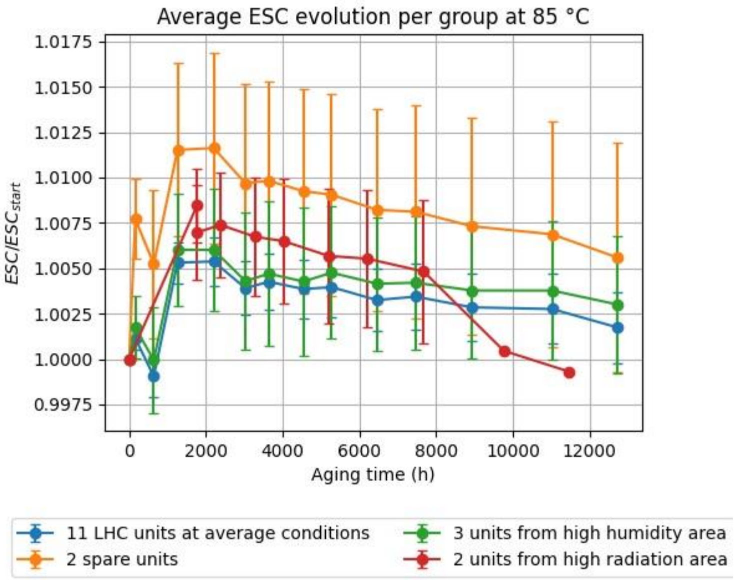


ESR at 100 Hz:

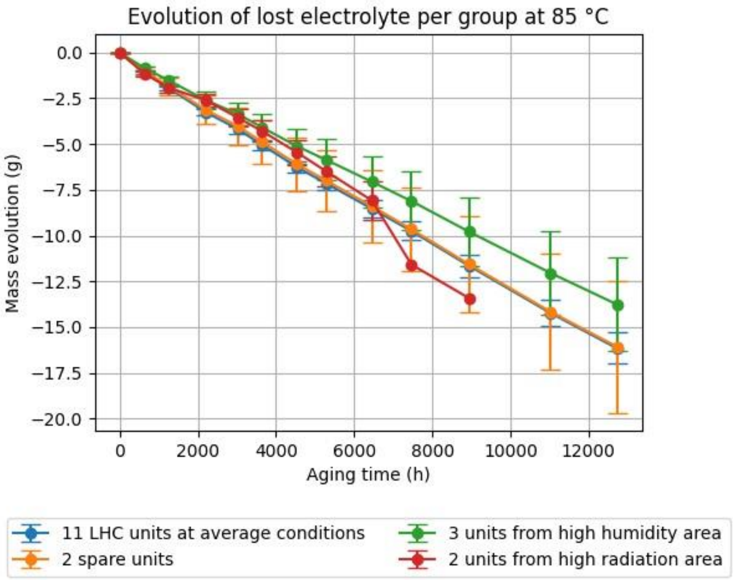


Evolution of the main parameters

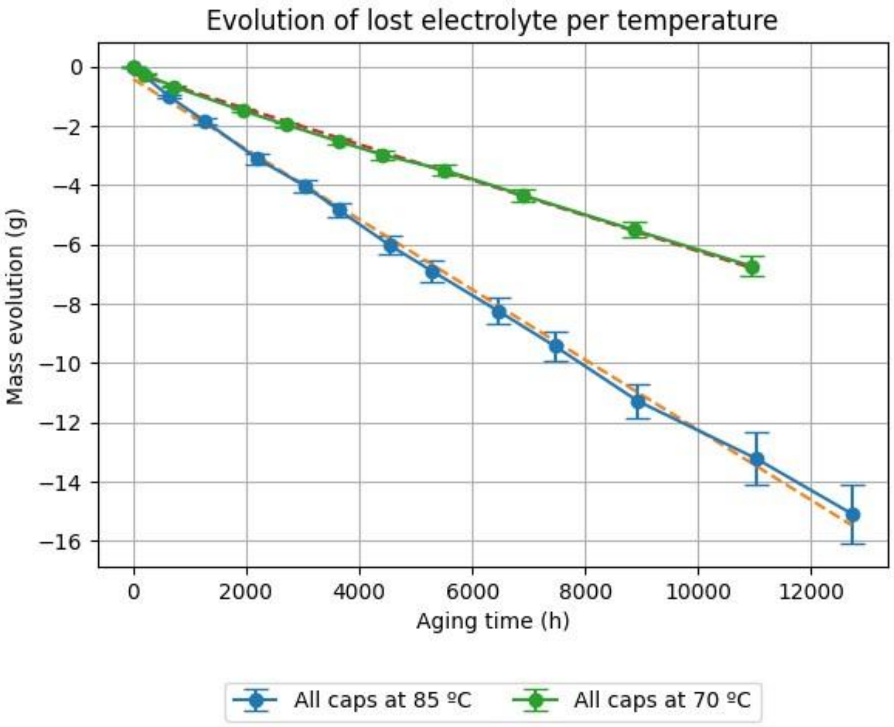
ESC at 100 Hz:



Weight loss:



Comparison 85 ºC and 70 ºC



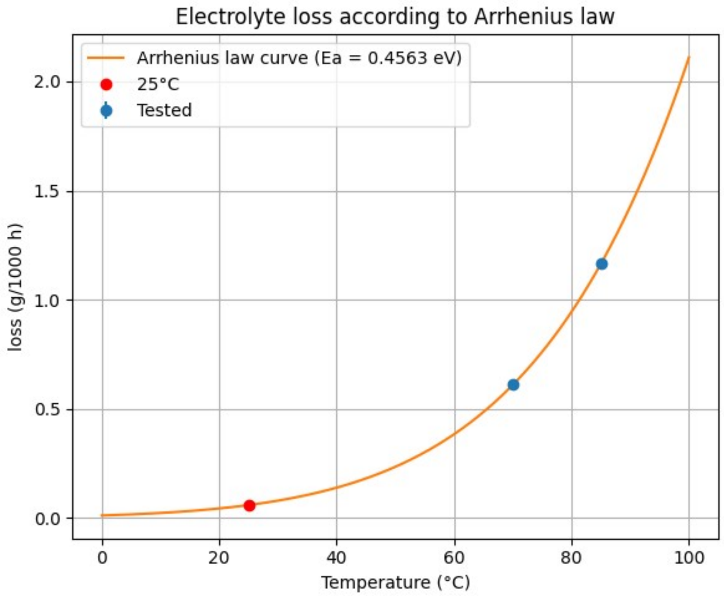
85 ºC:
(-1.18 ± 0.02) g / 1000 h

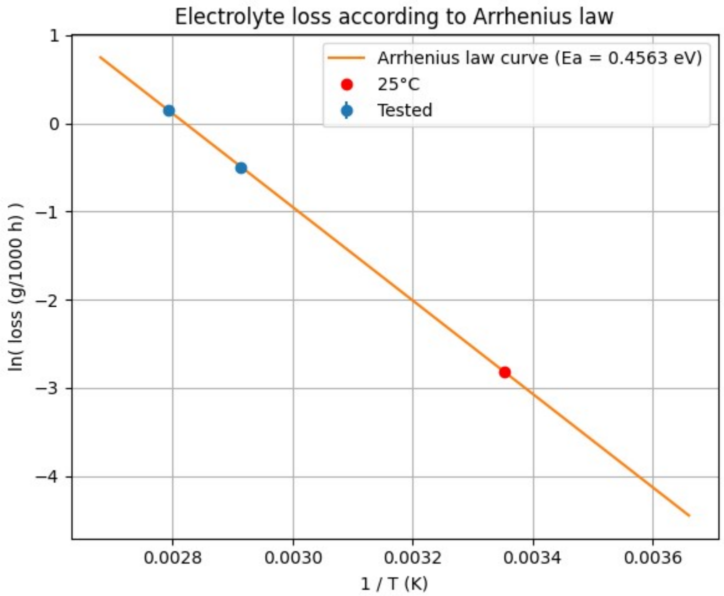
70 ºC:
(-0.60 ± 0.01) g / 1000 h

From 70 °C to 85 °C the ageing process is twice as fast!

Applying Arrhenius law

Acceleration factor between 85 °C and 25 °C (worst case): 19.6 h/h
Acceleration factor between 70 °C and 25 °C (worst case): 10.3 h/h





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Market candidates

- 7 different capacitor models from 5 manufacturers
- Rated voltage: 500 V
- Rated temperature: 85 °C for all but one model, rated for 105 °C
- Set up:
  - 3 ovens
  - 4 caps at 75 °C for each model
  - 4 caps at 85 °C for each model
  - 4 caps at 105 °C for the model rated for it
  - 2 caps from runs 1 and 2 added as reference in each oven

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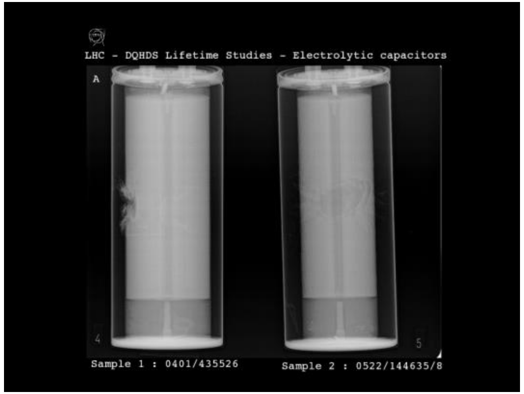
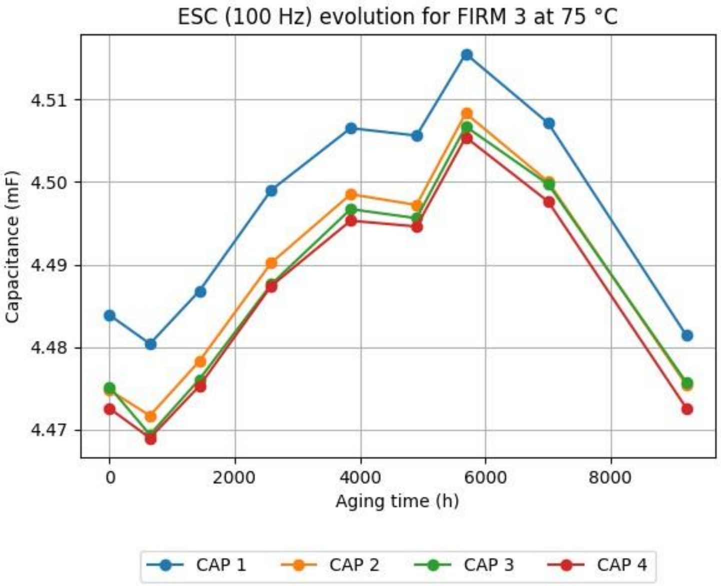
Test evolution

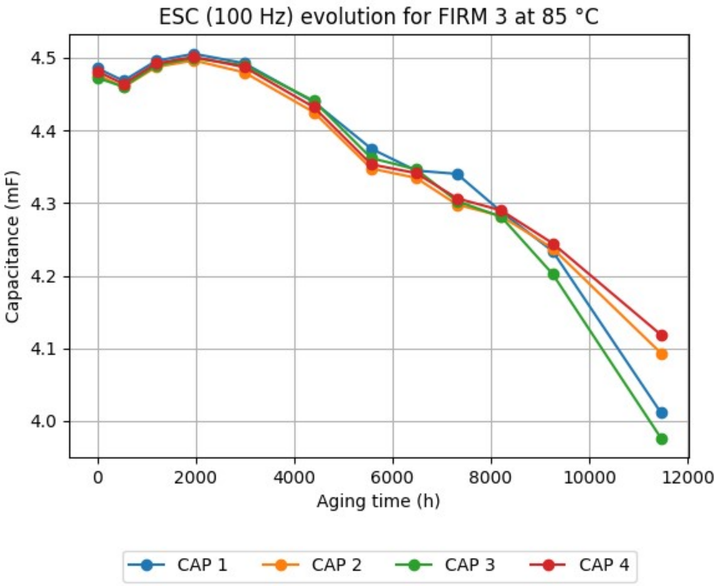
- 3 models showed failures early into the test → discarded
- Different evolution of their characteristic parameters:
  - Capacitance and ESR: very family-specific (see next slide)
  - Mass: loss of electrolyte has been very linear for all of them
  - Leakage: very low except for the failing ones



Some examples

In some cases, the initial "reforming" effect is stronger than the ageing, so a parabolic effect is observed





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Test finish

- The families without early failures went on for the full test length and more, including the reference ones used in previous runs
- Some of them had 1 or more capacitors failing throughout the test
- The best performing family has been chosen and will be installed at the test facilities of HiLumi
- After reception of the production batches, 12 more units have been aged to confirm the qualification test, yielding R(t=20y) = 95.32% at 25 °C from the total of units tested

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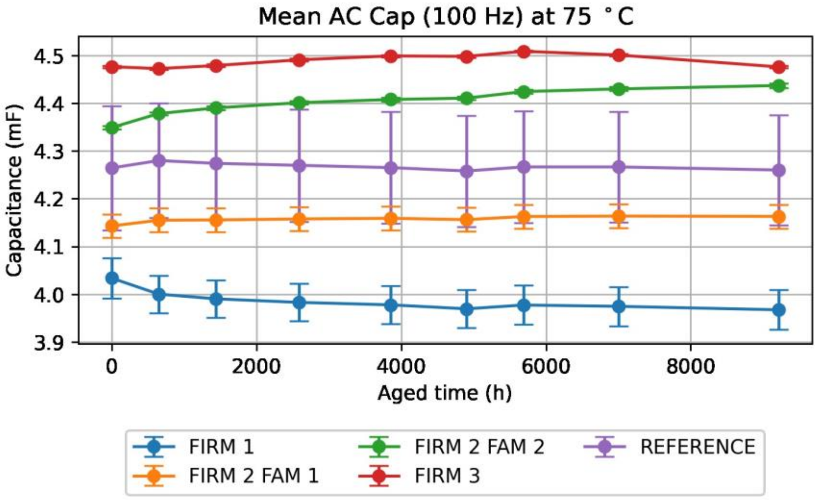
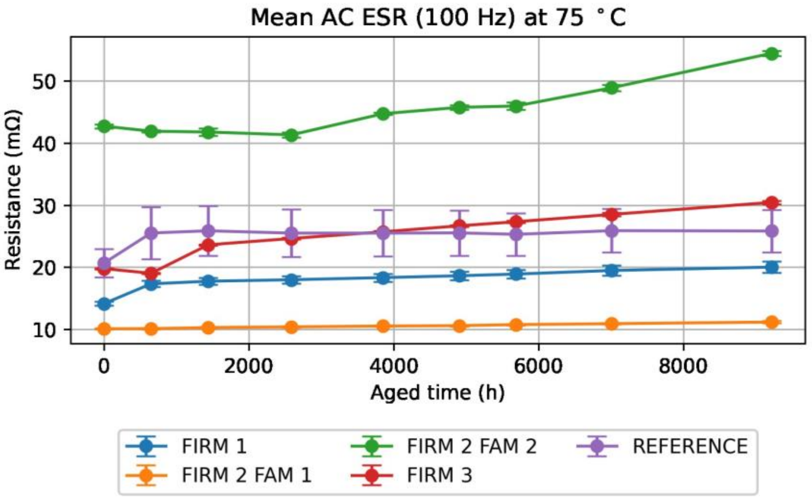
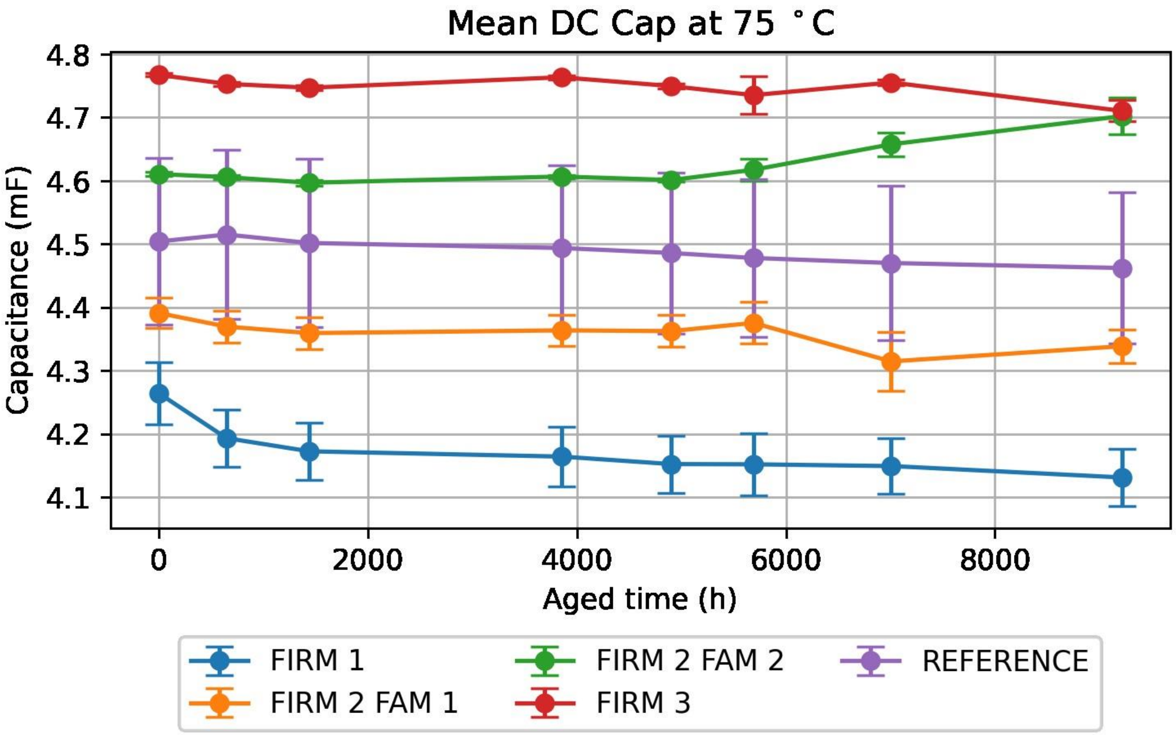
Test Results: AC values at 75 °C

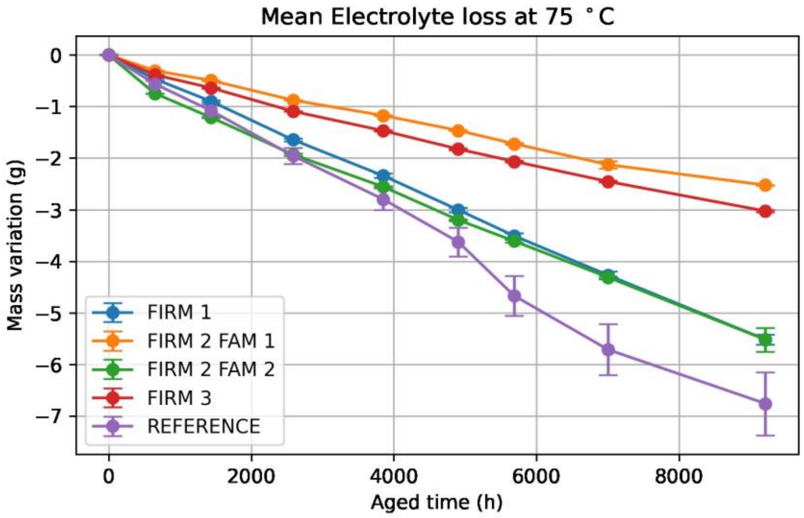


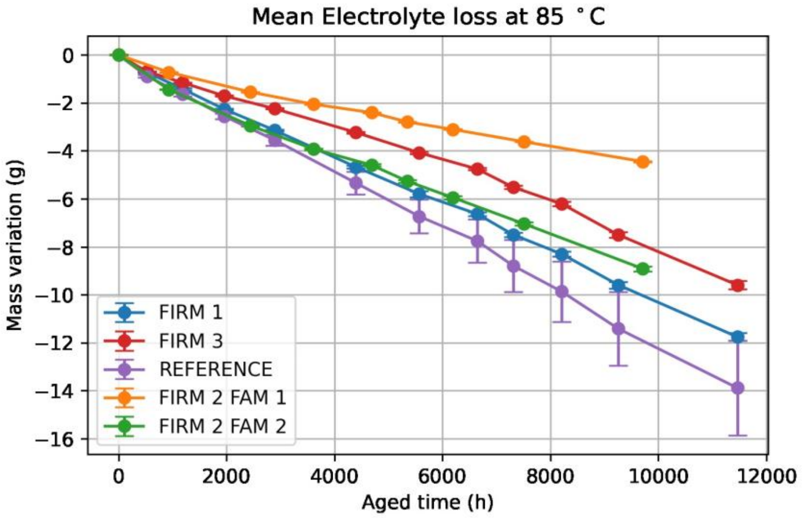


Test Results: DC values at 75 °C



Test Result: electrolyte loss

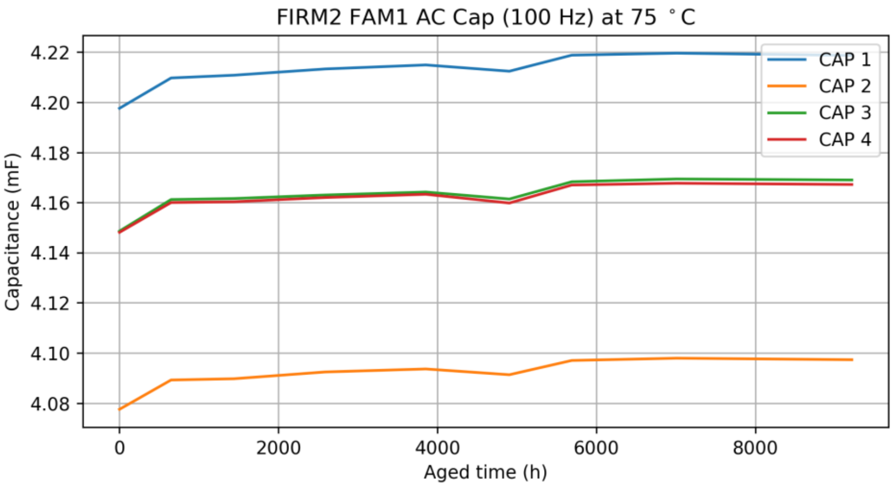


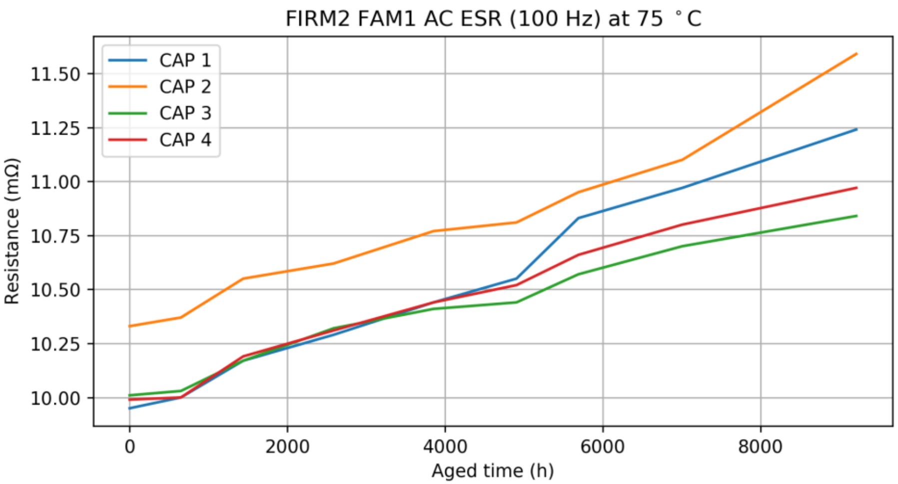


Test Results: Overview

Test group	Failures	AC Cap	AC ESR	DC Cap	Electrolytic loss	Leakage	Decision
Firm 1	1/8	FAIR	GOOD	FAIR	FAIR	FAIR	**FAIR**
Firm 2, family 1	0/12	BEST	BEST	GOOD	BEST	BEST	**BEST**
Firm 2, family 2	1/8	GOOD	FAIR	BEST	FAIR	GOOD	**FAIR**
Firm 3	0/8	GOOD	FAIR	GOOD	GOOD	FAIR	**GOOD**
Reference caps	0/8	GOOD	GOOD	GOOD	FAIR	FAIR	**-**
Firm 4	EARLY	-	-	-	-	-	**DISCARDED**
Firm 5, family 1	EARLY	-	-	-	-	-	**DISCARDED**
Firm 5, family 2	EARLY	-	-	-	-	-	**DISCARDED**

Best performing family: AC parameters





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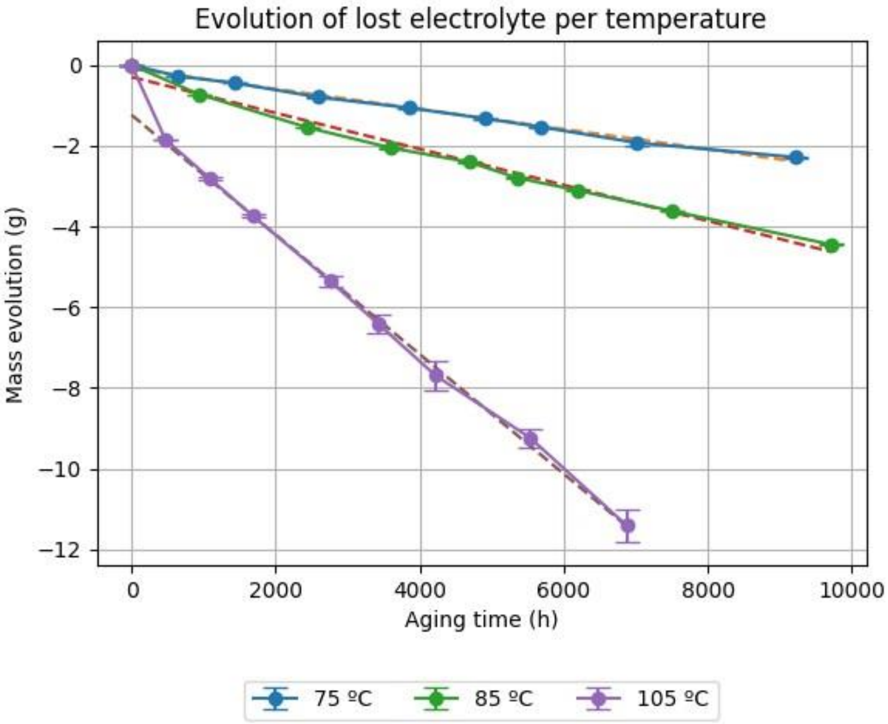
Best performing family: loss of electrolyte



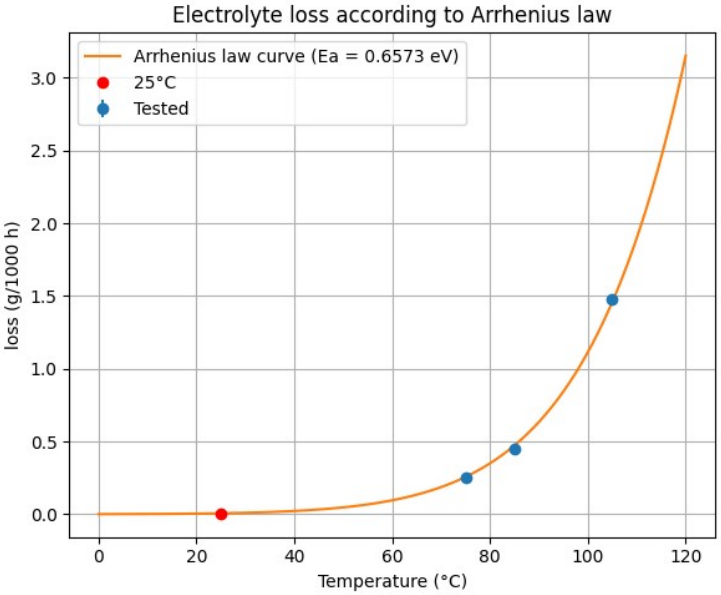
75 ºC:
(-0.25 ± 0.01) g / 1000 h

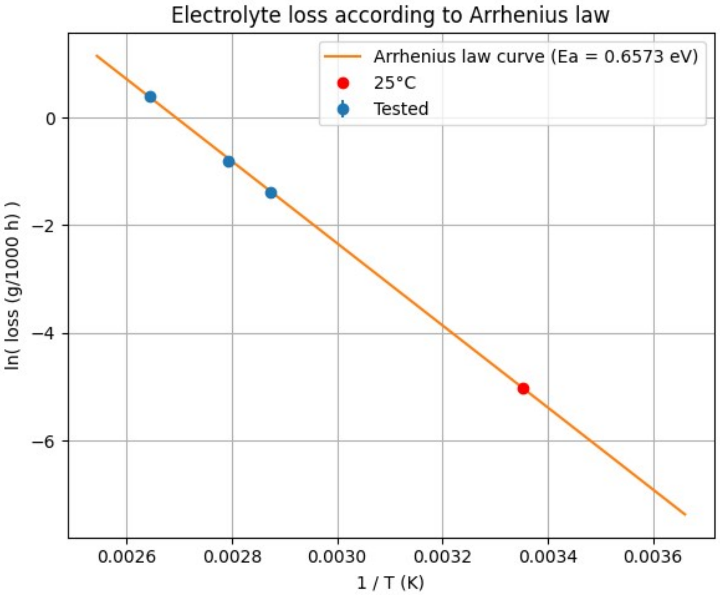
85 ºC:
(-0.45 ± 0.02) g / 1000 h

105 ºC:
(-1.48 ± 0.02) g / 1000 h

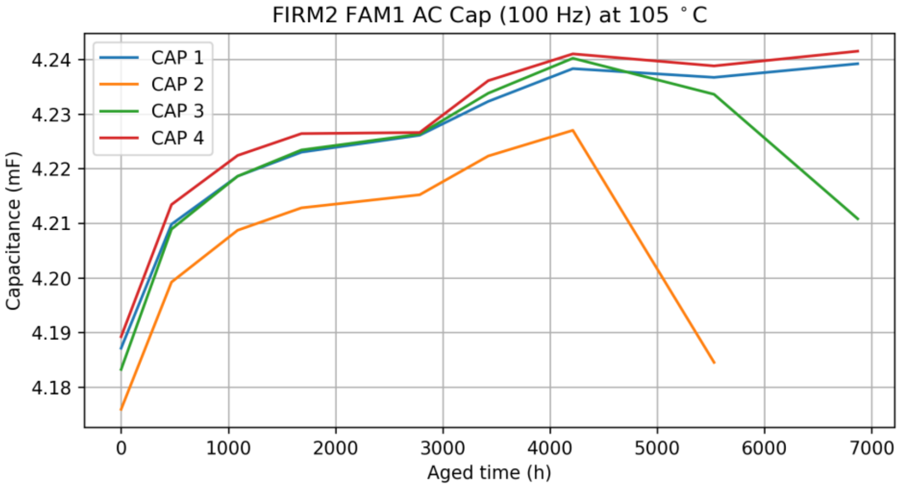
Applying Arrhenius law

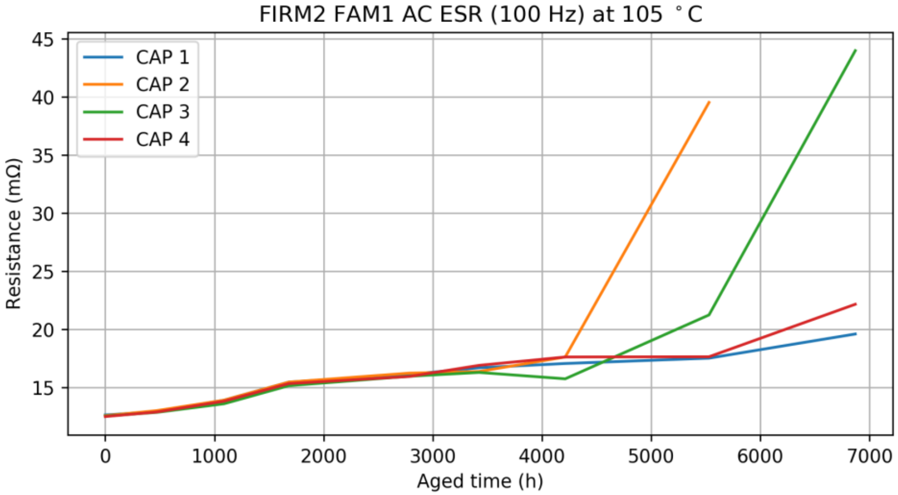
Acceleration factor between 75 °C and 25 °C (worst case): 39.4 h/h
Acceleration factor between 85 °C and 25 °C (worst case): 72.7 h/h
Acceleration factor between 105 °C and 25 °C (worst case): 224.2 h/h





Example of end of life





From the best performing family, the first failure happened after 4000 h at 105 °C, equivalent to about 102 years at 25 °C

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Summary

- High confidence that the capacitors currently installed are within expected lifetime
- 4 out of 7 families, from 3 different manufacturers, qualified according to the initial requested specifications for HiLumi
- Extensive tests done to cover -by far- the expected lifetime of the new HDS, allowing predictive maintenance
- Practical validation of the studies done within our collaboration with *Laboratoire Ampère* from *Université de Lyon*

Thank you very much for your attention

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