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Reliability run and data analysis of the accelerated aging 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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Abstract: This study evaluates the lifetime and aging process of the aluminium electrolytic capacitors to be used in the new protection systems of the High Luminosity LHC superconducting magnets. The accelerated testing and analysis of several groups of capacitors aged for more than one year provided insights into their expected lifespan and aging process. The results obtained have practical implications for maintenance and replacement schedules, as well as for selection and acceptance of capacitors for new Heater Discharge Power Supplies (HDS) equipment. The knowledge gained from this study ensures the safety and reliability of the LHC and its electronic components.

Keywords: Analysis and statistical methods; Data analysis; Detection of defects; Manufacturing

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1 Introduction

1.1 About the Heater Discharge Power Supplies

The Heater Discharge Power Supplies (HDS) units are a critical part of the Large Hadron Collider's (LHC) superconducting magnet protection system at CERN. Designed to act during a quench — a sudden loss of superconductivity — the HDS units prevent potential damage by quickly dissipating energy. Each unit contains six capacitors arranged in three parallel branches with two in series, charged to 90% of their voltage rating. With about 6,000 HDS units, the LHC operates with approximately 36,000 capacitors, maintaining roughly 3 kJ of energy in each HDS while in standby.

A quench occurs when a superconducting magnet experiences a localized transition to a normal resistive state, potentially due to variations in temperature or other disturbances. To avoid any consequent overheating, the quench protection system promptly detects the quench and activates the HDS. The stored energy in the capacitors is released into heater strips located alongside the magnet coils, heating them uniformly. This action induces a controlled and widespread quench, ensuring the dissipation of the magnet's stored energy across a large area to prevent damage. The reliability of capacitors within the HDS units is thus paramount, as they directly influence the efficacy and safety of the LHC's protective measures.

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1.2 Motivation

These capacitors are critical to system reliability, safeguarding the integrity of the superconducting magnets by maintaining charge reserves. As we approach the High-Luminosity (HL) upgrade, an additional 360 HDS units will be installed, necessitating the procurement of 2,160 capacitors suitable for a more demanding LHC environment (see table 1). The discontinuation of the capacitor model used so far requires a qualification process for alternatives.

Table 1. Capacitor requirements.

Parameter	Values
Capacitance	4.7 mF (±20%)
Rated Voltage	500 V
Usage Voltage	450 V
Min. Rated Temp.	85 °C
Operation Time	20 years
Discharge Tau	30 ms

Understanding the ageing mechanism of existing capacitors is crucial, as it directly impacts maintenance forecasting and resource allocation. A failure in these components could result in significant operational downtime and resource-intensive replacements, motivating and justifying the importance of this study for the continuity and efficiency of the LHC operations.

1.3 Types of failures

In the operational context of the LHC's HDS, we categorize capacitor failures into two types: parametric and catastrophic. Parametric failure is identified by a reduction of capacitance (beyond 10%), an increase in the initial Equivalent Series Resistance (ESR) (up to doubling the initial value), or an increase in leakage current above the manufacturer's specified limit. These are primarily attributed to the evaporation of the electrolyte. Catastrophic failures are more severe and include short circuits, open circuits, the activation of safety vents, or any physical breakage of the capacitor housing. The thresholds have been chosen in line with previous work at CERN and common practice in the industry [1, 4].

2 Ageing and measurement methods

2.1 Background

The concept of accelerated ageing has been adopted from prior collaborative research with Laboratoire Ampère at Université Claude Bernard Lyon 1 [1, 2]. These works laid the basis for the current study, effectively shrinking a 20-years lifespan into an acceptable testing timeline.

2.2 Arrhenius law

The degradation rate of electrolytic capacitors is governed by the chemical reactions occurring in the electrolyte. These reactions adhere to the Arrhenius law, described by the equation:

$$k = Ae^{-\frac{E_a}{k_B T}},$$

where k is the rate constant of the reaction, T is the absolute temperature in kelvins (K), E_a is the activation energy in electronvolts (eV), and k_B is the Boltzmann constant in eV/K. To deduce the activation energy, we monitor parameters that serve as proxies for k, and by comparing these at two different temperatures, we can derive E_a using the ratio:

$$\frac{k_2}{k_1} = e^{\frac{E_a(1/T_1 - 1/T_2)}{k_B}},$$

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For instance, with an activation energy of $E_a = 0.4$ eV, the ratio of operation times between 25 °C and 85 °C is given by:

$$\frac{t_{85\,^\circ\mathrm{C}}}{t_{25\,^\circ\mathrm{C}}} = 14,$$

implying that one hour of operation at 85 °C is equivalent to fourteen hours at 25 °C.

2.3 Procedure

Accelerated ageing tests are a critical component in assessing the long-term reliability of electrolytic capacitors under elevated stress conditions. The simplified procedure for these tests is as follows:

- The capacitors are charged to their rated voltage.
- To determine the Activation Energy (E_a), units from the same production batch are aged at two different high temperatures.
- The key electrical parameters, including Equivalent Series Resistance (ESR) and capacitance, are measured approximately every 1000 hours.
- Leakage current is monitored, and a visual inspection of the capacitors is conducted on a weekly basis to identify any potential physical degradation or failure.

Measurements. Key measurements taken at a standardized 25 °C include the following. These provide a direct assessment of ageing effects on capacitor performance.

- **Weight** (m)
- **AC, DC Capacitance** ($C_{\mathrm{AC}}, C_{\mathrm{DC}}$) from 100 Hz to 10 kHz
- **AC ESR** (ESR) from 100 Hz to 10 kHz
- **Leakage Current** (I_{leak})

3 Knowledge from LHC runs 1 and 2

3.1 Sample size

For the ageing study, 18 capacitors were aged at 85 °C and another set of 18 at 70 °C to assess reliability across temperatures. The sample size was chosen based on statistical models predicting over 98% reliability with 90% confidence, given zero failures in the sample [3]. This sample reflects diverse operating conditions experienced by the capacitors in the LHC, including variations in humidity, radiation levels, and usage among spares (figure 1(a)).

The capacitors were produced in the period 2003–2006, and have been in operation in the LHC tunnel since the start up phases of the collider in 2007, and effectively charged for 50’000 h. Most of them have been discharged less than 50 times onto quench heaters or, to a smaller extent, on dummy loads during commissioning periods.

3.2 Evolution of the main parameters

The ESC presents negligible reduction and even some gain at the start due to the oxide reforming, while the ESR growth is steady yet within acceptable limits. Weight loss due to electrolyte evaporation is linear and serves as the basis for activation energy estimation. Ageing accelerates with temperature, doubling the rate from 70 °C to 85 °C, with weight loss increasing from -0.60 ± 0.01 g per 1000 hours to -1.18 ± 0.02 g per 1000 hours (figure 1(b)).

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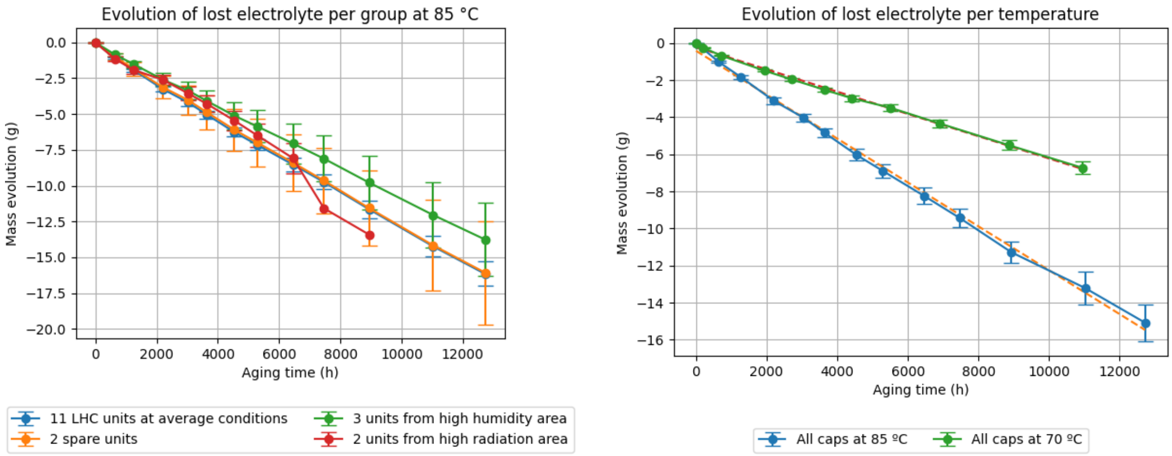


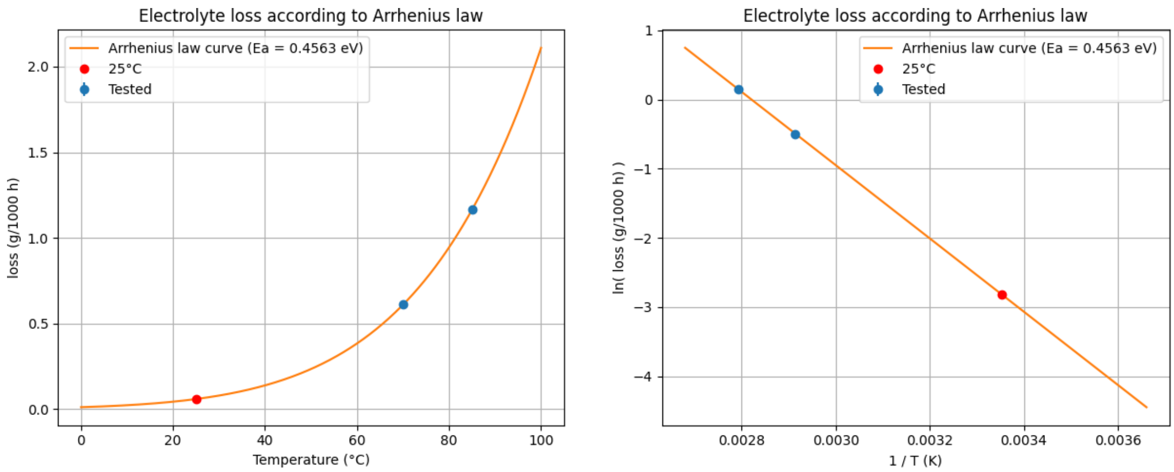
(a) Weight loss over time at 85 °C

(b) Comparison of weight loss at 70 °C and 85 °C

Figure 1. Weight loss as a function of temperature and time.

3.3 Applying Arrhenius law

We determine acceleration factors for the worst-case scenario to be approximately 19.6 between 85 °C and 25 °C, and 10.3 between 70 °C and 25 °C (figure 2).



(a) Weight loss rate vs. temperature

(b) Semilog loss vs. absolute temperature

Figure 2. Arrhenius law applied to ageing data, showing the rate of weight loss.

4 Qualification of candidates for the new production

4.1 Market candidates

The test started with seven capacitor models from five suppliers. All models are 500 V rated; one is rated for 105 °C, the rest for 85 °C. Testing has involved three ovens (one per temperature), with each model represented by four capacitors at 75 °C and 85 °C, and the 105 °C-rated model also tested with four capacitors at its rated temperature. Additionally, two capacitors from earlier runs are included in each oven for reference

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4.2 Test evolution

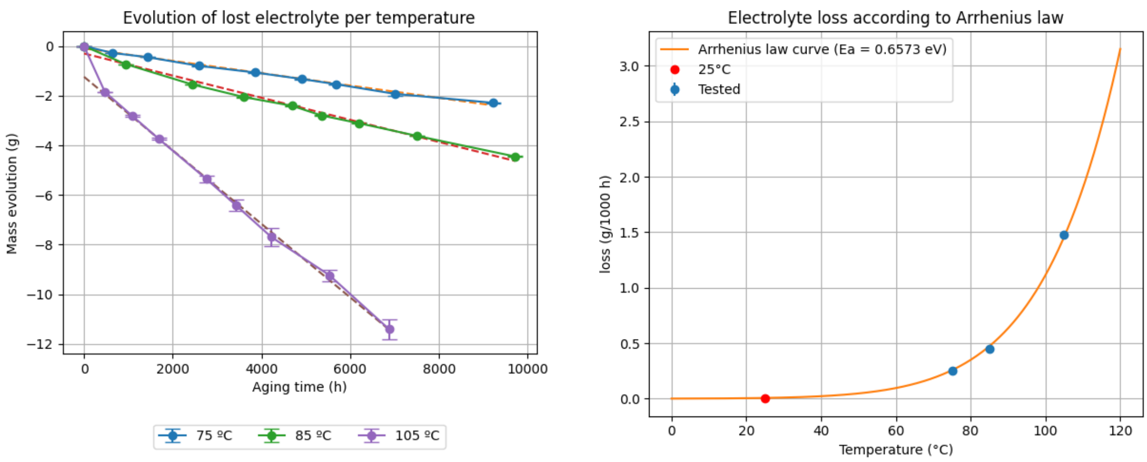
Initial testing led to the exclusion of three models due to premature failures. Observed trends in capacitance and ESR varied significantly across different capacitor families. Despite this, the loss of electrolyte mass was consistently linear for all tested models. Leakage currents remained minimal, except in those models that failed early on.

4.3 Results

Tested capacitor families, excluding early failures, endured the entire test duration, including reference capacitors from previous runs. Although some capacitors failed during testing, one family demonstrated superior performance and has been selected for installation in HiLumi test facilities with only one failure (large increase in ESR followed by an open circuit) after about 4000 h at 105 °C, which is equivalent to about 102 years at 25 °C.

Additional aging tests on 12 units confirmed the qualification test, resulting in an expected reliability of 95.32% over 20 years at 25 °C. Given the minimal failures, we derived this figure from models in [5], assuming an immediate failure of all capacitors if testing continued — an unlikely scenario — thus reinforcing the confidence in this model as the best from the qualification group to last 20 years.

The family that won the contest was the one rated for 105 °C, providing an additional data point for our analysis. The Arrhenius law fitting shows much higher acceleration factors than the current model used at the LHC, with 39.4 between 75 °C and 25 °C, 72.7 between 85 °C and 25 °C, and a remarkable 224.2 between 105 °C and 25 °C (figure 3).



(a) Weight loss at each temperature

(b) Arrhenius law fit (worst-case)

Figure 3. Weight loss characteristics of the best performing family of the qualification test.

5 Summary

In summary, the capacitors currently in operation are projected to meet their expected lifespans. Among the seven capacitor families tested from three manufacturers, four have met the qualification standards for the HiLumi project. The testing program has significantly surpassed the anticipated service life of the new HDS, providing a solid foundation for predictive maintenance strategies.

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