Electro-migration driven failures on miniature silver fuses at the Large Hadron Collider

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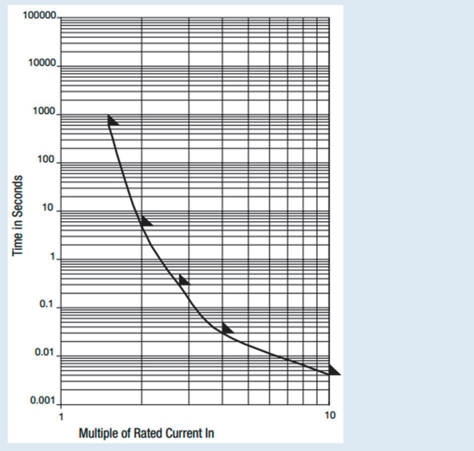
1.1 Introduction

At the Large Hadron Collider (LHC), the cryogenics instrumentation infrastructure uses fuse-protected high-voltage isolated temperature transducer cards. Approximately 1200 such cards of different families are installed and each of them is protected by a miniature fuse. The typical dc current consumption of the electronic cards is 0.3 - 0.5 A. During the periods 2008 - 2010 and 2014 - 2016, spurious fuse faults were observed at one family of cards operating at 0.5 A, whose fuse is based on a thin silver wire. Following the failures of the period 2008-2010, the fuse rating was increased from 1 A to 1.25 A and there were no further issues till the period 2014-2016. A study was launched to understand the underlying failure mechanism.

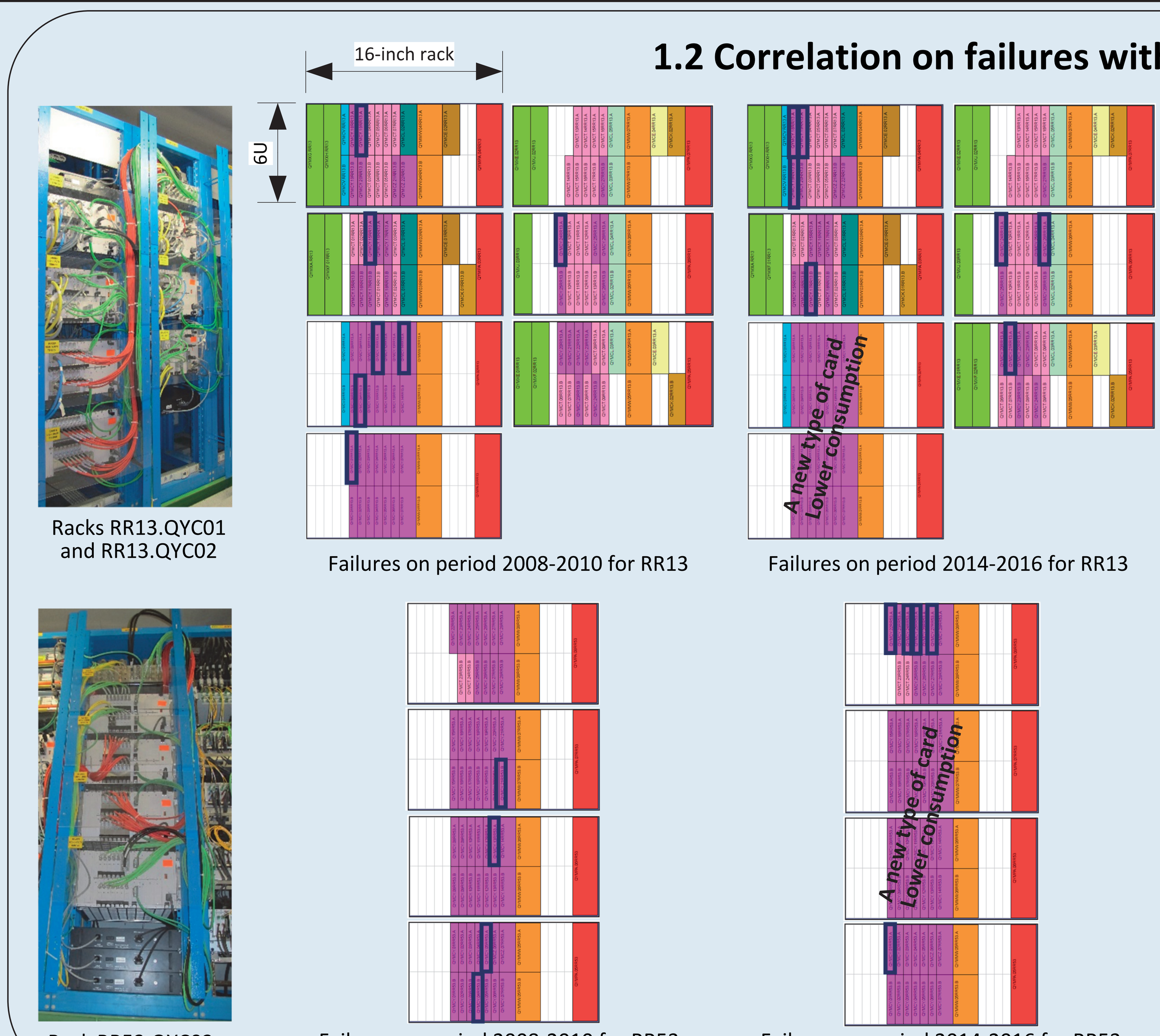
The fuse family used to protect the electronic cards:
Schurter MSF125 0034.xxxx.



Rated Current In	1.5 x In max.	2.0 x In max.	2.75 x In max.	4.0 x In max.	10.0 x In max.
0.1 A - 5 A	10 min	5 s	300 ms	30 ms	4 ms

Fuse current VS fuse opening time

1.2 Correlation on failures with operating temperatures



Racks RR13.QYC01 and RR13.QYC02

Failures on period 2008-2010 for RR13

Failures on period 2014-2016 for RR13

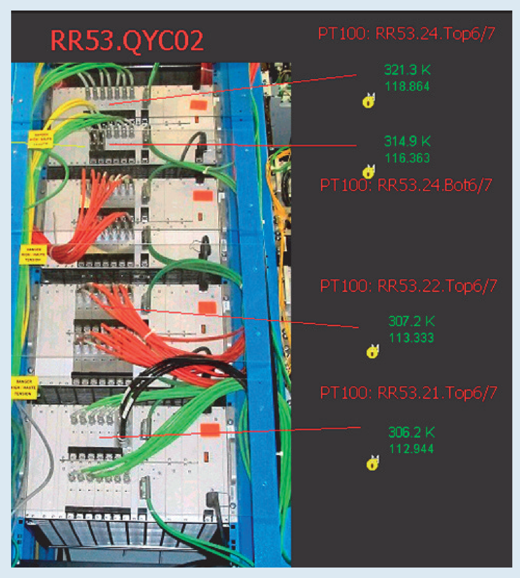
Rack RR53.QYC02

Failures on period 2008-2010 for RR53

Failures on period 2014-2016 for RR53

On the left, the racks containing LHC cryogenics instrumentation electronics are shown. Those racks are placed at 2 LHC locations where the most failures were observed during the periods 2008 - 2010 and 2014 - 2016. Each rack contains 3 or 4 double-level crates with various electronic cards. The failing card type is shown with a dark purple colour. The cards that actually failed are visualized with a blue square. After the first period, some of those cards where upgraded to another family as per updated requirements; no failures where observed at those newer cards which operate at a lower supply current.

It was observed that the failures were occurring mostly at the top level of the double crates indicating a possible correlation with the operating temperature. Those 2 LHC locations are among the warmest and in addition the cards were tightly packed without sufficient ventilation. Their operating temperature was measured in the range of 50 - 60 °C.



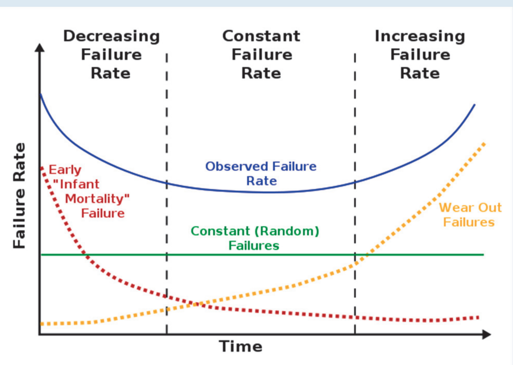
Profile of fuse temperatures along a rack. Fuses were equipped with a PT100 temperature sensor.

2. Weibull Reliability Analysis

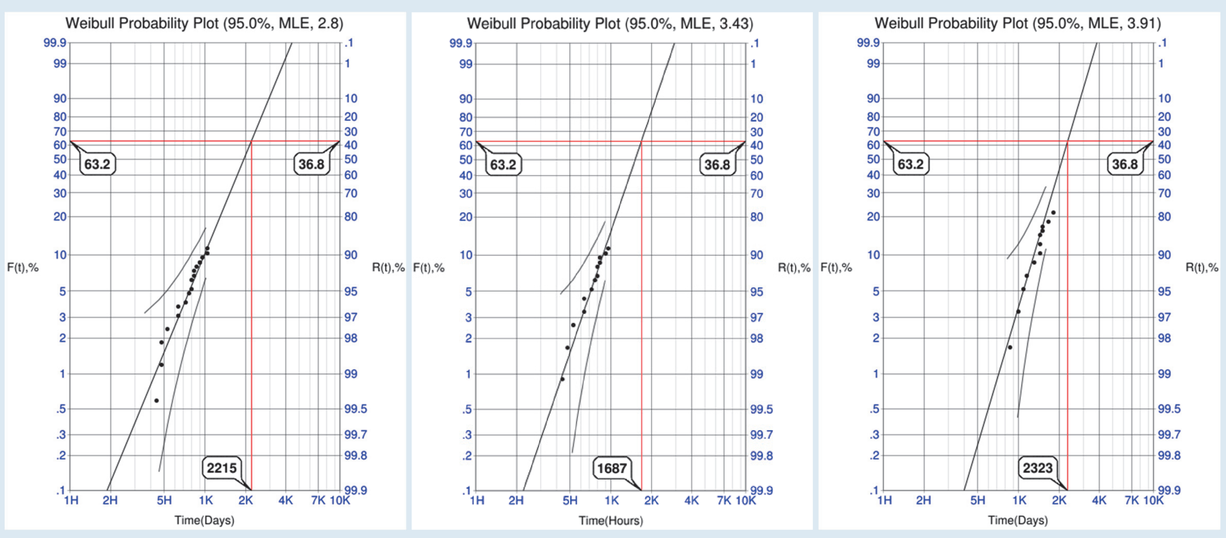
Weibull reliability analysis can be used to correlate failures, occurring over a period of time to either "early infant mortality", random failures or "wear out failures" as shown in the reliability "bathtub" curve. The analysis requires as precise as possible information on total operational time and the time of failure.

Some of the difficulties met while preparing the data include:

- Locating exact data for installations already operational over a period of 10 years.
- Tracking down possible exchange of cards for repairs.
- Calculating periods where the cards were unpowered (e.g. LHC long shut-downs).



The "bathtub" reliability curve.



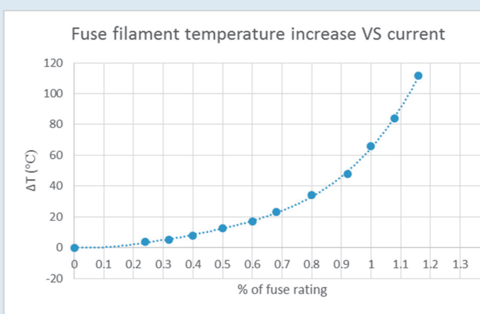
Period 2008-2010
Weibull distribution for 150 cards at 3 LHC locations RR13, RR53, RR57 (17 failures).
η = 2215 days, β = 2.8.

Period 2008-2010
Weibull distribution for 102 cards at 2 LHC locations RR13, RR53 (13 failures).
η = 1687 days, β = 3.43.
Reduced data set to compare with period 2014-2016 for same locations only.

Period 2014-2016
Weibull distribution for 46 cards at 2 LHC locations RR13, RR53 (12 failures).
η = 2323 days, β = 3.91.

The results of the Weibull reliability analysis are shown in the above charts. Weibull β factors >> 1 indicate strong end-of-life wear-out failures. When comparing periods 2008-2010 and 2014-2016, for the same LHC locations, it becomes clear that the increase of the fuse rating led to an increase of the MTTF (Mean Time To Failure) from 1687 to 2323 days but the underlying failure mechanism remained the same.

The MTTF increase can be explained by the increase of the fuse rating which resulted in a reduced operating temperature of the fuse filament (lower resistance). As per laboratory measurements shown on the right, the fusing element temperature decreased from +12.5 °C to +8 °C with respect to ambient temperature (typical card consumption is 0.5 A, loading of fuses was decreased from 50% for the 1 A fuses to 40% for the 1.25 A).

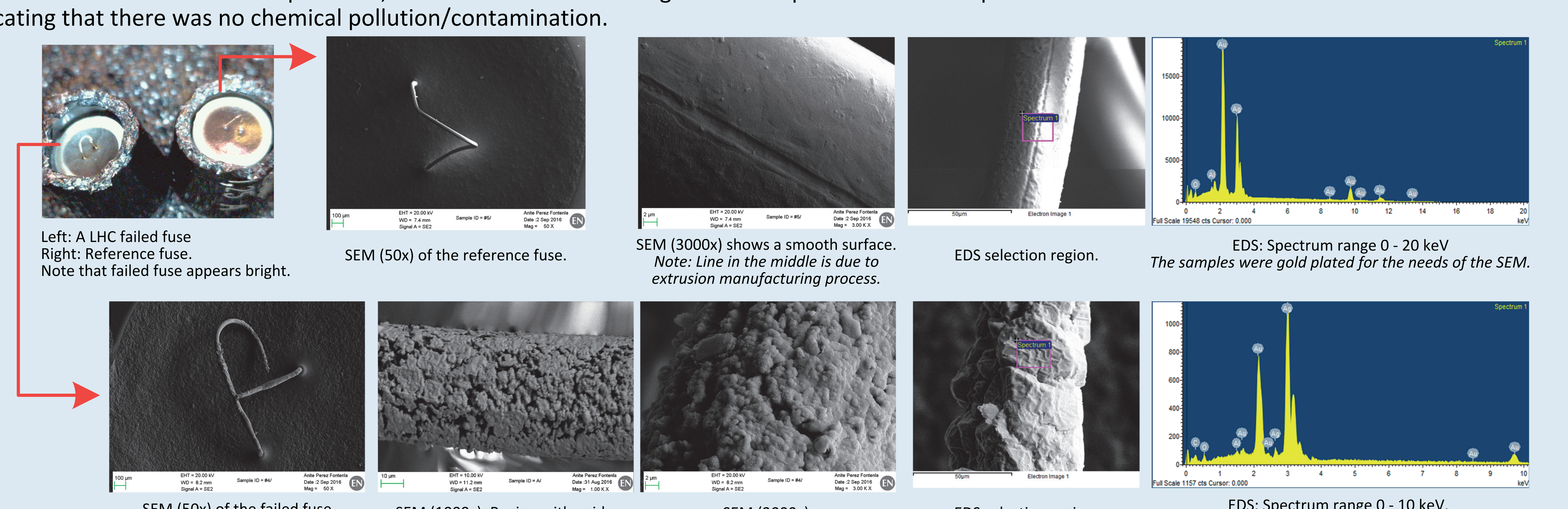


Fuse filament temperature increase versus In current (In, I nominal, as % of fuse rating). Experimental temperature measurements were taken by a thermal camera on a transparently sealed fuse.

Using the approximation of the Arrhenius model, a 4.5 °C decrease would lead to an increase of MTTF by 40% which is approximately the increase from 1687 to 2323 days.

3.1 Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS)

SEM & EDS of 2 samples, an unused reference fuse and a fuse that failed in the LHC, are shown below. It can be seen that the failed fuse has formed distinct regions of material voids and depositions, an indication of electromigration as explained later. No spectral differences can be observed between the 2 fuses indicating that there was no chemical pollution/contamination.



Left: A LHC failed fuse
Right: Reference fuse.
Note that failed fuse appears bright.

SEM (50x) of the reference fuse.

SEM (3000x) shows a smooth surface.
Note: Line in the middle is due to extrusion manufacturing process.

EDS selection region.

EDS: Spectrum range 0 - 20 keV
The samples were gold plated for the needs of the SEM.

SEM (50x) of the failed fuse retrieved from the LHC. There are distinct regions of voids and depositions.

SEM (1000x). Region with voids. The filament diameter increased from 46.5 to 54.4 um.

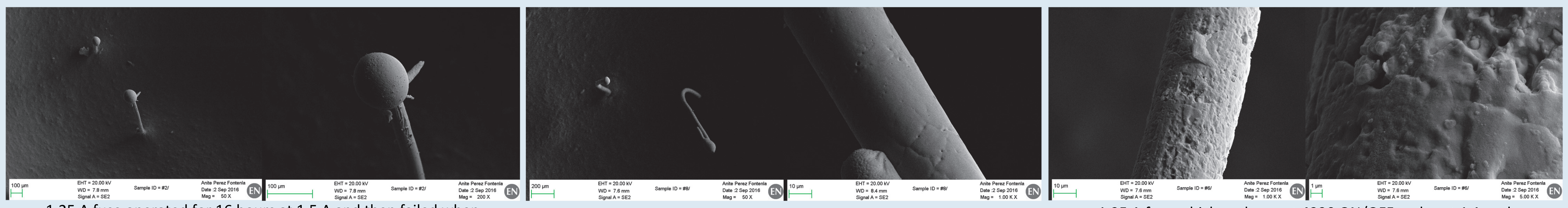
SEM (3000x).

EDS selection region.

EDS: Spectrum range 0 - 10 keV.
Identical with reference fuse.
The samples were gold plated for the needs of the SEM.

3.2 SEM on laboratory stressed samples

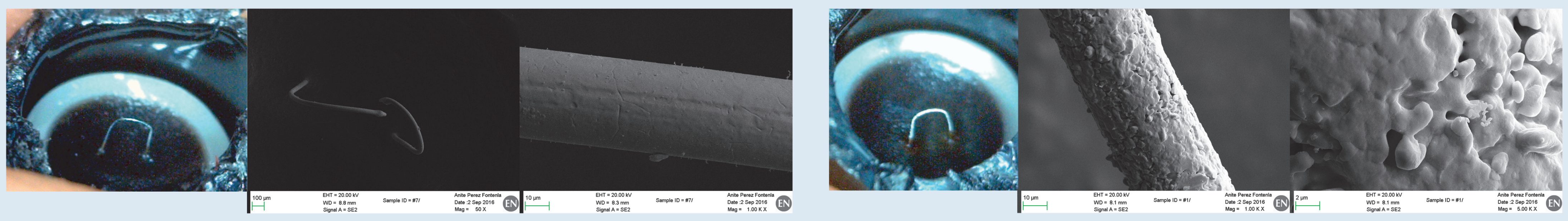
SEM analysis was performed on a series of laboratory stressed fuses of the failing type (1.25 A) in order to visualize those stresses.



1.25 A fuse operated for 16 hours at 1.5 A and then failed when the current increased to 1.65 A.

1.25 A rated fuse failure after operation for ~1 hour at 1.65 A.

1.25 A fuse which underwent 4320 ON/OFF cycles at 1 A and 576 cycles at 1.35 A. Fuse did not fail.



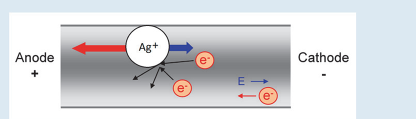
1.25 A fuse underwent 4320 ON/OFF cycles at 1 A and 576 cycles at 1.35 A. Fuse failed. Note that fuse element appeared initially intact with a low magnification optical microscope.

1.25 A fuse operated 120 hours at 1 A and 16 hours at 1.35 A. Fuse did not fail. Note that fuse element appears bright on a low magnification optical microscope having a similar appearance to failed fuses removed from the LHC

Top left and top center: Fuse failures on overcurrent show spherical structures due to material melting.
Top right: Thermal cycling stresses (no failure) form "cracks" on the surface.
Bottom left: Failures due to thermal cycling stress do not show spherical structures of melted material.
Bottom right: Extended operation at high currents revealed material transportation phenomena (electromigration) as seen on LHC samples.

3.3 Electromigration

The SEM images revealed effects identical to electromigration. Electromigration is the transport of material due to the momentum transfer between conducting electrons and diffusing metal atoms. The dislocated atoms may form voids at their original location and depositions at their final location.



Conducting electrons colliding with metallic ions

Bibliography studies have shown that pure silver is highly susceptible to electromigration due to its low activation energy and high mobility of its grain boundaries. Other metals such as aluminium and copper behave in a similar way. One of the methods for reducing the effects of electromigration is using alloys which tend to increase the activation energy and reduce the mobility of the grain boundaries.

$$\mathrm{MTTF} = \frac{A}{J^n} e^{\frac{E_a}{kT}}$$

Black's equation on MTTF

A: Constant, J: Current density, T: Temperature (kelvin)
E_a: Activation energy, k: Boltzmann's constant
n: Scaling factor (typical 2)

4. Accelerated lifetime tests

The typical resistance of an unused 1.25 A fuse is ~82 mOhm. Six fuses were removed from the LHC after operating for ~2000 days without a failure, their resistances are shown on the table on the right. The resistance increase is small taking into account measurements inaccuracies and fuse filament variations.

Location.Crate.Channel	Resistance
RR13.13.Top8/9	97.5 mOhm
RR13.13.Top6/7	89 mOhm
RR13.22.Bot12/13	87 mOhm
RR17.21.Top6/7	88.5 mOhm
RR17.24.Top8/9	87 mOhm
RR17.24.Top6/7	90 mOhm

A highly accelerated lifetime test was performed in an effort to reproduce in the laboratory the phenomena observed in the LHC and develop a method of fault prediction. Four new fuses of the original failing type and other candidates were tested. Below, only the data of the failing type is shown.

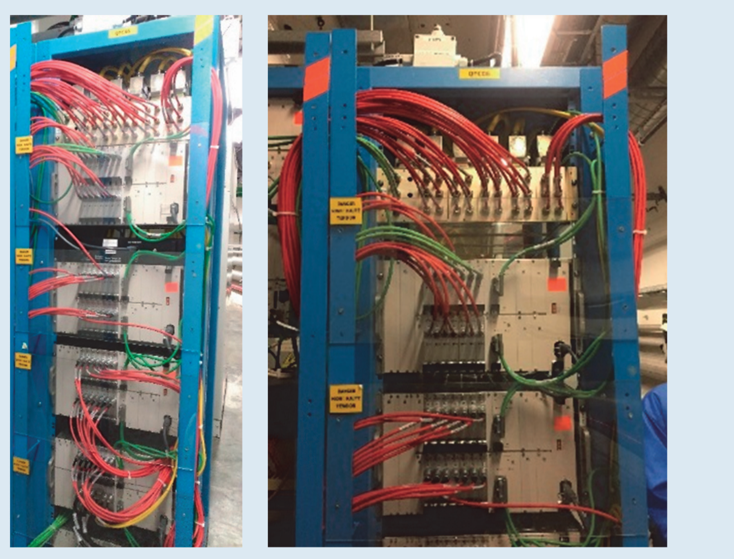
Fuse	Rating	Loading	Conditions	Measurements
#1	1.25 A	50%	1 day @ 125 °C, 2 days @ 175 °C and 15 days @ 150 °C	84.4 mOhm @ 0d, 94.8 mOhm @ 7d, 93.8 mOhm @ 10d, 100.6 mOhm @ 15d, 270 mOhm @ 18d.
#2	1.25 A	80%	14 days @ 150 °C	83.1 mOhm @ 0d, 85.9 mOhm @3d, 91.2 mOhm @ 8d, 91.3 mOhm @ 11d, 90.9 mOhm @ 14d.
#3	1 A	80%	1 day @ 125 °C and 2 days @ 175 °C	112.3 mOhm @ 0d, found failed on day 3.
#4	1 A	80%	18 days @ 150 °C	~112 mOhm @ 0d, 116.4 mOhm @ 4d, 124.8 @ 7d, 129.7 @ 12d, 137.9 @ 15d, failed found on day 18.

The accelerated test was run at temperatures of 150 °C and 175 °C greatly exceeding the maximum operating conditions of the fuses. For operation at 175 °C, some of the failures were attributed to material damage due to this high temperature. For the runs at 150 °C, there were not any material failures observed, but the increased resistances do not match those of the 6 fuses removed from the LHC.

A predictive formula based on resistance measurements could not be derived from the LHC measurements and the highly accelerated lifetime test.

5. Consolidation Year-End Shutdown 2016-2017

- A fuse with a higher stated reliability was used. Due to limited time, the new fuses were not tested under SEM/EDS to reveal their composition but such a test will be performed in the future.
- In certain cases, the electronic cabinet separation was increased to improve the natural convection resulting in a lower fuse temperature.
- Cooling fans were installed at some racks exhibiting higher temperature values; reduction of 20 °C was achieved in one rack.



Left: A cabinet with limited airflow on top-most crate
Right: Improved airflow by separation.

6. Summary/Conclusions

A family of electronic cards underwent failures over 2 periods 2008 - 2010 and 2014 - 2016. After the first period, the fuse rating was increased from 1 A to 1.25 A and no further failure was observed for ~4 years. Following the failures of the second period and the analysis presented here, it was concluded that the origin of the problem was electromigration and therefore a low MTTF for the selected fuse and the operating conditions. The manufacturer confirmed, on private communication, that the fuse has a basic MTTF of only 125,000 hrs.

- Statistical Weibull reliability analysis gave strong indications of the wear-out failure mechanism.
- Resistive measurements could not be reproduced by a highly accelerated lifetime test in laboratory conditions in high operating temperatures.
- SEM analysis was proven to be a reliable and effective method of assessing the status of the fuses. This method will become part of a lifetime assessment tool for similar devices.

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