

## The Robustness of Ready-to-Use Cathodes (RuC<sup>®</sup>) - A Mature Technology Available for the Primary Aluminium Industry

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### Abstract

The efforts to decarbonize the aluminium industry continue as smelters around the world implement initiatives to reduce their CO<sub>2</sub> footprint in the production of primary aluminium. On one side, the use of greener electricity as an energy source is being adapted at an increasing speed, but on the other side, initiatives to reduce energy consumption, such as new cathodic solutions based on copper-only conductors, have seen setbacks.

It has been confirmed and published that when using only copper as a metallic conductor in a cathode block to extract the current from one pot, the copper is alloyed, which increases its resistivity and volumetric expansion, leading to a rapid rise in cathode voltage drop (CVD), cracking of the cathode blocks and resulting in a short lifetime of the pot.

Thanks to the protected copper used with the RuC<sup>®</sup> technology, the above described effect is avoided. This is confirmed by the stable CVD evolution and long lifetime operation of the oldest group of RuC<sup>®</sup> pots discussed in this paper.

In addition, when applying modern cell design principles based on modelling, the increased electrical conductivity of the collector bar can lead to a more stable cell operation and optimized heat balance. This can result in a significant performance improvement.

**Keywords:** Ready-to-use Cathode RuC<sup>®</sup>, energy savings, pot lifetime, copper alloying.

### 1. Introduction

The aluminium industry is leading efforts to reduce its carbon footprint. According to the International Aluminium Statistics, the electrolysis process accounted for 71 % of the total greenhouse gas emissions of the aluminium sector in 2022, equivalent to 789 million tonnes of CO<sub>2</sub>e. The energy mix plays a significant role in the CO<sub>2</sub> intensity of aluminium production, with benchmarks below 4 t CO<sub>2</sub>e/t Al for renewable energy sources and 16 t CO<sub>2</sub>e/t Al for fossil fuels. To reduce the carbon footprint, smelters have successfully incorporated renewable sources into their energy mix and have adopted copper inserts to reduce energy consumption as the new standard design.

Additional efforts to further reduce energy consumption with new technologies like RuC<sup>®</sup> are currently being tested. Some of these tests have encountered operational issues related to the alloying of copper with aluminium.

This paper explains the history of RuC<sup>®</sup> development, the lessons learned, and the measures taken to improve the design's robustness. It also provides an overview of selected projects that have been operational for more than 1 700 days.

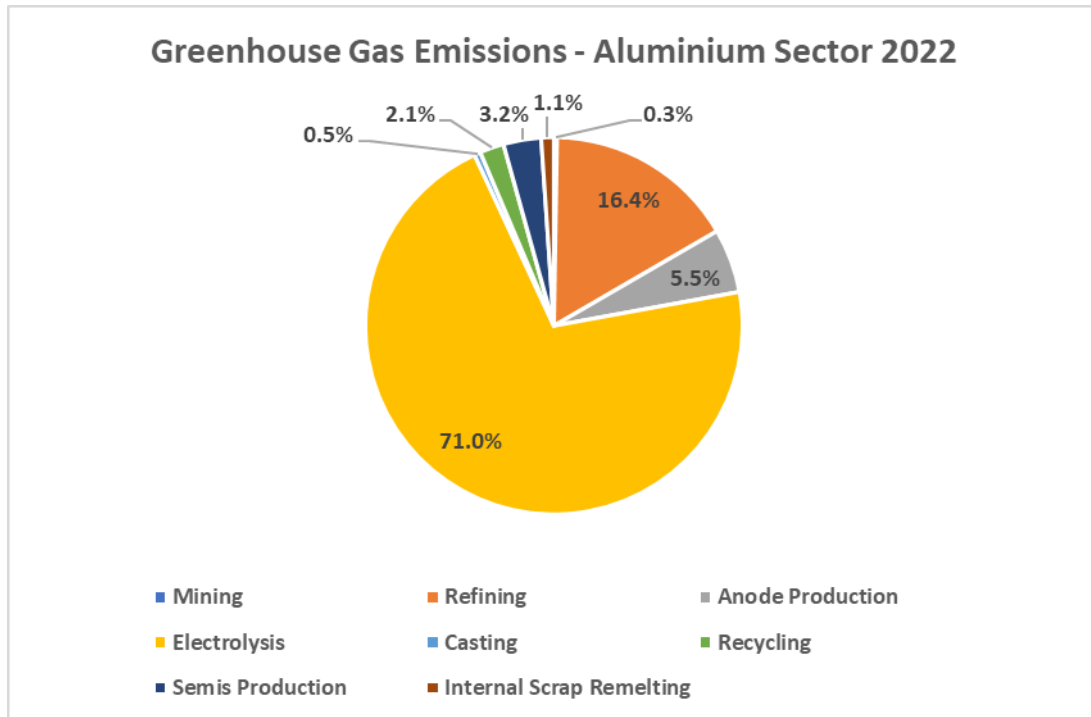


Figure 1. Greenhouse gas emissions - aluminium sector 2022 [1].

## 2. The Advantages of the RuC<sup>®</sup> Design

The Ready-to-use cathode (RuC<sup>®</sup>) was developed as a copper cathodic solution with the aim of eliminating the high-temperature casting process or sealing ramming paste operation needed to join the cathode block with the steel collector bars. By skipping this intermediate step, the overall safety of the shop floor workers is improved, enabling the smelter to concentrate on its primary objective of producing aluminium.

When replacing the steel collector bars with copper bars, the overall cathodic resistance of the assembly is reduced. Using modelling tools, a more insulating lining for RuC<sup>®</sup> can be designed to accommodate the higher heat losses from copper, resulting in a lower pot voltage and lower energy consumption in the pot.

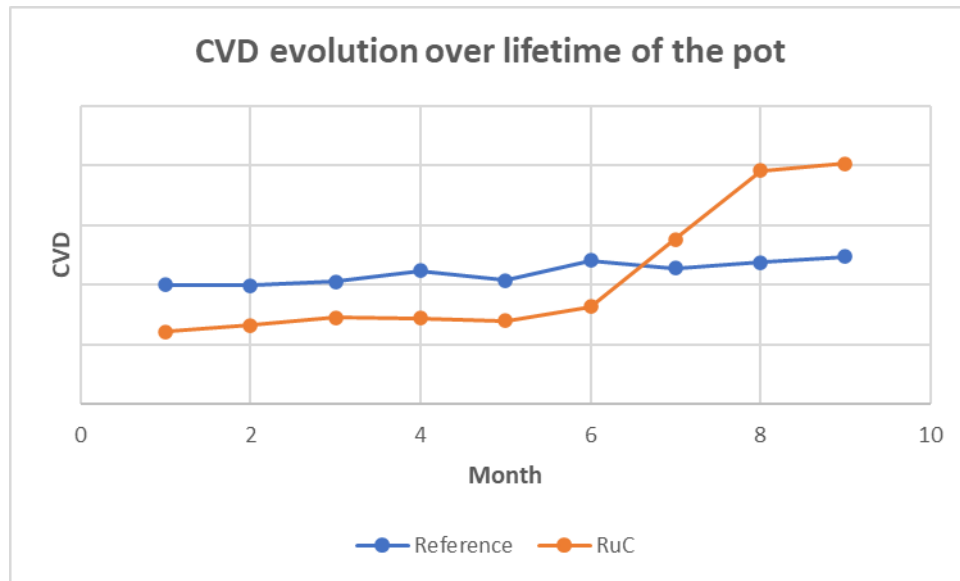
Because the Cu cross-section is smaller compared to steel bars, additional cathode material remains on top of the conductors, potentially extending the lifetime of the pot. Additionally, an improved current density distribution in the metal pad enhances the pot stability, enabling anode-cathode distance (ACD) optimization and improving current efficiency. Finally, at the end of the lifetime, there is high potential to recycle the copper bars.

## 3. The Early RuC<sup>®</sup> Trials

Starting in 2015, a few RuC<sup>®</sup> trials have been initiated with one or two blocks in each pot. During this time, the goal of RuC<sup>®</sup> was to have a simple design to reduce production costs. Full copper bars were mechanically fitted in direct contact with the cathode slot. The cathodic resistance of

the block remained stable after more than 10 months of operation [2], and follow-up trials were planned.

Full RuC<sup>®</sup> pots were installed with the same design principle as the trials with single blocks. The CVD and pot voltage savings were better than expected, with an initial CVD of only 60 % of the standard collector bar reference, representing an average CVD reduction of -85 mV. After 8 months of stable operation, the CVD of the RuC<sup>®</sup> pots rapidly increased to more than 4 times the initial value in a period of 3 months, as shown in Figure 2. The pots were soon stopped after 11 months of operation and an autopsy was carried out.



**Figure 2. CVD evolution of RuC pots and reference pots.**

The autopsy revealed that the pot was infiltrated with metal, which had accumulated below the cathode blocks. The origin of the infiltration was unclear, but the Cu bars were attacked and transformed. In areas with high metal infiltration, the bars were completely melted, while in others, there was a shiny golden-coloured copper alloy (aluminium bronze), as shown in Figure 3.



**Figure 3. Aluminium deposited on bottom of copper bar.**

Following this discovery, another RuC<sup>®</sup> project with single blocks was intentionally stopped after 420 days of operation to analyse the condition of the copper bars. The pot was tight with no

apparent signs of metal infiltration, but the copper bars were alloyed and exhibited a distinctive golden coloration on the surfaces, as seen in Figure 4.



Figure 4. Cu bars samples with different extent of alloyed copper.

Chemical analysis of the samples revealed 8.5 %wt of Al. The electrical resistivity of the samples was measured, see Table 1, and the value was 5 times higher at room temperature for sample #3 compared to pure copper. The electrical resistivity as a function of temperature also confirmed a higher value of resistivity for the alloyed material, as shown in Figure 5.

Table 1. Electrical resistivity of alloyed Cu bars.

Sample	Pure Cu	1	2	3
Electrical resistivity at 20 °C ( $\mu\Omega\cdot m$ )	0.017	0.063	0.022	0.089

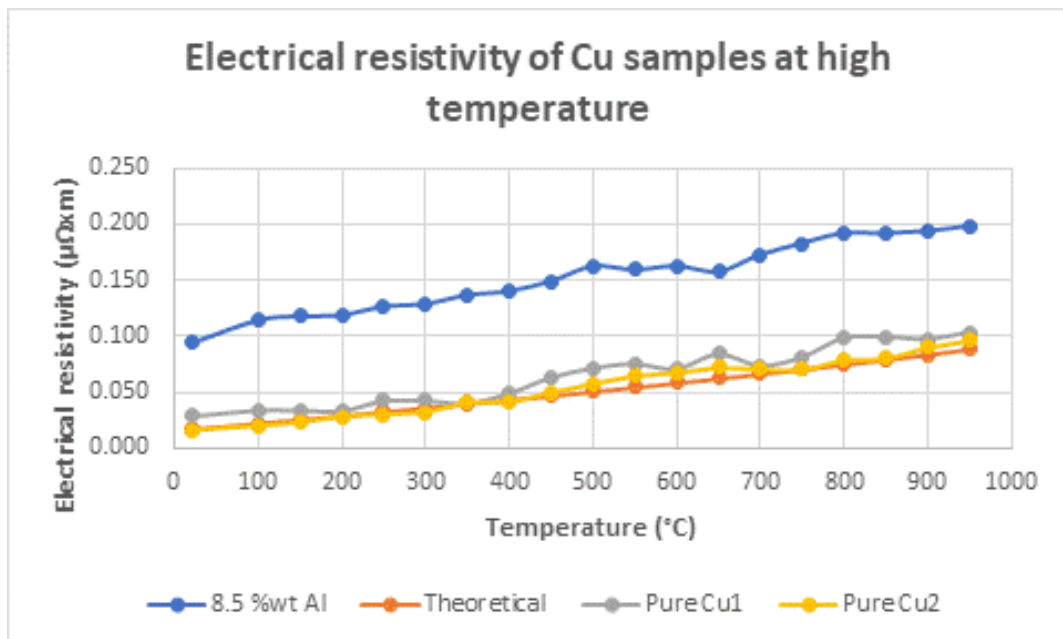
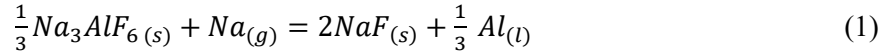


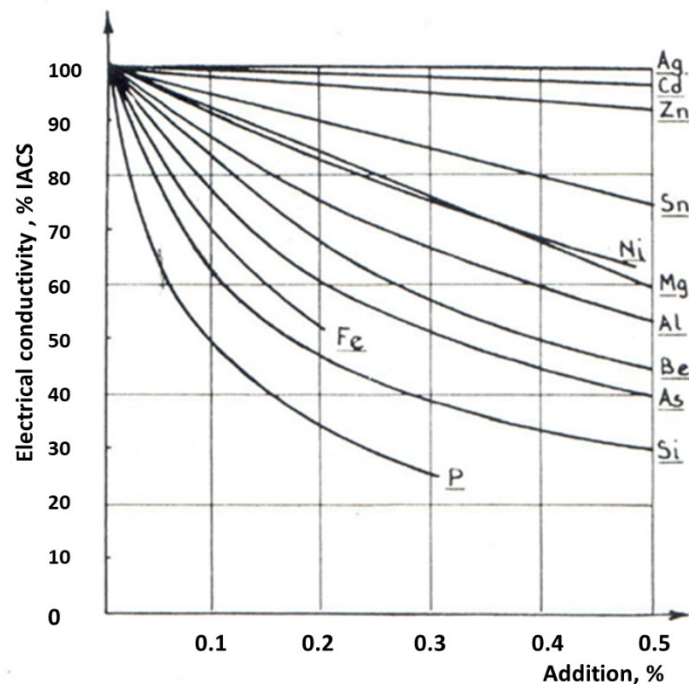
Figure 5. Electrical resistivity of Cu samples at high temperature.

Assuming that no metal has leaked towards the bottom of the cathode block, the presence of aluminium at the copper bar level can only be explained by the bath and sodium penetration. The reaction mechanism between the bath and sodium is a spontaneous reaction at 800 °C [3].



The bath in contact with sodium diffused through the pores of the cathode block, will produce aluminium in liquid form. The reaction of aluminium with copper should theoretically stop at 12 %wt Al due to the Na activity in the cathode block. However, as explained by Hagen and Gjesdal [4], higher %wt Al concentrations in copper can be found if there is a liquid Al source, which will produce a silver-coloured alloyed copper. Additionally, the aluminium bronze increases the volumetric expansion of the copper leading to cracking of the block.

After these experiences, it became clear that the copper needs to be protected by a barrier against aluminium. Even in tight cells, aluminium will be present as a result of bath and sodium penetration. Furthermore, this barrier must protect the copper from other alloying elements since already trace impurities could have a high impact on the electrical conductivity of the copper, as seen in Figure 6, which would increase the overall CVD of the RuC®.



**Figure 6. Electrical conductivity of Cu and its alloys. IACS = International Annealed Copper Standard. The conductivity of annealed copper is defined to be 100 % IACS at 20 °C.**

#### 4. Improved Copper Protection in RuC® Design

Several types of barrier protections were tested at laboratory scale in a modified Rapoport test to evaluate their robustness against bath and to reduce the diffusion of aluminium and silicon into copper. After selecting the most suitable barrier, new RuC® blocks were installed in pots that operated for more than 28 months before being stopped for a planned autopsy. The test blocks and the reference blocks had wires connected to the end of the steel bar for easy and reliable CVD

measurement. The RuC<sup>®</sup> CVD was designed to be higher than the reference. During the operation of the test pots, there were no indications of CVD degradation as seen in Figure 7 and the metallographic test also indicated a high purity of the copper bars.

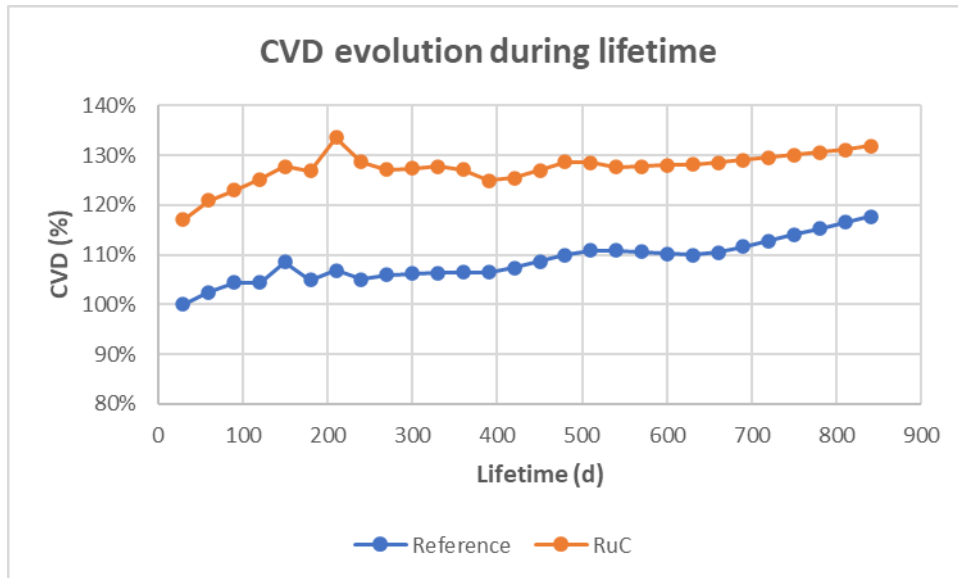


Figure 7. CVD evolution during lifetime with protected Cu.



Figure 8. Copper analysis after 800 days in operation. Sample taken close to the end of the block.

The results of the metallurgical analysis were presented and discussed previously in 2022 [5]. As shown in Figure 8, three spots were analysed with glow discharge optical emission spectroscopy (GDOES) and the measurements indicated copper purity above 99 %.

These positive results indicate that the barrier was protecting the copper and preventing the alloying process with aluminium. The barrier for the copper is included in the RuC<sup>®</sup> patent [6] and has been implemented in the RuC<sup>®</sup> projects currently in operation.

## 5. Performance Results of Selected RuC<sup>®</sup> Pots in Operation

The first batch of installed RuC<sup>®</sup> pots will reach the end of their lifetime in the coming years. Currently, there are several projects where the RuC<sup>®</sup> has been operating for more than 1 700 days and continues to exhibit good performance parameters. Below are a few examples for illustrative purposes.

The first example involves graphitized cathodes, comparing RuC<sup>®</sup> pots to cast iron sealed steel collector bars. The current density at the cathode block is 0.88 A/cm<sup>2</sup>. The average pot resistance reduction for RuC<sup>®</sup> during the project's lifetime is -0.196 μΩ. The increase in pot resistance between 1 200 days and 1 600 days is attributed to anode problems for both the reference group and the RuC<sup>®</sup> group, as shown in Figure 9.

Other key performance indicators, such as cathode resistance, show a stable evolution over the lifetime, as depicted in Figure 10. Manual CVD measurements were stopped after 600 days in operation and reintroduced at 1200 days upon request. The cathode resistance reduction remains constant, resulting in an average saving of 30 mV in cathode voltage drop compared to the reference pots. However, Figure 11 indicates an increasing trend in the noise level for both the RuC<sup>®</sup> pots and the reference pots over the project's lifetime due to the anode problems explained above. This project has been operational for more than 1 900 days.

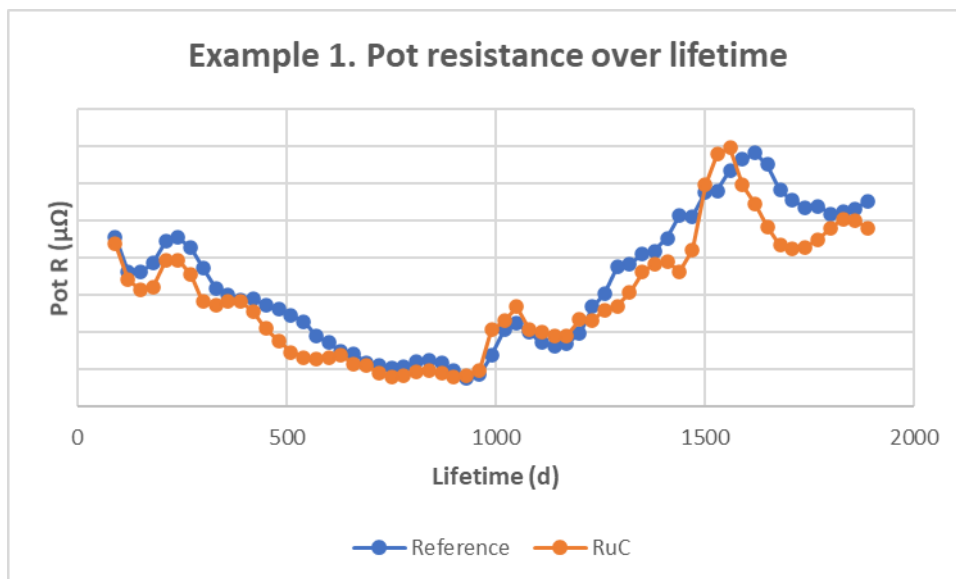


Figure 9. Example 1. Pot resistance over lifetime.

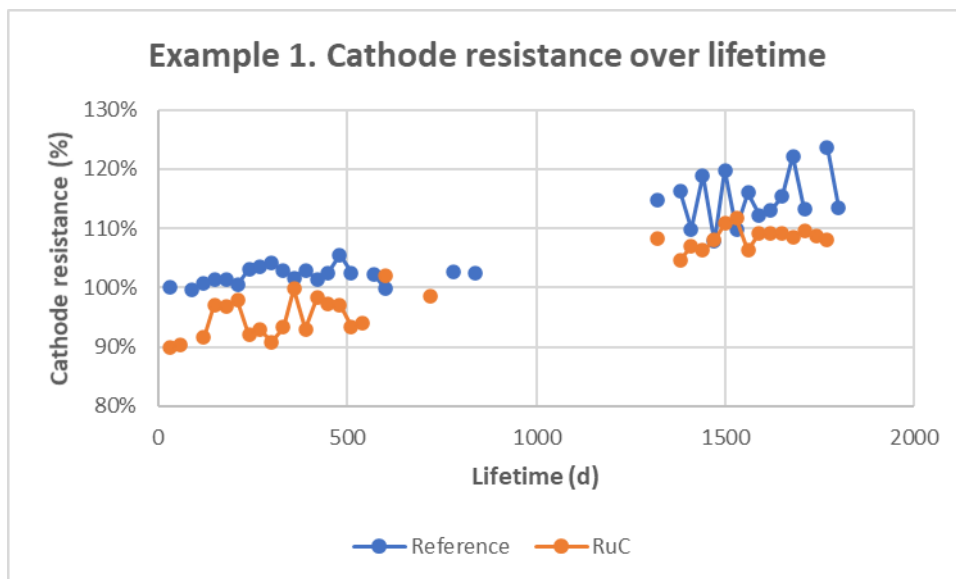


Figure 10. Example 1. Cathode resistance evolution.

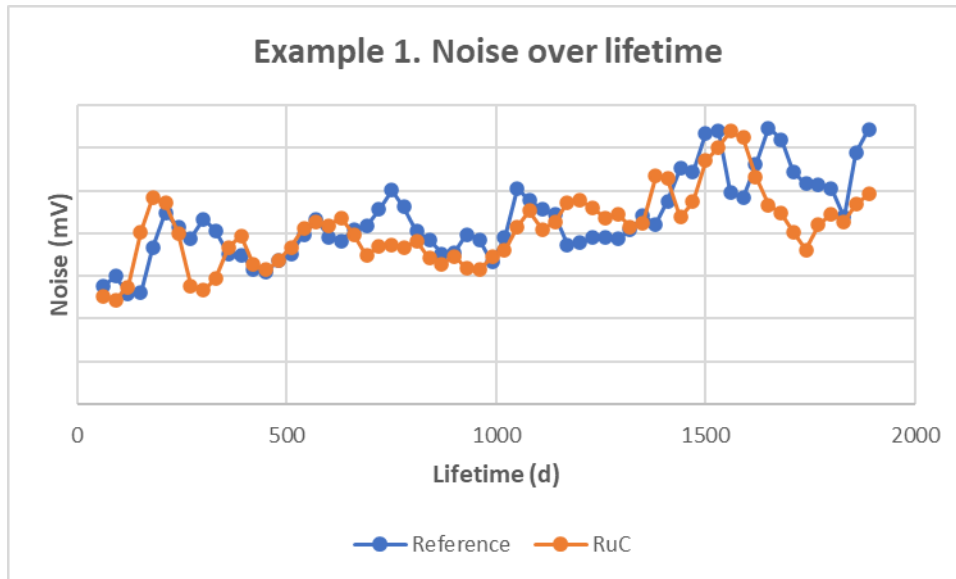


Figure 11. Example 1. Noise over lifetime.

The second example consists of graphitized cathodes, comparing RuC<sup>®</sup> pots to copper insert pots in a high amperage line. The current density at the cathode block is 0.91 A/cm<sup>2</sup> and the main objective of the project was to mimic the performance of the copper insert design.

Figure 12 shows the evolution of pot resistance for this particular project. The overall pot resistance with RuC<sup>®</sup> has been reduced by -0.160 μΩ. The RuC<sup>®</sup> does not show any faster increase in cathode resistance compared to the trend of copper insert pots, as seen in Figure 13. Despite the RuC<sup>®</sup> noise showing some peak values during the 500–600 days period, the average noise level is similar to the copper inserts, as shown in Figure 14. This project has been in operation for more than 1 700 days.

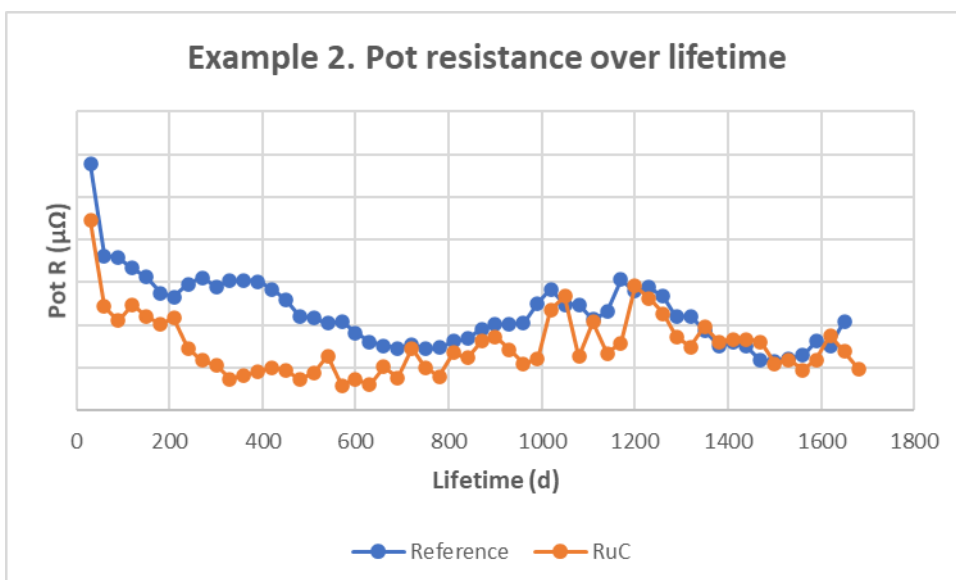


Figure 12. Example 2. Pot resistance over lifetime.

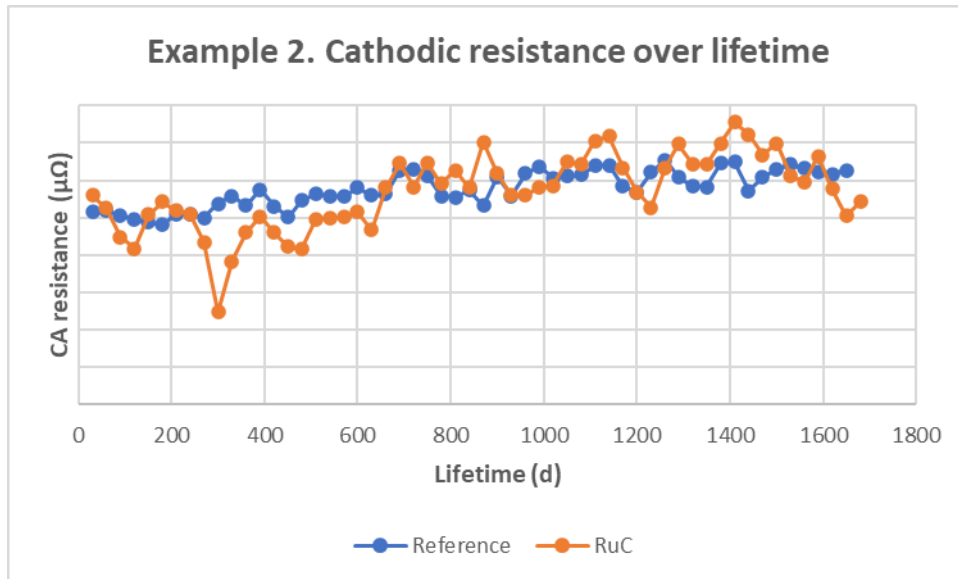


Figure 13. Example 2. Cathodic resistance over lifetime.

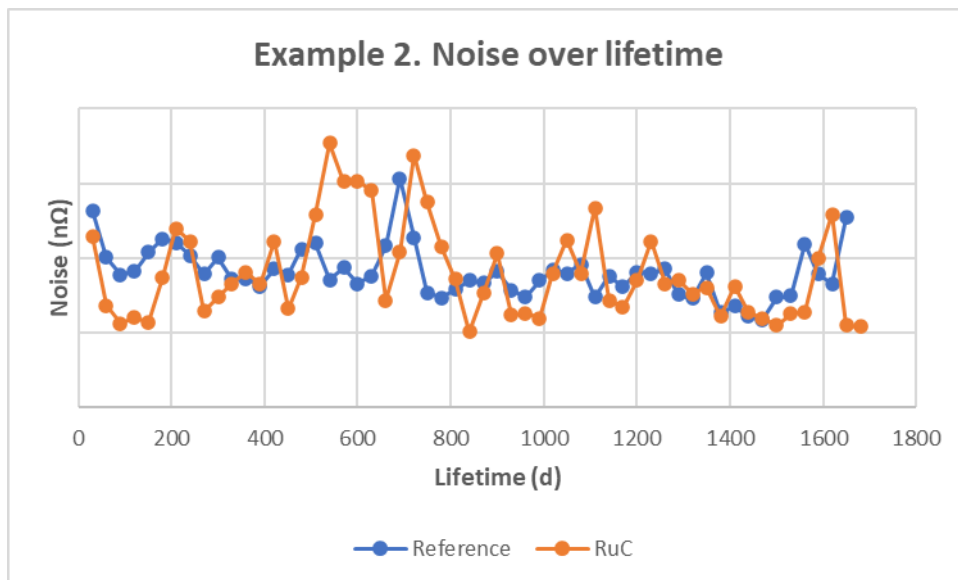


Figure 14. Example 2. Noise over lifetime.

## 6. Conclusions

The Ready-to-Use cathode (RuC<sup>®</sup>) was developed as a cathodic assembly that replaces the cast iron rodding or sealing paste rodding operation, and using full copper bars instead of steel collector bars. The lower electrical resistivity of the copper bars results in a lower cathode voltage drop (CVD), and with a proper lining design, the pot voltage can also be reduced, leading to decreased specific energy consumption.

By utilizing only copper bars fitted into the slot of the cathode blocks, the first RuC<sup>®</sup> blocks were installed in 2015. Initial performance exceeded expectations, but after a few months in operation, a rapid increase in CVD caused the pots to stop. An autopsy revealed that copper was reacting with aluminium, creating aluminium bronze, which significantly increased electrical resistivity and volumetric expansion of the copper.

To prevent the copper alloying process due to early metal leakages or bath and Na diffusion, a barrier was designed to protect the copper in the new RuC<sup>®</sup> design. Intermediate autopsies conducted after 28 months of operation showed that the barrier effectively protected the Cu. With this knowledge, the RuC<sup>®</sup> design was improved to create a more robust system.

Two examples of RuC<sup>®</sup> projects with operating lifetime exceeding 1 700 days were presented. Performance parameters such as pot voltage, CVD and noise indicated stable pots with normal CVD evolution over their lifetimes, suggesting that the alloying process is prevented or significantly slowed down by the protection barrier. In a couple of years, when the oldest pots reach the end of their lifetimes, full autopsies will be conducted to assess the condition of the copper bars and to explore the recycling potential of the bars.

## 7. References

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