A Novel Cathode Design Using Copper Collector Bars for High Amperage Technologies

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Abstract

The implementation of copper conductors in the Ready-to-Use cathodic system not only allowed to fully avoid rodding but also significantly decreased the specific energy consumption, reducing the carbon footprint of the Hall-Héroult process of high amperage technologies. The basic concepts, the cathode implementation and the operating figures in smelting technologies ranging up to 600 kA for more than two years in operation are highlighted. The robustness of the copper collector bar design is proven by stable low cathodic resistance allowing energy savings per kg aluminum, and the fully intact copper part was confirmed by an autopsy after more than thousand days in operation. Core samples were machined through the cathode and collector bars at different locations and chemically analyzed, concluding that most of the copper value can be recovered after its useful life through conventional recycling processes. Based on these positive results, further cells are planned to be started soon.

Keywords: Aluminum electrolysis cells, Cell design, Copper collector bars, Energy saving, Magneto-hydrodynamics.

1. Introduction

The concept of Ready-to-Use Cathodes (RuC®) was presented for the first time in 2016 [1] and a follow up on the performance of several RuC® high amperage projects is presented. The main philosophy of the Ready-to-Use Cathode is to avoid the costly and hazardous rodding process and to use copper conductors which offer additional advantages in terms of lower pot voltage, lower energy consumption, lower noise level, increased current efficiency, longer lifetime and can be easily recycled at the end of their useful life. Figure 1**Figure** illustrates examples of a cast iron-rodded copper-insert collector bar and a RuC® design. More than 1300 RuC® blocks are installed in 60 cells and started.

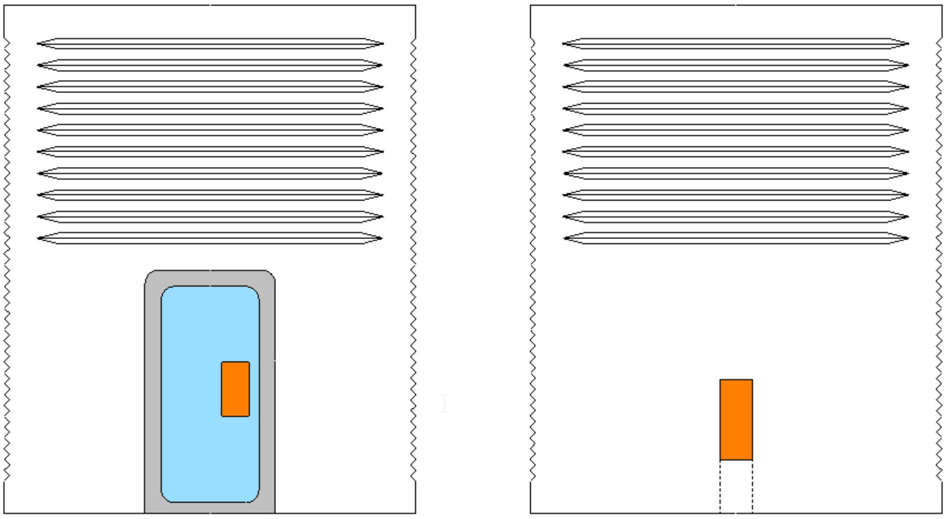

Figure 1. Copper-insert collector bar design example (left) and typical RuC® design (right).

RuC® is a flexible cathodic system, which allows for all smelting technologies an optimized design for thermal balance combined with an improved current distribution, improving the magnetic hydrodynamic (MHD) behavior of the cell, metal pad and lower cathode voltage drop (CVD). Energy saving is a result of the lower pot voltage and improved current efficiency (CE), reducing the carbon footprint of the Hall-Héroult process. By energy saving and increased productivity the electrolysis process gets "greener" and more economical with a lower carbon footprint. The fast and easy implementation caters to the world-wide greenhouse emission reduction targets.

The RuC® stability in CVD with low electrical contact resistance is achieved despite of the lower contact surface (-60%) compared to conventional cathodes. The low level and stable trend of CVD proves the robustness of the cathodic system.

Start-up procedures do not need to be modified when using RuC® but could even be shorter compared to conventional cathodes. Increased stability could be observed by faster stabilization in the early operation phase. By this the pot voltage set point can be reached faster and at a lower level.

This RuC® performance update presents only high amperage projects, operating in the range 300 kA to 600 kA. These RuC® projects are energy saving projects, other running projects aiming only at rodding avoidance and cell life expansion are not presented. RuC® is implemented in the most modern western smelting technologies as well in the Chinese flagship technologies of NEUI. The reference cells and their performance could vary from paste-sealed steel bars to cast iron-rodded steel bars with copper inserts, as well graphitized cathode blocks or semi-graphitic grades. The full copper recycling at the end of cell life constitutes a high residual value for the smelters. Several planned intermediate autopsies were conducted to validate the recycling value by an analysis of copper bars after 1.5 years and 3 years in operation. Metallurgical tests were performed on the collector bars and their integrity was confirmed. Less than 20 ppm additional impurities were found in the copper area close the surface of the bar, which allows the full recycling of copper in a standard and most valuable way.

Because of the high electrical conductivity of copper compared to steel and cast iron, RuC® needs much less metal volume inside the cathode block. The reduced metal volume is replaced by carbon cathode material which increases the distance from the collector bars to the cathode working surface. Compared to conventionally rodded cathodes, this provides 40-100 mm more wearable cathode material in height for erosion, which results in a longer cell life. In addition, the improved magneto-hydrodynamic (MHD) cell state, resulting from lower horizontal current densities in the metal further leads to even longer cell life. The presented RuC® cells have been now operated for 30-50% of the standard cell life. In-situ cathode surface profile measurements are planned (by Lancelot® 3D measurement system [2]) to confirm the life time improvement before the end of the cell life. First in-situ cathode surface measurements of running pots at 400 kA since more than 2 years confirmed, that, due to more uniform current distribution, RuC® average wear rate is 20% slower than for cathodes with standard collector bars.

2. RuC® Performance

2.1 400 kA and 600 kA NEUI Technology

600 kA NEUI technology represents state-of-the-art aluminium reduction in China. Over the past years, not only the size and the amperage of Chinese electrolysis cells have been increased but also the productivity of the cells thanks to higher current densities.

In 2019, 400 kA NEUI cells were started with RuC® blocks. Reference cathodes had cast iron-rodded steel bars. The target was to lower the cathode voltage drop (CVD) and achieve lower specific energy consumption (SEC). Cell life was also expected to be longer thanks to lower maximum current density at the cathode surface (more uniform electrochemical wear) and larger carbon height on top of the collector bars (+85 mm). Beside the cathode upgrade, the lining was modified to enhance the thermal insulation of the cells for maintaining a good thermal balance of the cell at lower internal heat generation.

These trial cells are now more than 800 days old, and their performance can be assessed profoundly. Thanks to the use of copper bars, the effective section of the collector bars is increased, and the CVD is significantly reduced (-98 mV - All time averages of performance indicators exclude the first 90 days of operation, see also Figure 2). The CVD evolution is stable and the increase over time is lower for the RuC® cells compared to the Reference cells.

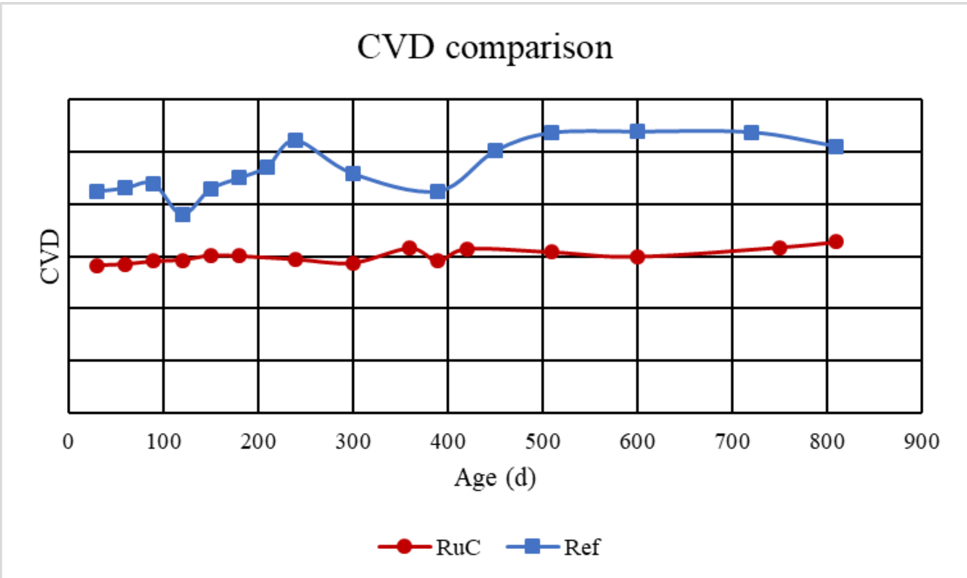

Figure 2. CVD of RuC® and reference cells over time, average difference -98 mV.

The heat losses of the RuC® cells are slightly reduced as mirrored in the lower cell voltage (- 23 mV, see also Figure 3). Thanks to the lower CVD, the anode-to-cathode distance (ACD) is increased and in combination with the enhanced current distribution in the cell, the magneto-hydrodynamic (MHD) stability of the RuC® cells is improved yielding a higher current efficiency (CE) (+1.1 %). As a result, the SEC is decreased by 0.26 kWh/kg as shown in Figure 4.

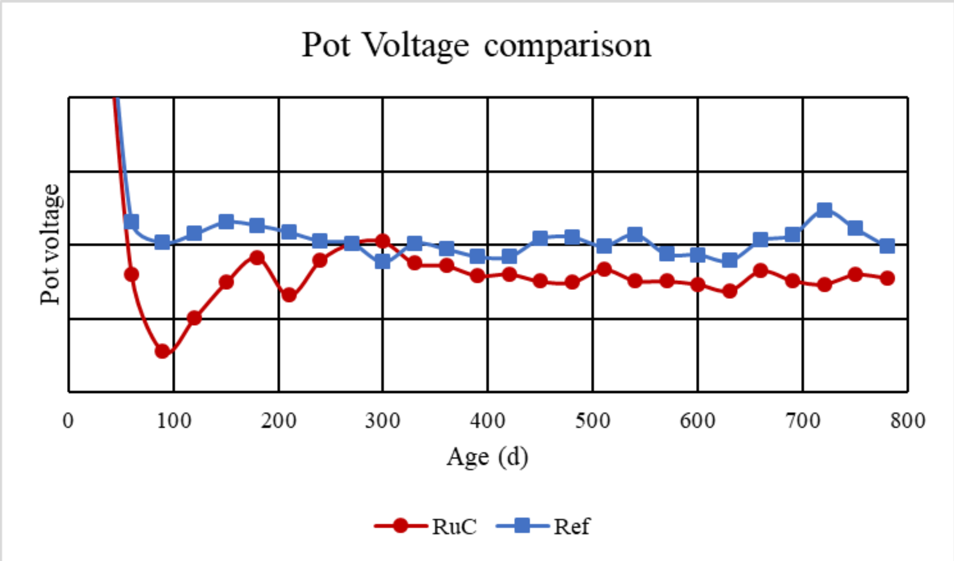

Figure 3. Pot voltage of RuC® and reference cells over time, average difference -23 mV.

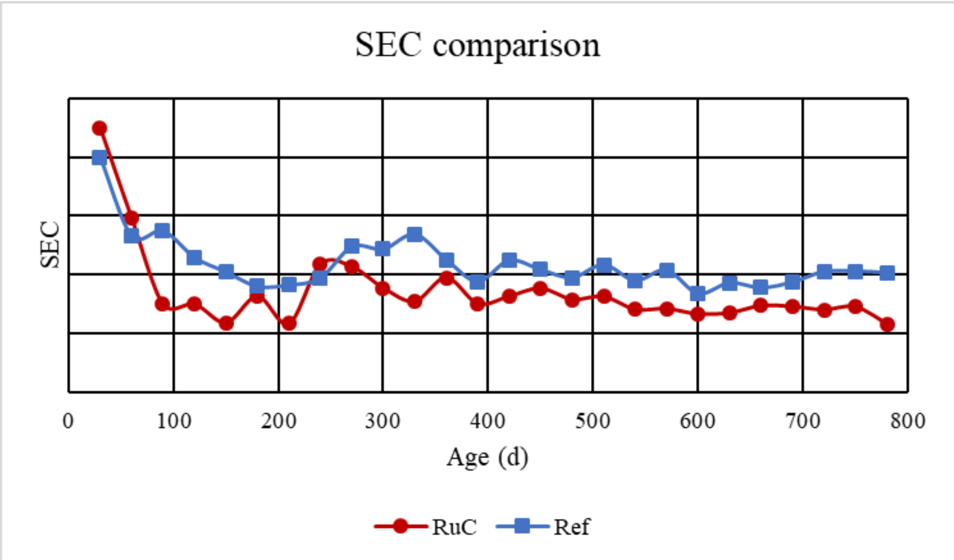

Figure 4. SEC of RuC® and reference cells over time, average difference -0.26 kWh/kg.

Based on the early results of the 400 kA cells, new RuC® and lining designs were developed for the 600 kA NEUI technology with the target to maximize the SEC savings. Additional modelling tools and resources were engaged to better predict the cell performance. In 2020, trial cells were started in a 600 kA line. After 300 days of operation, the normalization period is over, and the performance of the cells is promising.

The CVD is decreased by design but not to the same extent as for the 400 kA cells. As shown in Figure 4, the difference in CVD is -55 mV. The total heat losses, however, are more significantly reduced as indicated by the evolution of the cell voltage (see Figure 6). The difference to the

Reference cells is -72 mV. In terms of heat losses, RuC® cathode design is as important as the lining design and an optimum must be found between low CVD (ACD margin) and low heat losses.

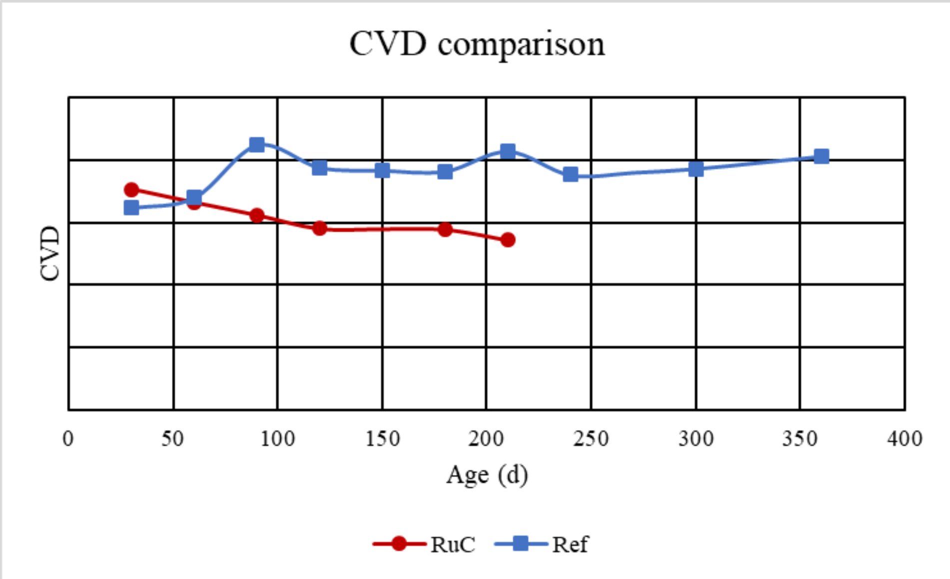

Figure 5. CVD of RuC® and reference cells over time, average difference -55 mV.

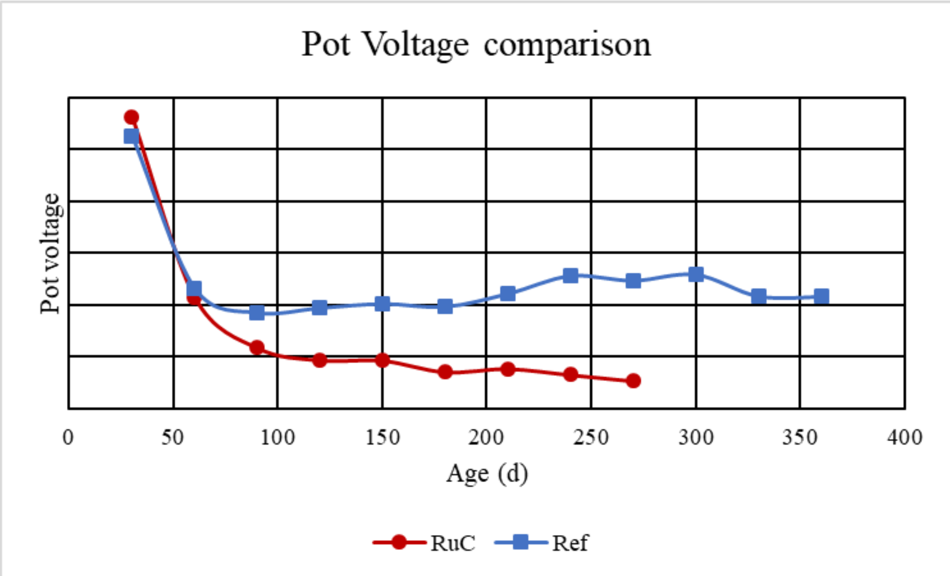

Figure 6. Pot voltage of RuC® and reference cells over time, average difference -72 mV.

Since the ACD could be lowered for the RuC® cells, the gain in cell voltage is larger than the CVD decrease alone. However, despite lower ACD, the current distribution in the cell is improved in such a way that the CE is increased as for the 400 kA cells (+1.1 %). It is noteworthy that anodic and cathodic current densities are higher for the 600 kA cells compared to the 400 kA cells, making the benefit of RuC® on the MHD state of the cells more sensitive.

Thus, thanks to the lower cell voltage and higher CE, the SEC is significantly reduced as shown in Figure 6 (-0.39 kWh/kg). This result confirms the potential of RuC® in terms of performance for the 600 kA NEUI cell and adds up to the other benefits that are the longer cell life (more uniform erosion, +70 mm carbon height) and the recyclability of the copper bars.

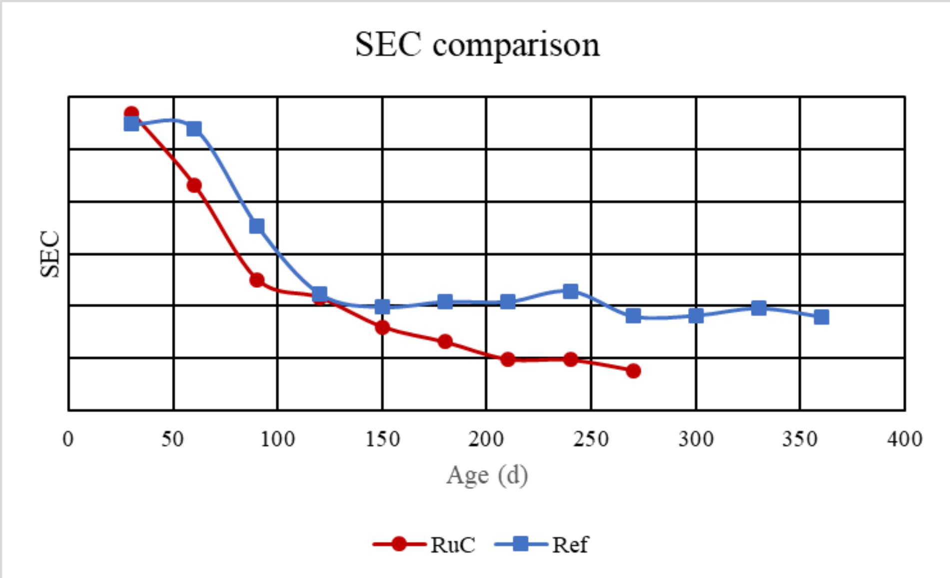

Figure 7. SEC of RuC® and reference cells over time, average difference -0.39 kWh/kg.

2.2 330 kA Technology

In year 2019, RuC® cells were also implemented in a 330 kA line. These cells have a similar design compared to the ones using 400 kA NEUI technology. The interesting feature lies in the continuous CVD data over close to 800 days which confirms the trend observed for the 400 kA and 600 kA NEUI cells. As shown in Figure 8, the CVD is significantly reduced (-116 mV) whereas the cell voltage is decreased but to a lesser extent (-56 mV, see Figure 9). The evolution of CVD is stable and the increase over time is lower than for the reference cells. This demonstrates that the evolution of the electrical contact resistance of the small copper bars inside the cathode is better than for the large cast iron-rodded steel bars.

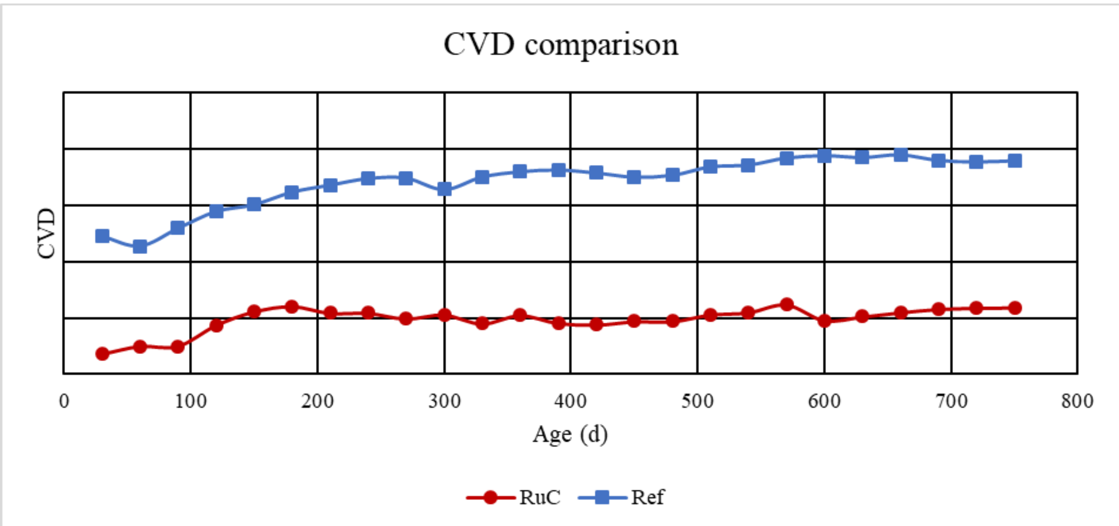

Figure 8. CVD of RuC® and reference cells over time, average difference -116 mV.

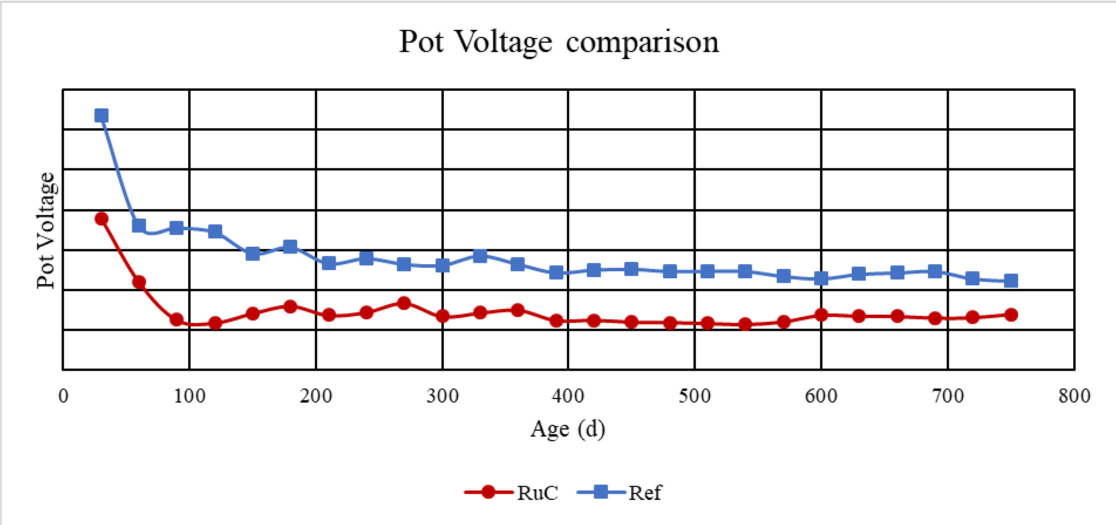

Figure 9. Pot voltage of RuC® and reference cells over time, average difference -56 mV.

For the same reasons as mentioned earlier (larger ACD, more uniform current distribution), the cell MHD stability is improved, and the CE is positively impacted (+0.7 %). All in all, the SEC of the RuC® cells is decreased by 0.27 kWh/kg in average after 800 days of operation.

A new design was proposed to further optimize the performance of the next RuC® cells to be started early 2022.

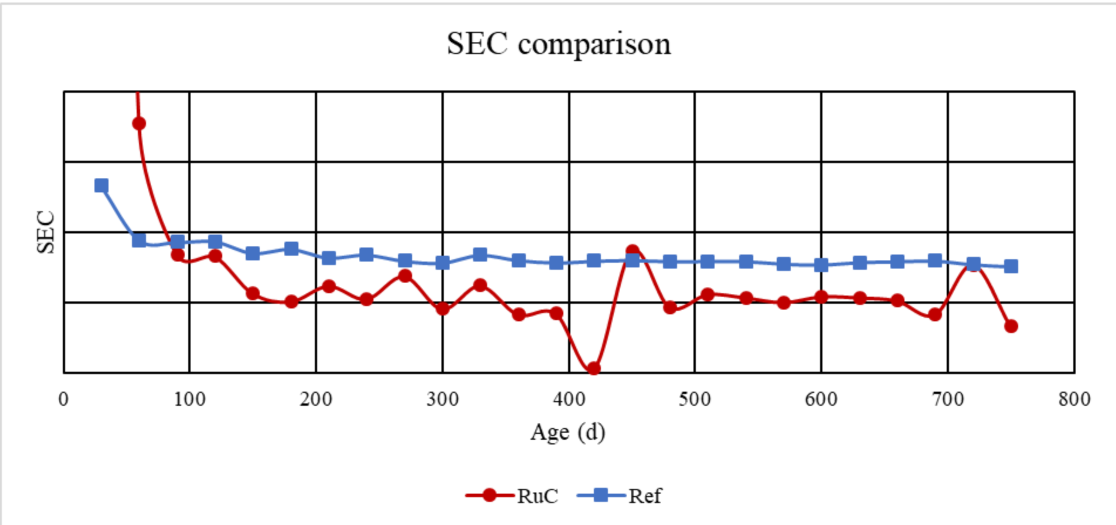

Figure 10. SEC of RuC® and reference cells over time, average difference -0.27 kWh/kg.

2.3 400 kA Technology

This last example is to show that RuC® is not specific to any technology and that it can be adapted to any cell, building up on the existing design to improve the cell performance. In the present case, the reference cathode uses cast iron-rodded steel bars with copper inserts. The cell lining remained untouched and only the cathode blocks were replaced with RuC® blocks. The cells were put in operation in 2019 and cell performance over 700 days of operation is presented.

The CVD changed only slightly (-25 mV, see Figure 11) but heat losses and hence cell voltage are significantly reduced (-115 mV, see Figure 12). Of course, the lower heat losses must provide the same heat balance at bath and metal level to keep the same ledge protection. It is important to remind that heat losses are not only determined by the cell thermal resistance but are also influenced by MHD parameters such as metal velocity (convection), metal level (lower with improved MHD), metal upheaval (ledge shape) or cell instabilities (beam movements, anode cover integrity). Thus, the enhanced MHD state of the RuC® cells contributes to lower cell voltage.

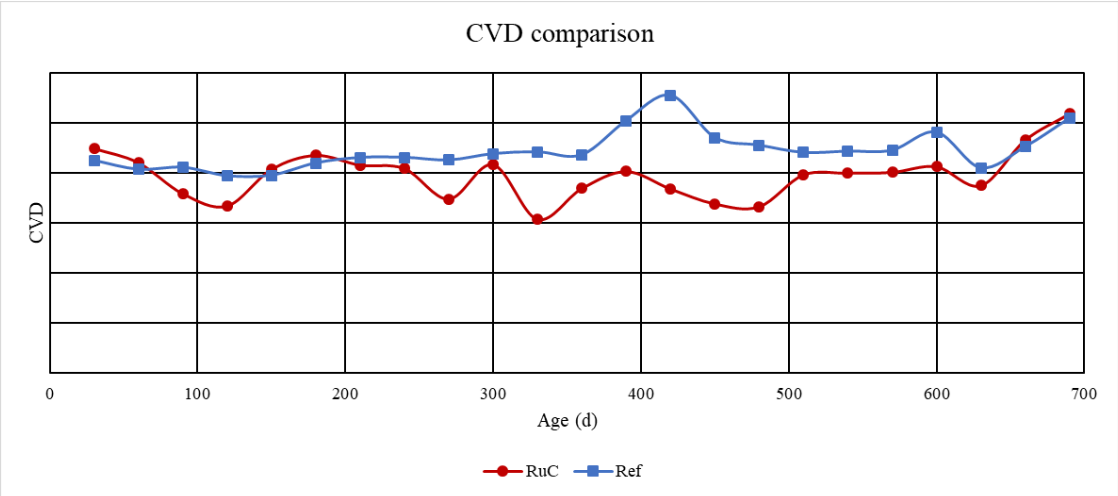

Figure 11. CVD of RuC® and reference cells over time, average difference -25 mV.

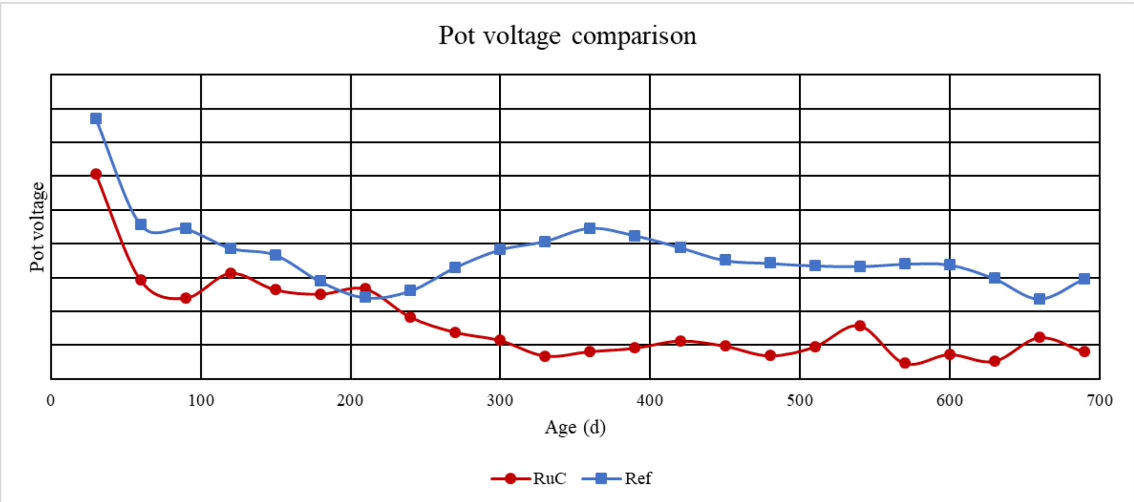

Figure 12. Pot voltage of RuC® and reference cells over time, average difference -115 mV.

3. Copper Analysis

A metallurgical analysis of copper samples was performed, which were more than 800 days in use in RuC® blocks. Figure 13 shows the copper cross section (polished) and 3 spots of analysis. Copper content and impurities were determined by glow discharge optical emission spectroscopy (GDOES) on these positions. All spots have shown copper contents above 99% with minor increase of impurities compared to the original material used. Given this high copper purity, the metal recycling companies can use standard reduction process and pay LME Cu for each kg minus a recycling fee, which ends up above 90% of LME as cash return.

Figure 13. Copper analysis after 800 days in operation, measurement positions

4. Conclusions

The operation of more than 1300 RuC® cathode blocks in 60 cells and data for more than 800 days of operation confirm that the aluminum industry has a new solution to minimize its carbon footprint. Indeed, a reduction of 0.3 kWh/kg represents a saving worldwide of 19 500 GWh/year or 2.2 GW power (for 65 million tons of aluminum produced per year). RuC® demonstrated a stable CVD performance in high-amperage cells with significant energy saving in between 0.2 to 0.5 kWh/kg and with high residual value on the copper bars.

5. References

1. Rene von Kaenel et al., Copper bars for the Hall-Héroult process, *Light Metals 2016,* 20 December 2016, 903-908.
2. Rafal Pacharzyna and Tomasz Oracz, Method for measuring surface profiles in working aluminium electrolysis cells, *WO 2013/068558*, filed November 11, 2012, granted May 16, 2013.