EGA Experience with Full Copper Cathode Collector Bars

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Abstract

Cathode voltage drop (CVD) is an important component of pot voltage. Many initiatives to lower CVD have been implemented in the industry. One of them is copper inserts in the collector bars which has been implemented successfully in many smelters. Recently, this idea has been pushed further by using full copper collector bars that are sealed in the cathode blocks in new, innovative ways without the need for cast iron rodding. The approach aims to achieve two key objectives: reducing CVD and improving current distribution in the pot. A previous paper described the design, preheat, start-up and performance of the proprietary and patented full copper collector bar design test pot (Cu pot) in Emirates Global Aluminium (EGA) [3]. Building on the initial encouraging results of the first pot, several other full copper collector bar pots have been put in operation in different EGA pot technologies. This paper describes the performance of these pots, comparing full copper collector bars pot to collector bar copper insert pots in terms of cathode voltage drop, specific energy consumption, and current efficiency. Results of autopsies of Cu pots are also presented, showing that due to direct contact between carbon and collector bars, an aluminium-copper alloy with high electrical resistivity formed in a surface layer of copper, which is getting thicker with pot age. This layer is ultimately responsible for faster CVD increase with pot age than expected.

Keywords: Full copper collector bars pot, Copper insert pots, Industrial trials.

1. Introduction

One of the recent EGA initiatives for lower specific energy consumption (SEC) in pots was the implementation of full copper collector bars in cathode blocks according to a proprietary, patented design [1-2]. The fist test Cu pot was started up on 10 May 2018 in D20 technology and was successfully operated until the age of 1002 days when it was stopped for cathode surface inspection and then restarted [3]. The average CVD gain was 121 mV with respect to a group of control pots with steel collector bars and 60 mV with respect to a group of collector bar copper insert pots at 275 kA, during the first 1002 days [3]. After the restart, the CVD was higher than before, but the pot continued operating until its planned cut-out at the age of 1405 days.

The initial results of the first Cu pot were encouraging, and EGA expanded the trials to other Cu pots, so that in October 2021 there were already 12 trial Cu pots in operation [3]. The expansion continued so that now EGA has experienced running 30 different pots with full copper collector bars across various technologies at both sites, Jebel Ali and Al Taweelah, with 60 % of these pots still alive. The majority of these pots are from the CD20 and D20 technologies, with only five pots each in DX and DX+ Ultra technologies. In full copper pots, average cathode resistance was by approximately 0.1 µΩ lower than in copper insert pots, regardless of the technology, except in D20, where the gain was approximately 0.16 µΩ. Figure 1 shows the distribution of trial Cu pots among different EGA technologies.

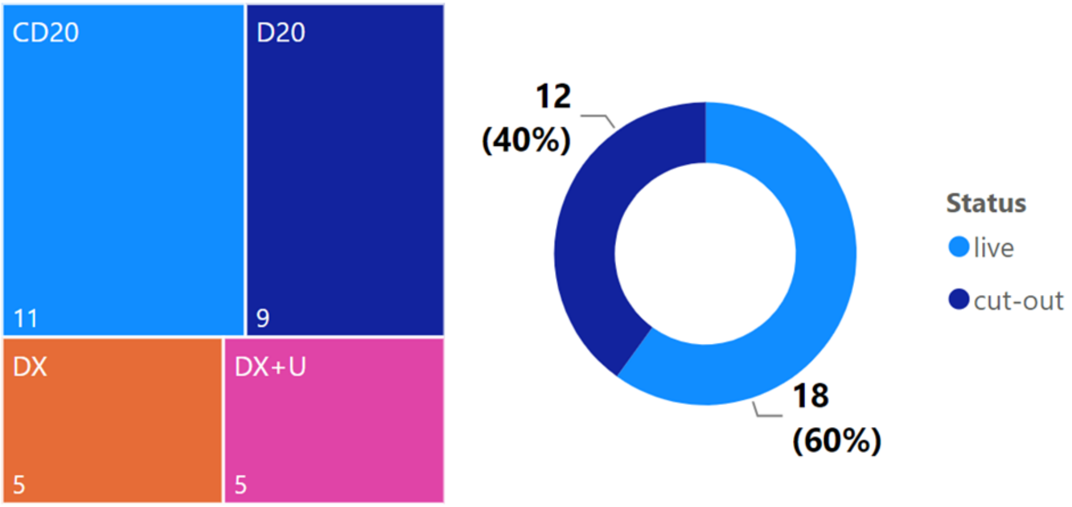

Figure 1. Trial Cu pots across EGA technologies as of June 2024.

Autopsies of several Cu pots were made, and varying degrees of damage on Cu collector bars was found. Most notably, the surface layer of the collector bars was converted to a copper-aluminium alloy of significantly higher electrical resistance and lower melting point than pure copper. This is consistent with the findings of other trials with full copper collector bars in direct contact with carbon [4].

2. Trial Pots

Table 1 gives all pots have or had ever operated with full copper bar design on EGA sites. Pot L5C251 (the fist row in Table 1) is the restart Pot L5C269 (the second row in Table 1); this is the first trial pot, described above. Of all Cu pots, only the first one was given special follow-up with many measurements reported in [3]. All other Cu pots were operating as the rest of the potline. Particular attention should be given to maximum bath temperature because of the low melting point of copper of 1084 °C.

The restart operation involving full copper pots was conducted on only two occasions. the first pot with full copper design, as previously mentioned, was one of them. It was intentionally restarted after 1,100 days to evaluate the condition of the cathode surface and to gain experience in restarting a fully copper pot, along with addressing the associated new challenges [3]. In contrast, the second restart attempt was entirely unplanned. It involved a CD20 technology pot with a full copper design, specifically Pot L5C159, which had to be cut-out after just 64 days of operation due to a special reason. The pot was subsequently restarted in Pot L5C092, which is still in operation and has now reached 1 174 days of service.

To assess the performance of each full copper pot, we selected a group of equivalent control pots from the copper insert collector bar design, ensuring that the control pots had the startup date within 1-2 months of the corresponding full copper pots and preferably from the same potline. We organised the copper pots into groups or batches based on their technology and start-up period. Using this classification, we matched each group of full copper pots with a corresponding group of control pots. There were 9 control pots D20, 18 in CD20, 10 in DX and 5 in DX+ Ultra.

Table 1. Full copper collector bar pots have or had operated in EGA.

Tech	Pot ID	Start Date	Status	Cutout Reason
D20	L5C251*	10-May-2018	Cut-out	Planned cut-out
D20	L5C269	10-May-2018	Cut-out	Planned cut-out
D20	L7C133	16-Dec-2021	Live	
D20	L9C101	19-Dec-2021	Live	
D20	L7C206	21-Dec-2021	Live	
D20	L7C224	23-Dec-2021	Live	
D20	L7C201	24-Dec-2021	Live	
D20	L7C237	27-Dec-2021	Live	
D20	L7C129	28-Dec-2021	Live	
CD20	L5C160	17-Sep-2020	Live	
CD20	L6C022	05-Nov-2020	Live	
CD20	L6C123	01-Jan-2021	Live	
CD20	L5C159	21-Jan-2021	Cut-out	Special reason
CD20	L5C092**	21-Jan-2021	Live	
CD20	L6C088	25-Jan-2021	Live	
CD20	L6C204	20-Sep-2021	Live	
CD20	L5C012	14-Oct-2021	Live	
CD20	L5C231	11-Jan-2022	Cut-out	Special reason
CD20	L6C228	27-Jan-2022	Live	
CD20	L6C049	28-Jan-2022	Live	
DX	2A159	08-Apr-2020	Cut-out	Special reason
DX	1A034	01-May-2020	Live	
DX	1A041	09-Jun-2020	Cut-out	Planned cut-out
DX	2B163	16-Jul-2020	Cut-out	Planned cut-out
DX	2B132	03-Oct-2020	Live	
DX+U	L5C277	29-Mar-2022	Cut-out	Planned cut-out
DX+U	L5C276	05-Apr-2022	Cut-out	Planned cut-out
DX+U	L5C275	16-Apr-2022	Cut-out	Planned cut-out
DX+U	L5C274	18-Apr-2022	Cut-out	Planned cut-out
DX+U	L5C273	30-Apr-2022	Cut-out	Planned Cut-out

* Pot L5C251 is a restart of Pot L5C269, with a restart date of 23 March 2021.

** Pot L5C092 is a restart of Pot L5C159, with a restart date of 10 April 2021.

3. Cathode Resistance

3.1 Overall Average Cathode Resistance

The primary objective of the Cu pots was to decrease cathode resistance and CVD. This objective was achieved, but to a lesser extent on the average than observed in the early life. Figure 2 gives the overall average for all pots. The difference in resistance corresponds approximately to 43 mV for D20, 23 mV for CD20, 44 mV for DX and 53 mV for DX+ Ultra.

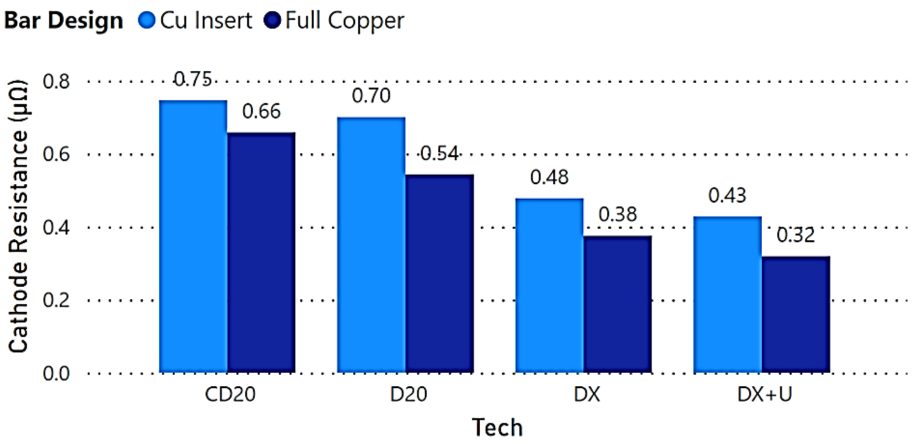

Figure 2. Average cathode resistance of Cu pots and control pots for each technology, either over lifetime for cut-out pots or until 24 April 2024 (the date of assessment as per Table 1).

3.2 Trends with Pot Age

Most copper pots initially exhibited very low cathode resistance, which then increased rapidly. However, some copper pots, particularly those from D20, as well as some of DX and DX+ Ultra pots, showed a period of stabilisation after a few months of rapid increase. During this stabilisation period, the cathode resistance became more consistent for an extended duration. It is likely that the formation of the Al-Cu alloy on the surface of the collector bars, as observed during the autopsies, decelerated once the alloy layer thickened. Additionally, as the cathode block became increasingly saturated with the bath, the rate of bath percolation diminished. This slowdown in percolation resulted in a reduced rate of aluminium deposition on the surface of the copper bars, which in turn stabilised the increase in resistance. Figures 3–6 present the trend lines of average cathode resistance (in microohms) versus pot life (in days) for each technology – CD20, D20, DX, and DX+ Ultra – comparing full copper pots to control pots.

To maintain the overall average trend of the Cu pots, a few exceptions where the cathode resistance trend deviated from the norm were excluded. Figure 7 illustrates examples of these exceptional trends for each technology.

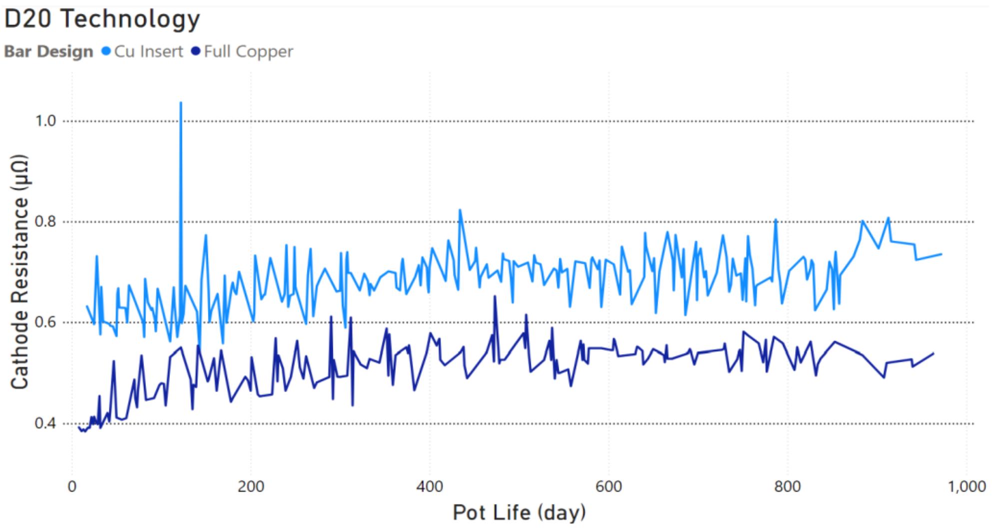

Figure 3. Average cathode resistance of Cu pots and control pots over pot life for D20 technology.

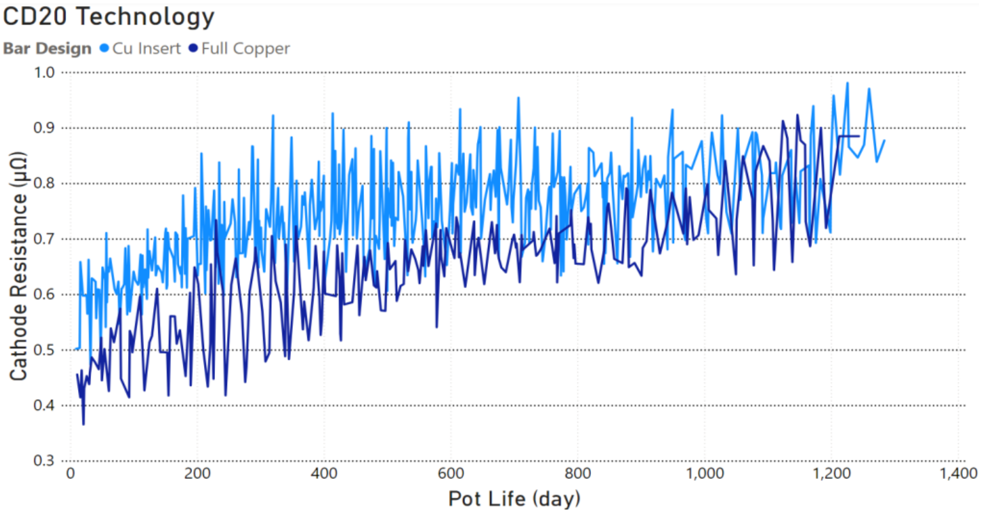

Figure 4. Average cathode resistance of Cu pots and control pots over pot life for CD20 technology.

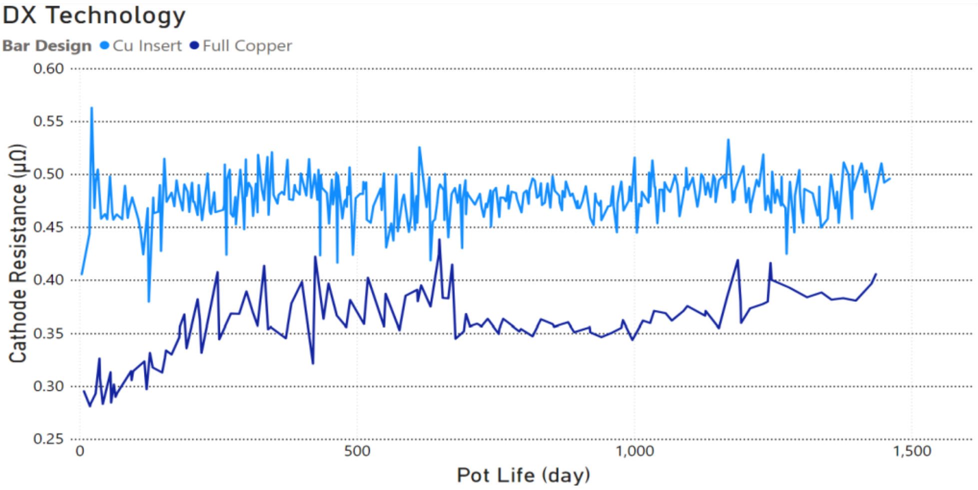

Figure 5. Average cathode resistance of Cu pots and control pots over pot life for DX technology.

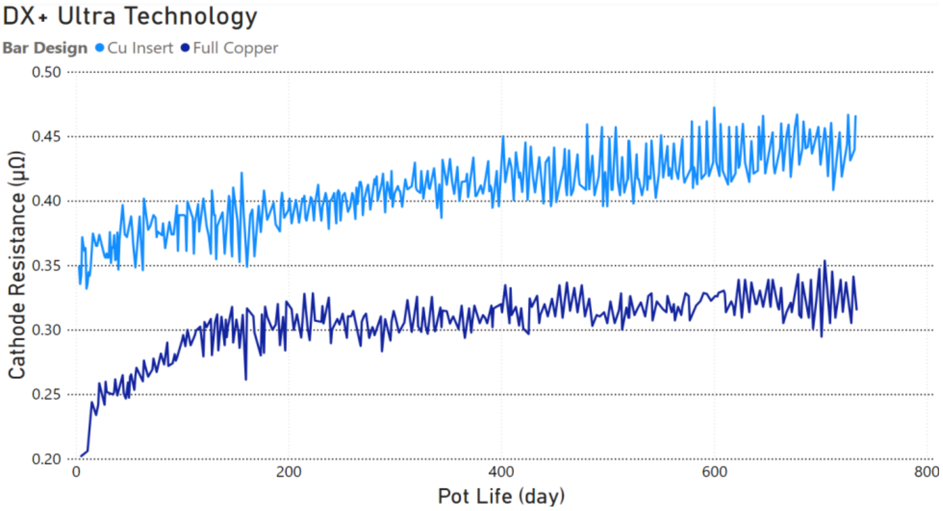

Figure 6. Average cathode resistance of Cu pots and control pots over pot life for DX+ Ultra technology.

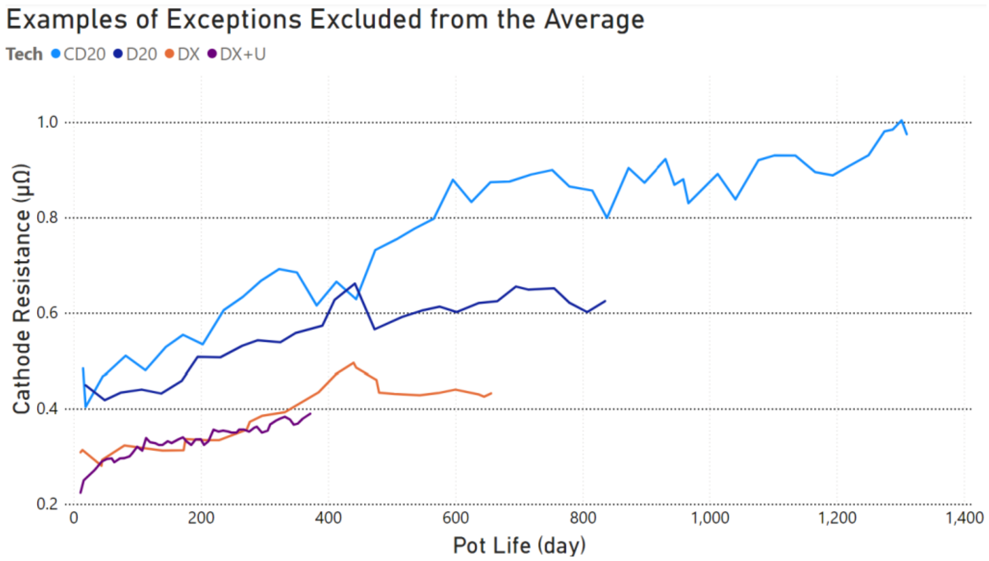

Figure 7. Example of few exceptions excluded from the average cathode resistance of Cu pots in each technology.

4. Cu Pots Performance

In spite of the lower CVD, the specific energy consumption in most full copper pots was higher than in their copper insert equivalents, with only a few pots showing low specific energy consumption. The primary issue appears to be that the copper bars are dissipating more heat, and require higher voltage, which hinders the ability to reduce energy consumption. Also, pot instability (noise) was in general higher in Cu pots that in control pots, and current efficiency was lower than in control pots. There were some differences between pot technologies. Figures 8-11 compares the average energy consumption (kWh/kg Al) over the pot life (days) for Cu pots and control pots in each technology

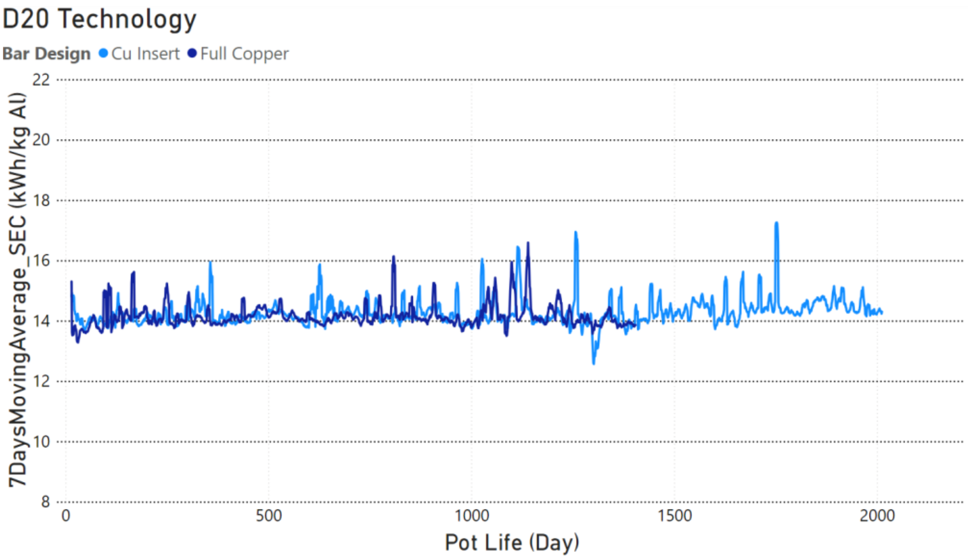

Figure 8. Average energy consumption of Cu pots and control pots over pot life for D20 technology.

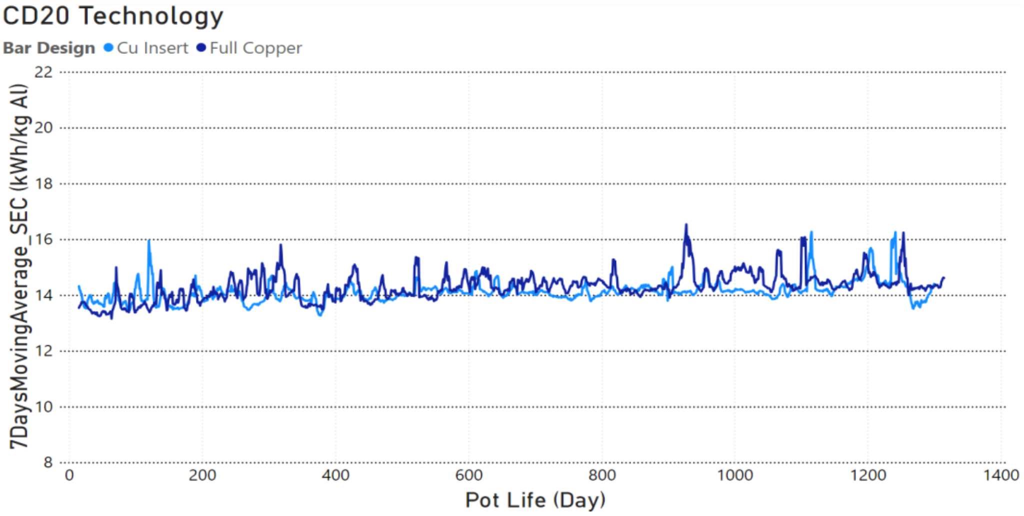

Figure 9. Average energy consumption of Cu pots and control pots over pot life for CD20 technology.

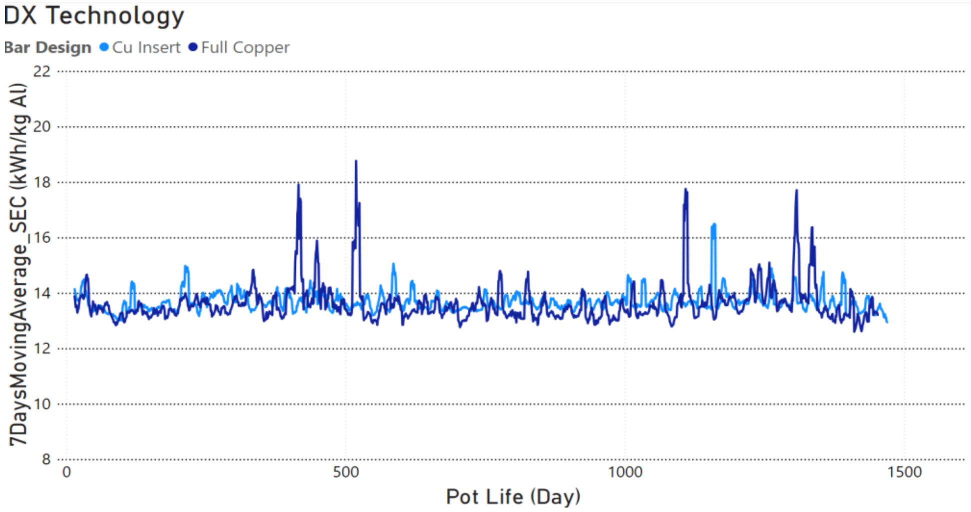

Figure 10. Average energy consumption of Cu pots and control pots over pot life for DX technology.

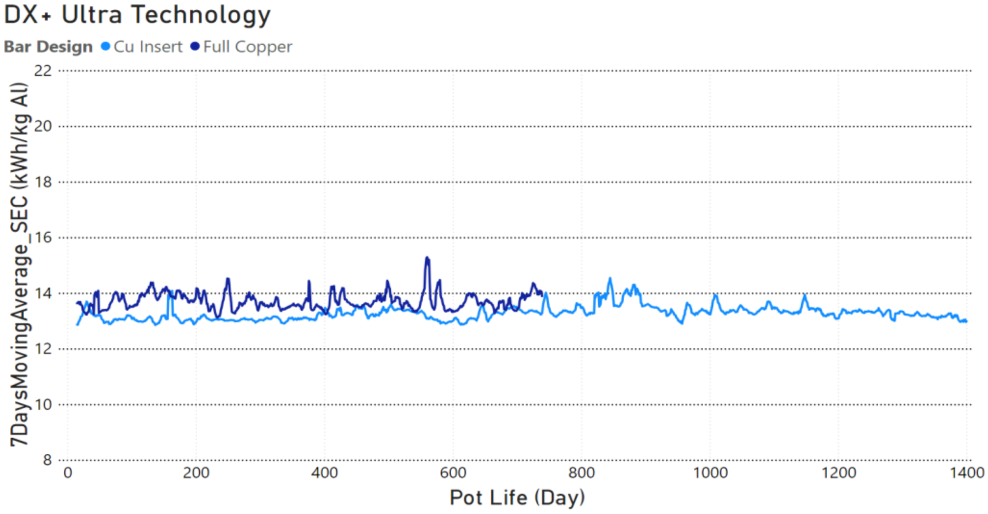

Figure 11. Average energy consumption of Cu pots and control pots over pot life for DX+ Ultra technology.

4.1 D20 Pots

The D20 trial group of Cu pots consists of only two sets of Cu pots. The first group comprised a single pot, which was the first Cu pot introduced at EGA in 2018. The second group, started up in 2021, included seven Cu pots, most of which have demonstrated relatively strong performance, particularly in terms of energy consumption. However, two pots from this group were found to be underperforming.

In the first Cu pot, which began operation in 2018, specific energy consumption was initially approximately 0.3 kWh/kg Al higher than that of the control pots during the first year after start-up. However, over time, this gap narrowed as the energy consumption in the control pots gradually increased. It is also worth noting that the current efficiency in this Cu pot was, on average, about 1.4 % lower than that of the control pots.

In 2021, seven D20 pots equipped with full copper bars were started up, all of which remain operational. Six of these pots are located in Jebel Ali Line 7, with the remaining one pot in Line 9. Over more than 850 days of operation, key performance indicators, including energy consumption, current efficiency, bath temperature, and anode effect frequency, have consistently shown strong performance. The specific energy consumption in these seven Cu pots has been consistently lower than that of their copper insert counterparts. In Potline 7, the average reduction in energy consumption was ~0.15 kWh/kg Al, excluding the underperforming pots L7C237 and L7C129 from the Cu pots and L7C099 from the control pots. The single Cu pot in potline 9 demonstrated an even greater reduction, with ~0.28 kWh/kg Al less than the control pot in the same line.

Additionally, the current efficiency in this group of Cu pots was relatively good. In Potline 7, the Cu pots showed a slight increase in current efficiency of approximately ~0.15 % compared to the control pots in Potline 7, again excluding L7C237, L7C129 and L7C099, while the Cu pot in potline 9 exhibited a greater increase, with a ~1.3 % higher than the control pot in the same line.

4.2 CD20 Pots

Overall, all Cu pots in CD20 showed generally an increasing trend in specific energy usage over the pot life, with significant fluctuations that grow in magnitude over time. Initially, the energy consumption fluctuates within a range of approximately 13.3 to 14.8 kWh/kg Al, but as the pot life extends beyond 200 days, these fluctuations intensify, with peaks reaching up to ~15.9 kWh/kg Al and occasional drops as low as ~13.5 kWh/kg Al. In the later stages, particularly beyond 600 days, the fluctuations become even more pronounced, with energy consumption peaking at around 17 kWh/kg Al and dipping to about 13.9 kWh/kg Al. along these variations, the baseline energy level increases from ~13.89 kWh/kg Al to ~14.43 kWh/kg Al, indicating that while the pot stability decreases, the underlying energy consumption increases. Compared to the control pots, the Cu pots demonstrated slightly higher and less stable specific energy consumption. During the first 600 days of pot life, Cu pots had a similar baseline energy level than the control pots of around 13.9 kWh/kg Al. After 600 days, when the fluctuation of Cu pots intensified, the average energy consumption of Cu pots became higher by ~0.25 kWh/kg Al compared to the control pots.

The current efficiency for Cu pots is relatively high during first 200 days, often exceeding 95 %, but as time progresses, there is a noticeable decline, with the trendline indicating a gradual decrease in efficiency. The data shows considerably less consistent performance, with efficiency cycles varying by approximately 5 %. Despite these fluctuations, the overall trend indicates a gradual decline in efficiency as the pot life progresses, eventually stabilising at a 2 % lower current efficiency compared to the control pots after 600 days of operation. This suggests that while there are short-term variations, the long-term performance of the pot tends to stabilise at lower efficiency.

4.3 DX Pots

In DX technology, the comparison of both net specific energy (kWh/kg Al) and current efficiency between Cu pots and control pots reveals subtle yet important differences in their average lines and variability. Net specific energy of Cu pots has a slightly lower average of ~13.5 kWh/kg Al compared to ~13.6 kWh/kg Al for the control pots, but the Cu pots exhibit greater fluctuations with higher standard deviation of ~1.1 kWh/kg Al versus ~0.4 kWh/kg Al for the control pots. Similarly, when comparing current efficiency, Cu pots again show greater fluctuations here as well, with a higher standard deviation of ~6 % compared to ~3 % for the control pots. Additionally, the overall average current efficiency of Cu pots is 0.7 % lower than the control pots.

A closer look at trial groups of Cu pots individually reveals key differences: Cu pots of 2B163 and 2B132, achieved a higher average current efficiency by ~2 %, and lower energy consumption by ~0.4 kWh/kg Al in comparison to the control pots. Conversely, the other Cu pots of 1A034 & 1A041, had a lower average current efficiency by ~2 %, and higher energy consumption by ~0.2 kWh/kg Al. On the other hand, 2B163 & 2B132 have shown an increasing cathode resistance over the past three years, averaging approximately 0.44 µΩ, while 1A034 & 1A041 have maintained almost stable cathode resistance over approximately 3.5 years, with an average of around 0.37 µΩ. It is worth mentioning that the start-up of each Cu pot was separated by only about 1-3 months. Additionally, both trial groups were built using the same potlining designs, with only difference that 2B163 & 2B132 were equipped with graphitized cathode blocks, while 1A034 & 1A041 used impregnated graphitized cathode blocks.

4.4 DX+ Ultra

Despite having a lower cathode resistance by 0.24 µΩ, equivalent to 115 mV at 480 kA, the average specific energy consumption (SEC) in the Cu pots was 0.36 kWh/kg higher than in the previous generation of Cu insert pots. Additionally, the current efficiency (CE) in the Cu pots was 0.27 % lower compared to the Cu insert pots.

5. Pot Autopsies

Autopsies of the pots aged between 64 and 1405 days revealed varying degrees of damage on Cu bars due to partial melting, particularly on the bottom and top surfaces. Figure 12 illustrates this damage, with the left image showing the bottom surface of a typical copper bar within the cathode block, and the right image showing the top surface of another copper bar after the cathode block was broken. These collector bars, taken from Al Taweelah DX pot 2B163 after a planned cut-out at around 660 days, showed no evidence of direct liquid aluminium penetration. Nevertheless, all the bars exhibited significant melting damages. The most pronounced signs of melting were observed on the bottom surface, where copper had leaked into the sub-cathodic refractory, leading to a loss of volume. A thin layer of bath, 1-2 mm thick, was also found between the copper bar and the cathode block along the side faces. Additionally, melting was evident on the top surface of the copper bars, particularly at the inner end and along the sides, as shown in the right image of Figure 12.

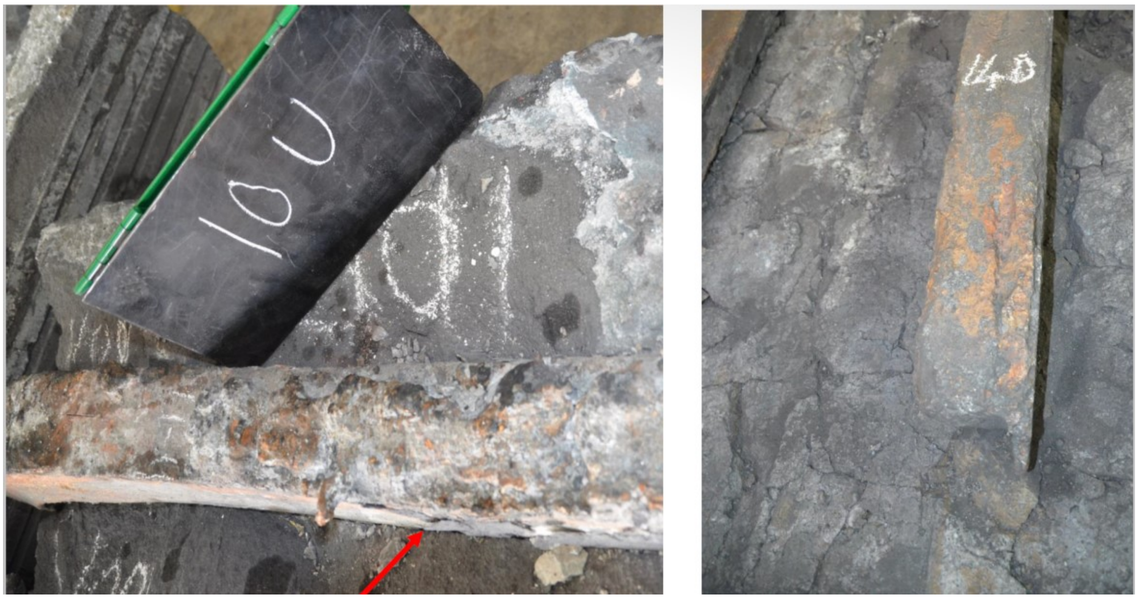

Figure 12. Bottom (left) and top surface (right) of typical copper bars.

A yellow metallic alloy was observed around the perimeter of all Cu bars, primarily on their top surfaces and along the top edges. When a typical Cu bar from the same pot (as shown in Figure 13) was cross-sectioned, it was found that this yellowing had penetrated 5–15 mm into the copper from all sides. Brinell hardness testing (BHN) and electrical conductivity measurements (%IACS) performed on the yellowed zones revealed that the electrical conductivity had decreased to approximately 20 % of that of pure copper, while the mechanical hardness had increased by about 60 % compared to the original hardness of pure copper. SEM/EDX analysis identified the yellow-colored alloy as a Cu-Al alloy containing approximately 5-10 wt.% Al, which is low aluminium content (Cu-Al) alloy. Notably, based on the Al-Cu phase diagram, this alloy's melting point is approximately 30–50 °C lower than that of pure copper.

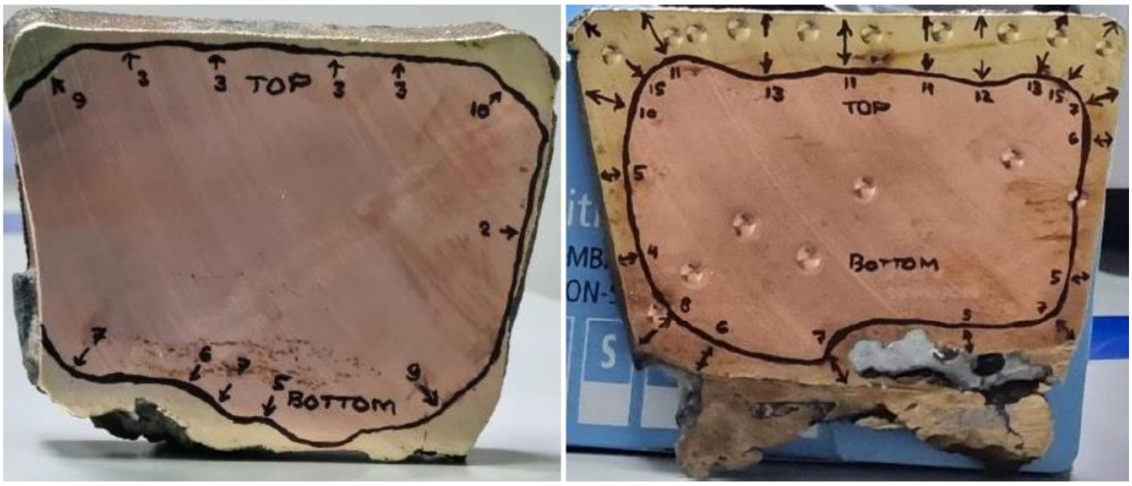

Figure 13. Marked boundary for yellow-colored alloy on cross-sectional surface of typical Cu bars. The numbers indicate thickness of the alloy in mm.

Given the absence of direct contact with molten aluminium, it is likely that the aluminium was deposited on the Cu bar surface through bath and sodium percolation via the cathode block porosity. As the catholyte bath already contains aluminium Al^{3+} ions, aluminium is preferentially deposited on the copper bar surface, where it diffuses and alloys with copper. Further explanations and a possible chemical reaction are given in [4].

Moreover, one DX+ Ultra Cu pot tapped out at upstream collector bar 5 early in its operational life, though this event was not catastrophic; the metal quickly solidified upon exiting the pot. The collector bar at the tap out location was subsequently removed, the window opening was sealed with refractory material, and the pot continued operating for an additional year. However, it eventually required to be cut out due to uneven current distribution among the collector bars around the tap out area, as depicted in Figure 14.

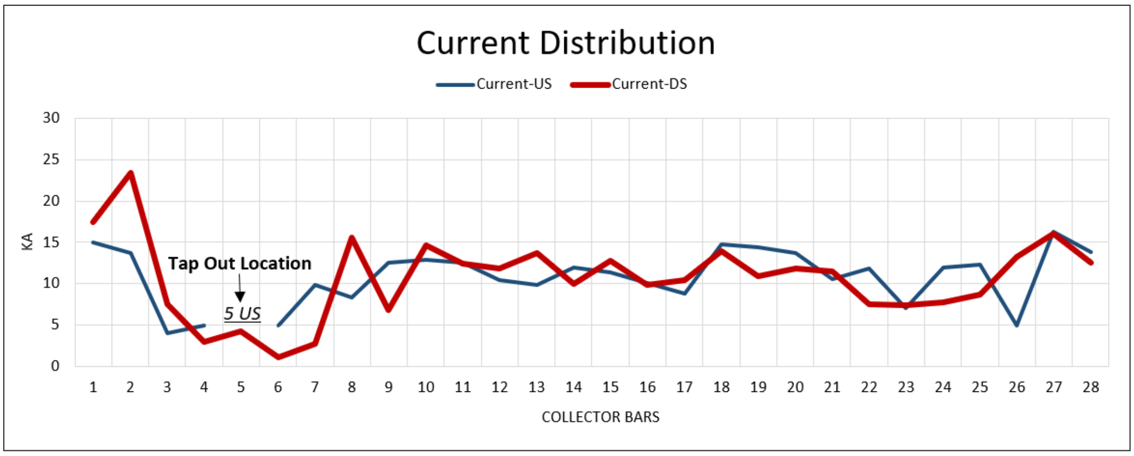

Figure 14. Current distribution (kA) across collector bars: upstream (US) vs downstream (DS), highlighting tap out location.

Figure 15 illustrates the copper bar where the metal tap-out occurred. The exact timing of this event remains unclear, as the metal analysis did not provide definitive indications. The issue was discovered only after 10 days of operation during routine checks on the collector bars, implemented as a precautionary measure. Despite this, as Figure 16 indicates, the copper content in the liquid aluminium remained below 0.1 % throughout this period, peaking at 0.06 % on the startup day before gradually declining. There was a slight increase on day five, from 0.03 % to 0.05 %, which then decreased again. This uptick might suggest that the tap-out occurred on this day, although 0.05 % is still considered a very low value. Laboratory analysis of a sample from the metal tapped out revealed a composition of 60 wt.% Cu and 30 wt.% Al, identifying it as a Cu-Al alloy with a moderate aluminium content and of a very low melting point, likely contributing to the tap-out event.

Figure 15. The location of metal tap-out from collector bar window showing the melted collector bar to cathode flexible connection (left), the same collector bar window after copper bar removal and sealed with refractory castable (right).

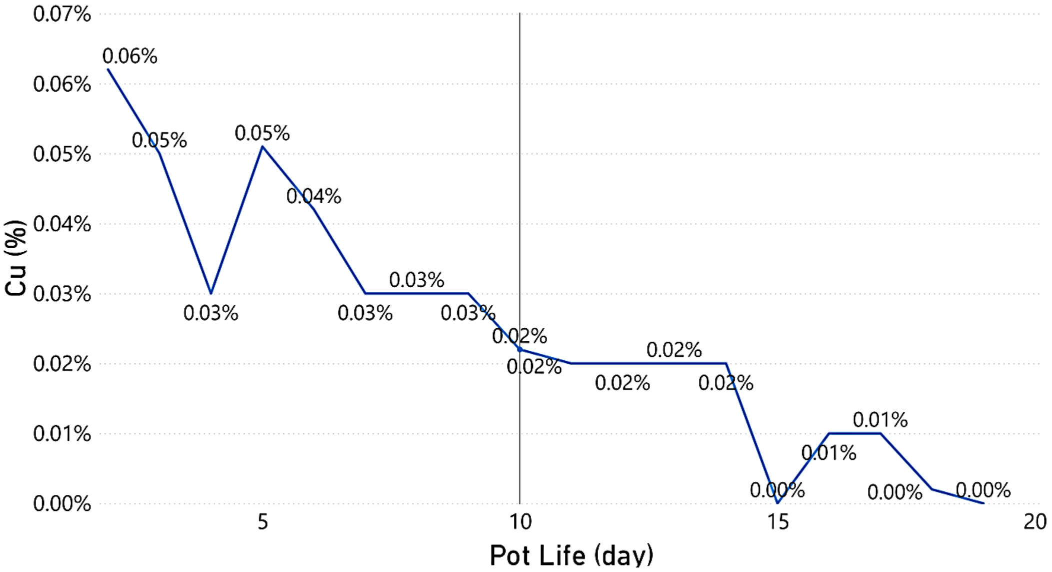

Figure 16. Cu content (%) over pot life (day) during the period surrounding tap-out discovery on day 10.

During the autopsy, it was revealed that this pot was experiencing infiltration through several T-joints, where the small joints (ramming paste between cathode blocks) intersected with the large joints (peripheral ramming paste). These intersection joints (T-joints), located above the collector bars, which were drawing low current, showed significant signs of infiltration, particularly at the location of the early tap-out. Aluminium carbide was observed along the T-joint toward the affected collector bars. The left photo in Figure 17 shows that the aluminium carbide penetrated through the T-joints and reached the end face of the cathode blocks at the level of collector bars, this photo was taken after the removal of the peripheral ramming paste. The right photo shows the cross-sectional cut of the copper bar viewed from inside the pot, highlighting the penetration of a silver-coloured Al-Cu alloy through the copper bars as they exit the cathode block.

Figure 17. Al_4C_3 penetration through the T-joint and end face of cathode blocks (left), and cross-sectional cut of copper bar highlighting silver-colored Al-Cu alloy penetration just before entry into the cathode block (right).

As depicted in Figure 18, it was observed that all collector bars with low current pick-up have converted into a silver-colored Cu-Al alloy within the cathode blocks. This suggests that all these Cu bars were most likely in a liquid state at the pot operating temperature, held in place by the solid portion at their outer ends where they exit the cathode block. Consequently, the pot faced a significant risk of a sudden cut-out due to multiple copper bars being compromised, exposing the potline operation to inevitable danger.

Figure 18. Cu bars of low current pickup after being taken out from the cathode blocks.

Our findings are also in alignment with other trials involving full copper collector bars in direct contact with carbon [4].

6. Conclusions

The Cu pots typically start with very low cathode resistance, which rises rapidly at first. However, this increase eventually slows down, leading to a period of stabilisation. The increase in cathode resistance typically ranges between 0.1–0.2 μΩ, depending on the pot technology. Autopsies suggest that the rapid rise in cathode resistance after start-up is due to aluminium dissolved in the bath percolating through carbon structure of the cathode blocks, where minimal sodium uptake occurs. This aluminium deposits onto the copper bars, forming a Cu-Al alloy with low aluminium content. The alloy begins forming on the outer surface of the bar and penetrates inward over time. Because the Cu-Al alloy has poor electrical conductivity, it directly causes the observed rise in cathode resistance after start-up.

As the cathode block nears saturation, bath percolation slows significantly, reducing the deposition of aluminium on the copper bar surface. Additionally, the increasing thickness of the already-formed Cu-Al alloy layer slows the formation of new Cu-Al alloy, leading to a gradual stabilisation of cathode resistance.

One key property of the Cu-Al alloy with low aluminium content is its relatively low melting point, which increases the likelihood of copper melting. Autopsies showed this melting in copper bars, starting from the inner end and extending to the upper edges and bottom surface. The molten copper sinks into the viscous sub-cathodic layers, reducing the collector bar volume. This loss of volume creates additional space for bath accumulation, which forms an insulating layer between the copper bar and the cathode block, further raising cathode resistance.

Moreover, as copper volume decreases or Cu-Al alloy forms, the contact resistivity between the copper and carbon increases. This higher resistivity can cause localised arcing, which generates heat and further melts the copper bar. This sets off a vicious cycle: as the bar melts and loses volume, contact resistance increases, leading to more arcing and heat generation, which further melts the bar, ultimately increasing cathode resistance. Since the copper is already operating close to its melting point, only a small amount of additional energy is needed to trigger localised melting. Once this cycle begins, it is difficult to break and it operates similarly to a snowball effect.

Another challenge with the performance of most Cu pots is their relatively high energy consumption and instability. The primary issue appears to be excessive heat loss through the copper bars, escaping outside the pot shell. This excessive heat flow prevents operators from making the necessary adjustments to optimise and reduce energy consumption.

7. References

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