Potlife and Pot Design Evolution at Alcoa Deschambault

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Abstract

Alcoa Aluminerie de Deschambault started its operation in 1992, 264 cells using AP-30 technology, with an initial nominal amperage of approximately 300 kA. Since then, more than 1600 cells have been started as part of regular operation. Through capital investments, people dedication, pot design optimization, improved process control and optimized operating procedures, the smelter increased amperage in many steps and is on its way towards 405 kA. Managing different pot designs at the same time, without compromising potlife, is of prime importance to optimize the smelter economics during amperage creep periods and during steady-state operation. This paper presents the results of potlife management and optimization methods, since the initial start-up, accounting for different new pot designs and the challenges that come with them and from the almost continuous amperage creep.

Keywords: Cathode design, Potlife, Process optimization, Amperage creep, Aluminium reduction.

1. Introduction

Aluminum is industrially produced using the Hall-Héroult process, based on carbon anodes [1]. A few other processes have been developed [2], although a limited subset such as inert anodes [3, 4], carbothermic reduction [5] or the Alcoa chloride process [6] were tried at different pilot scale stages over time and have yet to be deployed for industrial mass production.

The Hall-Héroult process [1] occurs within metallurgical reactors, called pots or cells, at about 950 °C, where a continuous current (100 to 600 kA) dissociates alumina (Al_2O_3) into aluminum (Al) and oxygen (O), as shown in Equation (1). Oxygen reacts with the carbon (C) anodes to produce carbon dioxide (CO_2) and the molten aluminum deposits at the bottom of the cell. This reaction happens within a molten fluoride salt bath containing the dissolved alumina.

$$2Al_2O_3 + 3C = 4Al + 3CO_2 \tag{1}$$

The pot sidewalls are lined with materials such as silicon carbide or graphite plates, which need to be protected from the molten bath by a frozen layer of bath. The bottom part of the cell is made of carbon-based cathode blocks, connected to electrical connectors to close the electrical circuit, and different layers of refractory and insulating materials. The pots are designed to dissipate sufficient heat in a way to keep a given layer thickness of frozen bath, called ledge, on its inner sides. In practice, the pots are designed to operate at a given current and electrical resistance with a specific molten bath chemistry. Deviations from those targets, or operating ranges, result in operation instabilities affecting the cell productivity (metal production rate), the electrical energy consumption, the metal quality, or the pot life duration.

In practice, excluding early failures [7], the pots need to be stopped and replaced either 1) preventively to manage the pot relining rate, 2) due to poor operation performance or 3) following a bottom or side failure. A bottom failure could happen locally if the cathode erosion reaches one of the steel collector bars. Such an event eventually dissolves part of the steel bar, thus leading to a molten aluminium leak. On the other hand, a side failure could happen locally on the side of the pot shell when the frozen ledge protection disappears, thus exposing the side-lining material to the molten bath. The bath eventually dissolves the material, reaches the steel shell, and eventually leaks out of the pot. Depending on leak location, bath and some molten aluminium may leak from the pot. In both cases, the pot needs to be stopped and replaced with a new one. As this replacement takes place, busbar and concrete floor damages from leakages may need to be repaired, therefore delaying the new pot start-up. Hence, managing potlife is a matter of maximizing potlife while minimizing the occurrence of side and bottom failures.

To maximize economic benefits from an operating smelter, aluminum producers are heavily relying on amperage increase to produce more aluminum with the same assets [8, 9, 10] without undertaking major pot technology modifications. One such example is the Alcoa Deschambault smelter, which started its operation in 1992, based on 264 pots using the AP-30 technology, with an initial nominal amperage of approximately 300 kA. Through capital investments, people dedication, pot design optimization, improved process control and optimized operating procedures, amperage was increased in many steps, as shown in Figure 1, and is on its way towards 405 kA.

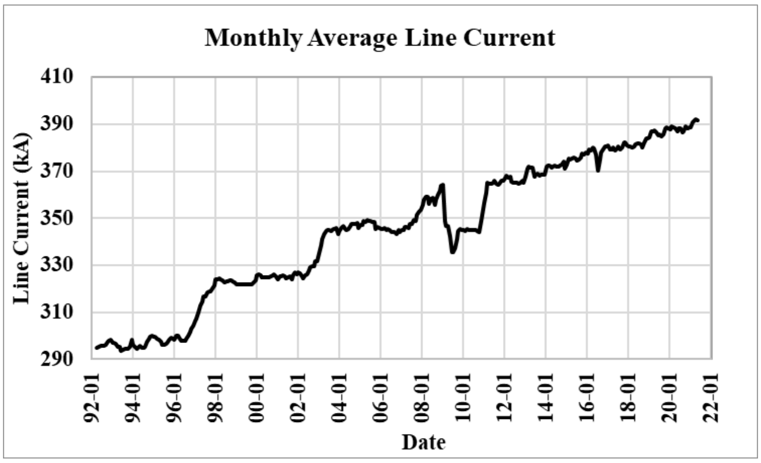

Figure 1. Monthly average line current at Alcoa Deschambault smelter.

However, increasing amperage generally requires converting to a different pot design, aimed to provide optimal and robust performance at the new amperage operating target. Due to the long cycle time to design and deploy a new pot design, in sufficient number to enable the amperage increase, smelters must generally operate different pot designs at the same time.

Simultaneously managing those different designs, without compromising potlife, is of prime importance to optimize the smelter economics during both amperage creep periods and steady-state operation.

This paper presents results from the Alcoa Deschambault smelter potlife management and optimization methods, since the initial plant start-up, accounting for different new pot designs and the challenges that come with them and from the almost continuous amperage increase.

2. Smelting Economics

Increasing the amperage has the potential to increase the profits generated from smelter. With low or no capital investment, smelter operators can increase the molten production with a significant reduction of conversion costs, for those additional tons. While raw materials and other consumables costs remain about the same, on a per molten aluminium ton basis, fixed costs and labor costs are diluted over more tons, thus increasing the margin. Assuming the Deschambault smelter, operating at 405 kA and 94.5 % current efficiency, increasing the line current to 410 kA generates an additional 3650 tons/year. Based on CRU's June 2021 production cost estimates, aluminium was produced for approximately 1470 $/t, for smelters with pot technology similar to AP-30. However, incremental tons from amperage increase are produced at a lower cost and was estimated at around 1160 $/t. While sales price, including regional premiums and other premiums was at around 2780 $/tons, this generated a margin of 1310 $/t for the nominal tons and 1620 $/t for the incremental tons, increasing margin by about 24 % for those new tons.

On the other hand, increasing or maintaining a good potlife is also important as it enables to control relining cost (materials and man-hours/t), spent potlining generation and treatment costs. Controlling potlife also enables adequate planning of the number of pots to be replaced each year, thus ensuring sufficient cathodes and other critical materials are ordered in time, but also to maintain as many pots in operation as possible to reduce lost production from stopped pots. Unplanned pot stops, or stopping more pots than the relining capacity, generate longer turnaround time before restart, hence leading to significant negative impact on the smelter economics.

For well controlled smelters, unplanned pot stops or long pot turn times around are not common. However, this may occur if a new pot design is introduced too rapidly, without proper testing, to enable an amperage increase, or if the amperage increase is performed with a pot design not capable to meet the new operating targets. Although a rapid amperage increase is appealing, it needs to be performed at the right time with the introduction of the new pot design, hence limited by the pot replacement rate.

3. Pot Design Evolution

More than 1600 pots were started since the Deschambault smelter started its operation. Figure 2 presents the number of started pots, on a yearly basis, and the average potlife achieved by those pots. During the first year, 200 cells were started, which is quite low when compared to the rapid pace performed at recent smelter start-ups. Due to operational issues, a low potlife of 987 days was achieved for the pots started during the first 3 years. The consequence was that 441 pot starts happened between 1993 and 1997, much more than what would be expected from a new smelter. Following this period of high start-up rate, the smelter managed to level the reline rate between 40 and 45 pots/y, if not for a few years. The reader should note that this paper was produced in June 2021, thus explaining the low number of pot restarts in 2021. Moreover, predicted potlife is used for pots started between 2015 and 2021 since not all pots started during those years were stopped.

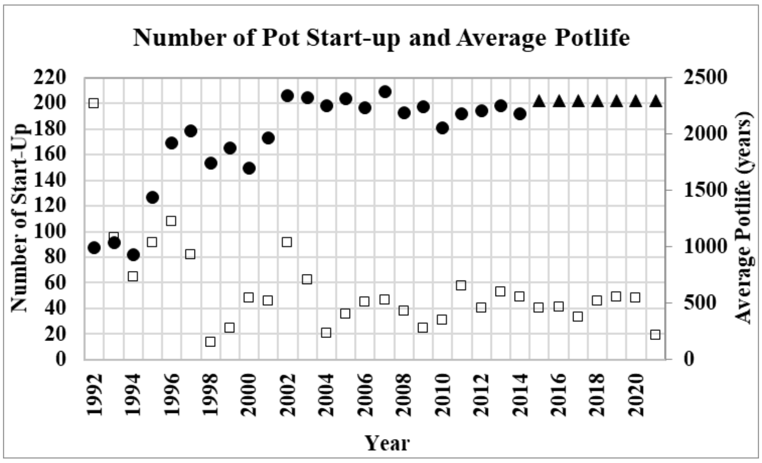

Figure 2. Number of pot start-up (□), realized average potlife (●) and (▲) predicted potlife on a yearly basis.

The Deschambault smelter is equipped with a 12 pots booster section, enabling to design and test operations of pots at higher amperage than the main potline. Many pot designs were tested in the booster, converging to 10 standard designs used over the life of the smelter. However, many other designs were also tested to converge towards the standard designs, for research and development purposes, or simply to manage cathode, bricks or ramming paste inventories. These standard pot designs are presented in Table 1, where their objectives, the number of pots stopped, the initial deployment year as well as the average failure age and the ratio of early (< 3 years) and young (between 3 and 5 years) failures. Figure 3 presents the cumulative probability of potlife for those standard designs.

Table 1. Standard pot design at Alcoa Deschambault.

Pot design family	**Objective**	**Number of pots stopped**	**Deployment year**	**Average Failure age (days)**	**Fraction of early/young failure (%)**
Original 30 % graphite cathodes	Plant-start-up	385	1992	1015	60/38
Graphitized cathodes	Improve operation stability	281	1995	1917	0.4/33
Increased carbon above bars	Improve potlife	68	2000	1975	0/16
GEN1, Copper Insert Collector Bars (CICB)	Improve potlife	194	2001	2494	0/11
Wide Bars	Improve potlife	8	2001	1824	0/50
GEN2, Low energy cathode (LEC)	Reduce energy consumption	195	2006	2265	0/5
LEC transition	Reduce energy consumption	14	2006	2205	0/0
Filler block GEN2 and GEN3	Improve operation stability	56	GEN2: 2006 GEN3: 2011	GEN2: 2541 GEN3: 2511	0/0
LEC GEN3	Increase amperage	144	2011	2215	0/5
LEC GEN4	Increase amperage	1	2015	2049	0/0
LEC GEN4+	Increase amperage	---	2020	---	---

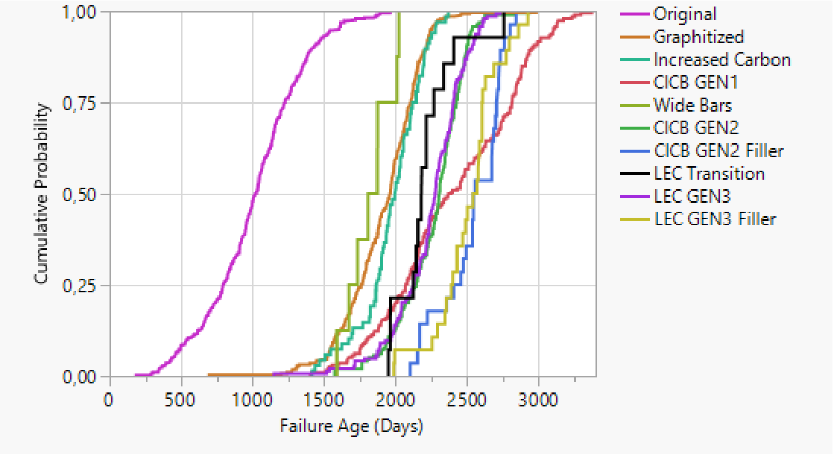

Figure 3. Cumulative probability failure age for standard pot designs.

3.1 Original 30 % Added Graphite

The original pot design intended for plant start-up was based on 30 % graphitic cathodes, which were already in use in large pots. Ramming paste and side wall material used for this design were also used in other smelters. After the start-up of the first 60 pots, operation requirements exceeded the available manpower capacity. A short break in start-up activity was taken in April 1992 for readjustment and pot start-up resumed in June 1992. Start-up was halted again in September 1992, for the same issue. Due to these pauses in start-up activities, only 200 pots were operated until January 1993, at which point the start-up resumed to reach full pot complement on March 13th, 1993. However, nine days later, the plant experienced its first pot failure. The pot design and operational practices were obviously not adequate for operation at 295 kA. This original pot design reached an average pot life of 1015 days, requiring an enormous effort from the plant's staff to maintain them in operation. The main mode of failure was side tap-out and could be explained by the following factors:

1. The pot technology was relatively new at that time and was a giant step from the previous technologies available in the industry,
2. The pot design was not suitable for operation at 295-300 kA to maintain good operational performance (high current efficiency and low energy consumption),
3. Lack of knowledge/comprehension of the overall pot operation of large pots (mainly thermal regulation and bath chemistry),
4. Lack of experience and sufficient process knowledge of local operators and plant staff.

In terms of pot design and operation, the failures originated from a rapid increase of the cathode voltage drop (CVD), due to cathode grade, but also due to the wrong location of some critical isotherms inside the pot (lack of insulation in the lower side-lining). This led to pot instability and required additional voltage within the anode-cathode distance (ACD), thus generating more heat. The high excess of AlF_3 recommended to maintain good current efficiency also exacerbated this situation, up to the point where the pot could not maintain sufficient side ledge protection. This created a vicious cycle of crust collapsing onto the cathode surface, which generated some more instability, until side failures occurred. In 1995, to address the side failures, silicon carbide bricks were introduced as side-lining material, but this modification alone did not improve the situation. Some tests were also performed with graphite side wall bricks without any real gains.

Fortunately, the smelter is equipped with a booster section and a new pot design using graphitized cathodes was tested. Performance achieved with this cathode grade was significantly better than the original 30 % graphitic cathode.

3.2 Graphitized Cathodes

In June 1995, the standard pot design changed to graphitized cathodes and silicon carbide side-lining to improve pot robustness and prevent side wall failures. This approach worked very well as the pot stability improved significantly and good pot performance was achieved (around 95 % current efficiency and 13.0 kWh/kg Al). However, after about 2 years of operation, a different problem appeared. It was observed that the cathode erosion rate was higher than expected and internal investigation predicted a short pot life in the range of 1500 to 1700 days. Different studies were performed to better understand the problem and find possible countermeasures. Cathode erosion was measured in operation and more precisely during the autopsy of 50 pots (400 measurement in each pot). The erosion can occur from three types of processes 1) mechanical erosion due to material movement over the cathode surface, 2) chemical erosion due to bath and metal reacting at the cathode surface and 3) electrochemical erosion due to the ongoing process of formation and dissolution of an aluminum carbide layer at the cathode surface [11]. Erosion patterns led to the conclusion that the main factor was electrochemical erosion. From there, the use of corundum and cutting of collector bar connections was introduced in 1999 to increase pot life above 2000 days on more than 65 % of the pots. This procedure became a standard practice within the smelter. Again, different pot designs were tested to improve results. During this period, development of a 3-D thermo-electric model was done with the expertise of external consultant using ANSYS [12]. A mechanical model was also built to study pot shell deformation.

3.3 Increased Carbon Above Collector Bars

A simple approach was considered to extend pot life and solve the cathode erosion failure mode. Adding more cathode material above the collector bars would provide for deeper erosion, before reaching the collector bars, and hence increase. Cathode dimensions were reviewed since there were no problem of cathode heaving, or high CVD or pot instability. The overall cathode block height was hence increased. Different tests were also performed to evaluate risk of changing cathodic bars configuration to increase furthermore the amount of carbon above cathodic bars. This allowed to turn the bars and reduce the vertical dimension of the bars within the cathode, and hence provide more carbon before reaching the bars. Both countermeasures allowed an increase of carbon height above the bar by 32 %. This improved potlife, but not matching the expected gains from the additional height above bars. Modeling showed that erosion rate is not a linear process. Hence, the additional gains were in the order of 60-90 days (3-5 %).

3.4 GEN 1 CICB

Copper insert collector bar (CICB) was initially developed to increase pot life. It was developed with the use of 3-D modeling tools mentioned above [13]. The main CICB goal is to redistribute the current density inside the pot and hence level the electrochemical erosion. The first prototype was installed in August 1999 within the booster section. This pot, as other R&D pots, was heavily instrumented to measure internal voltage drops and temperature within the cathode lining materials. This allowed to develop the knowledge and confidence around this new pot design in a very short period. Six additional prototypes were installed in 2000 and the technology was deployed in plant as soon as December 2001, which is quite aggressive for deployment. Meanwhile, CICB also showed a very high potential for amperage increase and improved pot stability, thus favoring the decision to rapidly deploy the CICB technology. Nevertheless, from a pot life perspective, CICB delivered expected results with an additional potlife of 400 days, with a significant amperage increase, from 325 to 345 kA. Another benefit of using CICB comes from the fact that copper (Cu) can also be used as a tracer to monitor metal infiltrations or excessive cathode erosion. This proved to be more effective than iron (Fe) alone and is considered a key to manage potlife.

3.5 Wide Cathode Collector Bars

A wider collector bar was also considered to improve pot life under the rationale that the wider bar cross-section would reduce current density in the cathode. This approach was developed in parallel to the CICB technology and eight prototypes were installed in parallel with CICB prototypes. This development was stopped around 2000, due to lack of flexibility for further developments at Deschambault. However, this approach may still be valuable for other smelters.

3.6 GEN 2 LEC

Up to 2005, sufficient electrical power was available from the grid to increase potline amperage. In prevision of the next amperage increase from 345 kA to 365 kA (allowed by CICB technology and operational improvements), many CICB pots were installed between 2003 and 2005. However, the smelter became power constrained in 2005. A different strategy had to be developed to continue increasing the amperage. From there, the main approach was to develop a pot design with a lower operating voltage, which would allow to increase the amperage within the same available power. This is where the concept of Low Energy Cathode (LEC) was introduced. While the literature showed strong limitations in this approach, modeling was used to develop an approach with a high anode current density, close to 1 A/cm^2. Modeling was performed using Alcoa's 2-D thermo-electric software. This pot design was applied as standard pot design during Spring 2006, following a thorough risk analysis process. The LEC concept is very good to reduce pot voltage but makes the pot much more sensitive to operational practices. Many operational practices were reviewed and improved with the involvement of floor operators, process technicians and engineers. Using this LEC concept, it was possible to increase load by about 15 kA without additional power. On the other hand, pot life dropped by about 150 days during this time as compared to first generation of CICB.

3.7 Filler Block for GEN2 and GEN3

In parallel with LEC pot installation, a different approach was revisited to improve pot stability and pot life. Although not well suitable in a power limited plant, or where power cost is high, a filler block design was tested, where a pre-formed anthracite block is inserted into the middle side lining to replace part of ramming paste and lining bricks. This design was tested to ensure different pot designs were tested and available in case the power availability situation would evolve differently over time. This was also helpful to improve knowledge on design change sensibility depending on operating condition. Filler block designs were used for comparison with both LEC GEN2 and GEN3 designs.

3.8 LEC Transition

This transition design was a temporary design intended to quickly deploy the LEC and capture benefit of amperage increase as soon as possible. It was simply used to avoid losing costly lining material already in inventory at the smelter. It is presented here for two reasons:

1- It is possible, and sometimes unavoidable, to use a temporary design while changing a plant operational situation, in this case going from being unconstrained to power-constrained.

2- As a warning. Such temporary designs require a very solid knowledge on pot design and a very good management and execution of operational practices. This kind of design requires special follow-up as it is operated outside of its operational range for most of its life.

3.9 CICB LEC GEN3, GEN4 and GEN4+

Power became available from the grid and this paved the way to increase the amperage to higher levels. GEN3, GEN4 and GEN4+, all based on CICB and LEC concepts, were designed to enable operation at increasingly higher amperage while maintaining sufficient robustness to process variability from operation or raw materials. Within the same shell, longer asymmetric anodes were deployed with deeper slots to reduce the anode current density and the bubble resistance. Longer cathodes were introduced to match the anode shadow and foster vertical current flow. Thinner sidewalls were introduced to dissipate more heat and provide additional space for the longer anodes. CICB was redesigned to optimized current density and heat dissipation from the collector bars. Insulating material was changed to optimize isotherms within the cathode and lining material.

4. Operational Practices

To take advantage of the different pot designs and support amperage increase, different operational improvements were deployed at the smelter. As such, most of the day-to-day operations and process control systems were reviewed and optimized. Floor operators received additional training for their work activities and were involved into many optimization activities. Their involvement, as well as rapid and effective intervention on problem pots, became even more important. Pot start-up and early operation are managed by dedicated teams and process technicians, ensuring continuous improvement for those key activities. At steady state, operating targets are also optimized on a pot-to-pot basis, ensuring all pots are operated as best as possible.

The use of STARprobe^{TM} [14] to measure and control superheat greatly helped to control the pot thermal balance and bath chemistry while protecting the sidewalls. This enabled to minimize side failures while keeping a high excess of AlF_3 to favor high current efficiency. However, a few procedures were instrumental to achieve high potlife.

4.1 Rapid Intervention on Sick Pots

Different monitoring tools were developed and deployed, and now converted into digital tools, to enable rapid detection and intervention of sick pots. STARprobe^{TM} is used routinely to monitor bath properties and off sequence for pots requiring more attention. This enabled to control superheat, instead of only relying on temperature and excess of AlF_3 alone. High superheat pots are reported and cared for by the technical team. Copper and iron in metal, from routine metal sampling, are used to detect metal infiltration of heavily eroded cathodes. Older pots are also sampled more often to minimize the time between samples and enable faster intervention if required. Copper and/or iron hits trigger intervention from the technical team to identify and fix problematic cathodes.

The alumina feeding control algorithm was improved to minimize anode effects. Many improvement activities were performed with operation and maintenance crew to minimize broken feeder/breaker occurrence and to minimize the reaction time to replace broken ones. Operators were also involved to reduce their reaction time to extinguish anode effects. This helped to reduce some of the thermal excursions and hence better protect side-lining.

4.2 Corundum / Collector Bar Cutting

As mentioned earlier, corundum patching became standard practice in 1999, to locally stop the electrochemical erosion before the metal pad could reach the collector bars. Heavily eroded cathodes are identified by different techniques by experienced operators. From there, pre-heated corundum spheres and grains (Figure 4) are applied over the eroded cathode area to fill the holes. The associated collector bars are also disconnected from the bus bar. The material fills the hole and disconnecting the collector bars prevents further electrochemical erosion. This technique was refined over time and is now performed by floor operators, when needed, as part of their regular activity. Hence, a rapid intervention can be performed to prevent a bottom failure, instead of stopping the pot.

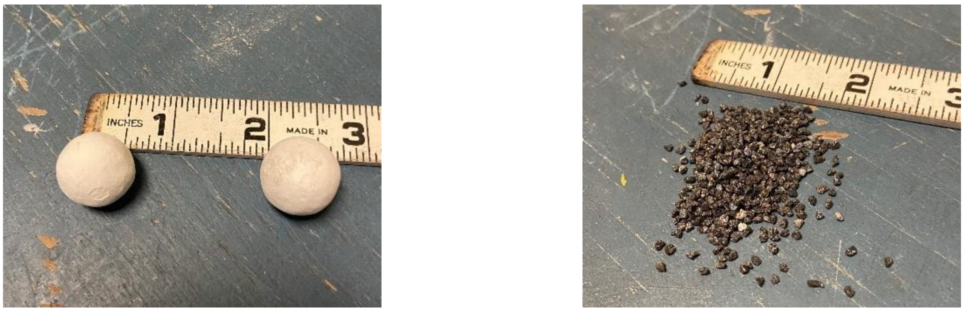

Figure 4. Corundum material used to patch cathode blocks. Left: spheres, Right: grains.

A corundum intervention costs a few hundred dollars and can maintain a pot in operation up to an additional 6 months. Figure 5 presents the number of corundum interventions performed over time at the Deschambault smelter. Over time, it was found that a pot can have many corundum interventions to extend its potlife, up to a point where the other cathodes start to erode too rapidly, or where the pot develops sustained instability from altered cathode current distribution.

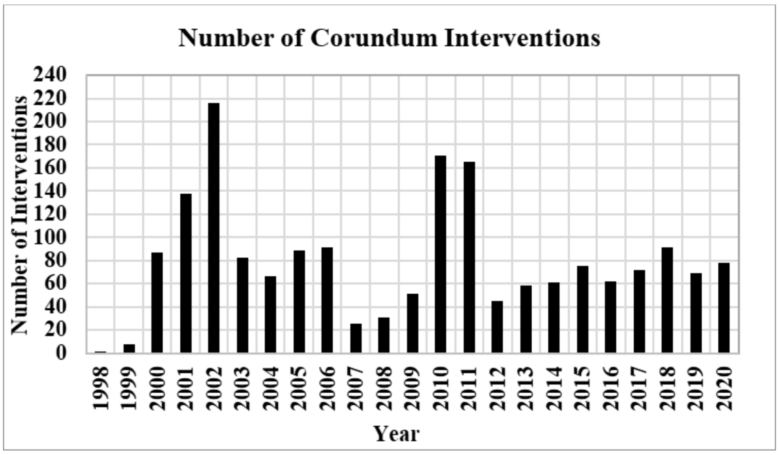

Figure 5. Number of corundum interventions over time.

4.3 Sidewall Cooling

As the amperage is increased, more heat needs to be dissipated from the shell. The new pot design is generally designed to achieve this. However, as the amperage is increased, many pots of the previous generation are still in operation and might be struggling with the increased heat to dissipate. This puts pressure on side ledge and lining materials and may lead to side failures. To compensate for that, the plant developed different counter measures based on compressed air. Emergency cooling kits were developed and deployed to rapidly cool down hot shell areas. Following the identification of a weak spot, the emergency kit is applied for a few days and is later replaced by a maintenance kit, which is better suited to cope with day-to-day operation. As shown in Figure 6, a hot spot can develop very rapidly on old pots and the emergency kits can rapidly cool down the area to acceptable levels. Figure 6 presents shell temperature data collected on a 1-minute basis, with an in-house temperature monitoring system, in front of anode 15. The shell first increases by about 35 °C between 8:00 h and 18:00 h on May 19th, and stabilizes at 320 °C until 6:00 on May 20th, before rapidly increasing to 620 °C in 20 minutes. The hot spot was detected, and an emergency kit was used to rapidly cooldown the area to approximately 210 °C, in less than 35 minutes. However, the shell is still at risk. Although nothing was found, the operators had to remove the emergency kit at 13:10 h, on May 20th, for a few minutes to remove and inspect anodes 15-16 for a possible spike. This time without the emergency kit led to an increase of the shell temperature by 145 °C. A few hours later, at 15:30 h, operators also had to remove the kit to change anode 13-14. This time, the shell increased by 75 °C. This shows the effectiveness and importance of the emergency kit and supports its replacement by a maintenance kit, out-of-the way for daily operation. Nevertheless, emergency and maintenance kits enable to maintain those pots in operation for an extended period, instead of cutting them out in emergency. For different parts of the shell, low pressure air is also used to control the shell temperature

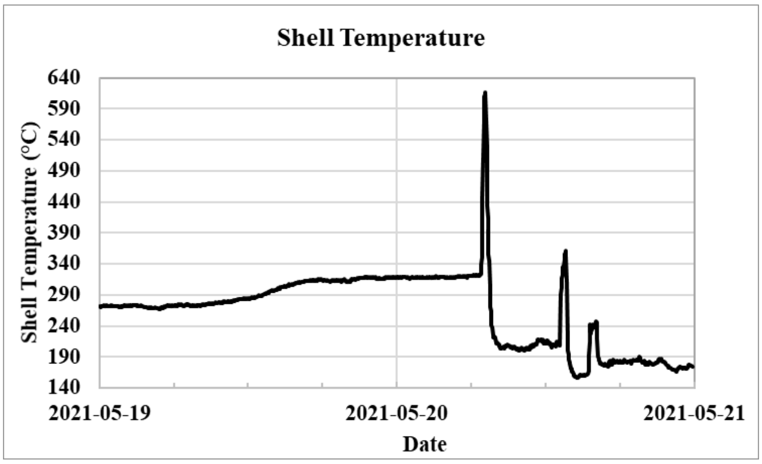

Figure 6. Shell temperature over time.

5. Results

Based on technical and operational improvements presented in this paper, Alcoa Deschambault managed to increase amperage while maintaining high potlife over the years. Figure 7 presents monthly average line amperage and potlife of stopped pots.

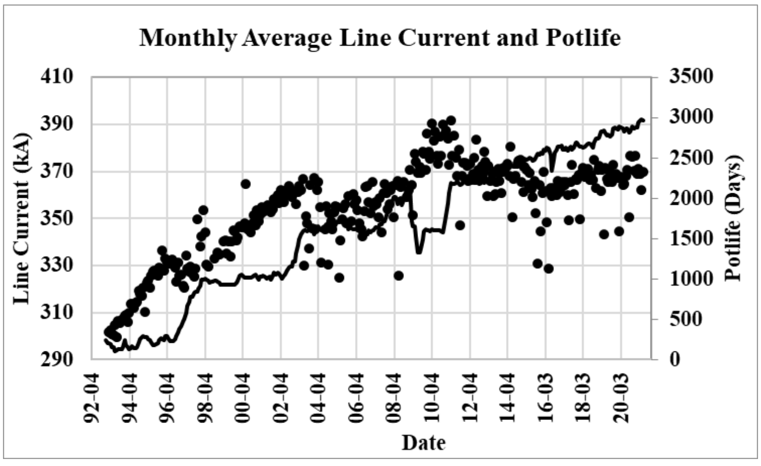

Figure 7. Monthly line current (-) and average potlife of stopped pots (●).

From the initial low potlife and amperage, the smelter managed to increase and sustain high potlife while increasing amperage by more than 35 %.

6. Conclusions

Managing potlife within an aluminium smelter is of prime importance to optimize financial benefits. Many factors have an impact on potlife; pot technology, pot design, materials, lining procedures, start-up, early operation, operational targets and day-to-day activities. Each aspect needs to be optimized to deliver high and consistent potlife.

However, amperage increase can jeopardize potlife in many ways as it typically comes with a new pot design, requiring to be operated in different ways than previous designs. Since its start-up in 1992, the Alcoa Deschambault managed to maintain good potlife while also performing significant amperage increase. To achieve such results, the Alcoa Deschambault team deployed many countermeasures.

- Development and deployment of new pot design,
- Operating many pot designs at the same time,
- Improved day-to day operation and process control,
- Rapid and efficient interventions on sick pots,
- Efficient ways to patch cathodes and cure hot shells.

Managing potlife and amperage increase is a continuous effort and requires everyone and every sub-system to operate efficiently.

Aiming to further increase its performance, Alcoa Deschambault is on its way to 405 kA and continues to work on solutions to increase potlife.

7. Acknowledgements

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