

Production Process and Control Optimization of a 240 kA Potline under SAMI's Deep Energy-Saving Cell Technology

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<https://doi.org/10.71659/icsoba2024-al024>

Abstract

In order to assist aluminum smelters to significantly reduce the energy consumption of primary aluminum production and promote the green transformation and high-quality development of the aluminum smelting industry, Shenyang Aluminum and Magnesium Engineering and Research Institute Co., Ltd (SAMI) has developed a Deep Energy-Saving Aluminum Electrolysis Technology System. In 2022, SAMI successfully applied this technology system to the 240 kA potline upgrading project of Guangxi Baise Guangtou Yinhai Aluminum Industry Company, achieving integrated application of Networked Self-equalizing Busbar Technology (NSBT), New Conceptual Cathode Technology (NCCT), “Long Healthy Life” potlining technology, Energy-saving and Eco-friendly Superstructure Technology, and new pot control system on the 240 kA potline. After recommissioning of the upgraded potline, the technical team proposed and developed a refined control process of gas preheating of the pots. By utilizing electric-thermal balance simulation, “Three-Low and One-High” Production Process Management Technology was developed, successfully increasing the operating current of the potline from 240 kA to 260 kA. Thanks to the design upgrade and production process optimization, the potline now operates stably with excellent KPIs, with average voltage < 3.945 V, the current efficiency > 94.5 %, and the DC power consumption < 12.450 kWh/kg Al. After the technical upgrading and optimization, the DC power consumption of the potline has been reduced by nearly 0.9 kWh/kg Al, and the annual primary aluminum production capacity has been increased by nearly 14 000 tonnes, with significant energy-saving and economic benefits.

Keywords: Aluminum electrolysis pot, Control system, Gas preheating, Low metal level, Production process optimization.

1. Introduction

In recent years, the gradual implementation of China's strategic policies such as “supply side reform”, “dual control of both energy and consumption”, “dual carbon” strategy, and “Tiered electricity pricing” has led to the peak production capacity of the high energy consuming electrolytic aluminum industry and accelerated green transformation. The industry's development

trend has shifted towards energy-saving upgrades and improvements in quality and efficiency. Simultaneously, aluminum smelters and research institutions are accelerating the development of energy-saving technology for aluminum electrolysis. They are focusing on optimizing the design of multiple physical fields and upgrading the production process, to explore the potential for energy conservation and consumption reduction throughout the entire process of aluminum electrolysis, including cell design, preheating, start-up, and production.

Starting from 2020, based on the improving thermal-electric-magnetic-flow multi physics field simulation and analysis technology platform in the development of electrolytic cells, SAMI has accumulated a lot of experience in deep energy-saving and consumption reduction of aluminum electrolysis cells by focusing on improving the magnetohydrodynamic (MHD) stability of electrolytic cells, reducing physical voltage drop, maintaining good thermal balance, improving gas collection efficiency, equalizing the distribution of alumina concentration, and improving digitalization and intelligence [1]. By conducting theoretical research using aluminum electrolysis cell multi physics field simulation as the primary method, combined with industrial experiments, potlines applications, and on-site testing verification, SAMI has successfully developed a deep energy-saving aluminum electrolysis technology system. The key sub-technologies included in this system are:

- Networked Self-equalizing Busbar Technology (NSBT)
- New Conceptual Cathode Technology (NCCT),
- "Long Healthy Life" lining technology,
- Energy-saving and eco-friendly superstructure technology,
- Narrow-Amplitude and Dual-Mode cell control technology,
- Preheating and start-up control technology,
- "Three Low - One High" Production Process Management Technology, etc.

In 2022, the aforementioned deep energy-saving technology system for aluminum electrolysis was successfully integrated and implemented in a 240 kA potline upgrading project of Baise Guangtou Yinhai Aluminum Co., Ltd (as shown in Figure 1). Once the significantly improved electromagnetic field, lining isotherm distribution, fume collecting and feeding efficiency had been achieved thanks to the application of the first four technologies mentioned above, the potline was set for a new target of 260 kA shortly after recommissioned. In this paper, production process management and control optimization, amperage increase from 240 kA to 260 kA will be described in continuation of the ICSOBA 2023 paper [2].



Figure 1. Aerial view of the 240 kA potline.

2. Narrow-Amplitude and Dual-Mode Cell Control Technology

The physical field design is the foundation of the electrolytic cell, while the control system is its operational brain. How to comprehensively improve the digitalization and intelligence level of the cell control system under the premise of safety and easy maintenance, achieve fine control of operation, improve the controlled rate of the main process technical parameters of the cell, is another key factor in ensuring current strengthening, production increase and consumption reduction.

2.1 Hardware Upgrade

SAMI has developed a new hardware layout architecture for cell control system with higher reliability and stability, abandoned traditional motherboard form of unit controllers and constructed a blade-type integrated control module. Each functional board is vertically installed on the universal motherboard with digital power supply, which can effectively utilize the internal space of the box, making it convenient for maintenance and insertion of various functional boards. Additionally, a multi-core CPU overlay computing architecture was introduced to significantly improve the system response speed and computing power.

The main technical features of the new hardware architecture of the upgraded cell control system:

- By adopting a multi-core CPU overlay computing architecture, compared to traditional cell controller, the computing power for cell voltage change tracking, noise detection, and material concentration prediction is significantly improved, greatly improving the response speed of the cell controller and the accuracy of process model judgment.
- The data transmission architecture has strong anti-interference ability, high reliability, low failure rate, and a robust self-diagnostic function.
- All operating conditions include hardware and software protection strategies to ensure production operation safety.
- High precision isolated collection of cell voltage data. 0–5 V range: accuracy meets 0.02 %, 5–100 V range: accuracy meets 0.3 %.
- The refresh frequency of the system's global data has been increased from 5 Guangxi Baise Guangtuo Yinhai Aluminum Industry 20 seconds per cycle to 1 second per cycle.
- LED (digital tube) + OLED (liquid crystal screen) composite display mode. Customized LCD screen display process parameters according to customer needs.
- Achieved single point crust-breaking and single point alumina feeding.
- Built a “one-stop” digital and auxiliary equipment selection service platform that can be equipped with more than ten types of aluminum electrolytic cell production process control supporting equipment, including various production process indicator lights, busbar position monitoring devices, intelligent crust-breaking, portable remote control, etc.

Figure 2 shows some typical cell control facilities after the upgrade of this project.



Figure 2. Some upgraded cell control facilities diagram group.

2.2 Software Upgrade

The main technical features of the upgraded software:

- Concentration control algorithm. Utilizing the computing power advantage of the multi-core CPU overlay computing architecture, the collected voltage and current signals are optimized through multi-stage progressive filtering. This effectively filters out the impact of signal transients during cell operation, reduces the interference of voltage and current anomalies on concentration calculation, lowers the inertia of alumina concentration changes, and reduces the risk of sudden anode effects and alumina precipitation.
- Upgrade of fluctuation control algorithm. The filter algorithm has been improved to more accurately distinguish high noise and low noise. In cases of abnormal cell fluctuations, the system will automatically exit the alumina concentration tracking mode and enter the fluctuation control mode to achieve “Dual Mode” automatic switching. This helps reduce the disordered disturbance of the cell through special alumina feeding strategy.
- Noise algorithm. Timely perform automatic correction in the early stages of increased noise. The introduction of an improved maximum flatness filter (Butterworth filter) makes the calculation of resistance peaks smoother and the output of peaks more accurate,

achieving effective narrowing of voltage and resistance fluctuation amplitude, which is beneficial for adjusting material balance. The changes in the resistance slope algorithm before and after upgrade are shown in Figure 3.

- Control process of anode change. Control the alumina concentration in stages according to the anode change cycle, so that the feeding cycle can be adaptively adjusted. After anode change process, the cell can quickly enter a stable period (as shown in Figure 4).
- Introduced a big data analysis and evaluation system for aluminum electrolysis production, establishing a production management database for electrolysis cells, to achieve precise evaluation and scientific management.

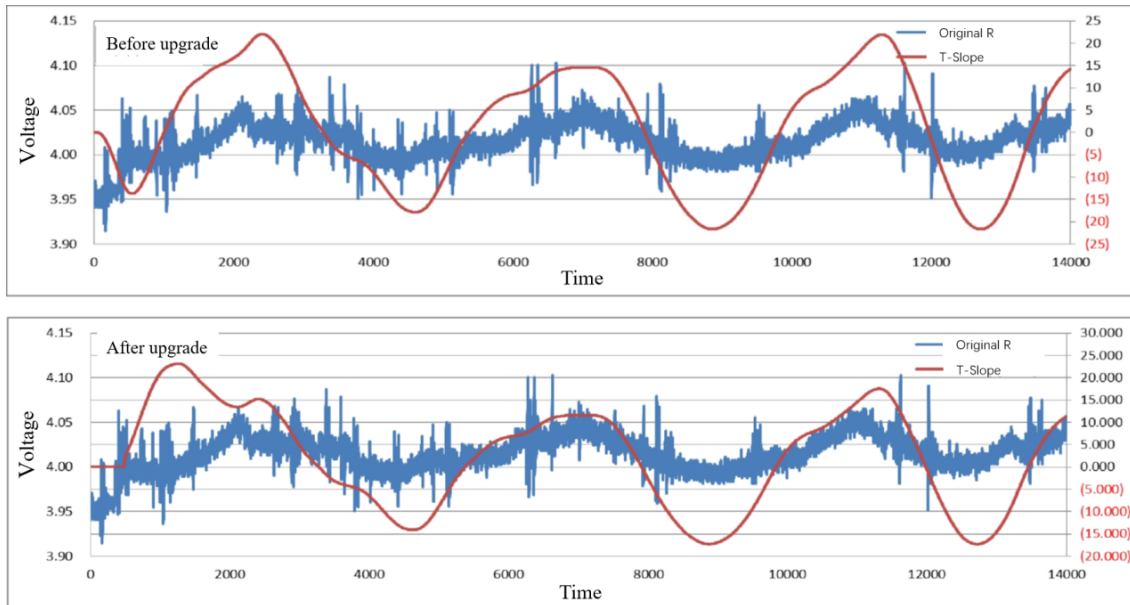
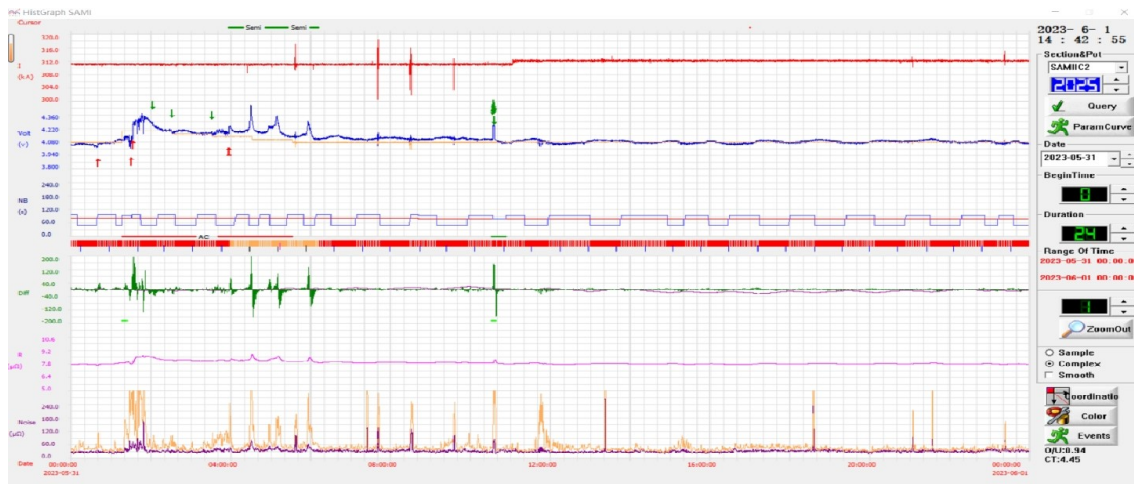
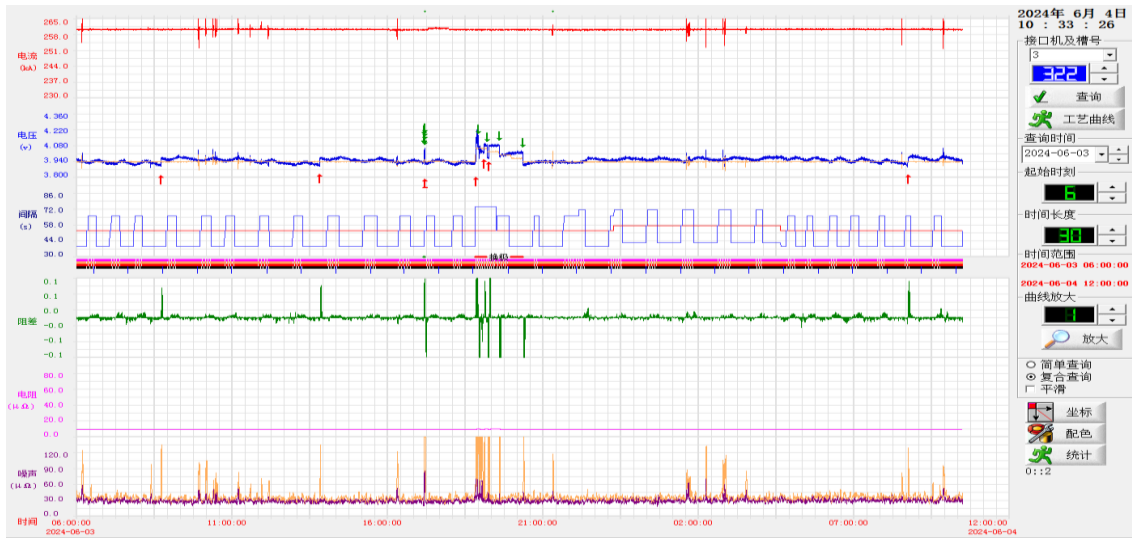


Figure 3. The changes in the resistance slope algorithm before and after upgrade.

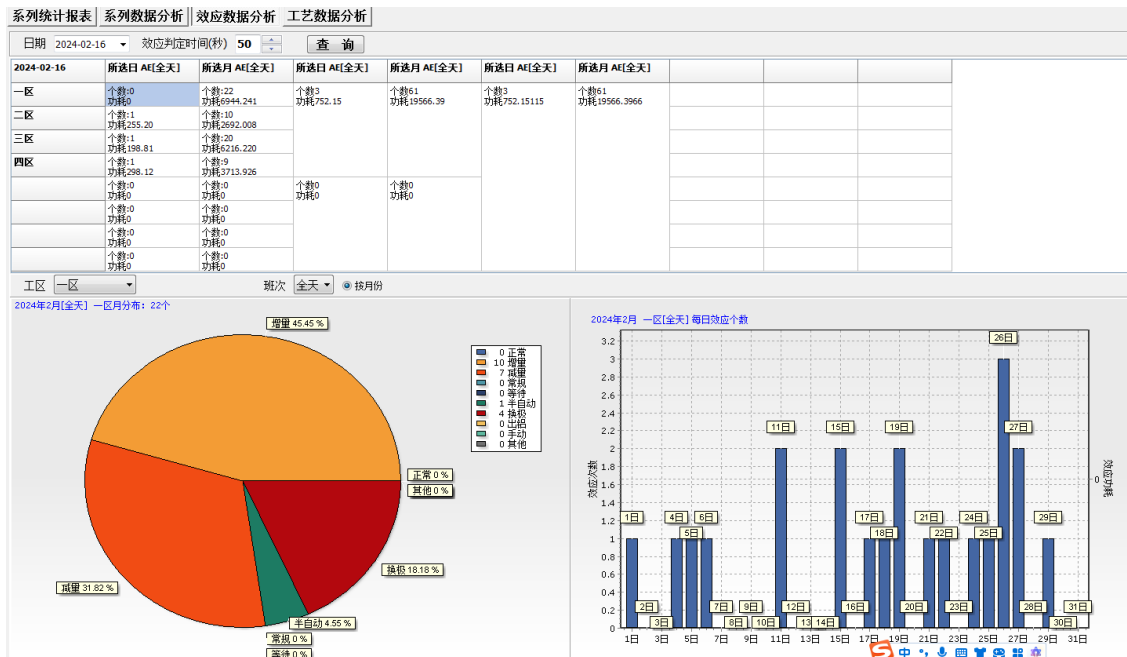


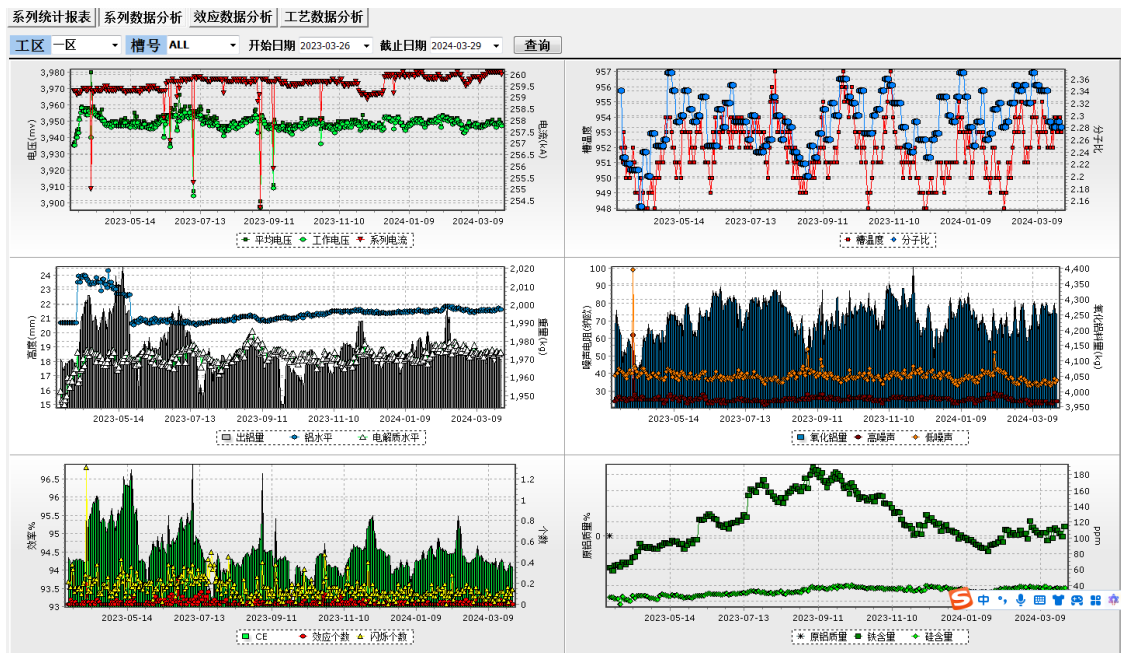
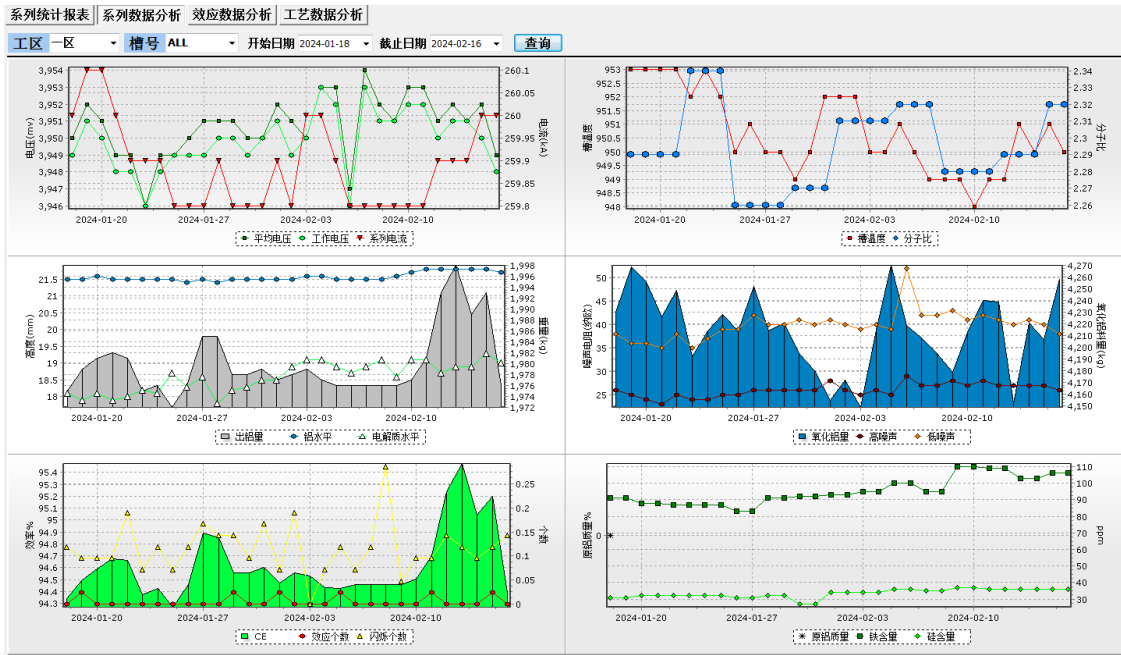
(A)



(B)
Figure 4. Operation curves of cell after anode change.
Top: (A) before upgrade, Bottom: (B) after upgrade.

Some interface of the software system of the cell controller after upgrade are shown in Figure 5.





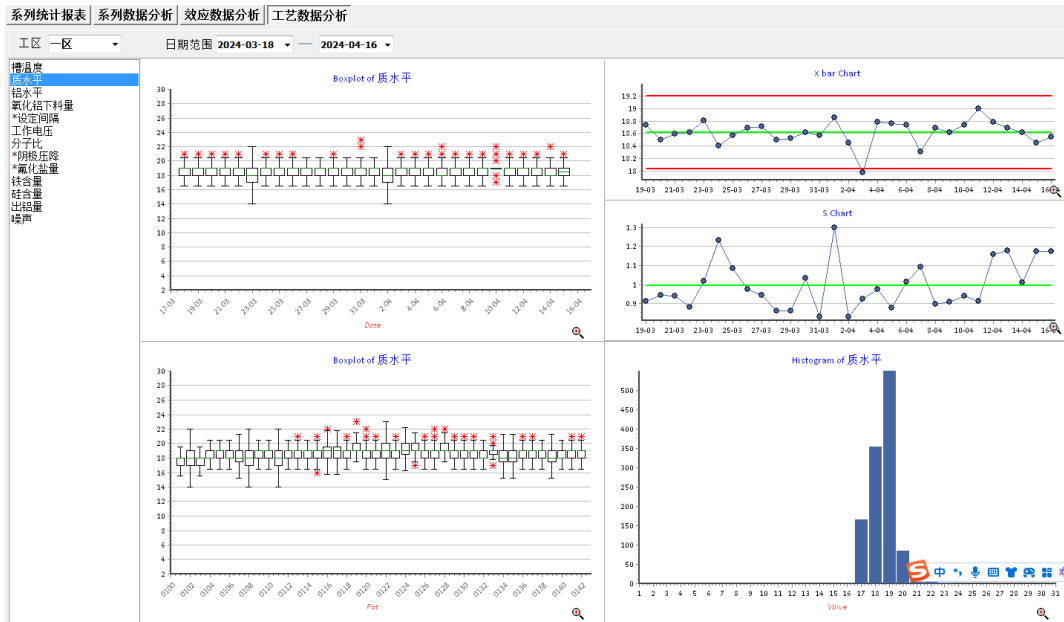


Figure 5. Some interface of the software system of the cell controller after upgrade.

3. Preheating Control

In this potline, double anode design, and coke granule preheating process was used before the upgrade. The relatively poor flatness of the double anode assembly bottom makes it difficult to uniformly control the current distribution during cell preheating, leading to the generation of porosity and cracks in the paste. In this project, the technical team upgraded the preheating method from coke granule preheating to a refined gas preheating process for better uniform temperature control.

3.1 Optimization of Preheating Time and Heating Rate

To optimize temperature control during the preheating process and prevent local overheating from causing internal thermal stress concentration in carbon materials, creating conditions for the long-term safety and stability of lining materials, especially carbon materials, after current intensifying, the following measures were implemented:

- Adopt a segmented temperature increase gradient.
- The main stage for removing water adhering to carbon paste and other lining materials is between 200–300 °C. The heating rate should be slowed down sufficiently to allow for slow drying of the paste.
- The key period for concentrated baking of carbon paste is between 600–700 °C. Similarly, the heating rate should be slow in this temperature range to ensure sufficient baking.
- The total preheating time was extended from 72 hours to 96 hours, and the constant temperature holding time of the target temperature of 950 °C was shortened to 3 hours to avoid over-burning of carbon paste.

The optimized temperature rising curve is shown in Figure 6.

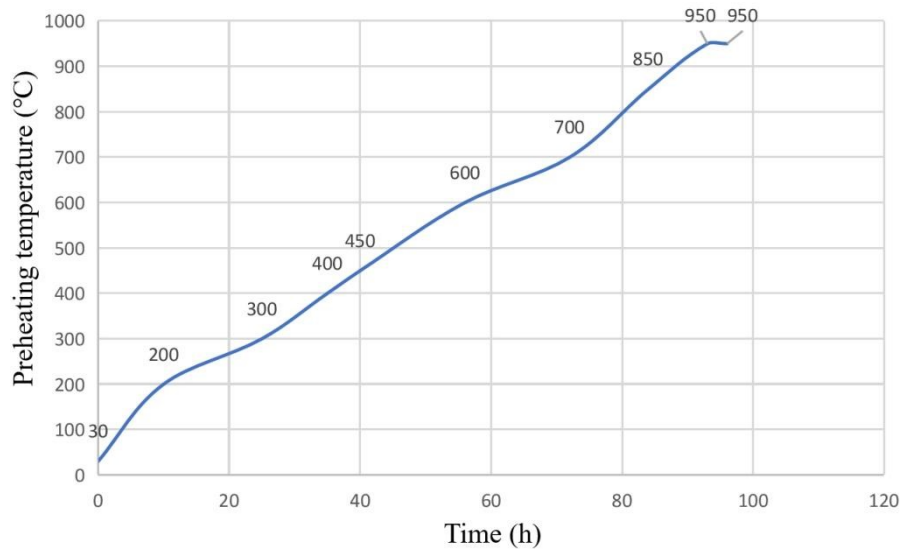


Figure 6. Temperature rising curve during preheating process.

3.2 Temperature Analysis of Steel Collector Bar During Preheating

To monitor the steel collector bar end temperature during preheating process and compare coke preheating (09# cell) with gas preheating (37# cell), it was observed (see Figure 7) that the temperature of the steel collector bar increased linearly during the coke preheating process. In contrast, the upward trend of the steel collector bar end temperature was basically consistent with the temperature rising gradient during gas preheating process. Before start-up, the maximum steel collector bar end temperature in the 09# cell was 300 °C, while the minimum temperature was 145 °C resulting in a relatively large temperature deviation. However, in the gas preheated cell (37# cell), the maximum and minimum temperature were 236 °C and 203 °C respectively with a smaller temperature deviation. This upgraded gas preheating process control strategy helps to ensure uniform preheating of the lining materials.

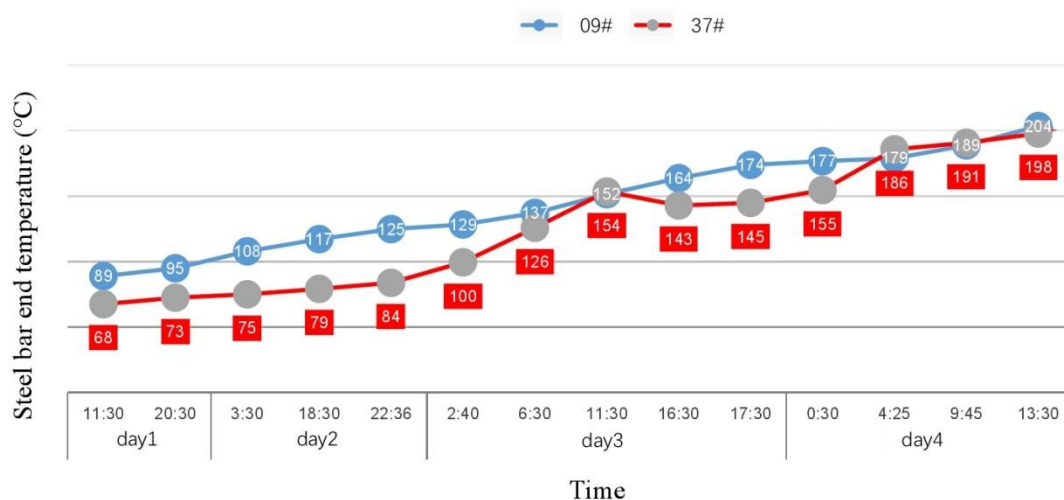


Figure 7. Comparison of steel collector bar end temperature with two preheating methods.

4. “Three Low – One High” Production Process Management Technology

SAMI conducted systematic research and analysis on both new and old aluminum electrolysis cell technologies. We explored the restrictive relationship between key process technology conditions in depth from a theoretical perspective. The technical team broke the current situation

of high metal height production operation management which had commonly used by domestic aluminum smelters for many years, and organically combined actual production operation management with various cell design concepts. With the assistance of thermal balance simulation methods, SAMI has developed a “Three-Low and One-High” production process precision management technology. This technology focuses on maintaining low metal height, low voltage, low cryolite ratio (CR), and high current efficiency.

4.1 Restrictive Relation of Key Technical Conditions Analysis

4.1.1 The Relationship Between Metal Height and Horizontal Current

During the production of aluminum electrolytic cells, horizontal current can cause fluctuations in the aluminum liquid interface, secondary reactions of aluminum, and corrosion of the lining wall by the melt, all of which must be controlled. Therefore, it is always advisable to minimize the horizontal current in the metal pad to improve the MHD stability of the cell whether in the design or actual production process. There are currently many technologies available to reduce horizontal current, such as curved cathodes and variable cross-section steel collector bars [3, 4], etc. Additionally, there are ways to improve the stability of electrolytic cells through operational management, such as increasing the metal height.

With the advancement of new research and analysis methods, we can quantitatively analyze the impact of metal height on the electric field, thermal field and magnetic field of the cell. This allows us to determine the optimal metal height for cell operation. SAMI had developed and applied NCCT technology in this project [2], which can achieve a significant reduction in horizontal current and cathode voltage drop (CVD). By establishing an electrical-thermal physical field simulation model, we can simulate and optimize control the magnitude and distribution of horizontal current in the metal pad [5] (as shown in Figure 8).

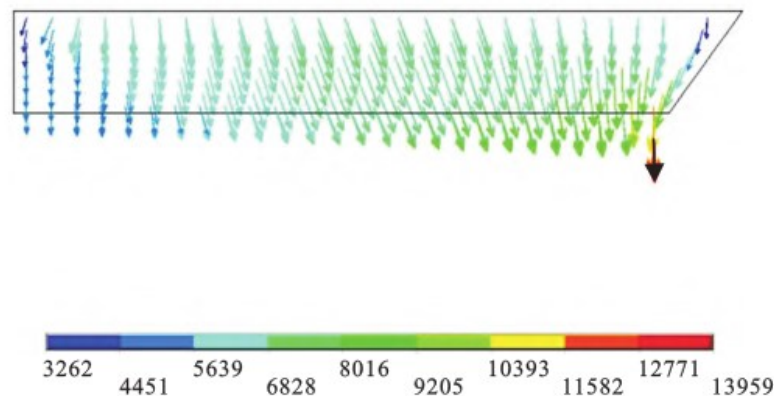


Figure 8. Horizontal current distribution in the metal pad of cell.

4.1.1.1 The Relationship Between Metal Height and Horizontal Current under Traditional Cathode Structure

In traditional cells, the design form of the cathode structure determines that the horizontal current in the metal pad is mostly higher, under normal production metal height, generally around 6 000–10 000 A/m². In this study, the horizontal current in the metal pad with a typical traditional cathode structure was calculated by SAMI under the condition of 20–32 cm metal height. The results are shown in Figure 9.

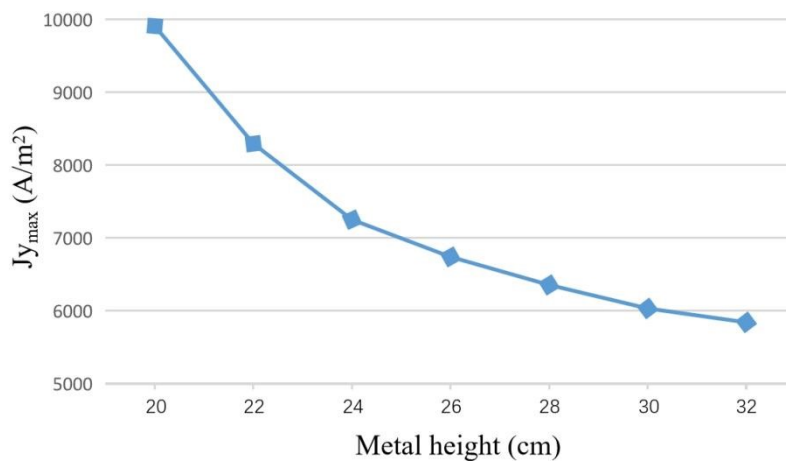


Figure 9. The relationship between metal height and horizontal current in traditional cathode structure.

As Figure 8 shows, in traditional cathode structures, increasing the metal height in the lower range (20–26cm) effectively reduces the horizontal current in the metal pad. But as the metal height continues to increase, the decrease in horizontal current decreases and tends to stabilize. This indicates that traditional cathode structures can effectively reduce the horizontal current in the metal pad by increasing the metal height in the lower range. Nevertheless, when the metal height exceeds 26cm, the decrease in horizontal current is no longer significant.

4.1.1.2 Between metal height and horizontal current under NCCT

For aluminum electrolysis cells using NCCT, the horizontal current in the metal pad has been significantly reduced to below 5 000 A/m². The design value has been further suppressed. Figure 10 shows the calculation results, indicating that for aluminum electrolysis cells using NCCT technology, due to the low design base value, the effect of increasing the metal height on reducing the horizontal current in the metal pad is no longer significant in a larger range (20–32 cm).

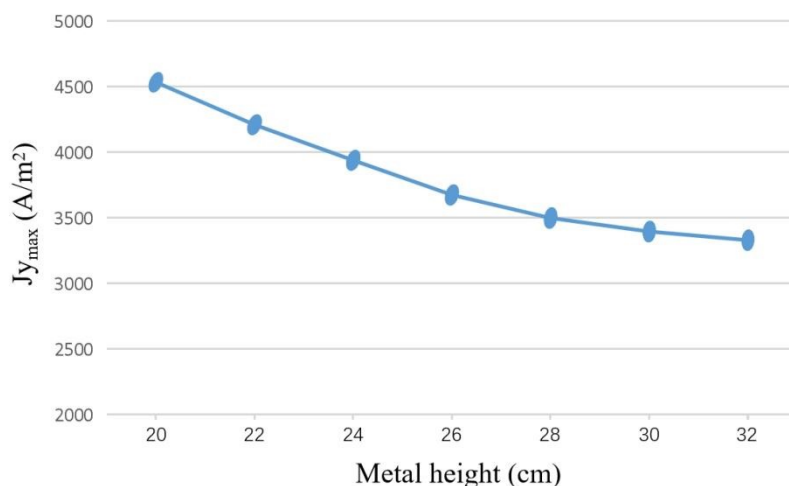


Figure 10. The relationship between metal height and horizontal current under NCCT.

SAMI's research has also found that in the busbar configuration with significantly improved MHD stability, the importance of further reducing the horizontal current diminishes. This reduction may have negative effects on thermal balance and alumina dissolution.

4.1.2 The Relationship Between Metal Height and CVD

The ideal shape of the ledge requires a reasonable thickness and shorter toe, which helps in achieving a smaller deformation of the metal pad and a lower horizontal current, ultimately leading to higher current efficiency. If the ledge toe extends too far into the anode projection, it can result in an increase in local cathode current density and the generation of reverse horizontal current, which can negatively impact the MHD stability of the cell. On the other hand, CVD is closely linked to the thermal balance of the cathode area in the electrolytic cell. Therefore, under different CVD conditions, the influence of metal height on the shape of the ledge can vary significantly.

4.1.2.1 The Relationship Between Ledge Shape and Metal Height in Traditional High CVD Cell

Due to the differences in structural design level and material properties, the design value of traditional cell CVD is relatively high, generally between 270 mV and 310 mV. With the increase in cell age, CVD gradually increases to more than 330 mV. We investigated the effect of metal height on ledge shape at 300 mV CVD and a cell voltage of 4.020 V. The calculation results are shown in Figure 11. It can be seen that under traditional high CVD, the ledge of the cell gradually becomes thinner with the increase in metal height, and the length of the ledge toe gradually increases, but the change is moderate.

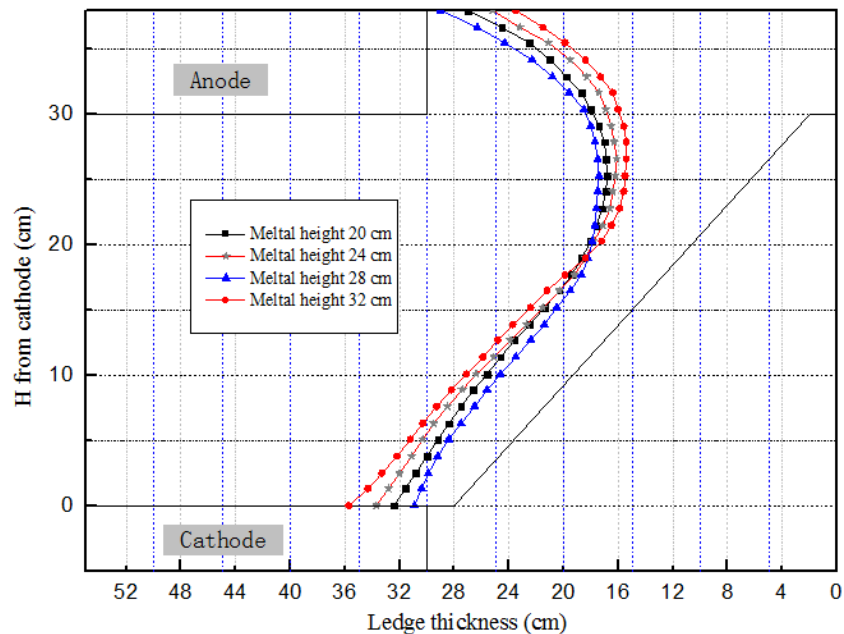


Figure 11. Variation of ledge shape with metal height under traditional CVD design.

4.1.2.2 The Relationship Between the Ledge Shape and Metal Height Under Graphitized Carbon Cathode with NCCT

The CVD design value of the cell using 100 % graphitized carbon cathode with NCCT technology can be reduced to below 200 mV. We investigated the effect of metal height on the ledge shape at 195 mV CVD and a cell voltage of 3.945 V. From the calculation results in Figure 12 we can see, the variation range of the ledge and ledge toe corresponding to the change of the unit metal

height increases obviously, and the length of ledge toe is more sensitive to the change of metal height.

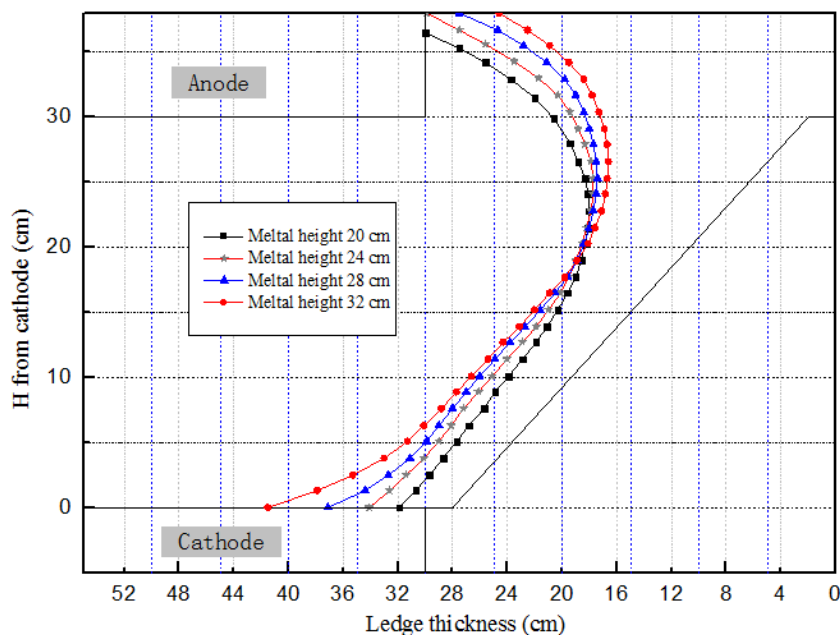


Figure 12. Variation of ledge shape with metal height under NCCT low CVD design.

4.2 “Three Low - One High” Production Process Management Technology

4.2.1 Process Parameters Control Window

SAMI has developed a refined, data-driven, and centralized technology parameters control scheme based on local factory conditions, and formed a precise management technology system of “Three-Low and One-High” production process with low metal height, low voltage, low CR, and high current efficiency with a new standard for controlling the main process technology parameters during the normal production period of the electrolytic cell (see Table 1).

Table 1. Typical “Three-Low and One-High” control window.

Item	Traditional technology	“Three-Low and One-High”- Pure electrolyte system	“Three-Low and One-High”- Complex electrolyte system	Key features of “Three-Low and One-High”
Set voltage, V	4.04 ± 0.10	3.93 ± 0.02	3.8 8± 0.02	Low
Bath temperature, °C	935~965	948~958	938~948	
Metal height, cm	25~35	20~22	20~22	Low
Bath height, cm	16~20	17~19	17~19	
Superheat, °C	7-20	8-12	8-12	
CR	2.30~2.60	2.25~2.35	2.25~2.35	Low
Anode cover thickness, cm	16~22	14~16	14~16	
CE, %	89~93.5	93.5~94.5	93.5~94.5	High

Note: This 240 kA potline uses a pure electrolyte system (lithium and potassium content < 1 %).

Thanks to the upgrade of the cell control system and the meticulous management of the “Three Low - One High” Production Process Management Technology, the process technical conditions are well controlled. We conducted a one-year comprehensive monitoring and test on the main process technical parameters of the potline from March 27, 2023 to March 27, 2024.

4.2.1.1 Voltage

As shown in Figures 13 and Figures 14, during the monitoring period, the qualification rate of voltage control reached as high as 95.10 %. After upgrade, the cell has achieved long-term stable operation at low voltage, with an average cell voltage completion value of 3.950 V and an average voltage deviation controlled within 15 mV. The potline operating trend is stable.



Figure 13. Set voltage curve during the monitoring period.

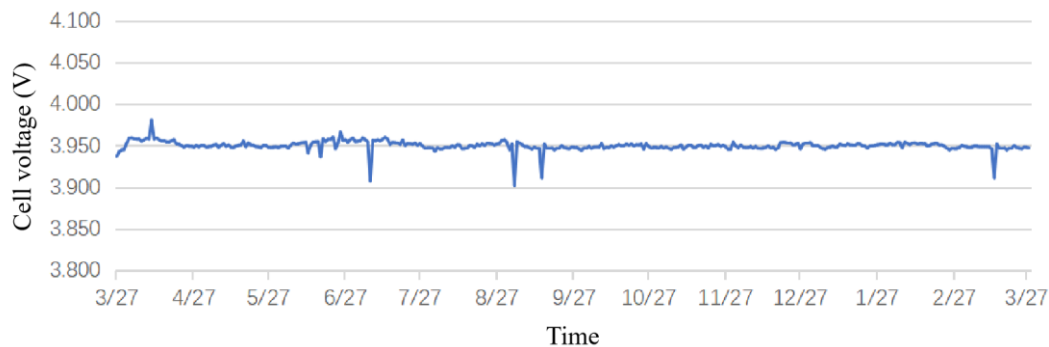


Figure 14. Cell voltage curve during the monitoring period.

4.2.1.2 Metal Height

According to the core control requirements of “Three Low - One High”, the metal height control rate during the monitoring period was 100 %, with a control range of 20–22 cm, as shown in Figure 15.



Figure 15. Metal height curve during the monitoring period.

4.2.1.3 CR

Under stable cell conditions, low CR was beneficial for improving current efficiency. However, when the CR dropped below 2.25, significant fluctuations in cell operation occurred. The technical team conducted an exploration and determined that the optimal CR control range was between 2.25 and 2.35, and the CR controlled rate exceeded 90 % during the monitoring period (see Figure 16).

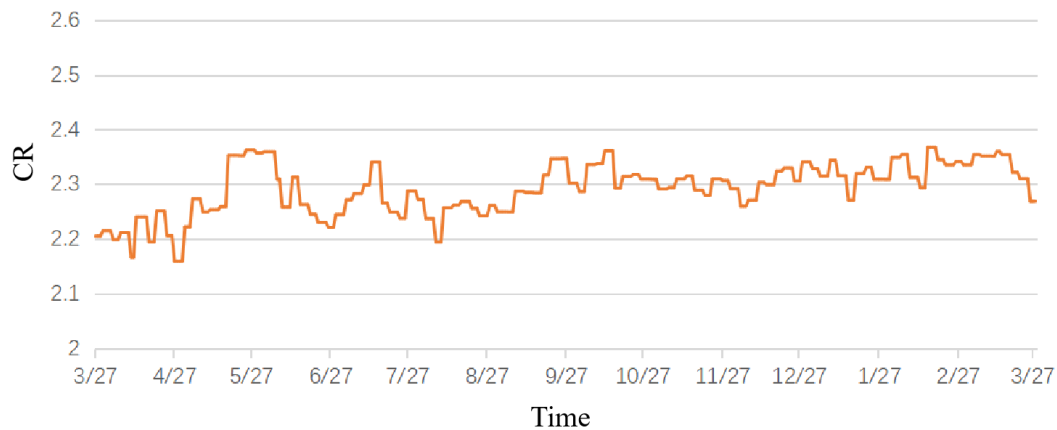


Figure 16. CR curve during the monitoring period.

4.2.1.4 Bath temperature

During the monitoring period, the standard for bath temperature control was 948–958 °C , with an average actual bath temperature of 952.3 °C. As shown in Figure 17, the qualified rate of bath temperature control was 91.4 %.

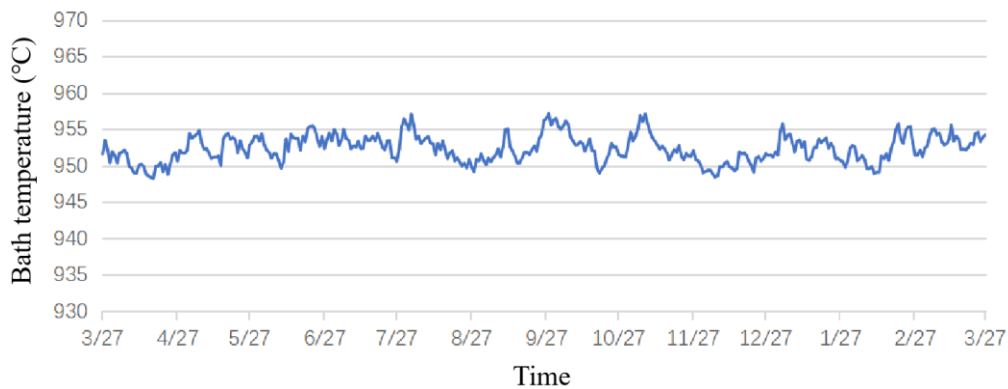


Figure 17. Bath temperature curve during the monitoring period.

4.2.1.5 CE

Through iterative control and optimization of process technical conditions, the “Three-low and One-High” technology has gradually matured, achieving an amazing story with high current efficiency production. The current efficiency curve during the monitoring period is shown in Figure 18.

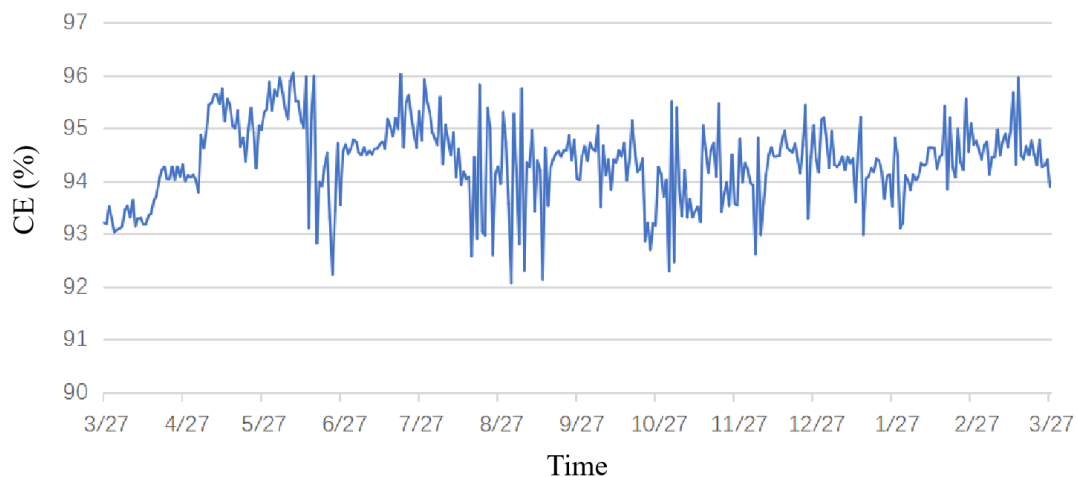


Figure 18. CE curve during the monitoring period.

5. Potline Performance

Starting from November 2022, the technical team steadily implemented gradient current intensifying work, which was carried out in four stages: 250 kA, 255 kA, 258 kA, and then 260 kA. Ultimately, achieving positive thermal balance control of the cell under low voltage and low energy consumption conditions. Figure 19 shows the current intensifying curve.

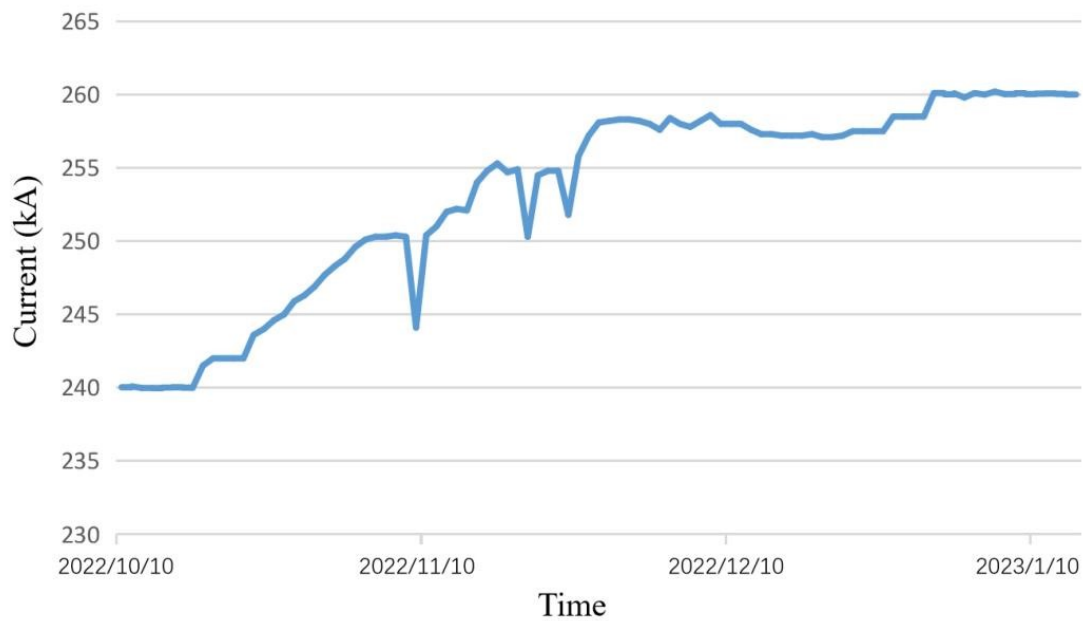


Figure 19. Current increase curve.

Table 2 shows quarterly KPIs since 2023 after amperage increase from 240 kA to 260 kA. It has been an amazing practice of this potline in terms of various performance KPIs. The potline had the best performance in 2024 at 260 kA after “Three Low - One High” Production Process Management Technology successfully implemented and maintained. Meanwhile, the potline has demonstrated excellent environmental KPIs with low AE frequency and duration.

Table 2. Summary of KPIs.

KPI	Unit	Before upgrade	After upgrade				
			2023 Q1th	2023 Q2nd	2023 Q3rd	2023 Q4th	2024 Q1th
Number of cells	/	164	164	164	164	164	164
Cell current	kA	240	260	260	260	260	260
Cell voltage	V	4.030	3.951	3.950	3.949	3.949	3.948
Current efficiency	%	89.96	94.28	94.40	94.48	94.65	94.72
DC power consumption	kWh/kg Al	13.350	12.491	12.472	12.458	12.436	12.423
Bath temperature	°C	954	953	953	953	952	952
Bath height	cm	18.2	18.9	18.8	18.8	18.8	18.7
Metal height	cm	28-30	20.6	20.8	21.0	21.3	21.5
Cell Noise	mV	25	16	17	17	16	16
Cathode voltage drop (CVD)	mV	315	195	195	196	196	196
Cryolite ratio (CR)	/	2.45	2.25	2.26	2.30	2.32	2.33
Gross carbon consumption	kg/kg Al	0.490	0.485	0.476	0.468	0.472	0.465
AE frequency	AE/p-d	0.05	0.026	0.021	0.018	0.016	0.015
AE duration	s	23	8.9	7.7	7.1	4.3	3.1

In Table 2, gross carbon consumption is calculated as:

Gross carbon consumption = (Current month anode purchase quantity + Last month anode inventory - Current month anode inventory)/(Current month aluminum production).

In recent years, the gross C consumption of China's aluminum smelters has been significantly reduced, mainly for the following reasons: (1) The butts are very thin, only 155~160 mm; (2) Many aluminum plants design the top shape of the anode carbon block to be small to minimize the weight of the butts; (3) Appropriately increase the overall height of anode carbon block; (4) The above three reasons also lead to the lengthening of the anode change cycle and the reduction of gross carbon consumption.

6. Conclusions

The optimized Gas Preheating Process in this project improves temperature control, prevents local overheating that could cause thermal stress concentration in carbon materials, and establishes conditions for the long-term safety and stability of lining materials, particularly carbon materials, after current increase.

Through the control algorithm and model innovation of the pot, SAMI has developed Narrow-Amplitude and Dual-Mode Cell Control Technology. Additionally, a new pot control system has been designed with high integration, low maintenance, easy expansion and increased digital intelligence. As a result, the control rate and current efficiency of main process parameters have been greatly improved.

The precision management technology of the “Three Low - One High” production process achieves stable maintenance of the superheat, regular legde shape, long-term stable CVD in the pot, as well as high current efficiency and low energy consumption during operation.

The excellent design of physical field, upgraded control system, and refined production process management technology has laid a solid foundation for the successful implementation of current increase in this potline. The application of SAMI's deep energy-saving aluminum electrolysis technology system not only brings substantial economic value to smelters by increasing production and reducing consumption, but also significantly reduces their carbon emissions through lower energy and net carbon consumption.

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