

Cell Design Modifications to Reduce Specific Energy Consumption

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Abstract

The Hall-Héroult aluminium reduction is an energy-intensive process with Specific Energy Consumption (SEC) ranged in 12–15 kWh/kg Al, with around 50 % of energy efficiency. Thus, reducing energy consumption through investment in advanced technologies and practices can enhance manufacturing competitiveness and collaborate to reduce the aluminium industry carbon footprint.

Along the years, Aluar implemented a continuous research and development program that led to several upgrades of the original cell designs. Since 2018, the introduction of copper inserts in collector bars to reduce cathode resistance in Lines C and D, the consequent redesign of the lining to maintain thermal balance, and the installation of shell cooling fins have resulted in the reduction of 0.5 kWh/kg Al. This paper highlights the improvement process and the road map to convert 384 cells to a more energy efficient design, which is currently under way.

Keywords: Hall-Héroult reduction cells, Collector bar copper inserts, Cell autopsy, Cell design.

1. Introduction

Mainly due to energy costs and global decarbonisation goals, the industry is continuously improving its energy efficiency, looking for innovative alternatives to produce aluminium. In the last decades, many smelters have modified their cells in order to reduce the specific energy consumption (SEC) of the Hall-Héroult process, achieving a state-of-art design close to 12 kWh/kg Al [1-2].

Aluar started its operations in 1974 installing two Montecatini P155 end-to-end side-worked prebake (SWPB) lines, with 200 cells each, running at 150 kA. After diverse upgrades implemented in the last 50 years, Lines A and B are operating close to 200 kA [3]. As a first expansion stage, Line C was started in 1999 with 144 side-by-side AP Technology™ AP18 cells running at 180 kA, which have been gradually transformed to AP Technology™ AP22 since 2006 in order to increase the line current up to 220 kA. In 2007, a second expansion phase put Line D into operation with 240 AP22 cells. At present, Aluar has an installed capacity of 456 000 tonnes per year, and an average energy consumption of 13.7 kWh/kg Al.

The worldwide use of copper in collector bars motivated the development of Aluar's most recent projects to reduce SEC, based on in-house cell redesigns. This paper focuses on the major changes implemented in Lines C and D, and on the main project milestones that lead to the on-going

transformation process. Since the so-called “al23” design could run at up to 235 kA, it could enable future amperage increase potential.

2. Cell Design

The al23 is the first comprehensive change done to standard cells, and the applied modifications aim to improve both energy efficiency and magnetic compensation. The initial phase of the project started in 2016, and the characteristics are the result of extensive research and modelling work, tests, measurement campaigns, prototypes, detailed engineering, collaboration projects, decision-making, risk analysis, validation, and comparison of different alternatives; looking for an optimal cost-benefit ratio that increases profits and minimises implementation period.

Two years later, 7 al23 cells were successfully started in Line D. These first prototypes are still running, with more than 2200 days in normal operation and no registered failures. Black paint details on the super-structure helped floor operators to distinguish the new design inside the room (Figure 1). Once the validation stage was completed, a second trial of 12 cells started in Line C in 2020.



Figure 1. First al23 cell started in September 2018.

The al23 cells registered a reduction of 0.5 kWh/kg Al in the specific energy consumption, stable cathode resistance below 0.9 $\mu\Omega$, and ~150 mV voltage reduction compared to standard design cells.

The main modifications are copper inserts in collector bars, longer cathode blocks and cooling shell fins. Therefore, since copper has a higher electrical and thermal conductivity, it was necessary to adjust the lining to compensate the extra heat extracted through collector bars. The latter is necessary to maintain the thermal balance and, more importantly, to keep isotherms at the desired location, avoiding cold cathode blocks. In addition, the use of longer cathodes in the same shell requires a side lining resize, resulting in a larger volume of liquid bath and/or enough room for bigger anodes, enabling future amperage increases.

2.1 Copper Cored Collector Bars (CCCB)

The potential benefits of using copper in collector bars can be resumed as follows, promoting in this way lower energy requirements and/or a line current increase:

- Lower cell voltage, due to its lower electrical resistance,
- Higher productivity, due to higher current efficiency obtained by lower metal velocities, lower metal heave and higher cell stability,
- Longer lifespan, due to more uniform cathode surface erosion.

The first stage of the al23 project involved the thermo-mechanical analysis of the cathode assembly with different copper insert dimensions, both in length and diameter, in search of the optimal ratio between magnetic compensation and costs, as well as specified tolerances to guarantee good electrical contact at the working temperature. The numerical models were developed by CAETE and the 3D thermal model results is shown in the Figure 2.

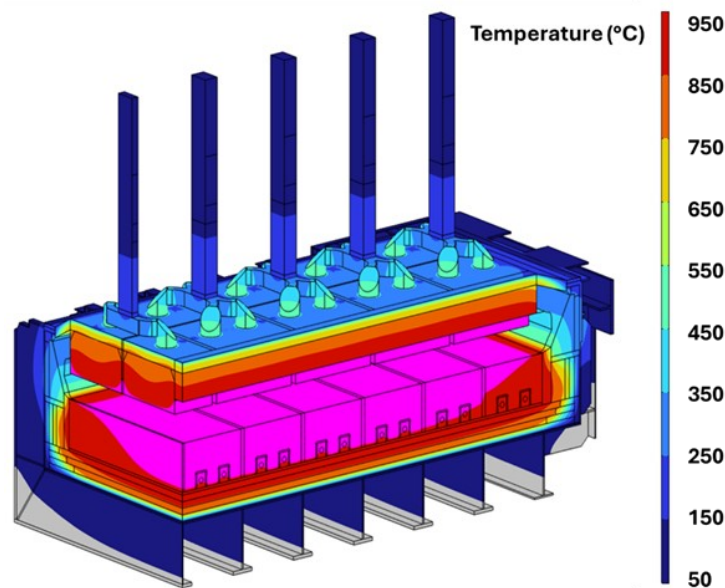


Figure 2. Electro-thermal numerical model temperature results for al23.

The use of CCCB helps to redistribute the current along the collector bar, reducing the current density in cathode block ends, ensuing a higher magnetic compensation and lower magnetohydrodynamic (MHD) instability.

During the modelling stage, development of different simulations helped to understand not only thermal and MHD cell behaviour, but also the impact of each modification on operational and process parameters.

2.2 Extended Cathode Block

The al23 proposed an 80 mm longer cathode block to compensate the resulting 40 mm anode-to-cathode offset previously achieved due to the line current increase from 180 kA to 220 kA. This modification implies that anodes and cathodes are now in the same line, reducing horizontal current densities, increasing MHD stability, and enabling future anode dimension increases. There were no modifications in the size of the shell, consequently this cathode length extension inevitably led to thinner side lining and isotherms displacement to the sides.

2.3 Lining Materials

Both copper inserts in collector bars and longer cathode blocks required a lining redesign, not only in sides but also in pillars and bottom lining in order to redistribute heat flux, get a proper

isotherm distribution, and keep thermal balance. Since copper extracts more heat through collector bars, the goal was the reduction on thermal losses to minimize energy consumption. It also simultaneously attempted to achieve a safe ledge profile, adequate position of 865 °C isotherm, keeping it inside refractory brick layers to protect the insulation, and a proper insulation temperature [4].

In al23 design, vermiculite and calcium silicate boards replaced the original insulation bricks to compensate the extra heat, and avoid voltage increases that may override electrical copper benefits. The use of lower thermal conductivity materials allowed their resize and relocation in the cell. Due to the increased cell cavity, extra simulations analysed the alumina distribution along the cell and the MHD effect of the anode cycle pattern.

2.4 Shell Cooling Fins

In order to reduce the energy requirements and to minimize heat losses, the al23 project proposed to turn off the existing Forced Convection Network (FCN) at a moderated line current close to 220 kA. Thus, cooling fins help to achieve thermal balance adjusting heat loss to the cell thermal demands and reduce shell temperature. As shown in Figure 3, there are four long steel plate fins in each section, welded at long sides of the shell and corners, behind shell reinforcements. These fins are long enough to cover both the metal-bath interface region and the upper part of the cathode blocks, covering most of the available area. The use of the existing FCN would enable a potential amperage increase in the future.

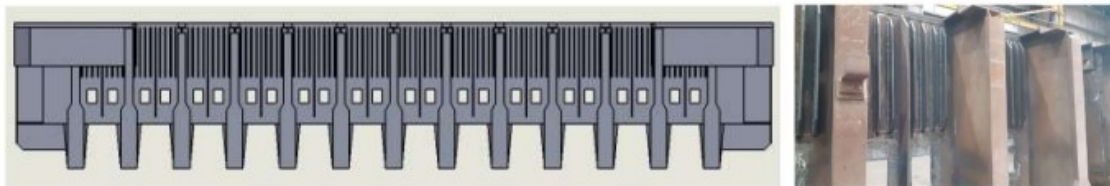


Figure 3. Shell cooling fins in al23 design.

3. Design Validation

The validation procedure should involve, apart from a good process variables performance, the lining temperature monitoring, and an autopsy, mainly because of financial consequences that a weak design could imply. In absence of early failures, it is usual to perform a partial or total autopsy after 2 years in operation, not only to identify failure modes in advance, but also to accelerate the implementation of the new design [5].

As a first stage, 16 thermocouples were set in different locations between insulation and refractory layers during the construction of the first prototypes, to monitor both side and bottom lining temperature distribution. This procedure was very useful to understand the heat flux distribution throughout preheating, start-up, and early life, and to validate mathematical thermal models [6]. The results achieved all the design targets.

After 2 years in operation, in August 2020 a planned al23 cell shutdown allowed cathode inspection first, and a controlled demolition afterwards. The surface of cathode blocks presented a slightly W-shaped erosion pattern and no delamination; therefore, the inspection did not reveal areas of concern.

As shown in Figures 4 and 5, the expected erosion rate, preserved refractory and insulation layers, and location of isotherms confirmed the lining temperature, heat flux and ledge profile registered

during the operation. There was no metal infiltration in small joints, big joint or beneath cathode blocks, as well as attacked collector bars.



Figure 4. Cathode surface inspection of the first prototype.



Figure 5. Controlled demolition of the first prototype.

Process performance and promising results of the in-house al23 design after the autopsy boosted the construction of 12 more al23 cells, which has started in Line C since September 2020. Ledge profile, cathode current distribution and lining temperature measurements also registered good performance running at 220 kA, with FCN turned off and the expected reduction in energy requirements. In 2023, one of these 12 cells went to a planned shutdown to carry out a new cathode inspection. Again, erosion rate was similar to expected values, and no failure modes were identified; the design was thus finally validated. This cell was electrically preheated, successfully restarted, and it is in normal operation.

4. Design Performance

The main goal of the al23 project is to reduce the energy requirements of Lines C and D below 13 kWh/kg Al, and the results registered in the last 6 years are promising since the beginning.

The 12-month average key performance indicators and process variables are shown in Tables 1 and 2 respectively, for both trial cells and a reference group. The al23 cells are operating with a lower cathode resistance and similar instability levels despite of less metal height. The increase in the anode effect frequency may be associated with the operating window, so it is under study.

These results demonstrate that the use of copper and an extended cathode block contributed to a reduction in horizontal current densities and better current distribution.

The a123 cells exhibit a 0.8 % higher current efficiency when compared to the reference group, calculated using tapped metal and metal inventory. Considering the same current efficiency for both groups, the registered reduction in specific energy consumption is 0.50 kWh/kg Al. Thus, the difference in SEC could be even higher than the one presented here.

Table 1. Summary of key performance indicators (KPIs).

KPI	Reference Group	a123 Design
Line current (kA)	217	217
Total cell voltage (V)	4.24	4.08
SEC @94.5 % CE (kWh/kg Al)	13.38	12.88
Anode effect frequency (#/cell-day)	0.18	0.36
Metal purity (%)	99.88	99.84
Cell age (months)	38	37

Table 2. Summary of control parameters.

Process variable	Reference Group	a123 Design
Bath temperature (°C)	960	960
Excess AlF ₃ (%)	12.10	11.20
Bath level (cm)	18.5	18.5
Metal height (cm)	18	16
Sodium content in metal (ppm)	82	91
Cathode resistance (μΩ)	1.4	0.8
Instability level (nΩ)	65	64
Forced Convection Network (FCN)	on	off

In terms of thermal balance, a123 cells are working with lower superheat and good ledge profile. As shown in Figure 6, the average ledge profile measured in an a123 cell along its cell life and the corresponding shell temperature are not only quite stable but within the expected limits.

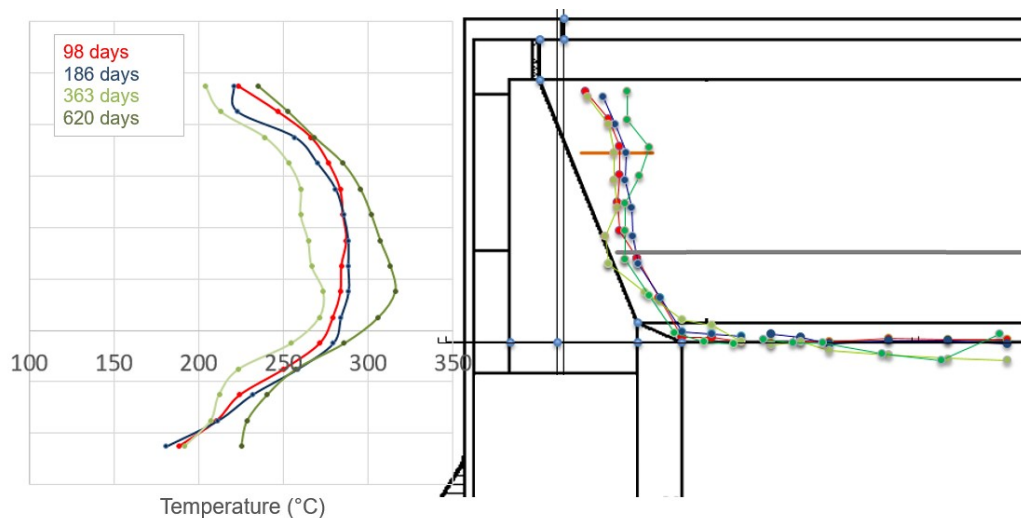


Figure 6. Shell temperature and ledge profile along cell life.

In terms of cathode resistance in al23 cells, it is almost constant along the cell life, registering values around $0.8 \mu\Omega$ (Figure 7). In addition, the data from thermocouples inserted in the lining of some prototypes during its construction, the performed cathode inspections and the controlled demolition carried out are all consistent with process performance and measurements along these years.

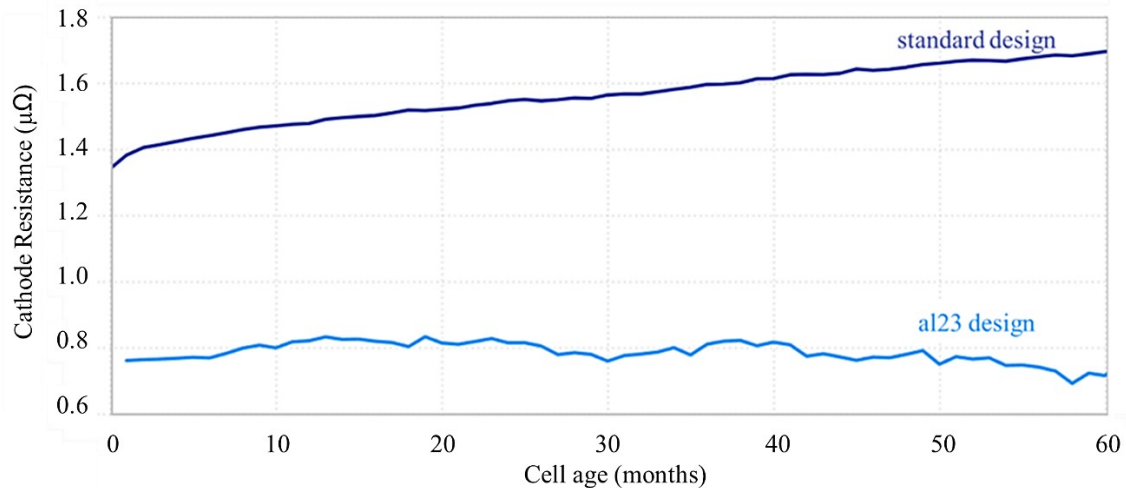


Figure 7. Average cathode resistance along cell life, for standard and al23 designs.

Until now, there are no indications of metal infiltration; and no copper increase events were registered in metal quality analysis. No failure modes have been identified yet, and there have been no early failures that could indicate weaknesses in al23 design.

As a conclusion, the implemented modifications help to insulate the cell and to reduce energy requirements, while they would put up with line current increases in the future. According to MHD and thermal modelling, al23 design has amperage increase potential and can operate up to 235 kA with the help of FCN.

5. The Way Forward

In 2023, the corresponding economic analysis shows that the al23 project has positive profitability. For this economic valuation, savings only in energy consumption were considered due to lower total voltage, without considering other potential benefits such as longer life span or higher productivity (higher current efficiency).

Cathode surface erosion measurements were done only in 2 al23 cells after 2 years in operation, without registering significant differences. Consequently, considering that the first prototypes are still in operation, the economic valuation assumes similar erosion rates.

As a result, the company decided to extend the al23 design to the 384 cells of Lines C and D, starting in 2025. Thus, a diligent and efficient plan to define the standard operating procedures for the cell relining as well as the replacement of the lining material stocks are in process.

Today, 18 al23 cells are operating with the expected results, and it is planned to have 50 cells by the end of 2024. With this in-house new design, Aluar has reached a new goal, and it is on its way to reduce its energy consumption. At the current relining rate, and considering the material stock change, Lines C and D full conversion to al23 design could be completed by 2031.

6. Conclusions

The al23 project started in 2016 with the objective to develop, model, build and operate a new cell design in Lines C and D that improves its energy efficiency. The main modifications are the use of CCCB and longer cathode blocks to reduce the horizontal current density distribution and improve MHD stability, the use of cooling fins in the shell to avoid the use of a forced convection network and minimize heat losses, and the redesign of the lining to compensate the extra heat extracted through the collector bars.

The al23 has demonstrated good performance and achieved expected results since the start-up. The gross specific energy consumption is reduced in 0.5 kWh/kg Al and it will help to reduce the total energy requirements of the smelter after full conversion. On the other hand, the new design has amperage increase potential.

Last, but not least, Aluar has gained considerable knowledge about cell design and operation parameters that could bring to future revisions in order to keep on continuous improvements.

7. Acknowledgments

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