The Successful Testing and Implementation of AP30 Technology Spinoff Cell Designs at Alcoa Fjarðaál

Katarzyna Mirek-Sliwa[1], Brian Zukas[2], Ketil Rye[3], Patrice Doiron[4] and Kristinn Ingimarsson[5]
1. Pot Design Manager
Alcoa – Operational Excellence Center of Excellence, Kristiansand, Norway
2. Senior Smelting R&D Engineer
Alcoa – Operational Excellence Center of Excellence, New Kensington, USA
3. Smelting Technology Manager
Alcoa – Operational Excellence Center of Excellence, Mosjøen, Norway
4. Global Manager Modelling and Pilot Operations
Alcoa – Operational Excellence Center of Excellence, Deschambault, Canada
5. Technical Manager
Alcoa Fjarðaál, Reyðarfjörður, Iceland
Corresponding author: Katarzyna.Mirek-Sliwa@alcoa.com

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Abstract

In April 2007, Alcoa Fjarðaál smelter started its first cell using the Aluminium Pechiney technology AP30 platform, fitted with an Alcoa cell lining design intended for an initial nominal amperage above 300 kA. The AP30 technology was also used at Alcoa Deschambault smelter since 1992, which was at the time the state-of-the-art cell technology. Based on already proven technology solution, supplemented with our fundamental knowledge and experience, Alcoa decided to use the same platform for its Fjarðaál smelter. Since then, the Fjarðaál smelter has tested and deployed different cell designs that have demonstrated excellent performance. The third reline wave has been ongoing since March 2020. Aiming to increase the amperage above 380 kA, Alcoa Fjarðaál initiated a large-scale trial of new cell designs. In addition to already available developments, two new conceptual cell designs were developed targeting specific characteristics of the smelter. Performance tests were carried out on a group of 10 cells using a given design and 20 cells with a different design. Operational performance metrics were statistically compared to the selected reference standard design. This paper presents a description of Alcoa's cell design change governance and a comparison between the different designs.

Keywords: Alcoa Fjarðaál, AP30 technology, Cell design, Load increase, Amperage increase.

1. Introduction

The Alcoa Fjarðaál Aluminium plant started production in 2007, with operation of one potline with a total of 336 cells and nowadays presents a capacity above 340 kt/year. The AP30 technology was chosen for deployment based on the successful operational results demonstrated in Alcoa Aluminerie de Deschambault Canadian smelter that started operation with 264 cells using AP30 Technology in 1992. Since that time this aluminum plant has started more than 1600 cells in the regular operation [1], consequently verifying the process performance as a part of internal line current increase programs including multiple campaigns of special field measurements.

The AP30 line at Fjarðaál has had two relining waves and is presently undertaking its third relining generation with planned testing of two new modified cell designs with the intention of increasing amperage towards 390 kA. Table 1 summarizes the cell design development at Fjarðaál.

Table 1. Summary of Alcoa Fjarðaál plant cell linings generations.

Cell Design AP30	Deployment date	Target nominal load (kA)	Objective	Average cell life	Number of cells
FJA 1st Gen v. 1	April 2007	365-380	Technology transfer	2273	338
FJA 1st Gen v. 2	April 2008	365-380	Amperage increase	2118	2
FJA 2nd Gen v. 1	April 2011	380	Amperage increase	2108	11
FJA 2nd Gen v. 2	July 2012	380	Amperage increase	1724	3
FJA 2nd Gen v. 3	May 2014	380	Amperage increase	2307	443
FJA 2nd Gen v. 4	April 2019	380	Amperage increase	---	28
FJA 3rd Gen v. 1	February 2020	390	Amperage and cell life increase	---	48
FJA 3rd Gen v. 2	September 2020	390	Amperage increase	---	78
FJA 3rd Gen v. 3	July 2021	390	Amperage increase	---	150
FJA 3rd Gen v. 4	October 2021	390	Reduce energy consumption and amperage increase	---	10
FJA 3rd Gen v. 5	December 2021	390	Reduce energy consumption and amperage increase	---	19

The economic strategy used for developing the plan for amperage increase was to increase production through modifications of the cell design and optimization of process control for stable operation at higher amperage. The existing infrastructure capacities of electrolysis, rodding shop, casthouse, alumina distribution systems, available rectifiers, machines, equipment as well as manpower were anticipated to be used as is. Through efforts to improve cell design and operational excellence, Fjarðaál presently operates at a line load of 380 kA and is targeting 390 kA. The main challenge in the creep program is the power availability. This restriction led to higher demands for voltage savings and CE improvement for the new cell design.

Figure 1 presents the evolution of line load versus specific energy consumption at Alcoa Fjarðaál. In October 2010, there was a rapid drop in the current from 377 kA to 365 kA due to fire in a transformer at the substation. The power outage lasted for 2.3 h, but no cells were curtailed [2].

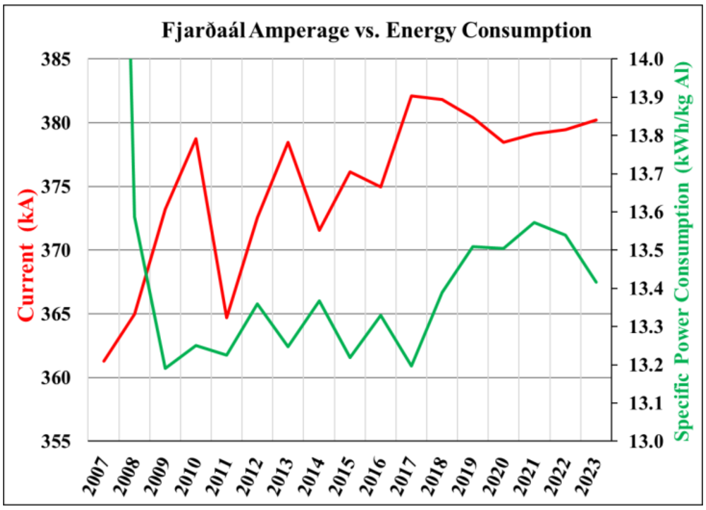

Figure 1. Evolution of line current and specific energy consumption at Alcoa Fjarðaál, per yearly average.

This paper presents operational test results from AP30 spinoff cell designs over two years and key milestones in the development of new cell designs at Alcoa, as defined in our cell design change governance system.

2. Milestones in the Development of Spinoff AP30 Cell Designs

Alcoa has implemented a standardized system for managing new cell design deployment to minimize the potential risk of cell design failure, which could seriously impact plant production and financial health. This system helps to ensure that the overall project criteria is being met and that quality thermo-electro, magnetic and mechanical modelling results are being achieved.

2.1 Cell Design Change Governance System

The Cell Design Change Governance System mitigates the risk for new design deployment. The systematic methodology is applied at every stage of the project, from the initial plant request for a design change until the new cell design is used as the new standard.

To reach full deployment, a new cell design typically goes through five successive stages:

1) Project definition (modelling request): This usually involves a business case or a defined operational challenge, describing the present standard cell behavior with the use of special measurements and input from manufacturing analysis. The future operating targets conditions are usually determined for one or more KPIs, e.g.: amperage, CE, cell voltage, power consumption, cell life, cell lining cost and other miscellaneous specific characteristics for the project. Stage 1 is concluded with a notification request for the new design development.
2) Modelling assignments: Based on thermo-electro-magnetic numerical simulations models are defined to reflect the actual cell behavior. A feasibility study with modelling and in-depth sensitivity analysis is performed to optimize the conceptual proposal for operational testing.
3) Testing: Aims to minimize the financial risk to operations, while collecting sufficient information and operational experience with the new cell design. Stage 3 is structured in subtest cell populations: where in the first year only 3–5 new test cells are started gradually expanding up to maximum 40 % of the total reline in the last test year. Reference cells with the base design are selected having the same age and cathode manufacturer. It takes approximately 2.5 years to complete the test phase and it is concluded with a thorough cell autopsy.
4) Evaluation: An assessment of the regular operational parameters of the test cell performance is aligned with dedicated special measurement campaigns over the test period. This technical information is applied to validate the thermo-electric modeling predictions versus operational data. Depending on the outcome of the evaluations, a decision is made to expand or terminate the test.
5) Full deployment: An acceptance in a final "stage gate review" leads to full deployment. Overall, it takes about 10 years from project definition until full cell complement, during which time the plant might define new strategies or targets and request new design changes. Figure 2 presents the stages for the design change deployment pipeline.

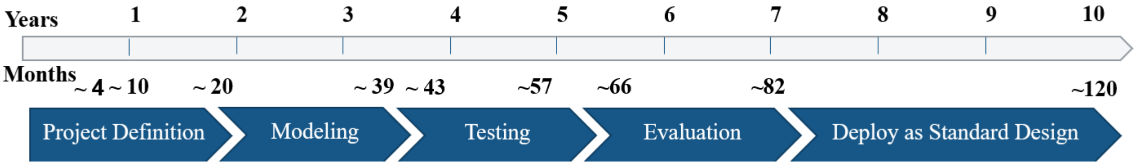

Figure 2. Cell design change governance deployment pipeline.

2.2 AP30 Spinoff Test Cells Development

In the last quarter of 2019 Alcoa Fjarðaál had defined the amperage increase objectives and issued an official request for the cell design development. The limitations from existing power contract emphasized importance of reducing the energy consumption.

Before any actual cell development work could be advanced the main cell operating parameters and technical documentation on cell construction were evaluated. The minimum technical input was considered to include, but not limited to, geometric data on anode and cathode assembly, cell shell with cell lining materials, and historical process data related to electrical, chemical and thermal performance [3].

The preliminary modelling study delivered results to understand and describe the "base case". The conceptual cell design success criteria were based on:

- Constraints in available contracted power, restricting the cell voltage,
- Use of the existing infrastructure,
- Heat and voltage balance ensuring sufficient protective ledge thickness and toe ridge,
- Magnetic stability and critical ACD,
- Robustness of cell operability expressed as voltage range envelope at target amperage.

2.2.1 Cathode Assembly Modeling

The general approach of modelling is always evolving at Alcoa to be the most adapted to the industrial demands. Alcoa is advancing modelling capabilities with COMSOL platform, which provides supplementary knowledge to our in-house developed cell design software.

The cathode assembly modelling component of the AP30 cell was studied in COMSOL. The optimization was accomplished during a parameter study of copper insert dimensions and its position in the steel collector bar. The effect of different parameters variation on maximum cathode current density and voltage drop was examined. The ridging effect was also a consideration. Figure 3 presents an example of an AP30 COMSOL cathode assembly model.

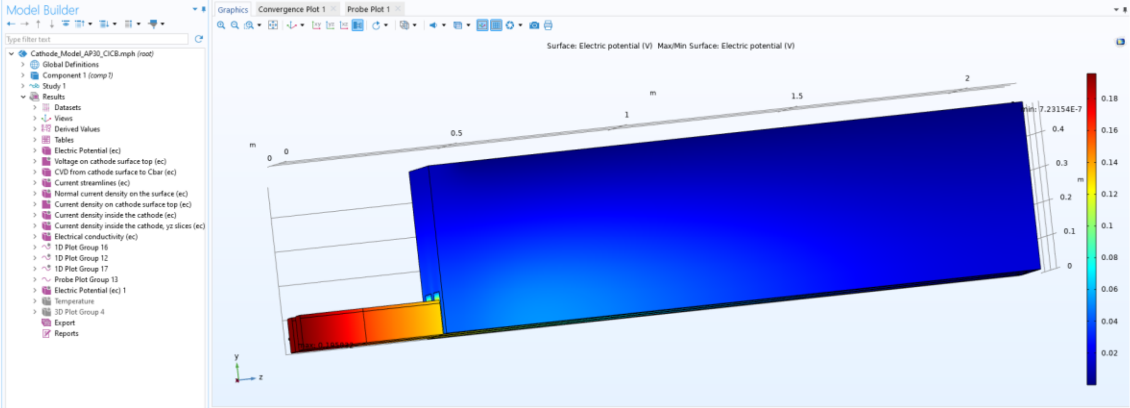

Figure 3. AP30 COMSOL cathode assembly model.

2.2.2 Cell Design

The COMSOL results on cathode voltage drop (CVD) and geometry for the modified cathode assembly were incorporated in Alcoa in-house developed software dedicated to overall heat and voltage balance cell design modelling.

The cell heat and voltage balance at equilibrium is essential while modeling. At equilibrium, the protective layer of frozen electrolyte is formed on inner walls of the cell at a given bath temperature, acidity and interpolar distance [4]. A significant amount of the energy supplied to the cell is lost to the surroundings. The amount of heat required to maintain the operational bath and molten metal temperature, as well as for heating the alumina and carbon reactants and dissolving the alumina in the bath varies depending on the technology but is typically between

40-50 % of the generated heat. The current density and interpolar distance are the main components impacting heat generation in the cell. In practice heat input is defined by cell voltage and amperage. The heat loss is given mainly by cell design, thermal insulation and material properties degradation with aging, anode size and anode cover material thickness.

There is a permanent movement of the molten metal pad and the electrolyte in the cell, caused by the presence of magnetic fields and gas bubbles formed at anode. The interpolar distance has to be sufficient to prevent short-circuiting and extensive back reaction between metal and carbon dioxide. The interpolar distance is therefore a critical factor for cell's thermal control and design [5]. In principle, when intending to design a cell with increased interpolar distance, the cell heat and voltage balance has to be adjusted by cell lining insulation to enable higher heat dissipation. Likewise, when intending to increase cell voltage during operation, the new cell heat and voltage balance is achieved by process tuning.

Too high internal heat in the cell results in melting of the protective freeze leaving the lining materials exposed to the molten bath. On the other hand, too little internal heat results in excessive thickness of solidified electrolyte and sludge formation at the cathode bottom. This decreases the available cathode surface, negatively impacting the operation.

The computational simulations of 32 alternative pot design scenarios have been conducted to find optimal solutions for cell thermal equilibrium and expected KPI, as specified by the amperage increase program.

The key criteria for assessment of pot design models at 390 kA were:

- Lower or similar cell voltage drop to the baseline operation at 380 kA.
- Similar or higher CE than the baseline operation at 380 kA.
- ACD limitation for process stability and operational robustness.
- Thermal profile (isotherm distribution) predicting minimum cathode temperature and maximum temperature in the insulation layers.
- Side ledge thickness and toe ridge in the cell.
- Bath chemistry, temperature and superheat similar to the baseline operation at 380 kA.
- Construction cost.

The cell design and sensitivity analysis were concluded with two final model alternatives.

Test Design #1
A model that aimed to address the specific operational challenges present at the smelter. This approach indicated lower energy saving compared to Test Design #2, that was not completely in line with power contract constraints. The Fjarðaál plant had already installed 3 test designs with similar modelling assumptions and was interested to explore the potential to improve cell operation. The presumed contributors to energy saving would be on CVD reduction and operational excellence. The major modification in comparison to reference AP30 was to bottom lining heat dissipation, shift of the center of the highest side heat flux in the cell and cathode assembly modifications.

Test Design #2
A model that was directly dedicated to maximize the potential for energy saving and cell life improvement, including a concept to temper the shell steel exfoliation rate. The sidelining heat distribution was emphasized in finding a new heat and voltage balance. The presumed contributors to energy saving would be on CVD reduction and current efficiency (CE) improvements.

3. Test of AP30 Spinoff Cell Designs

The conceptual cell designs passed technical evaluation and tests have been launched, comprising of 10 cells of Test Design #1(TD#1) and 20 cells of Test Design #2 (TD#2). The risk of test failure was considered low, since the proposed designs originated from other proven designs operated by Alcoa. TD#1 and TD#2 were relined in the cathode workshop facility and successfully started operation within Q4 2021 and Q1 2022, respectively. Based on the age in operation, cathode grade and manufacturer, a group of standard design cells from the regular operation was selected as the reference for the statistical results comparison. The test cells have been distributed throughout the potrooms. After the first 60 days of the trial period the cells were meeting regular process control targets. Alcoa subject matter experts and Fjarðaál plant technical staff have established collaboration for operational support and evaluation of the test cells.

4. Performance Test Results

The test and reference cells have been operating in one line over the trial period May 2022–April 2024. The line amperage was kept stable at 379.5 kA until February 2023, when load was increased. The summary KPIs for the trial period is shown in Table 2. Current efficiency for the cell designs was excluded from the benchmarking, since Fjarðaál did not report specific CE per cell, only for the full line.

Table 2. Comparison of key performance indicators for AP30 spinoff cell designs versus reference standard design, test data May 2022–April 2024.

KPI	Unit	Test period May 2022–April 2024		
		Test Design #1	Test Design #2	Reference Design #3
Amperage	**kA**	379.7	379.7	379.7
Resistance	**μΩ**	6.87	6.55	6.71
Net Cell Voltage	**V**	4.33	4.21	4.27
Instability	**μΩ**	0.116	0.096	0.108
Excess AlF_3	**wt%**	11.07	11.04	11.31
Bath Temperature	**°C**	964.9	964.8	961.8
Superheat	**°C**	14.3	12.3	12.1
Bath Level	**cm**	15.6	15.9	16.0
Metal Level	**cm**	23.8	22.4	22.3
Iron	**%**	0.08	0.09	0.09
AE Frequency	**AE/cell/day**	0.27	0.14	0.18
AE Duration	**s**	7.0	4.0	5.9

Bath temperature was approximately 3 °C higher for the both test designs and there was also deviation in Superheat from the reference group. The chemical cell control with slightly lower excess AlF_3 could explain the difference [5]. The bath and metal levels were comparable, except increased metal level for TD#1. Test Design #1 demonstrated the highest AE frequency and instability. TD#1 behavior revealed large sensitivity to operating conditions, which manifested through challenges to sustain process stability. It could have been caused by multiple factors, but variation in metal pad levels, increased anode problems and muck formation are the most plausible reasons for the observed behavior. Since December 2022, more resolute remedial actions were taken to increase both the metal level and the anode-cathode distance. Consequently, related to that a cell voltage increased of ~60 mV in comparison to Reference Design #3.

The statistical comparison indicated that Test Design #2 is providing better results. The reduction in cell resistance enabled a reduction of ~60 mV and ~110 mV against the Reference Design #3 and Test Design #1, respectively. During the test period, the cells seem to indicate sufficient ACD as they did not experienced stability issues, nor high temperature excursions. The test performance data are given as 7-days moving average in Figures 4–10. Figures 11–12 show test performance results as accumulated values.

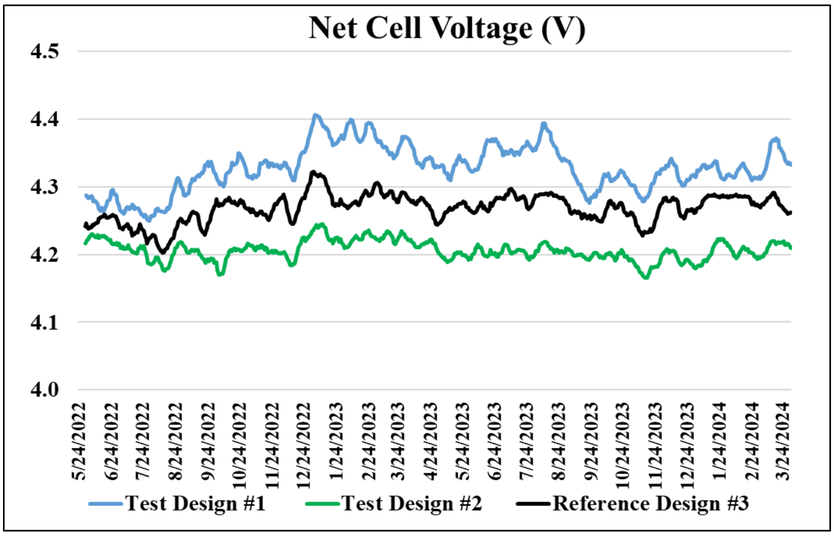

Figure 4. Performance test – cell voltage (including external loss).

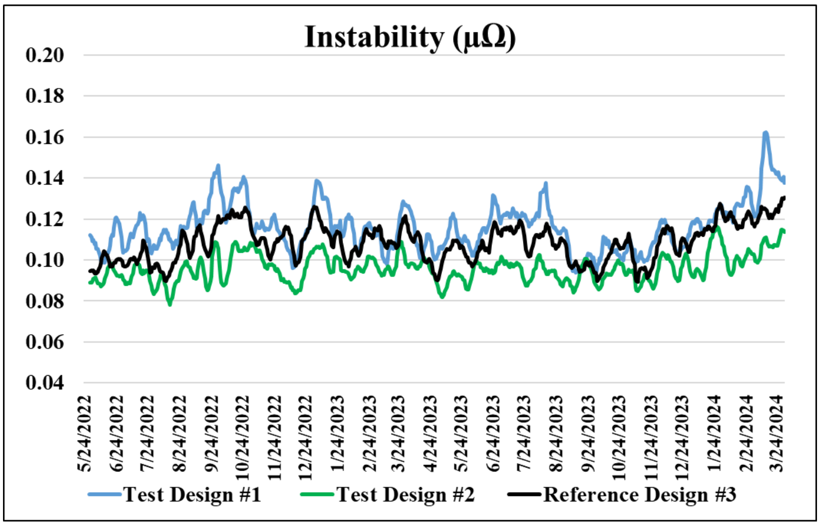

Figure 5. Performance test – instability magnitude.

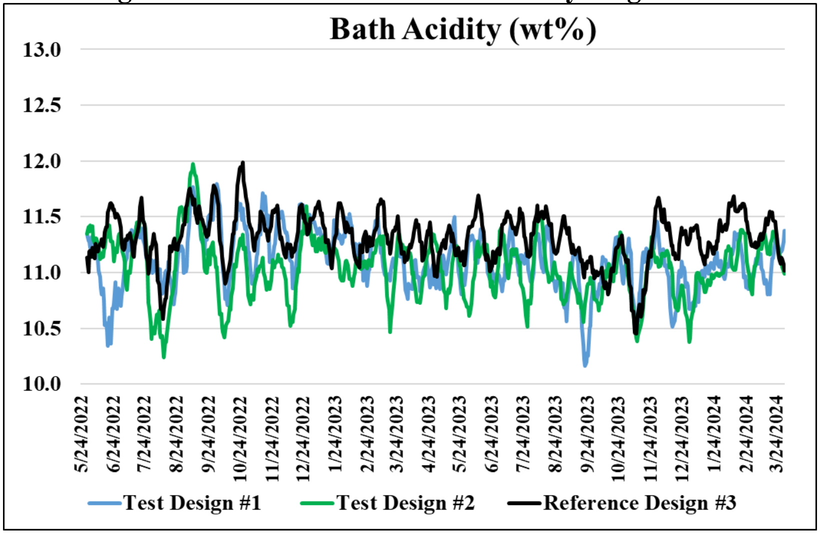

Figure 6. Performance test – excess AlF_3.

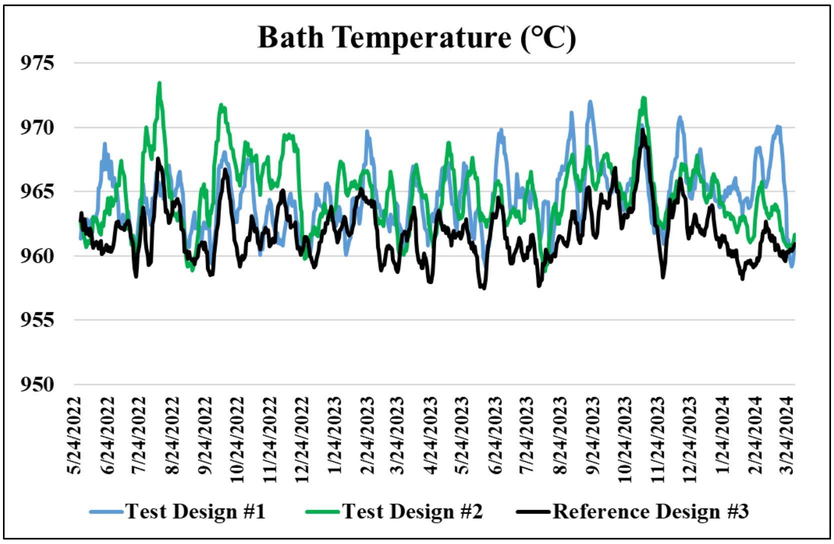

Figure 7. Performance test – bath temperature.

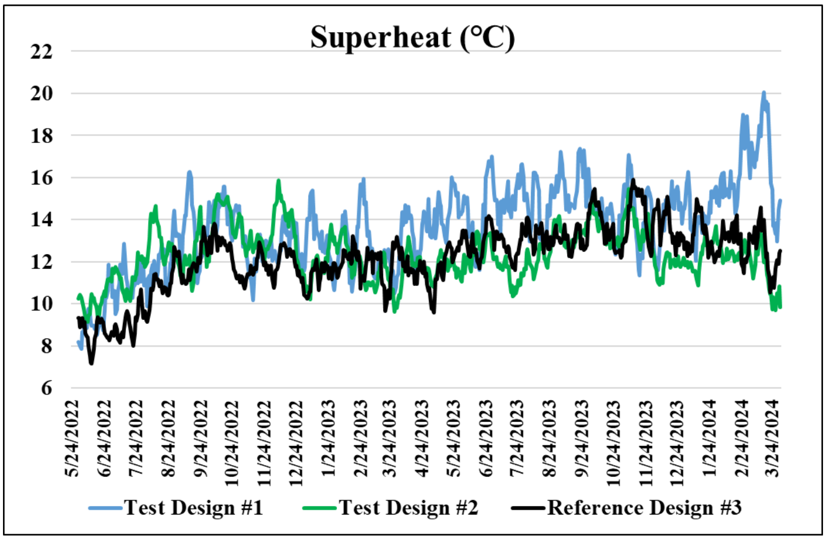

Figure 8. Performance test – superheat.

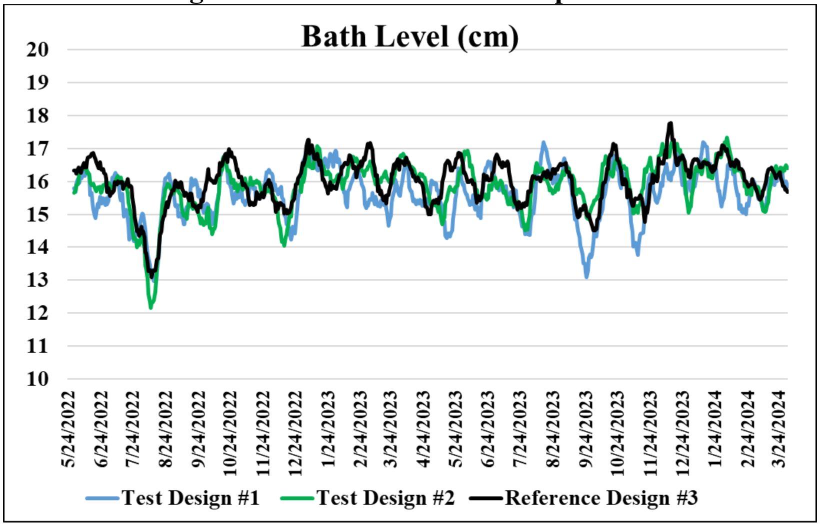

Figure 9. Performance test – bath level.

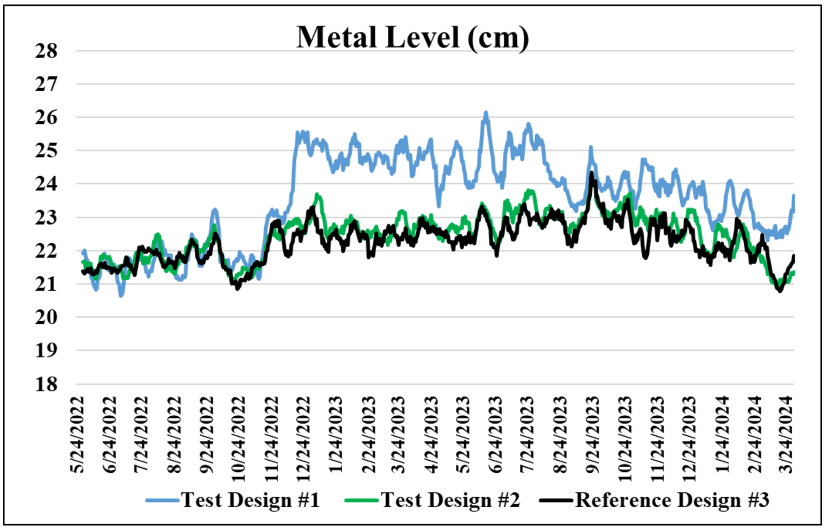

Figure 10. Performance test – metal level.

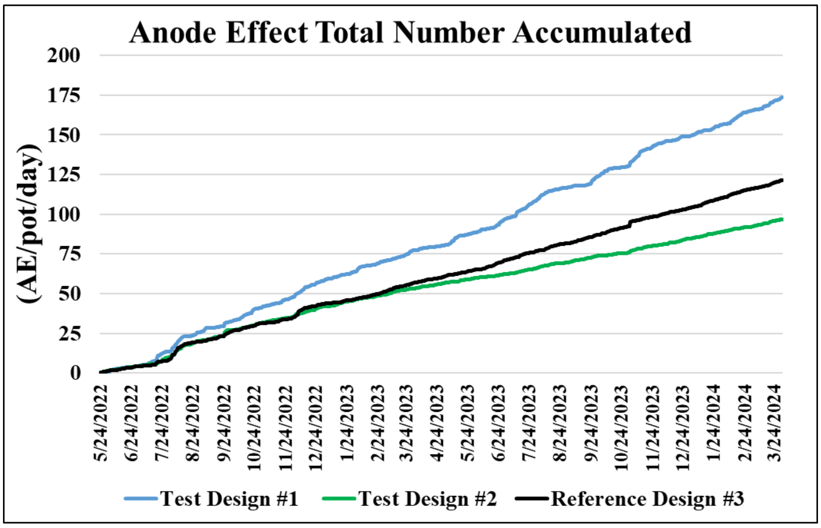

Figure 11. Performance test – AE accumulated.

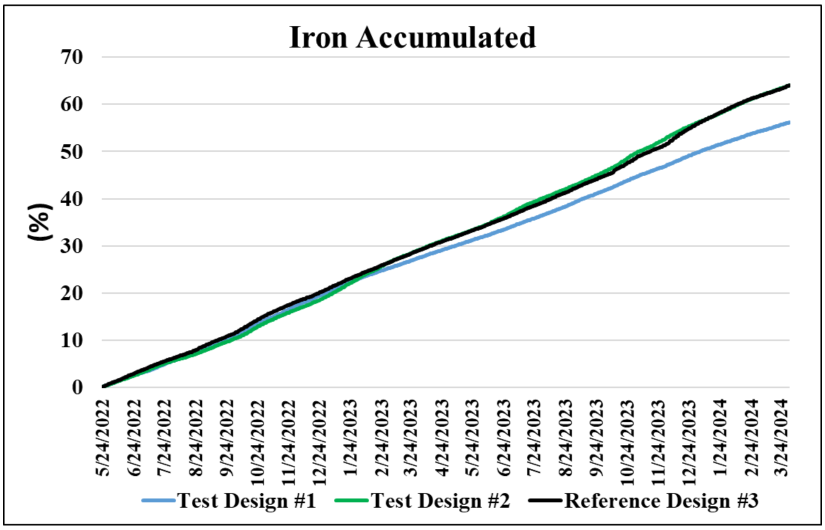

Figure 12. Performance test – Fe accumulated.

4.1 Special Measurement Campaign

As a part of the requirement for the Cell Design Change Governance system, special field measurements campaigns were conducted, in addition to routine measurements, for all three groups in February 2023 and May 2024. Alcoa R&D technical specialists in collaboration with Fjarðaál metal plant performed the following measurements:

- Cell voltage drop mapping,
- Ledge and ridge profile,
- Cathode current distribution,
- Steel shell temperature,
- Steel shell deformation,
- Steel shell exfoliation,
- Autopsy.

4.2 Conceptual design model validation

Computational analysis of operational data, in connection to measurements campaign results, was executed to validate the thermo-electric models of the trial cells in terms of operability prediction at higher amperage. Based on the actual relation between modeling and cell behavior characteristics, it was confirmed that Test Design #1 would struggle to deliver stable operation at 390 kA, whereas process simulations for Test Design #2 predicted capability to robust operation beyond 390 kA. An example of thermal profiles comparison, including freeze isotherm, is given in Figures 13–14 for TD#1 and TD#2.

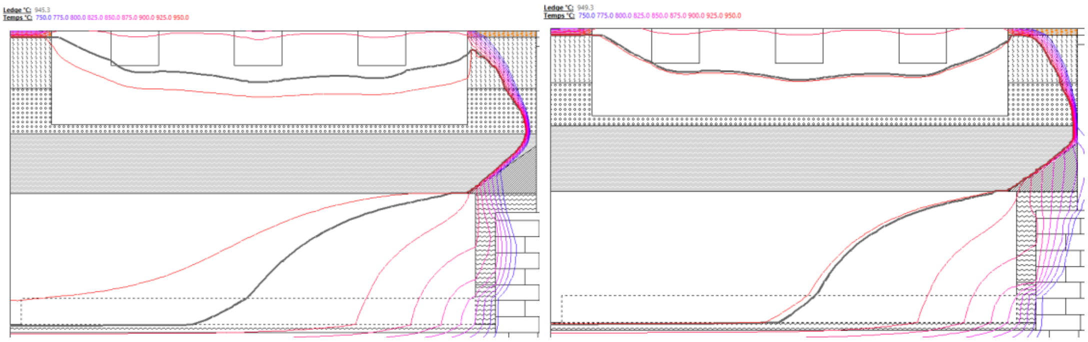

Figure 13. Test Design #1 modelled conceptual design (on left) and based real data validation prediction on 390 kA (on right). Isotherms range 750 – 950 °C, 25 °C step. The black isotherm corresponds to freeze profile.

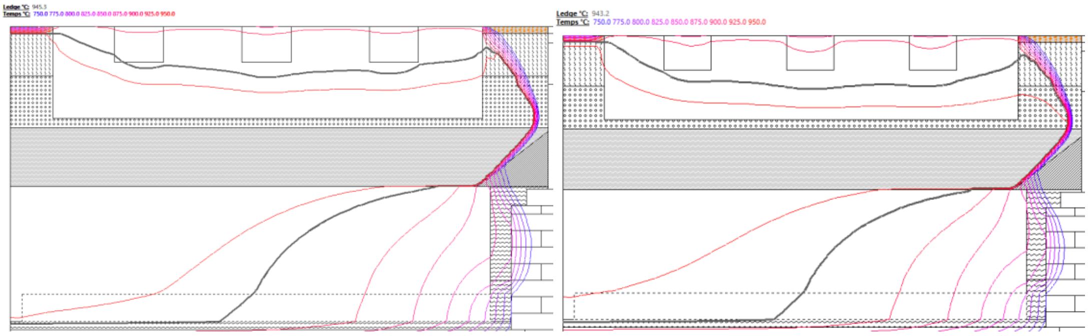

Figure 14. Test Design #2 modelled conceptual design (on left) and based real data validation prediction on 390 kA (on right). Isotherms range 750 – 950 °C, 25 °C step. The black isotherm corresponds to freeze profile.

4.3 Failure Trial Test Design #1 Performance

Test Design #1 suffered particularly from non-oscillatory instabilities (NOIs) that have been seen in other Alcoa AP30 spinoff designs and P-255 cells in the past [7]. These instabilities tend to form rapidly and without indication of the cell becoming unstable. This type of instability has been attributed to excessive ridge developing on the cathode and implementing operational practices to help reduce ridge growth was found to be helpful. The occurrence of non-oscillatory instabilities is automatically detected by the unique shorting behavior that they produce, as seen in Figure 15.

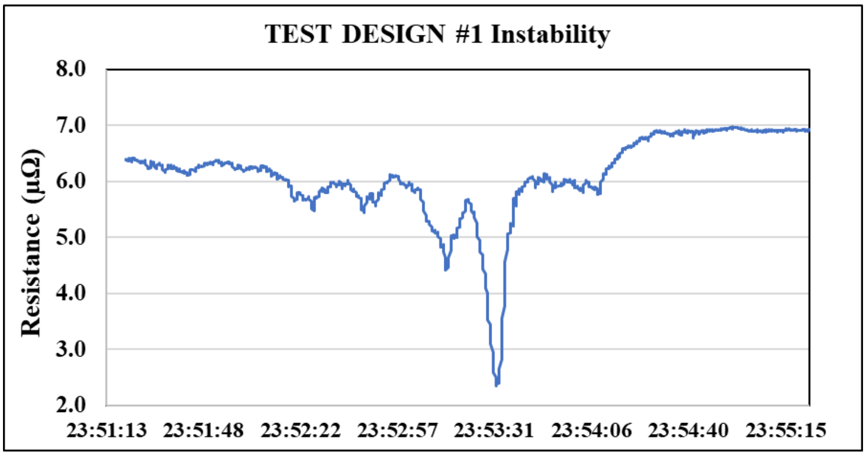

Figure 15. Example of the change in resistance signal that occurs during a non-oscillatory instability as seen in a Test Design #1 cell.

For TD#1, the daily number of shorts detected would increase in the days following a time when metal accumulation occurred in the cell. After the accumulated metal had largely been removed from the cells, the increase in shorting counts would rise. An example of this is shown in Figure 16. When the cell would be operating with higher metal levels, increased heat loss would be expected to occur through the cell sidewalls. This would be expected to favor the tendency of ridging. Then as the metal levels are reduced, the stabilization offered by a deeper metal pad is lost and any excessive ridging present would favor the generation of NOIs. As seen in Figure 10, TD#2 also experienced very similar patterns of metal level increases as TD#1, since these tended to be driven by line-wide, short term operational delays. Test Design #2, however, proved to be more robust to these changes in metal levels.

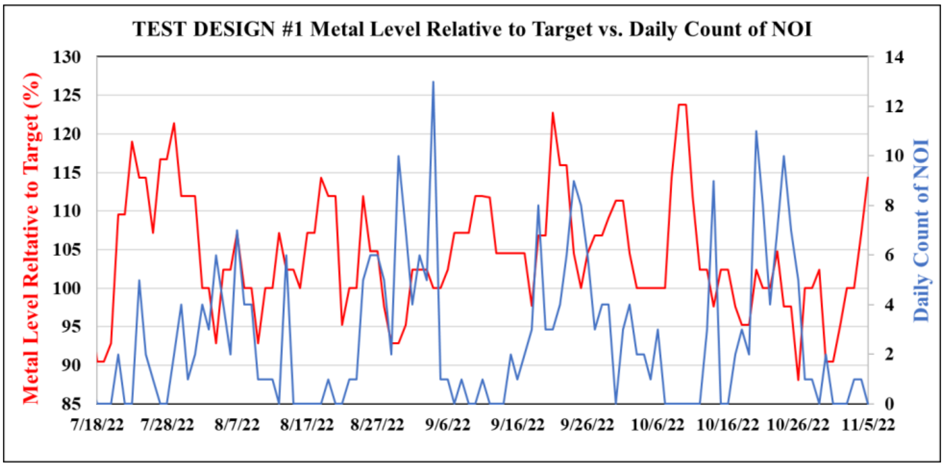

Figure 16. Plot of metal level relative to target and daily count of NOIs detected versus time for a Test Design #1.

Operating under the assumption that the stability issues seen in TD#1 were primarily due to excessive ridge formation, changes to operational targets were initiated. At first, an increase in the target resistance for TD#1 was applied to both operate the cell with a larger ACD and also to increase the heat generation to help reduce ridging. This did not yield a drastic improvement in reducing the peak number of NOIs detected following periods of high metal levels. After this observation, an increase in the metal level target was made to determine if operating with both a larger ACD and higher metal levels would stabilize the cell. This combination provided a level of stabilization that then enabled small steps in reducing target resistance to be explored as a means of process optimization for this design. However, as seen in Figure 4, it was not possible to lower the resistance enough to be comparable to TD#2 and still operate stably.

While to date these changes appear to have helped reduce the sensitivity of TD#1 to large swings in metal pad levels, this design still suffers from higher levels of instability than TD#2, as seen in the most recent data presented in Figure 5. Test Design #1 still appears to more readily perturbed by the presence of muck or anode problems than Test Design #2. A difficult operational cycle can develop when Test Design #1 is perturbed by the presence of muck. When muck induces higher noise or more frequent NOIs, current efficiency suffers and the ability to properly feed alumina is degraded, making overfeeding and in turn more muck formation likely. To break out of this cycle, manual interventions were at times needed to help stabilize TD#1 cells when it was suspected that muck was the cause of frequent NOIs. Generally, muck was suspected to be the cause of NOIs when no large changes in liquid levels had occurred recently. When muck is present on the cathode, as in the case of excessive riding, it would result in the formation of horizontal current flows and make NOIs more likely to occur.

5. Conclusions

AP30 Technology in Fjarðaál has evolved towards new standard design intended for operation at high amperage. Through dedication of Alcoa technology development experts and combined efforts with plant engineers, the conceptual study simulation modelling for the development of the new test design, installation and start-up, performance test was completed successfully within 3 years' timeframe. In June 2023, it was decided to implement Test Design #2 at Fjarðaál. Test Design #2 is not only superior to Test Design #1, but also more robust than Reference Design #3. Test Design #2 has been proven to run with excellent stability, reduced cell voltage, more over computational analysis predicts its capability to aluminum production beyond targeted 390 kA.

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