Low energy start-up for low energy cells

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Along with the development of low energy cells, Hydro developed a range of operating strategies for low energy cell operation. Amongst these, a method for starting-up cells using as little energy as possible, along with eliminating anode effect-producing PFC emission was developed. This paper presents the results and benefits of such procedures, that cover protection of the cathode surface, reduced energy during preheating and early life and emissions elimination during start-up.

Vision and challenges about low energy operation

Over the last few years, Hydro has started publishing on the results of its efforts in developing low energy electrolytic aluminium cell technology aimed both at retrofitting in its smelters as well as equipping its upcoming brownfield expansion in Karmøy[1], [2], [3], [4]. It is the company's vision to be a leader in low energy, low emission aluminium production technology as part of its 'Bigger, Better, Greener' approach. The long-term objectives include the development of affordable reduction cell technology that approaches an energy consumption of 10 kWh per kg aluminium, and achieve a company-wide neutral carbon footprint by the year 2020.

The contribution of Hydro's Primary Metal Technology team touches many aspects related to these goals. On the electrolytic cell technology development front, efforts focus on developing low-emission, low-energy cell technology compatible with heat recovery and carbon capture. The low-energy cell technology development team has made steps in designing cells able to sustain such demanding operation. The advances achieved in reducing electrical resistivity in all conducting elements of the electrolytic cells, the reduction of heat loss of the same cells, together with design optimisation of the potshells and superstructure result in technologies having significantly increased capabilities. While these new cells remain fully able to operate in a more "traditional" mode, e.g. at common voltage and amperage, they have the capacity of being run at much lower energy consumption.

This capacity is however not sufficient to guarantee stable low-energy operation in the long term. Indeed, sustained low energy operation requires changes in the process control strategy. The low heat loss of such cells makes them more sensitive to thermal deviations caused by common issues encountered during operation. The low-energy operating mode is implemented by using parameter sets and control code that reduce heat input and ACD variations. For example, low energy operation involves running the cells at reduced superheat compared with traditional operation. The low superheat in turn demands that adapted operating parameters for heat balance, alumina feeding and event handling be modified to ensure that a sludge-free and low anode effect frequency operation is maintained.

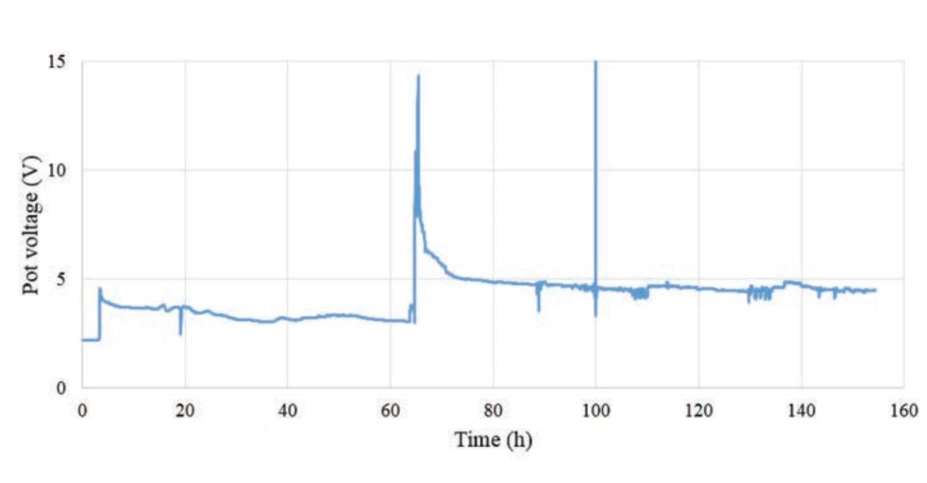

Fig 1. "Traditional" cell preheat and start-up voltage curve

One critical element needed to sustain low-energy operation is to ensure that the linings exit unscathed from start-up and early life. Indeed, autopsies have shown that cells sometimes have bath or metal infiltrations that can cause rapid lining damage, making operation at low energy impossible and also significantly shortening potlife. Live measurements show that such infiltrations tend to happen early in the life of the cells, often within the first few days of operation. Careful analysis of the events happening during this critical period have led to modifications of the start-up and early life targets and procedures that decrease the risk of damaging infiltrations. Another target of this work is to reduce the time and energy required to start the cells; luckily, this objective is very compatible with the lining protection target mentioned above, so no compromises had to be done.

Traditional cell start-up strategies

Although it is usually a single and relatively short event in a cell's life, start-up is one of the most critical part of it. Indeed, bringing a cold, empty, freshly lined cell to a hot, liquid-filled and aluminium-producing state without causing damage or infiltrations is not straightforward. A complex, interlinked array of thermal expansion, shrinkage, sodium-driven expansion and deformations affect the various parts of the cell assembly during the various phases of preheating, start-up and early life. Moreover, these interactions are dynamic and do not happen simultaneously all over the cells: some areas like the corners tend to evolve slower than others, further increasing the complexity of the process. The sensitivity of a cell to damages further increases when it is larger and lightweight like Hydro's newest cell technology.

The activities leading to a normally operating cell can be divided into five stages:

- Cell lining: where the potshell is lined according to specifications
- Cell preparation: where the lined cell is equipped with anodes and insulation in order to be preheated
- Cell preheating: where the prepared cell is heated to a desired temperature
- Cell start-up: where liquid bath is poured into the preheated cell and anodes lifted to start the electrolytic process
- Early life: where the operating parameters reach specified targets that aim at establishing long term, stable operation

There are multiple variations on each of these stages in the industry. Every smelter has its own recipe, targets and limitations (in-situ lining, gas preheating or fast turnaround for example) that lead to compromises in the way every stage is performed. A range of procedures are therefore used, leading to significant variations in preheating quality, heating rates and chemical conditions during early life. These variations are most often not or only partially measured so that they are either accepted or simply ignored. These compromises often lead to similar results: bath is poured onto insufficiently or unevenly preheated cathode, then freezes over large areas of the cathode, leaving only a small area for the current to flow. This results in a high voltage developing in the cell (the "start-up anode effect"), with the typical voltage reduction following as the frozen bath melts and more cathode surface becomes available to carry current.

Fig 1 presents the voltage evolution typical of a traditional preheat and start-up. One can appreciate the start-up anode effect (followed by a genuine one shortly afterwards) and slow voltage reduction following, all needed to compensate for the high heat loss and insufficient cathode temperature achieved during preheating.

Fig 2 presents an example of uneven preheating, where a hot spot has developed under an anode.

The periphery of the cathode in particular, where the ramming paste sealing sits, experiences highly variable baking speed and exposure to sodium from the bath, making its development as a dependable seal a matter of luck. In **Fig 3** presenting the same area as **Fig 2** but as a thermogram, one can see the large temperature variations (here of more than 300°C) between the cell centre and sides.

Fig 2. Example of a hot spot developing under an anode during preheating

It is well accepted that preheating cells at a higher temperature is instrumental in achieving low voltage, smooth start-up. The exact definition of "higher cathode temperature" varies a lot between smelters. Indeed, the exact way cathode temperature is measured has a strong impact on the result, and may be deceiving. In the example of **Fig 3**, temperature differences of more than 300°C exist between the centre and side of the cathode blocks. Measuring the same positions on every block, like shown in [6] can lead to false confidence that the cathode is evenly preheated. Typical temperatures obtained during traditional preheatings vary widely over the cathode surface, from above 1000°C in the centre and hot spots, to below 500°C in the corners and cold spots. Due to these differences, attempting to preheat a cell to higher temperature results in even larger temperature differences between the centre and sides of the cathode, not mentioning the presence of cold and hot spots randomly distributed over the cathode surface.

Fig 4 presents the temperature evolution at the top edge of cathode blocks at different positions in the same cell during a "good" preheating and after start-up. The different heating rates at the different positions is clearly demonstrated.

Other issues with traditional preheatings involve large temperature differences in cathode blocks that have caused cm-size cathode spalling in graphitized blocks, also robbing months or years of potlife.

Cells that must be restarted are somewhat more robust against damages than freshly lined cells since they have already gone through the ramming paste baking step. Restarted linings (unless they have been extensively repaired) behave more like a monolithic vessel that is much less prone to infiltrations. Therefore, quicker preheating methods are used to restart cells, like the metal start or the "crash" start-up [5] procedures.

Hydro's low energy cell start-up

It is indeed possible to preheat cells and reach high and very even temperatures using gas or fuel preheating. These solutions have their own set of extra cost, logistics and safety issues that often deter their widespread use. Electrical preheating is however the method of choice at most

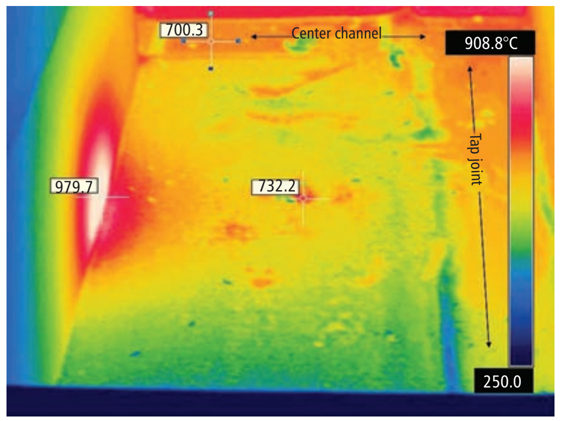

Fig 3. Thermogram of the same area of Figure 2 showing the temperature variations of the surface

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Fig 5. Laying graphite stripes close to the side of the cathode

of Hydro's plants, including for the newest low energy HAL Ultra cells. For the start-up of these low energy cells, a number of simple modifications to the "traditional" method are implemented to achieve a high cathode temperature (950±50ºC) over the entire cathode surface at the end of the preheating. This is key to achieving an anode effect-free start-up (less than 5V) and quick achievement of low energy operation.

Preparation for preheating

Materials and design of resistor bed

Materials used and preparation methods form a critical part of the preheating work. The heat generating layer on which the anodes are resting during preheating is modified in many ways. First, whereas a thin coke layer is traditionally used, thicker graphite stripes constitute a better choice. The stripes are also laid close to the side of the cell, to concentrate the heat generation where it is most needed, accounting for the higher heat loss on the sides of the cell compared with the centre (see **Fig 5**). Second, graphite has many advantages over coke for this purpose. Coke's electrical resistivity decreases continuously as it heats up, causing a vicious circle for preheating: hot spots have lower resistivity, causing a larger current to flow there, which in turn causes even more heat generation (see left of **Fig 6** from [7]). Graphite has a similar tendency at lower temperatures, but the resistivity stops decreasing around 750ºC, and increases at higher temperatures, as shown in right of **Fig 5**. Increasing electrical resistivity at higher temperatures acts as a brake to further increase of heat generation, helping to avoid hot spot development, and even out heat generation by "pushing" current to colder, more conductive areas of the cathode.

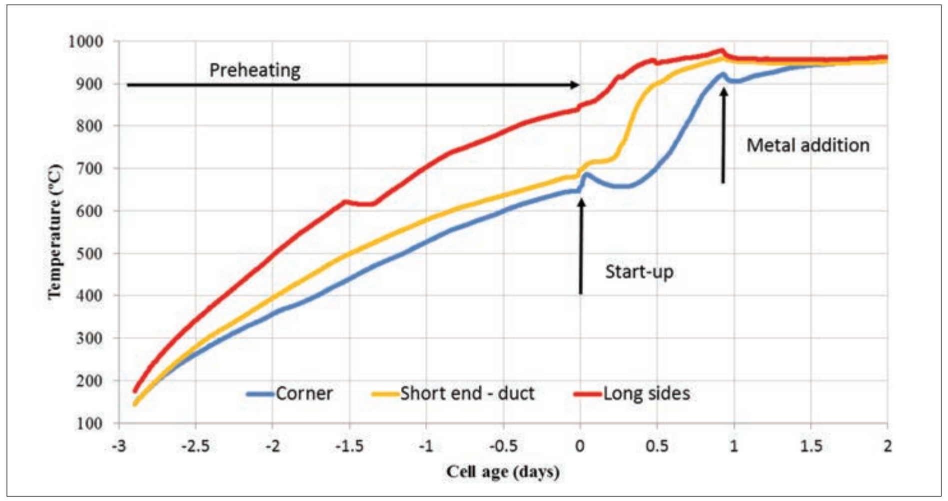

Fig 4. Temperature evolution at the top edge of cathode blocks during preheating and start-up

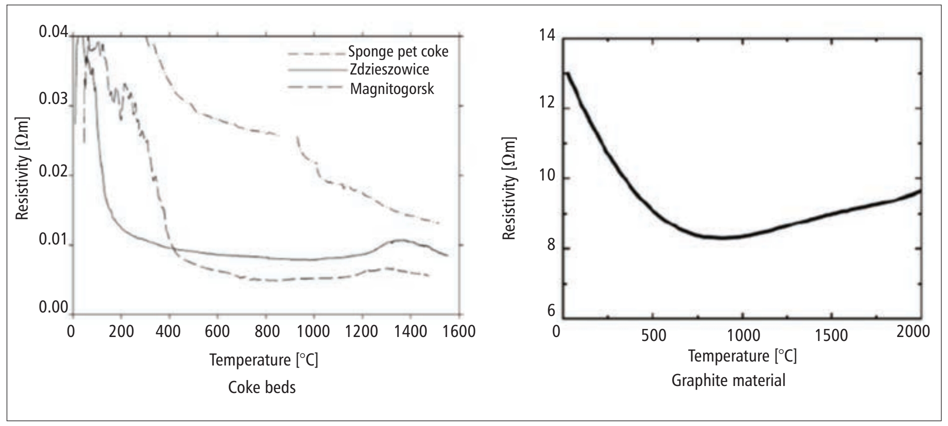

Fig 6. Resistivity of coke beds (left) and of graphite (right) as a function of temperature

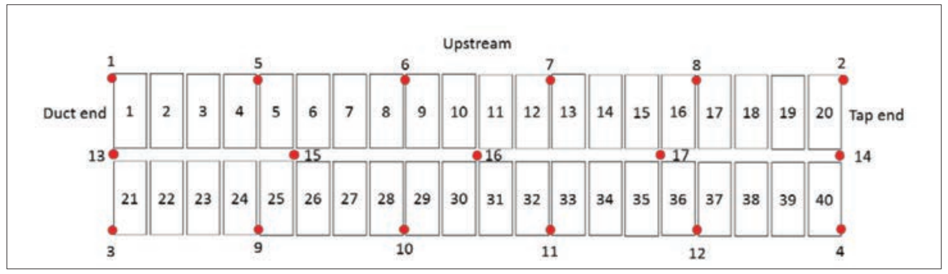

Fig 7. Placement of thermocouple on the cathode for detailed preheating follow-up

Placement of thermocouples to follow cathode temperature

Another critical element in cell preparation is ensuring a proper follow-up of the cathode temperature during preheating. To achieve this, an array of thermocouples designed to cover both the coldest and warmest areas of the cathode is used as shown in **Fig 7**. The thermocouples on the outward ends of the blocks are 50mm from the edge. Not every cell is so equipped of course, since identical cells behave very similarly, but new designs are fully followed-up so that a typical behaviour is defined. Such detailed instrumentation helps follow whole areas, or specific parts, like long sides, corners, or short ends. Even more extensive coverages have been made for specific studies.

Insulation of the anodes

In order to use less energy, the low energy cells are insulated using a mix of stiff Rockwool insulating slabs and more flexible fibre insulating mats where needed. Crushed bath is used to fill the gaps left unprotected. As demonstrated in **Fig 8**, no exposed carbon or holes are tolerated in the prepared cell, leaving no easy exit for the heat during the preheating. A collateral benefit of such tight protection is that the cathode surface experiences very little air-burn during preheating. Indeed, previous measurements have shown that hole in the anode protection let streams of air enter between the anodes, leading to air-burn on the anodes and the cathode surface. The attacked anodes will produce unwanted carbon dust (and will be replaced within a month), but the cathode surface damage is permanent, and unfortunately happens near the edge of the blocks, right where maximum cathode erosion will happen during potlife. The air-burned thickness can be up to 3cm, or

Fig 8. Prepared cell ready for preheating

roughly six months of potlife.

Preheating follow-up

Cathode temperature follow-up is only one tool to enable decision-making during preheating. It helps monitor heating rates of the various parts of the cathode, and decide if cell voltage should be changed, or when the cathode is ready for start-up. But not all cells have thermocouples, and even with many thermocouples as on **Fig 7**, it is not enough to monitor the preheat in sufficient detail to ensure no cold or hot spot develop. Hot and cold spots tend to be small so that chances are that those spots will not be seen by a thermocouple. Moreover, thermally driven deformation of the cathode during preheating cause movements that easily result in local loss of contact between an anode and the resistor bed (causing a cold spot), or to the contrary increase the local pressure between the bed and an anode (recipe for a hot spot), see **Fig 9**. These cold and hot spots translate into easily measured current changes in the affected anodes (as mV drops measured on the anode stems). Regular (every four hours) anode stem mV measurements allow early detection of anode current changes, and decide on actions to avoid cold and hot spot development.

Actions performed during the preheating include anode disconnection, flexes pressure release and manual anode block shaking. Careful preheating follow-up results in quite even temperature distribution, like in the example given in **Fig 10**.

Preheating targets and start-up

The voltage targeted during preheating depends on the time target for the preheating duration. In Årdal's Reference Centre the preheating take place typically during the weekend, so a comfortable duration of 72 hours is aimed. The better insulation used allows using lower voltage and total energy, yet achieving higher and more uniform overall cathode temperature. As seen in **Fig 11**, even if it is a bit longer, the low voltage used for the low energy cells results in using 10MWh less for a HAL4e cell preheat.

Since cathode temperature is so important in order to achieve low energy start-up, it is natural that it is the criterion on which the decision to pour bath is made: a minimum temperature on all measured points must be reached before bath pour is initiated (see **Fig 12**). This however has the potential to make the start-up operation planning difficult, especially in the context of a plant start-up, where delays can have far-reaching ripple effects on work organisation. To ensure that cells are ready for start-up in a timely manner, Hydro uses a separate set of targets and corrective actions on heat input meant to ensure that heating rates stay within tight ranges during preheating.

Start-up itself is a simple operation, but here also a number of criteria are instrumental in achieving lining protection and low energy. Number one is to avoid metal in the bath at initial bath pour. Indeed, since ramming paste shrinks from

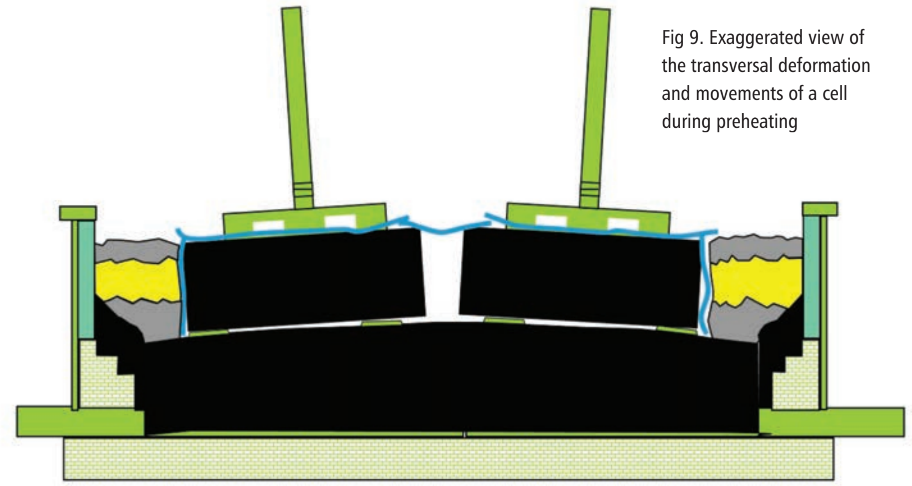

Fig 9. Exaggerated view of the transversal deformation and movements of a cell during preheating

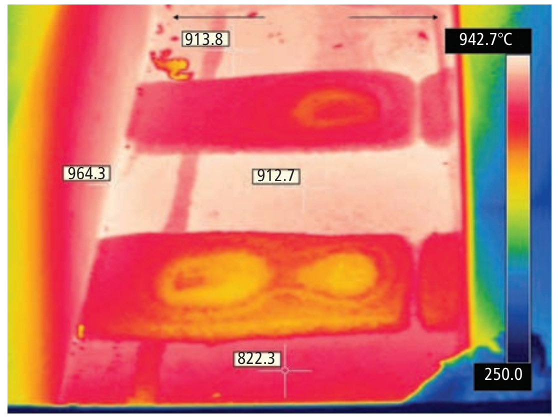

Fig 10. Cathode temperature distribution achieved during Hydro's HAL Ultra preheating

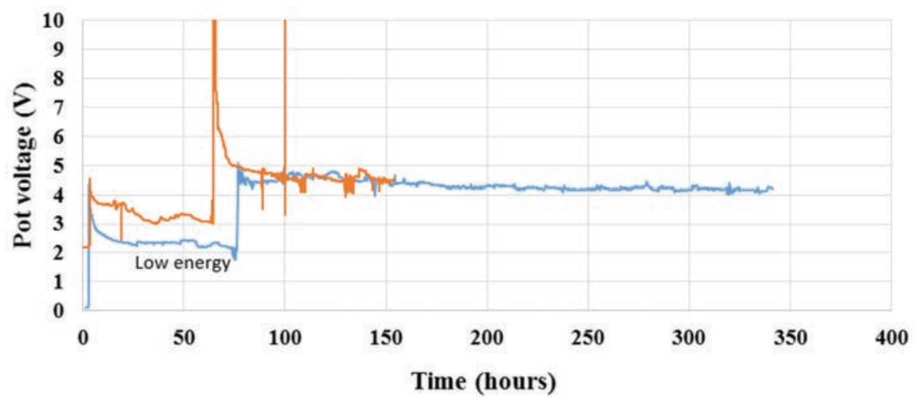

Fig 11. Cell voltage evolution during preheating and the first few days of early life for traditional and low energy strategies

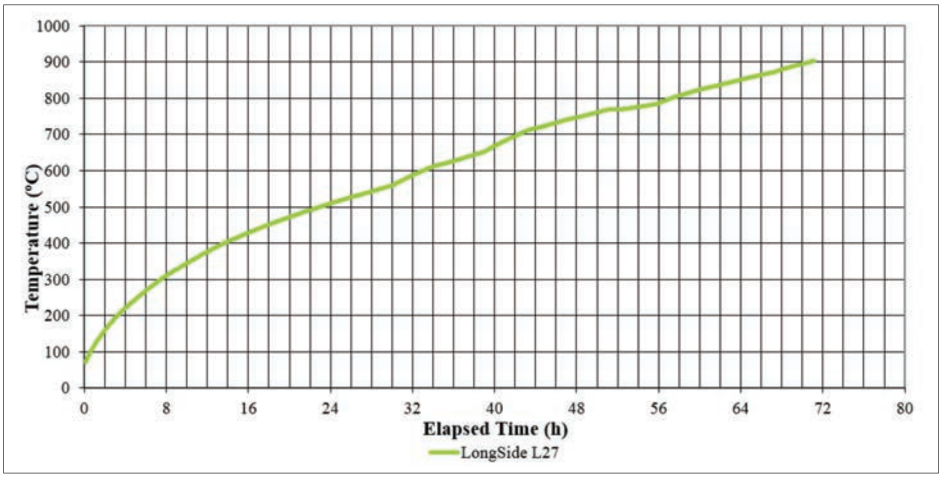

Fig 12. Example of long side temperature evolution during HAL Ultra preheat

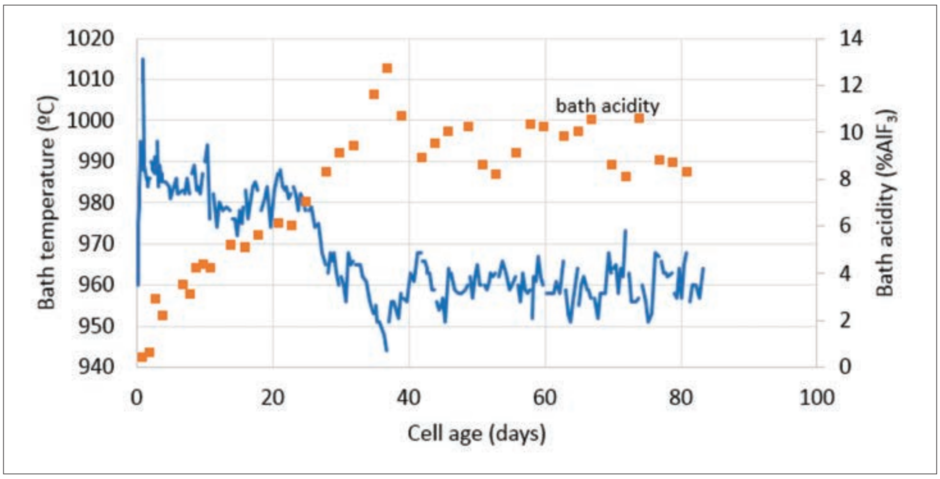

Fig 13. Bath temperature and acidity during early life and beyond for a low energy cell

its maximum volume on baking, gaps can open between the joints and cathode blocks in the hours after start-up. Metal present on the cathode at this time will infiltrate deep into the lining and start destroying it.

Number two is to avoid high energy input by keeping ACD below a given limit. This can be made difficult by the combined deformations of the cathode/potshell assembly and of the superstructure/anode beam that result in the ACD being reduced under the central anodes of cells. This needs to be addressed otherwise anodes can fail; it is done by temporarily lifting anodes in that area, until metal is added and anode cover done, which cools down the superstructure and straighten it.

The low initial ACD, along with the warm cathode contribute to achieving start-ups where voltage rarely exceeds 5V, again reducing energy use. The early alumina addition produced by the sodium carbonate as it reacts with AlF_3 during start-up further contributes to avoid a true anode effect by lack of alumina in the bath. The elimination of the "start-up anode effect" not only contributes to reducing energy consumption, but it also eliminates a high, uncontrolled energy spike on the cells that result in overheating and thermal stress.

Early life operation

After start-up, early life begins. During this critical phase, the cell's lining and potshell expand as they heat up to equilibrium temperature, the rammed joints bake and shrink, then start Rapoport expansion. Also during that phase, bath temperature vary quickly and by large amounts as metal is added on the first day of operation, then start covering the anodes. All these events create risks that a combination of thermal events team up to open gaps in the lining, opening a way for deadly infiltrations.

Hydro's low energy cells behave the same way as higher energy ones, but having less energy input makes them more robust against large variations. Indeed the low voltage achieved early in life ensures a rapid growth of ledge at bath level, building a cryolite ledge reserve that helps buffer later acidity swings. This rapid ledge build up is supported by early and timely sodium carbonate additions (including a fair amount in the periphery of the prepared cell as shown in yellow in **Fig 9**).

Careful target resistance adjustments are made as operations are performed that affect the cells' heat loss, like metal addition, liquid level change, anode cover or bath acidity changes.

Benefits of Hydro's low energy start-up

The procedure and targets outlined above form part of the operational changes Hydro has implemented in order to use and protect the low energy capability of the HAL Ultra cell family. It is not limited to those cells however. Part of the new operating practices are being implemented in Hydro's potlines using much older technology. Indeed, no cell is harmed when smoother, better-controlled start-up practices reduce heat stress and variations.

The reduced voltage used for preheating, along with the elimination of the start-up anode effect and the lower voltage quickly achieved by low energy cells accumulate to savings in the order of 32MWh per cell until the age of two days. Lower PFC emissions due to the absence of anode effect at start-up and later also improve the environmental performance of the procedure.

While any benefits in terms of cell longevity have yet to be proven, the demonstrated low energy consumption of these cells, together with the lining measurements confirm that their linings exit early life in excellent condition. ■

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