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Low Energy Cell Development on AP Technology ™

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Abstract

During this decade the energy market is changing rapidly and new smelter projects may face large ranges of energy block size, significantly different energy prices and environmental regulations. To provide more choice in this complex and changing situation, Rio Tinto Alcan announced two years ago a new strategy of developing flexible solutions. On the same platform have been developed cells at very high productivity and cells with low energy consumption. This strategy has been delivered with the APXe and AP60 cells, able to operate with the same framework in the range 500-600 kA with energy efficiency between 12.0 and 13.2kWh/kg. This new development incorporates an environmental dimension, aiming to reduce dramatically the air emissions of future smelters. The prototype results have confirmed the feasibility of such ambitious targets and shown that innovation is a key factor to develop the cell of 2020's, at low energy consumption and reduced environmental footprint.

Primary aluminium and energy outlook

Aluminium production growth

The long-term demand outlook for aluminium has been strong and is likely to remain so. Significant growth in demand will be driven primarily by the continued urbanisation and industrialisation of emerging economies, particularly those of China and India. Aluminium demand is expected to grow by four to five per cent a year over the next two decades [1].

Just looking at the last decade (Figure 1), world aluminium demand has grown from 25Mt in 2000 to 42Mt in 2010 and the demand forecast for coming years is beyond 5% annual growth, with annual demand close to 55Mt by 2015.

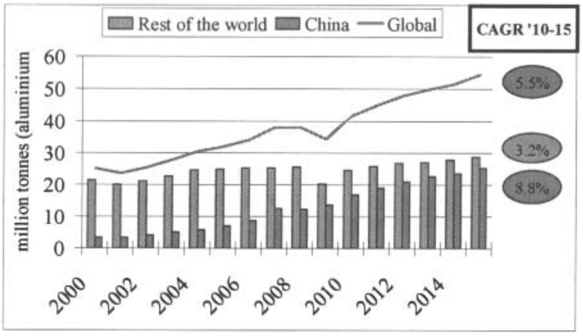

Figure 1 – World demand for aluminium between 2000 and 2015

In order to satisfy this stronger demand, energy availability will be a key factor for the industry. Table 1 summarizes the expected annual electrical energy consumption in relation to the primary aluminium production for the year 2015. This consumption is of the same order of magnitude as the total electrical energy consumption of France and Germany combined. To cope with the anticipated aluminium production growth the equivalent of 5600 MW of power generation capacity has to be started each year, and this is the capacity of several nuclear reactors.

Smelter Energy efficiency	15000	kWh/t
Worldwide aluminium production in 2015	55	Mt
Smelter Electricity consumption	825	TWh
Primary Aluminium sector electricity consumption	990	TWh
France+ Germany Electricity consumption (2009)	1 085	TWh
Annual growth (+5%/year) electricity consumption	50	TWh
Annual growth (+5%/year) power capacity	5 651	MW

Table 1– Electricity consumption for aluminium smelters

In addition to this massive demand for power, there are signs of a fundamental shift in the energy price paid by aluminium smelters. After 2 decades of stability in the eighties and nineties the average price paid by the smelters increased from around 20USD/MWh to above 30USD/MWh in the last decade. Upward pressure on the energy prices paid by smelters is expected to continue.

Energy efficiency

Since the beginning of the aluminium industry great efforts have been made to improve energy efficiency. In the first half of the 20th century, energy efficiency was halved (see Figure 2). This effort was particularly important in Europe where energy was already more expensive and less available than in North America at that time. At the beginning of the seventies the most energy efficient smelters were able to operate below 13 DC kWh/kg (for example at the Auzat smelter in France).

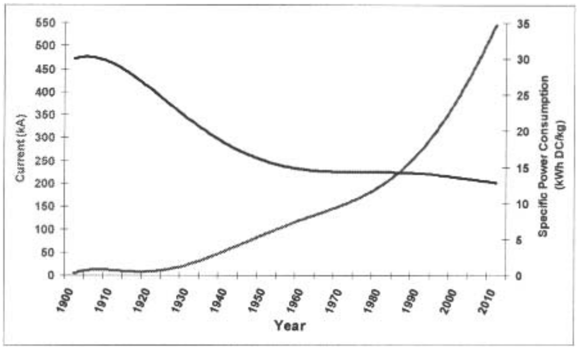

Figure 2 – Evolution of line current and energy efficiency

In the last two decades, only limited improvement was observed, because priority was given to increasing cell productivity with the result that cell amperage increased dramatically. It has tripled, for example between the AP18 operating at 180 kA in the early eighties and the new AP60 cells operating at close to 600kA today.

In the years to come, with the expected increasing demand for electricity and a correspondingly increasing price, it will be vital for the aluminium industry to make great improvements in energy efficiency. The main dilemma is to determine what will be the optimum target for the cell design, particularly with regards amperage and specific energy consumption.

Economic evaluation of the optimal cell design

Economic model of the future cell

Before launching the detailed cell design program, a key task was to determine the optimal technical and economic targets for cell of the future.

The principle of the study was to develop a full techno-economic model of a greenfield smelter project able to evaluate the main economic KPIs of the project.

The main steps of the project evaluation model are presented in Figure 3.

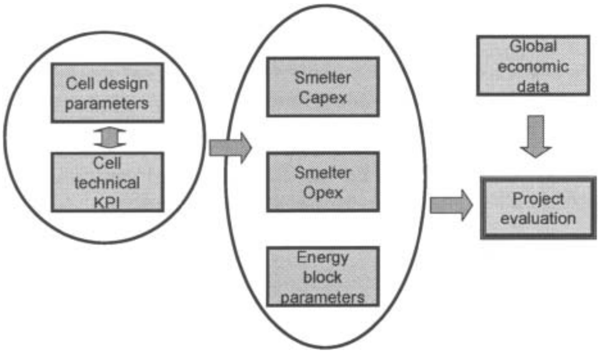

Figure 3 – Stages of the Project Evaluation Model

The first layer of modelling is technical: the main cell parameters are described according the main characteristics of the cell design. These cells parameters include geometrical data (anode size, anode number, shell size and so forth), electrical data (resistance distribution within the cell) and chemical data (bath composition and temperature). From these technical data the main cell KPIs are calculated: cell voltage, specific energy consumption, current efficiency, internal heat and so on.

In the second stage the main technical and economic characteristics of the future greenfield smelter are determined according to the cell data coming from the first stage. A detailed calculation enables calculation of Opex and Capex for the different plants within the smelters (potline, gas treatment centre, carbon plant, rodding shop, casthouse, etc.) taking into account the energy block parameters (size, price of the energy).

The last stage evaluates the profitability (NPV, Capex/t, etc.) of the future smelter project, taking into account the global economic outlook (LME price, raw material price, inflation, etc.). An important phase was to validate the model for a real smelter project.

The model was mainly used to determine the most profitable cell designs versus the energy block size and energy price. A sensitivity analysis was carried out in which different cell designs were compared. An example of calculation results is shown in Figure 4, in which the NPV difference between high productivity design and low energy design is evaluated in relation to energy price. The high productivity design with higher specific energy consumption exhibits reduced NPV beyond 50USD/MWh, whereas the low energy design creates more value under these conditions.

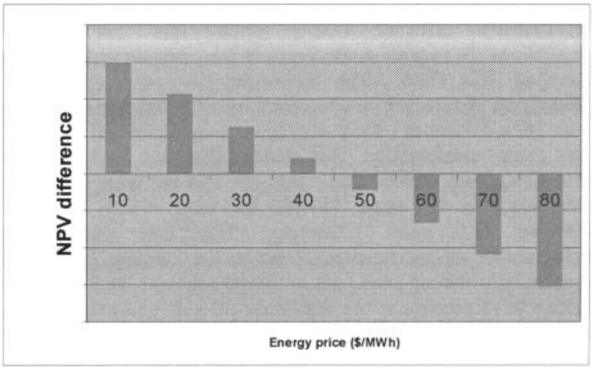

Figure 4 – NPV difference between high productivity and low energy cell design versus energy price

Low energy cell will be a key element to reduce the negative impact of higher energy price on smelter profitability. In addition, for limited energy blocks, the low energy option enables greater production of aluminium with the same power block size, creating higher NPV than does the high productivity cell.

Vision for optimal cell design

As indicated previously, the energy price is expected to increase in the coming decade, and it will therefore be essential to develop low energy cell designs operating between 13.0 and 12.0kWh DC/kg and ultimately very low energy cells at below 12.0kWh DC/kg (Figure 5), although this is technically very challenging.

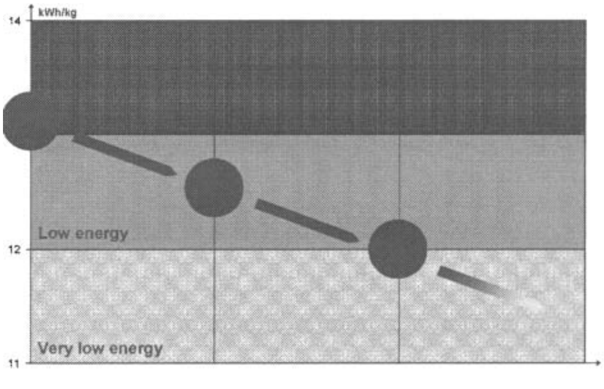

Figure 5 – Vision for low energy cell development

At the same time, in order to ensure high project profitability, cell productivity has to be maintained at a very good level by using cells with the maximum shell area in order to maximize the productive surface areas of both anode and cathode. For this reason Rio Tinto Alcan decided to develop a new cell generation based on the AP5X platform. As Figure 6 shows, two technologies are being developed and tested in parallel using the same optimized framework (busbars, shell, superstructure). The AP60 cell will operate at 600kA with energy consumption in the 13-13.3kWh/kg range, similar to that of the AP40. The APXe cell will operate around 500kA with an energy consumption target of 12kWh/kg.

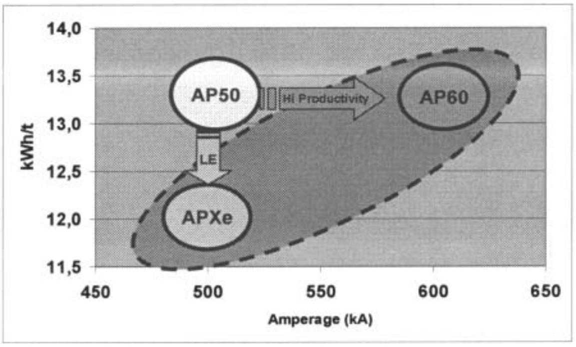

Figure 6 – Operating regions of the new AP cell technologies

In addition to energy efficiency and cost-effectiveness, the AP60 and APXe comply with Rio Tinto Alcan's demanding HSE Standards. After the validation of the AP60 cell at the Arvida Smelter, AP60 technology centre (Quebec, Canada) and the APXe cell in the LRF Pilot Plant (Laboratoire de Recherche des Fabrications, Saint Jean de Maurienne, France), these two technologies will enable Rio Tinto Alcan to stay in the vanguard of the reduction technology for the benefit of its own pipeline of internal growth projects, and of the projects of its partners and customers.

The same approach has been developed on the AP40 platform with the AP40 Low Energy cell able to operate below 12.5kWh/kg at 400kA.

Technical challenge of low energy cell

To reduce cell specific energy consumption (SEC) it is necessary to lower significantly the heat loss dissipated by the cell's external surfaces. Using the well known set of equations, it is possible to describe the relationship between SEC and heat losses.

$SEC = 2.98\ V_{pot}/CE$ (in kWh/kg)

Heat loss $= I \times (V_{pot} - V_{ext} - 1.648CE - 0.48)$ (in kW)

With V_{pot} : pot voltage, CE: Current Efficiency (as a ratio), I : Amperage in kA, V_{ext}: external voltage drop

Application to the AP50 pot

An AP50 pot working at its nominal operating point ($I = 500$ kA, $CE = 0.95$, $V_{pot} = 4.24$ V) presents the following characteristics: SEC = 13.3kWh/kg and Heat loss = 949kW.

For low energy operation, if the target is an SEC of 12kWh/kg (10% reduction), the new heat loss will be 742kW, corresponding to a 22% reduction (assuming constant current efficiency at 95%). Figure 7 shows that in order to obtain a 10% reduction in SEC, it is necessary to lower the heat loss by more than 20%, if SEC is initially 14kWh/kg. But if the initial SEC is 9.5kWh/kg then the heat loss has to be reduced by 40% to reduce SEC by 10%!

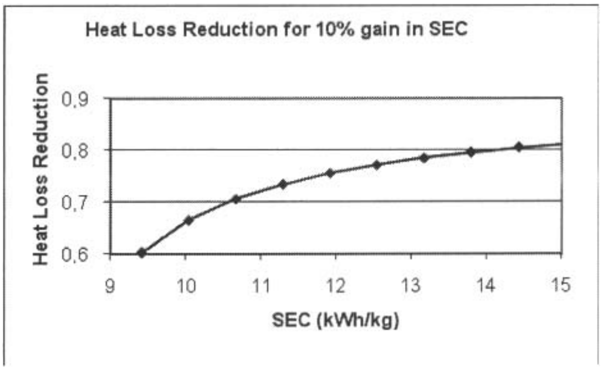

Figure 7 – Reduction in heat loss for a 10% improvement in SEC for a standard cell.

Heat loss reduction

Analysis of heat loss distribution shows that the largest dissipation takes place at the top of the cell, through the anode cover and the anode conductors, and also at the side of the cell, through the shell sides and the collector bars.

If we examine the different components of heat loss, many ways can be found to reduce them:

- Cover: heat losses can be lowered by increasing thickness or by using a material of lower thermal conductivity. A significant gain can also be obtained by reducing the gas suction flow rate and improving the hood insulation.
- Anode conductors: the main opportunity is to optimise the stub cross section in order to reduce the heat flux while not increasing too much the overall anode assembly resistance.
- Shell sides: improving the lining insulation, except for the zone where heat must be extracted to form the protective ledge at the bath-metal level.
- Cathode conductors: reducing the cross section of the collector bars while avoiding an excessive increase in the cathode resistance.

In summary, ways for limiting the heat loss are of two kinds: those with a pure thermal action, like using better insulating materials, and those which require a compromise between reducing heat loss and increasing voltage drop, such as reducing the cross-sections of anode stubs and collector bars.

Voltage reduction

The cell potential (V_{pot}) equation defines the main opportunities for reducing specific energy consumption.

$SEC = 2.98\ V_{pot}/CE = 2.98/CE \times (V_{ext} + V_{anode} + V_{cathode} + V_{bath} + V_{electrochem})$

An analysis of each factor associated with reducing SEC yields the following:

- CE : current efficiency has to remain as high as possible, even when operating with a low Anode-to-Cathode Distance (ACD).
- V_{ext}: all external resistances must be reduced while maintaining good magnetic stability and low capex.
- V_{anode} and $V_{cathode}$ must be reduced whilst keeping in mind the trade-off between resistance reduction and heat dissipation increase: increasing anode stub diameters or collector bar cross-sections will lower the voltage drops, but will also increase the heat fluxes transmitted through these conductors. Using more conductive materials will also increase the heat fluxes through the conductors.
- V_{bath} : squeezing ACD or using lower resistivity bath can have a significant affect on SEC. The challenge of lower ACD operation will be to maintain high current efficiency.
- Designing low energy cells requires optimizing different thermal equilibria, which in turn involves finding the optimal trade off between:
  - low ACD and high current efficiency
  - reducing anode and cathode voltage drops without excessively increasing the heat fluxes through the conductors

APXe cell development

The development of the APXe cell started in 2008. After a clear definition of the technical and economic targets, intensive modelling and engineering studies took place. An enhanced magneto-hydrodynamic modelling tool, calibrated on operating AP50 cells, confirmed the very good stability of the APXe and AP60 busbar designs. Figure 8 shows the results of a stability study showing that the APXe cell can operate with ACD close to 20 mm without using any additional means to stabilize the metal pad (e.g. drained cathode, baffled cell, high metal pad height).

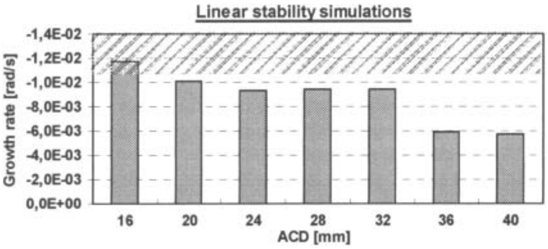

Figure 8 - Growth rate of APXe cells versus Anode-Cathode Distance (red hatching shows stability design limit).

This high stability is the ideal condition for operation at low ACD and is a key means of reducing the bath voltage drop.

The cell design has required innovative solutions in order to reduce the cell resistance significantly while simultaneously reducing the heat losses. For example, the pot exhaust flow rate has been dramatically reduced without jeopardizing fluoride emissions. The superstructure and shell have been fully redesigned, with substantially lower costs, increasing the profitability of both the APXe and the AP60.

After engineering work in the LRF Pilot Facilities, the APXe was started in December 2010, (see Figure 9).

Fig 9 - APXe cell in LRF Pilot Facilities.

Trial results

The initial target is to achieve a potline SEC of 12.2DCkWh/kg by the end of 2011. This figure includes all the external voltage drops, in particular the voltage drops in the crossover and in the process loop, which means that the cell energy consumption (calculated using cell voltage) has to be below 12.0kWh DC/kg.

Amperage

The cell was started at 500 kA and the amperage was adjusted during the year to maintain thermal equilibrium The low amperage period (February to June 2011) is connected to maintenance works in the LRF substation.

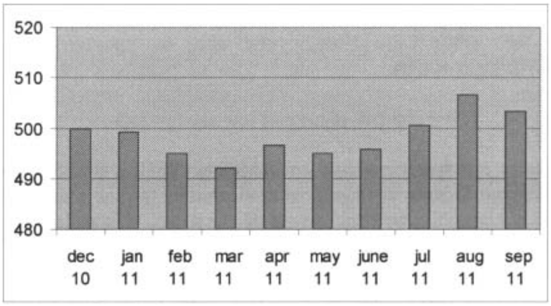

Fig 10 - APXe monthly average amperage (kA)

Cell voltage and thermal equilibrium

Following a structured approach, the cell voltage (Fig 11) and thermal equilibrium (Fig 12) was gradually fine tuned with the following results.

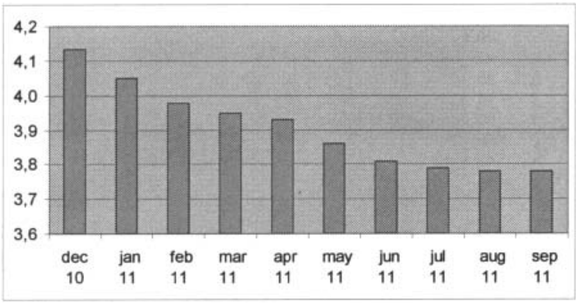

Fig 11: APXe cell voltage (V)

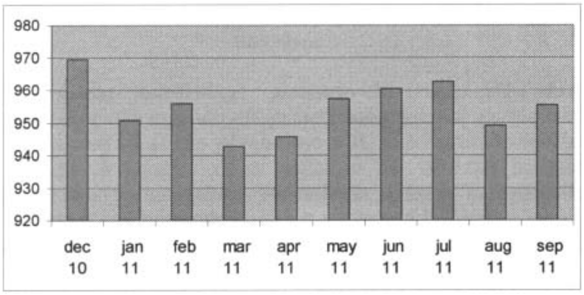

Fig 12: APXe bath temperature (°C)

Current efficiency and energy efficiency

Due to the stable thermal equilibrium ensured by the pot process control system Alpsys and the high MHD stability, a very good level of current efficiency was achieved despite operation at low Anode Cathode Distance (ACD).

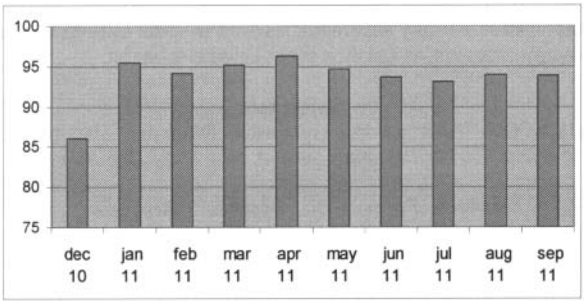

Fig 13: APXe Current Efficiency (%)

The specific energy consumption (Figure 14), calculated by adding the cell voltage and all the external voltage drops expected in a future smelter, has decreased regularly to reach the first target of 12.2 kWh/kg DC. These results are very promising and an action plan is in to go below 12.0kWh/kg DC in 2012

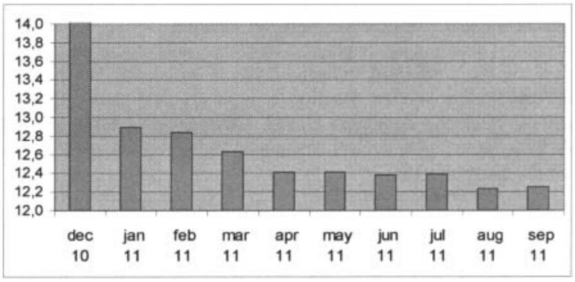

Fig 14: APXe Specific Energy Consumption (kWh/kg)

Next steps

The AP50 prototype cells were able to operate above 500 kA by early 2000 [2], enabling a step change in cell productivity. Since that time the latest developments have made it possible to reduce the specific energy consumption by 15% compared with that of the first cell generation [3]. The 12.0 kWh/kg target has nearly been reached. Using this accumulated experience, new steps to go toward 11.5 kWh/kg are already planned, with the start up of two improved APXe cells in the coming months.

Environmental challenges

Context and objectives

The pressure on the aluminium industry to reduce its environmental impact continues to grow and may limit future industry growth if major improvements cannot be achieved. Despite historical improvements, fluoride emissions remain one of the most acute environmental issues facing aluminium smelters.

To ensure that the new APXe cell will surpass future regulatory and corporate expectations, the objective of 0.20kgFt/tAl at the roof vent was set for the technology. This corresponds to 50% of the emissions from a typical modern smelter.

A few plants have already been able to reach such low levels [4]. However, for APXe, this has to be achieved while respecting the constraints imposed by the cell process conditions, and in particular the very low pot flow rate necessary to minimize heat extraction. Reconciling these two opposite objectives (low flow and emissions) has required improvement activities to be conducted on the superstructure suction and hooding designs. As an illustration, Figure 15 represents the specific pot flow rate (Nm^3/tAl – base 100 for AP18) for different AP pot technologies.

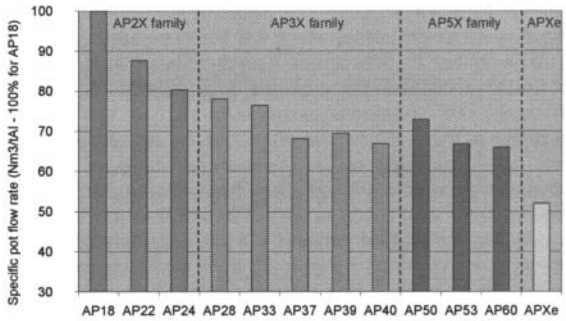

Figure 15 – Design specific pot suction flow rates for different AP pot technologies

The APXe technology environmental features

Most of the roof vent emissions occur when the pot is being serviced and a smaller fraction – typically less than 30% – is emitted when the hoods are closed. Other sources external to the pot contribute to the overall emissions, including the spent anodes and the crust bins [5].

Emitting less than 0.20kgFt/tAl at the roof vent requires minimizing all of these different contributions. In parallel to the APXe project, Rio Tinto Alcan is developing solutions to reduce the spent anode and crust bins emissions [6]. The "open cell" contribution is itself addressed through the development of the Jet Induced Boosted Suction (JIBS), which allows for a significant increase in the pot flow rate while the hoods are open [5]. These technologies will be included into the future APXe technology package.

As part of the APXe development, the focus was on improving the cell collection efficiency because of the specific low pot flow rate constraint. This was achieved by optimizing the pot suction design and significantly reducing the pot leakages.
Computational Fluid Dynamics (CFD) tools were used to evaluate different solutions. Special attention was paid to the position, number and shape of the suction hoods in the superstructure. Figure 16 represents the CFD modelling of an APXe cell during anode change under degraded conditions (pot flow rate and cell tightness lower than design). It allows visualizing the location of HF emissions, and determining if a proposed design change results in any improvement.

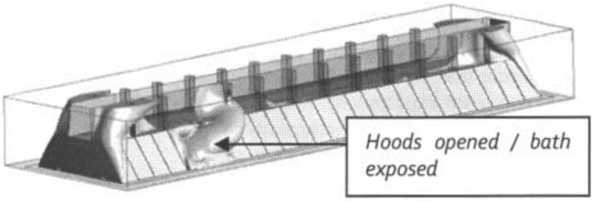

Figure 16– CFD modelling of an APXe cell

With respect to pot tightness, the overall open surface area (with closed hoods) was reduced by more than 50% compared to the previous AP50 superstructure generation.

Results

The first APXe prototype, which has been operating at the LRF since December 2010, benefited from these latest design changes. In order to confirm the expected improvement in collection efficiency, HF emissions were measured at two different locations: at the roof vent and just above the cell. Measurements were also conducted on a reference pot equipped with the previous superstructure design, including with standard hoods, as opposed to the new hoods on the APXe. Pot flow rate was varied to establish the relation between the pot emissions and the pot suction flow. As shown in Figure 17, these measurements confirm the expected benefit from a combination of this new design and tight hooding. These measurements have also been used to extrapolate the expected environmental performance of an APXe potline operating under standard industrial conditions, and this confirmed that 0.20kgFt/tAl is achievable.

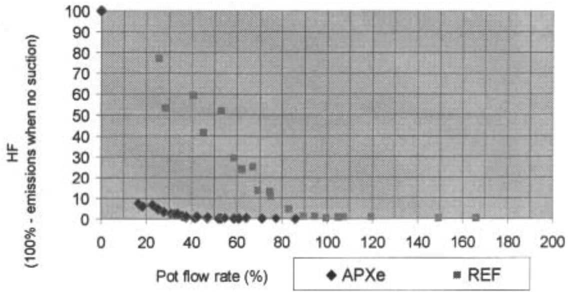

Figure 17– Roof vent emissions versus pot flow rate for the APXe and a reference AP5X cell (closed hoods)

Conclusion

After 125 years of operation, Hall-Heroult process cell productivity has improved dramatically through the development of high amperage cells. However, energy efficiency improvement levelled off after the seventies. In the coming decades, the challenge of massive demand for Aluminium in a restricted energy future will necessitate the development of low energy cell designs. After intensive economic and technical studies Rio Tinto Alcan decided to rapidly launch two new cell technologies that use the same generic cell equipment:

- AP60 cell, benchmark of cell productivity,
- APXe, operating at low energy consumption.

These two versions will make it possible to deliver optimal solutions for greenfield projects starting in the next few years.
The first APXe cell was started in December 2010 and has already delivered very promising results: after less one year of operation, the 12.2kWh/kg target has been achieved with very low fluoride emission at particularly low gas suction rates. More ambitious targets are already planned for the coming months. Some of innovative solutions developed on the APXe cell can also be deployed in existing aluminium smelters in order to reduce their energy consumption and their environmental footprint.

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