Modelling and measurements to support technological development of AP60 and APXe cells

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Abstract

With the successful start-up of the new Arvida AP60 smelter in Canada as well as the validation of the APXe cells at Saint Jean de Maurienne in France at a specific energy consumption of 12.2 kWh/kg, Rio Tinto Aluminium has demonstrated its leadership in the development of efficient reduction cells for the benefit of its own projects and its partners and customers. To reach these high productivity and low energy objectives through technological development activities, research and development operation teams rely on modelling and measurements to improve heat balance, electrical and magnetohydrodynamic (MHD) equilibria. Cell design and performance are continuously improved by using the comparison between measurements and models in order to reach new ambitious targets.

Keywords: AP60 cells; APXe cells; cell design and performance; cell modelling; cell measurements.

1. Introduction : AP pot development by modelling and measurements

In the early 1980's, the development of AP technology pots was already supported by numerical simulation. At that time, the pot design was optimized with software developed internally at Laboratoire de Recherche des Fabrications (LRF). Two types of models were used, magnetic field model for pot stability calculation and thermo-electric (TE) models for the busbars design and for the cells thermal balance [1]. Nowadays, several modelling tools are extensively used by for the Rio Tinto dual strategy cell development with AP60 for high energy and APXe for low energy cells [2]. The AP60 will operate at 600 kA and more with specific energy consumption (SEC) of about 13.0 kWh/kg, while the APXe operates at around 500 kA with energy consumption close to 12 kWh/kg (see Figure 1).

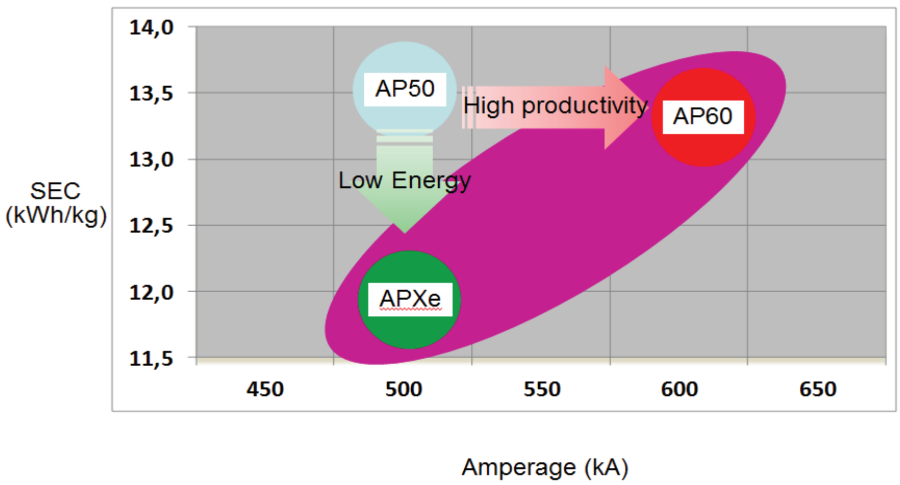

Figure 1. Operating regions of the new AP cell technologies.

2. Modelling tools: TE, MHD and MHD-TE models

The models development in RT takes into account different trade-offs between complexity, running time and accuracy. It involves also a well-balanced equilibrium between the complexity of physical phenomena, and accuracy of measurements and of properties of materials.
Four main models are used for the design and optimization of the AP60 and APXe cells.

- A 3D thermo-electric model representing a single slice. It takes into account the voltage drop, Joule effect, and overvoltages, as well as the heat transfer mechanisms inside and outside the cell. This model predicts accurately both the temperature and the voltage distribution. Being only a single slice, this model is relatively light and fast to run, making it well suited for work on cell design and rapid analysis of different alternatives.
- The busbar thermo-electric model which can predict both, the temperature and the voltage field in the external conductors around the cells. It can be used in normal, bypass or multiple bypass modes.
- A full pot MHD model focused on metal and bath velocity calculation, metal-bath interface deformation and finally pot stability evaluation. The MHD model is also able to calculate alumina distribution [3, 4, 5].
- A coupled MHD-TE model for a complete pot geometry which is used to calculate the temperature field and ledge. This model takes into account the velocity field [6].

3. Modelling and measurements on AP60

At Rio Tinto Arvida Smelter (Jonquière, Canada), in the new AP60 potline, the full validation of the cells and equipment is taking place with already two years of operation [2].

3.1. Magnetic field and metal velocity

In AP60 technology, the busbars configuration was designed to offer the lowest possible vertical magnetic field, the component causing the forces which affect the bath-metal interface. Magnetic fields were also measured on an AP60 cell; the agreement is excellent between the predictions and the measurements (Figure 2).

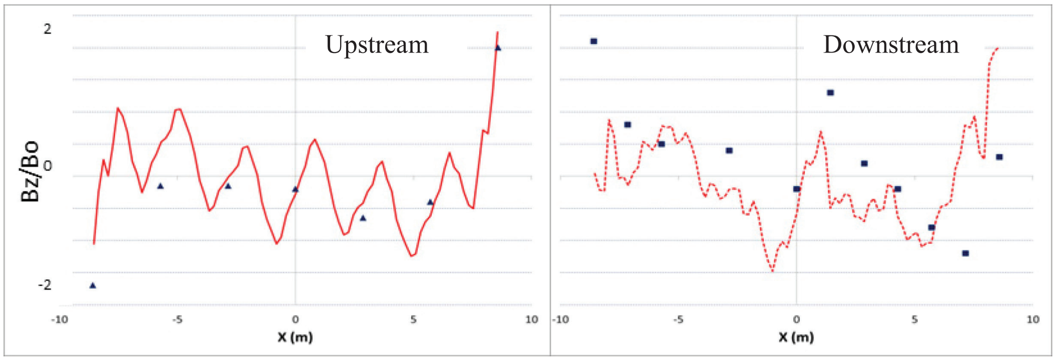

Figure 2. Vertical magnetic field measurements versus model results. (Bo: reference magnetic field).

Metal velocity measurements were also carried out on four AP60 cells. Table 1 shows that the maximum measured velocity is close to the prediction (Figure 3).

Table 1. Metal velocity measurements and prediction for AP60 cells.

4 cells	Max. velocity	Prediction
Measurements	18.2 cm/s	15 cm/s

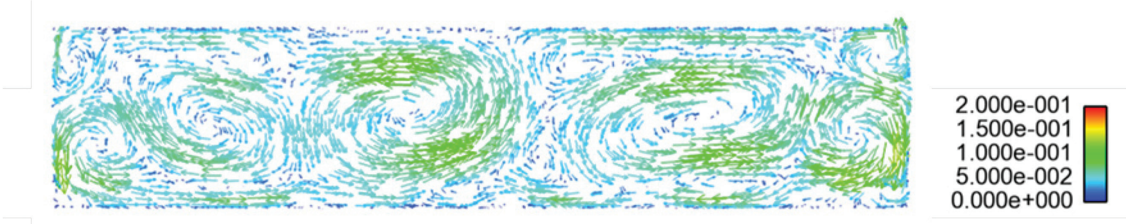

Figure 3. Predicted AP60 metal flow pattern.

The flow pattern calculated in the metal pad shows circulation pools of low intensity (around 10 cm/s) instead of the more cohesive, large eddy flow pattern usually seen.

3.2. Cathode erosion

It is important to know the erosion rate of a cell design in order to predict cell life to avoid pot failure and to plan pot lining of future generations. In the AP60 smelter, cathode erosion evaluation was made on 21 pots 500 days old at 26 different measurement points. The average cathode erosion rate measured is about 43 mm/year with a maximum erosion rate of 56 mm/year. These results are in line with cathode erosion rates measured on pots operating above 500 kA and are also in line with expected AP60 cell life of 72 months.

3.3. Electrical measurements

A typical voltage balance on a Hall-Héroult cell contains five main components voltage: anode voltage drop (AVD), bath (including bubbles) voltage drop, back EMF, cathode voltage drop (CVD) and external conductors voltage drop (Vext). The design of the cell components enables us to predict by modelling their electrical resistance, e.g., the network of aluminum busbars and the multi-materials anode assembly made of steel stub rodded into carbon block.

Except in the bath, in which the reduction of alumina into aluminum occurs, the other voltage drops can "easily" be measured (AVD, CVD and Vext). In the AP60, these values are determined during measurement campaigns.

Table 2 summarizes the AP60 anode assembly electrical measurements. Based on the voltage breakdown, it shows the low contributions of the anode beam-to-anode rod contact and of the anode rod itself in the AVD. Prior to the measurements, the AVD was also predicted by using the pot thermo-electric model. The predictions are included in Table 2. They match the measurements quite closely, which is to be expected as this part of the model was calibrated on a very similar anode from Saint-Jean-de-Maurienne.

Table 2. Summary of anode assembly electrical measurements for AP60.

Anode component measurements 100% = Total AVD meas.		**Voltage drop [%AVD]**	
		Measurements	**Model predictions**
	Beam-rod Contact	3	3
	Rod	6	6
	Clad-Upper Stubs	14	12
	Upper Stubs-Carbon	77	78
	Total AVD	100	99
Clad-to-Upper-Stub	Side Channel	17	15
	Middle	12	10
	Center Channel	15	14

The measurements of CVD and Vext, characterizing the busbars network are very close to the model predictions from the cell thermo-electric and busbars models.

3.4. Alumina dissolution: x % Al_2O_3 distribution

The alumina dissolution model was used to optimize the alumina distribution in AP60 pots. After an optimization process (Figures 4 and 5), the variance is much improved as shown in Table 3.

Table 3. Results of alumina dissolution model for AP60 before and after optimization.

%Al2O3	Min	Variance	Mean
Before opt.	1.54	0.22	2.63
After opt.	1.76	0.07	2.60

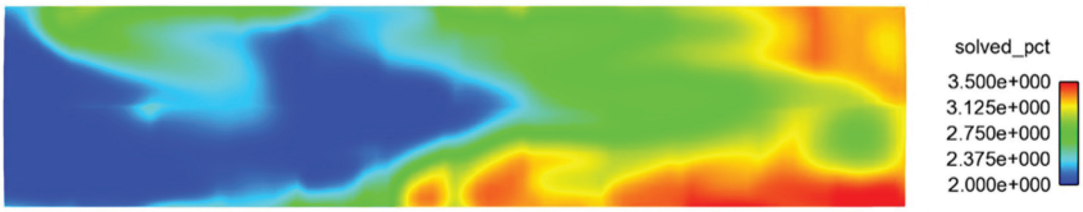

Figure 4. AP60 dissolved alumina concentration in xAl_2O_3%.

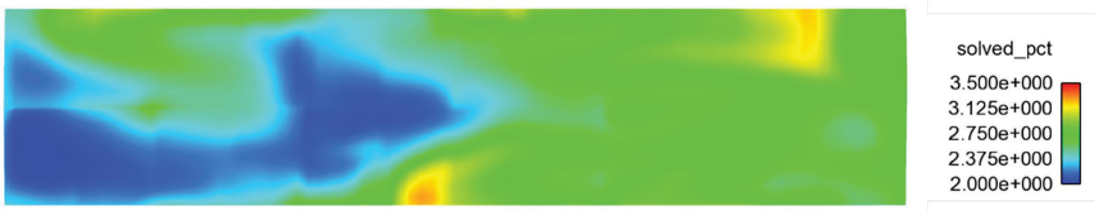

Figure 5. AP60 optimized dissolved alumina concentration in xAl_2O_3%.

3.5. Busbar temperature measurements

Additionally to the busbars electrical measurements, the temperatures were measured at several characteristic locations. This operation aimed to validate the design which was developed by using the busbar model (Table 4).

Table 4. Busbar temperature measurements and model results.

Location		**Temperature [°C]**	
		Measurements	**Model predictions**
Negative flexibles	3 cells	112	103
Anodse risers	3 cells	104	102
Pot-to-pot busbar	3 cells	30	31

3.6. Thermal measurements

The energy consumption of a cell technology is primarily driven by the electrical performance of its different components. The designer can also modify the thermal range of operation of a particular design. A cell within its operation range displays robustness to disturbances. An indicator to confirm a cell is operating within its thermal range is the ledge profile. If it becomes too thin, erosion of the sidewall will occur, which can lead to cell failure. On the other hand, if the ledge becomes too thick, there will be difficulties carrying out routine tasks like anode changing. Furthermore, growing ledge onto the cathode surface can provoke instability.

Four AP60 cells were measured for ledge profiles and shell temperature, as shown in Figure 6, where "y = 0" represents the cathode surface. A comparison with the model prediction is also shown on the figure. The ledge profile gives a good protection of the sidewall lining at the altitudes wetted by liquid electrolyte. The maximum shell temperature doesn't exceed 400 °C which is a good point for the shell life duration.

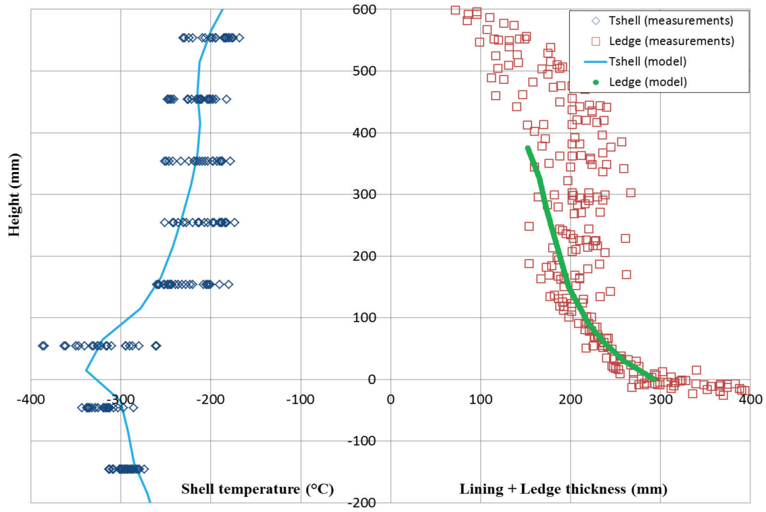

Figure 6. Shell temperature and ledge thickness in AP60.

Table 5 presents temperature measurements on different components of the AP60 cell: anode clad, collector bars and the bottom shell. Three cells were measured. These cells yielded an average bottom temperature of 115 °C. The table also includes the results from the thermo-electric model. The anode clad and shell bottom temperatures are well predicted, but there is a certain error for the collector bars. This is partly caused by the high thermal gradient existing on the external part of the bar making the comparison between model and measurements more difficult.

Table 5. Anode clad and collector bar average temperatures for AP60 cells.

	T [°C]	Model predictions[°C]
Anode clad	228	240
Collector bars	383	318
Shell bottom	115	111

3.7. Gas suction measurements

Measurements are carried out in the duct leaving the cell with a Pitot tube and a thermocouple. Table 6 presents the measurements taken on four AP60 cells. The model prediction is also included in Table 6.

Table 6. Measured cell exhaust gas temperature and flowrate on AP60 cells.

Cell	Flowrate [%max]	Gas temperature [°C]	
		Measurements	Model prediction
4 cells	100 %	100 °C	105 °C

3.4. Performance data: Vpot, CE, SEC

The AP60 plant started in September 2013 and was validated in August 2014 [2]. The performance data for the last year are presented in Table 7 and compared to the predicted values.

Table 7. Performance data on AP60 cells from Sept. 2014 to Aug. 2015.

Data	Units	Measurements	Model prediction
Amperage	kA	570.7	570
DC global SEC	kWh/kg Al	13.09	13.24
Current efficiency (CE)	%	95.9	94.5
Anode effect frequency (AEF)	nb/p/d	0.02	0.1

The AP60 technology is fully validated with better performance than expected due to an excellent current efficiency value. The very low value of anode effect frequency must be also noticed.

4. Modelling and measurements on APXe

At LRF, Saint Jean de Maurienne, three APXe prototype cells are in continuous trial. These trial pots give to Rio Tinto a strong advantage for testing new innovative solutions. It gives the possibility to test each cell at various amperages.

4.1. Magnetic field and metal velocity

To validate the APXe magnetic model, the magnetic field was measured. The result is given in Figure 7. The mean discrepancy between measurements and model on the vertical component is rather small.

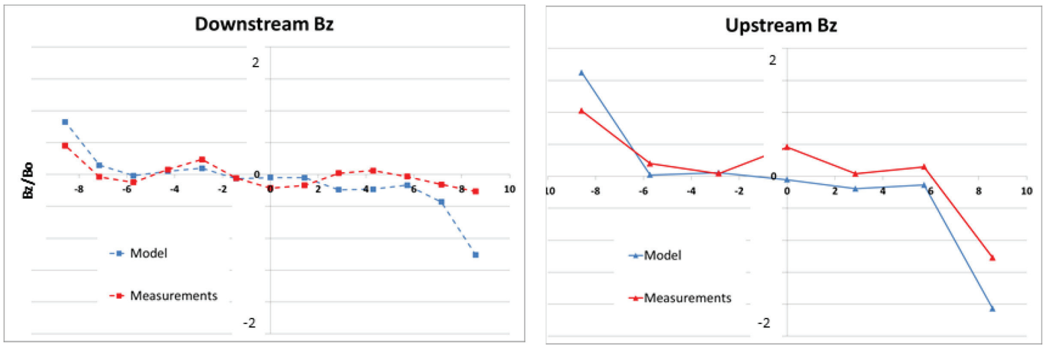

Figure 7. Comparison between vertical magnetic field measurements and model. (Bo: reference magnetic field)

Metal velocities in APXe were measured at 510 kA. Figures 8 and 9 show the velocity field obtained by modelling and by measurements. The model can predict correctly the vortexes and flow direction.

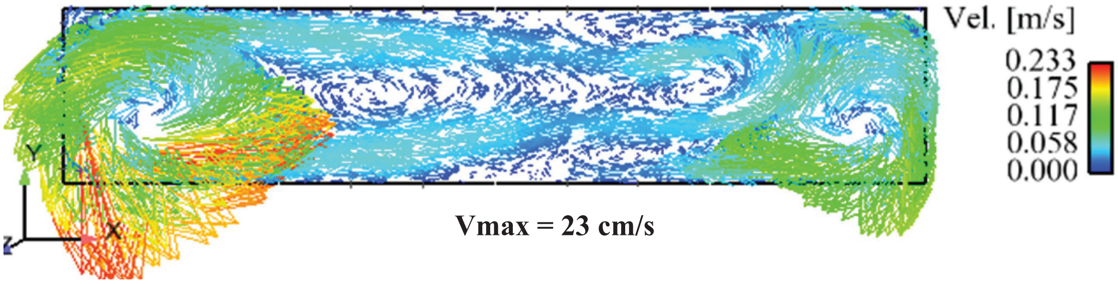

Figure 8. Velocity field at mid metal height.

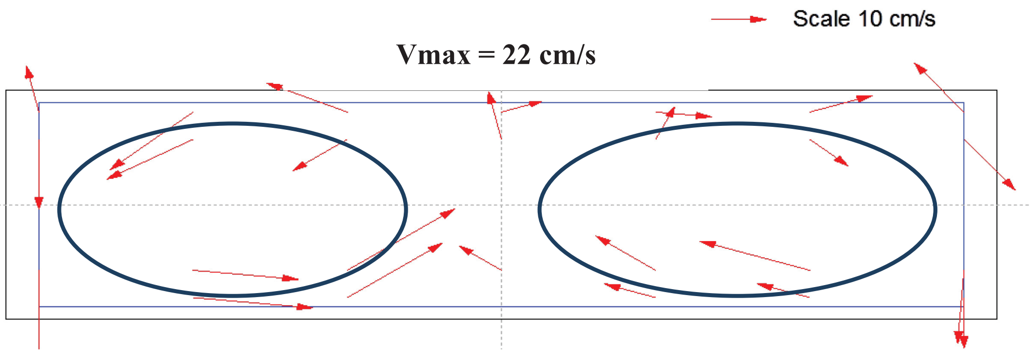

Figure 9. Velocity measurements results.

Metal upheaval measurements were performed. The model results are given on Figure 10. The order of magnitude of the maximum metal upheaval is in good agreement between measurements (Figure 11) and model. In both model and measurements, there is an elevation in the middle along the length of the cell.

ΔH = 6 cm
under anode panel

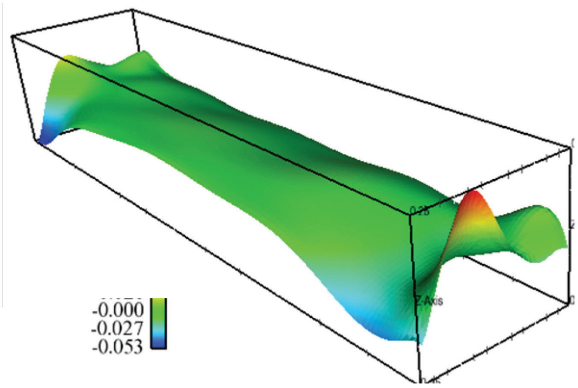

Figure 10. Metal upheaval obtained by simulation.

ΔH = 7 cm

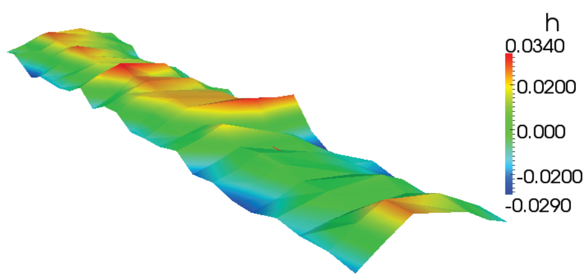

Figure 11. Metal upheaval obtained by measurements under anodic plan.

4.2. Alumina distribution

Low energy cells lead to wide variation of alumina concentration distribution. This is due to lower bath volume especially in the ACD, and due to lower heat available for the alumina dissolution. This is why modelling software is necessary.

Measurement campaigns were done on APXe cells to validate our model. Figure 12 shows the alumina distribution at mid height of the ACD. We can see that the dissolved alumina distribution can be improved with a variance at 0.40 $\%Al_2O_3$ compared to 0.07 $\%Al_2O_3$ on AP60. This work is in progress and will be presented in a next publication [5].

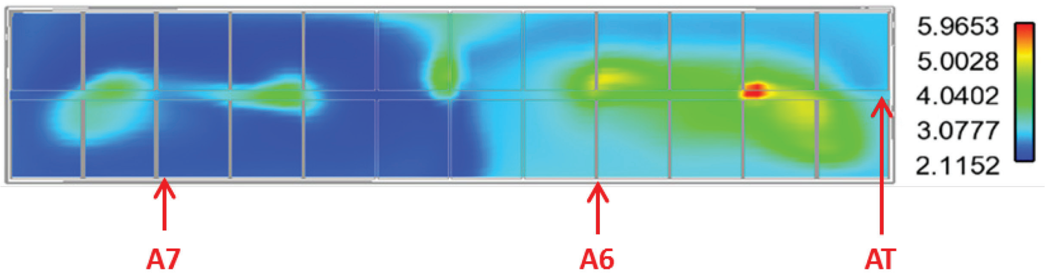

Figure 12. APXe modelled dissolved alumina distribution at mid ACD.

The results of the measurement campaign are given in Figure 12. The comparison between measurements and model confirms the difference between the two sides of the pot.

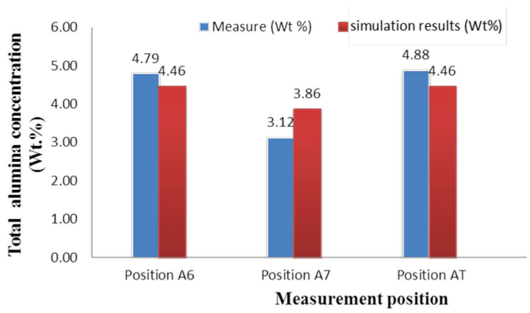

Figure 13. Alumina concentration model and measurements comparison.

4.3. Electrical measurements

For cathode and external voltages, measurements and modelling results are in very good agreement. We were confident on this validation as the model had been adjusted on numerous cases of cathodes and anodes with similar designs. The cathode resistance remains stable month after month. This is a good validation of the robust thermal control of the pot (Figure 14).

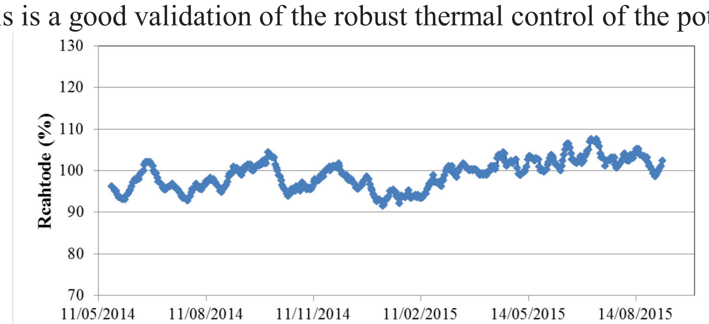

Figure 14. Cathode resistance evolution on APXe.

4.4. Thermal measurements

A good agreement is obtained between the model results and measurements data for shell temperatures and ledge profile (Figure 15). On the temperature graph, the difference between upside and downside temperatures is due to the very specific MHD conditions of the prototype pot workshop (Figure 7) with a high impact of liquids on upstream side.

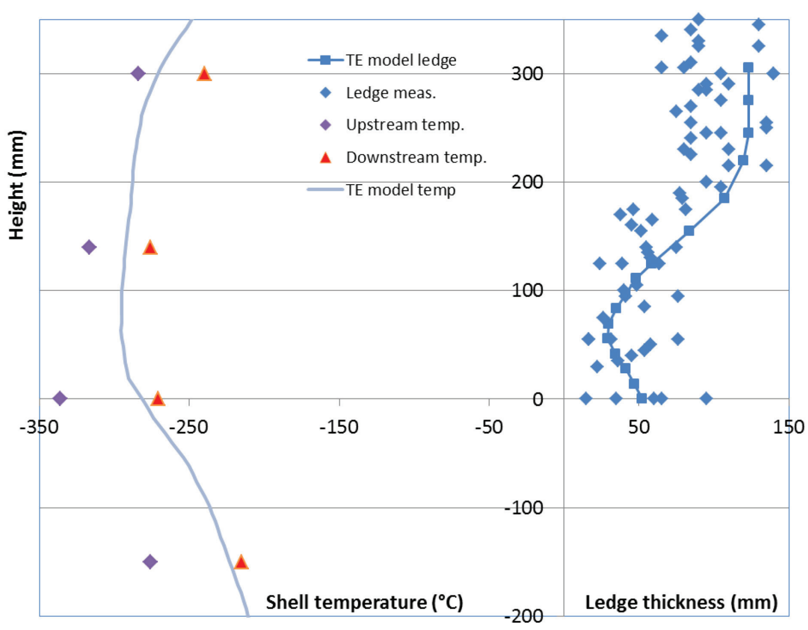

Figure 15. Shell temperature and ledge thickness on APXe.

4.5. Gas suction measurements

On APXe pot, the gas suction measured temperature is very similar to the temperature obtained in the TE slice model.

Table 8. Gas suction temperature.

Flowrate = 100 %	**Measured Tgas**	**Model prediction**
Tgas	101 °C	105 °C

4.6. Performance data

The performance of the latest version of APXe has been established over seven months (Table 9 and Figure 16). Specific energy consumption and current efficiency were stable with very satisfying values at 12.200 kWh/kg Al.

Table 9. Performance data on APXe cells from sept. 2014 to march 2015.

Data	Unit	Performance	Model prediction
Amperage	kA	508	505
Pot voltage	V	3.75	3.696
DC global SEC*	kWh/kg Al	12.210	12.196
CE	%	94.4	93.1
AEF	nb/p/d	0.19	0.10

* SEC is determined for a full potline taking into account all external conductors.

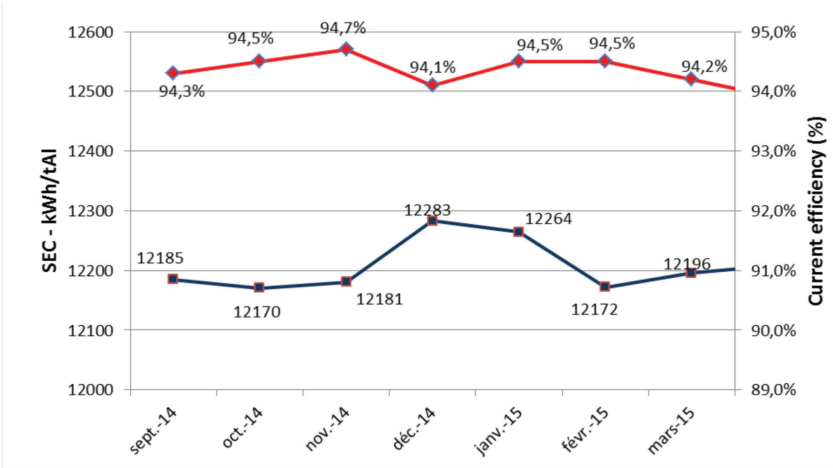

Figure 16. Specific energy consumption and current efficiency on APXe.

5. Conclusions

The development of new AP technology cells, AP60 and APXe, requires continuous improvement of our numerical models in order to solve increasing difficulties with higher amperage and lower ACD, lower bath volume and lower space for building the sidewall ledge.
The model development in Rio Tinto is associated with intensive measurements for the validation of the different parts of the model: physics assumptions, numerical solution methods and material properties.

In the last two years, AP60 and APXe have confirmed their expected performance which is a complete validation of our development process, based on modelling and measurements. The next evolution of AP technology - AP64 at 640 kA and APXe at very low energy under 12 kWh/kg Al - will be done with strong support of our modelling tools.

6. References

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