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DUBAL CELL VOLTAGE DROP INITIATIVES TOWARDS LOW ENERGY HIGH AMPERAGE CELLS

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Abstract

In recent years, DUBAL has focused its energy and resources towards reducing energy consumption of aluminum electrolysis cells. The main ambition, though, was to take the available world-class DX+ Technology, the highest cell amperage technology currently operating in DUBAL, and build upon it further. For that, several voltage drop initiatives were initiated and trials have been conducted on numerous DUBAL cell technologies to demonstrate and prove the newly developed low energy concepts, and more importantly to facilitate the transition from DX+ cell technology to DX+ Ultra cell technology which incorporates all the voltage drop solutions. The initiatives tackled lower energy concepts around four fundamental categories; anode voltage drop, bath voltage drop, cathode voltage drop, and external voltage drop. In-depth mathematical models were used, through commercial software packages to design and predict these concepts. In addition, measurement programs were setup and organized with trials conducted to validate the model predictions. In this paper, the voltage initiatives and trials shall be evaluated in detail, with particular emphasis on the analysis of copper insert cells.

Introduction

DUBAL has engaged in self-development of in-house proprietary reduction cell technology since the 1990s. DX and DX+ Technologies have been designed, modeled, tested and optimized during this development process [1 - 3]. The success of the two stories has encouraged the team to drive further. Over the past 30 years, DUBAL has been extremely energy conscious while increasing its amperage. In fact, optimizing energy efficiency is a key pillar in DUBAL's strategic objectives. Today, considering the significance of the cost of energy, DUBAL is committed to developing even lower energy-high reduction cells. D18+ demonstration cells witness hitherto the largest effort in this direction with net specific energy consumption of 12.67 kWh/kg Al, net cell voltage of 4.04 V and current efficiency of 95.05 % (June 2012 – September 2013) at 202 kA [4].

The voltage drop initiatives act on key energy consumers of a cell design. Cathode voltage drop, for example, can be improved by introducing copper inserts in the collector bars. Certainly, copper inserts have been used in aluminum electrolysis cells for more than fifty years but the recent drive towards low energy consumption has spread their use in high amperage cells [5 - 6]. DUBAL uses its own design of copper inserts which have proven the claimed benefits during industrial trials. Another example is the external voltage drop, and that can be improved through cell busbar design. Busbars are simply the means of transferring current from one cell to another, and do not contribute directly to metal production. Thus, improving energy consumption in that aspect is boundless, as long as MHD and metal stability is respected. In this paper, the means by which the voltage drops are improved will be demonstrated.

Voltage Drop Initiatives

Four voltage drop initiatives have been set in motion in order to reduce energy consumption to less than 12.49 kWh/kg of aluminum by reducing anode, bath, cathode, and external voltage drops. These include longer anodes with four stubs, higher saw cut anode slots, larger stub diameter, deeper stub hole depth, reduced ACD, larger collector bar cross sections, optimized busbar design with split anode risers and copper inserts in the cathode collector bars. Among these, busbar optimization and copper inserts contribute the most to the cell voltage reduction. The baseline for the electrical parameters starts with the 5 DX+ demonstration cells in DUBAL. The overall projected gain in net energy consumption is 1.08 kWh/kg Al, from 13.52 to 12.44 kWh/kg Al. Figure 1 illustrates the breakdown of voltage drop reductions from the proposed initiatives for DX+ at 440 kA.

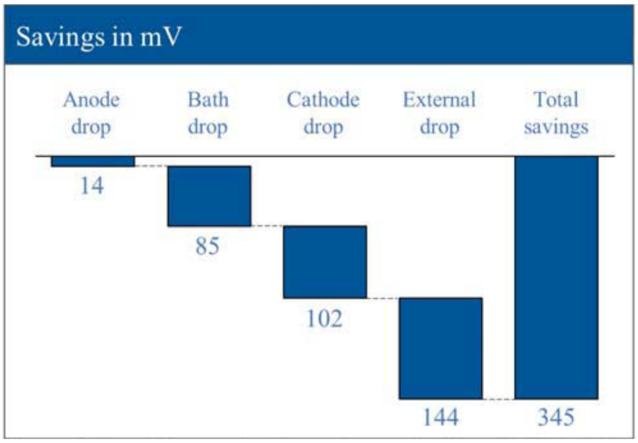

Figure 1. Breakdown of voltage drop reductions in DX+ Ultra from proposed initiatives, at 440 kA.

. Copper inserts have been implemented on other DUBAL technologies: D20 and DX. Other initiatives have been implemented on an industrial implementation of DX+ cell technology in EMAL Potline-3, including larger collector bar cross section, and increased busbar cross sections. The remaining initiatives will all be included in the DX+ Ultra cell technology; larger stub diameter, deeper stub holes, busbar redesign, and novel cathode flex design. Table I illustrates what each stage of DX+ benefits from in terms of initiatives, the gains DX+ demonstration cells and DX+ Industrial (EMAL Potline-3) already witness, and what will finally be realised with DX+ Ultra.

Table I: Summary of the DX+ electrical parameters with evolution of the voltage drop initiatives.

Initiatives	DX+ Demo. Cells	DX+ Industrial	DX+ Ultra
Longer anodes (Stage 1: +25 mm)	✓	✓	✓
Reduced ACD	✓	✓	✓
Higher saw cut anode slots	✓	✓	✓
Larger collector bar cross-sections	✗	✓	✓
Larger busbar cross-sections	✗	✓	✓
Copper inserts	✗	✗	✓
Busbar redesign	✗	✗	✓
New cathode flexible design	✗	✗	✓
Longer anodes (Stage 2: +20 mm)	✗	✗	✓
Larger stub diameter	✗	✗	✓[1]
Deeper stub holes	✗	✗	✓

[1]: Larger stub diameter will not be implemented at the start-up of the DX+Ultra demonstration cells to re-use DX+ demonstration cells anode assemblies.

Table II summarizes the evolution of the voltage drop initiatives, illustrating the transition from DX+ demonstration cells baseline to DX+ Ultra.

Table II: Summary of the DX+ electrical parameters with evolution of the voltage drop initiatives.

DX+ Parameters	Demo. Cells Before	Demo. Cells After	Indus-trial	Ultra
Amperage (kA)	440	440	440	440
Current efficiency (%)	95	95	95	95
Net cell voltage (V)	4.310	4.250[2]	4.170	3.965
Specific energy (kWh/kg Al)	13.520	13.332	13.081	12.438

[2]: Net cell voltage does not include higher anode slots which were implemented later during 450 kA operation.

One additional initiative was implemented on the 5 DX+ demonstration cells and already generalized on the Industrial application of DX+ (EMAL Potline-3). It is therefore not included in Figure 1, Table I, nor in this entire paper. However, it was a significant step towards lowering energy consumption of DX+ cells. The anode yoke assembly was converted from a 3-stub configuration to a 4-stub configuration starting December 2011. This was done during lower amperage operation. The yoke assembly was designed to provide the optimum voltage drop along with comparable or improved mechanical strength. Extensive mathematical modeling was performed to predict the performance of the new assembly. Thermo-electric models were developed to calculate voltage drops and estimate the heat loss from the top surface of the cell. This information was used to modify operational parameters in order to maintain the heat balance of the cell. The gain in this conversion was equivalent to 43 mV at 440 kA operation.

The following sections of the paper discuss the four voltage drop initiatives in detail; review the mathematical modeling predictions for the initiatives and evaluate those predictions on the trials conducted in DUBAL.

Anode Voltage Drop

The trials of the anode voltage drop initiatives include larger stub diameter, and greater stub-hole depth. The larger anode stub diameter and deeper stub hole have been modeled and analyzed; a gain of 8 mV and 6 mV voltage drop is predicted from this step, respectively. The trial for these stub changes will be included with the DX+ Ultra implementation, but DUBAL has had experience with such stub changes on other anode assembly configurations.

Bath Voltage Drop

The trials under the bath voltage drop initiative include reduced ACD, longer anodes, and higher saw cut anode slots. The reduction of ACD by 1 mm was achieved in DX+ demonstration cells, on 23rd February 2013, giving a voltage saving of 40 mV. The longer anodes test involves two stages which will increase the length by a total of 45 mm. The first stage involves 25 mm increase and is already implemented in the 5 DX+ demonstration cells. The voltage reduction of 20 mV from the first stage has been confirmed in the demonstration cells, since January 2013. The average net cell voltage since the implementation of the two trials was 4.25 V, 60 mV lower than 4.31 V before the trial. The energy consumption decreased from 13.52 kWh/kg Al to 13.33 kWh/kg Al at 95 % current efficiency.

Higher saw-cut anode slots (+ 50 mm) were introduced in the DX+ demonstration cells in April, 2013. The higher slots improve the transfer of bubbles under the anodes towards the center channel, reducing overall bubble resistance in the bath until later in anode life. The estimated bubble voltage drop reduction was 10 mV. During that time, the cells were already operating at higher amperage of 450 kA. The base resistance of the cells was reduced by 0.03 μΩ and consequently, the cell voltage by 13 mV.

In the second stage, anode length will increase by 20 mm. This increase requires a modification of side lining to a thinner SiC layer, which will be implemented in the DX+ Ultra. However, no problems are expected because similar thin side lining configurations have been already tested successfully in other DUBAL technologies.

Cathode Voltage Drop

The trials under the cathode voltage drop (CVD) initiative include larger cathode collector bar cross section and collector bar copper insert. The larger collector bar cross section will provide a gain of 22 mV, calculated with validated mathematical models [7]. This is already implemented in industrial application of DX+ technology (EMAL Potline-3) where the first cell was cut-in on the 9th of

September, 2013. Therefore, it is still too early for cathode voltage drop model validation with measurements.

On the other hand, copper inserts in the collector bars are being trialed on two DUBAL technologies, D20 and DX. For DX+, the expected gain on cathode voltage drop is 80 mV; equivalent to 0.251 kWh/kg Al at 95% current efficiency. This will be demonstrated in DX+ Ultra cells. Currently in DUBAL, two copper insert designs are being trialed. Copper insert design 1 shows an average gain of 67 mV at 270 kA. Copper insert design 2 shows an average gain of 72 mV at 250 kA and 79 mV at 385 kA. Table III shows the measured cathode voltage drop for copper insert design 1 and design 2 in D20 cells versus standard cells, along with the model predictions. Similarly, early indication of DX copper insert cells (Copper insert design 2) shows an excellent performance. Since then, measured average cathode voltage drop reduction is 79 mV compared to a non-copper cell of the same design; the model predicted 67 mV reduction at 385 kA. This is shown in Table IV.

Table III: Cathode voltage drops of D20 copper insert cells and standard cells

Cathode Voltage Drop	Design 1	Standard cells	Design 2	Standard cells
Amperage (kA)	270	270	250	250
Measured CVD (mV)	184	251	159	231
Predicted CVD (mV)	167	247	151	227
Gain in CVD (mV)	Measured: 67 mV Predicted: 80 mV		Measured: 72 mV Predicted: 76 mV	

Table IV: Cathode voltage drops of DX copper insert cells and standard cells at 385 kA.

Cathode Voltage Drop	Design 2	Standard Cells
Measured CVD (mV)	166	245
Predicted CVD (mV)	174	241
Gain in CVD (mV)	Measured: 79 mV Predicted: 67 mV	

Figure 2 and Figure 3 show the long term measurement data of cathode voltage drop in D20 cells for Copper insert designs 1 and 2 respectively, against standard cells, which are all consistent over time. Figure 4 also shows early indications for DX copper insert cells with cathode voltage drops over a 6-month period. Data clearly suggests that, for all cells on both technologies, the cathode voltage drop does not deteriorate with time.

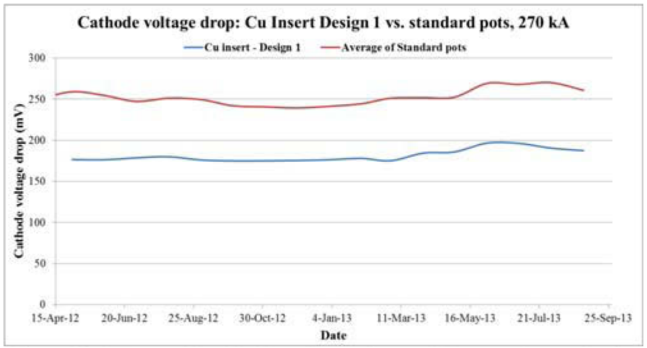

Figure 2. Measured cathode voltage drop of Copper insert design 1 cells vs. standard cells at 270 kA, consistent over time.

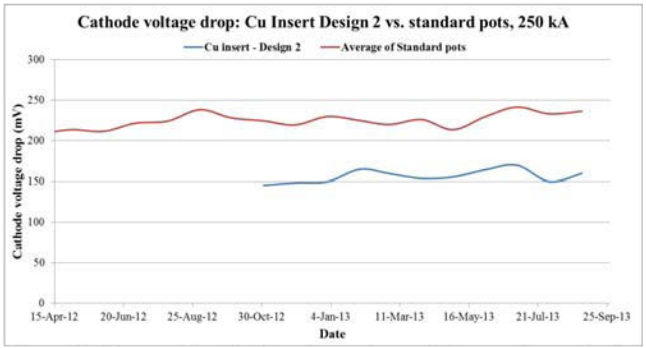

Figure 3. Measured cathode voltage drop of Copper insert design 2 cells vs. standard cells at 250 kA, consistent over time.

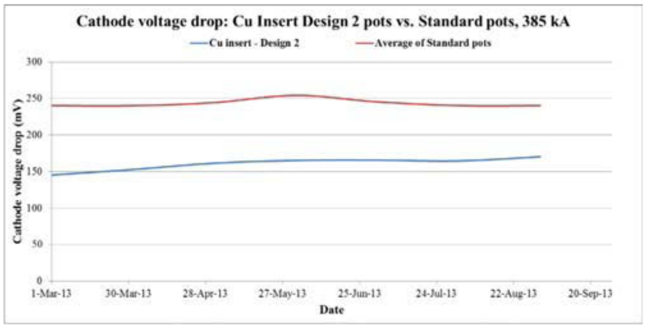

Figure 4. Measured cathode voltage drop of DX Copper insert Design 2 cells vs. standard cells at 385 kA, consistent over time.

In copper insert cells, modifications were done to the lining to compensate for the increased effective thermal conductivity of the collector bars. This was necessary to maintain thermal balance and, more importantly, to keep isotherms at the desired place and avoid cold cathode blocks. The measured freeze profile is shown in Figure 5. These are as predicted by models. The freeze in copper insert cells is quite similar to regular cells.

In general, there is very close agreement between all model results and the measurements. This confirms the model validity and provides confidence and reliability to all the model predictions for DX+ Ultra cells with copper inserts.

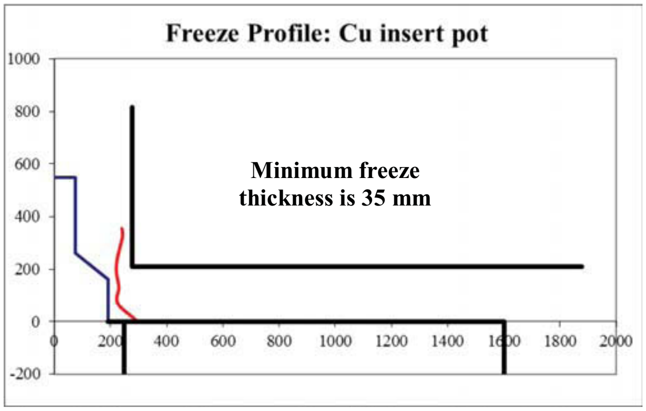

Figure 5. Measured freeze profile of Cu insert design 2 cells.

External Voltage Drop

The external voltage drop initiative includes an increase in the busbar cross sections, a limited busbar redesign, and a new collector bar flexible design. The increase in busbar cross sections by +16.67% provides a gain of 48 mV. It was calculated with validated mathematical models and it is already implemented in industrial application of DX+ technology in EMAL Potline-3. The models were previously used for DX technology as well to predict the change of external voltage drop for an increase of busbar cross-sections of 20% from DX demonstration cells to DX industrial cells. Several design validation campaigns done on those cells have all confirmed model predictions at different amperages.

Busbar redesign: While keeping the four anode riser at the same location as DX+, the redesign includes a split riser configuration providing a voltage reduction of 80 mV at 440 kA. Although busbar voltage drop is typically reduced by using larger busbar cross sections, the new design offers this gain with a reduced mass of aluminum busbars. This principle is well known: it reduces the mass of the busbar because of the improved length/area ratio of downstream to upstream busbars between the exit from the collector bars and the equipotential point on the anode busbar ring [8]. The reduction of busbar mass in DX+ Ultra is approximately 10 tons per cell compared to DX+ Industrial. The design also allows for a reduction of cell to cell centerline distance from 6.3 m to 6.0 m. This increases the annual production per potroom building area from 7.26 t/m^2 to 7.60 t/m^2, calculated for 360 cells and one central passage. Moreover, the reduction of aluminum mass per cell and cell-to-cell centerline distance significantly reduces the capital cost of the technology. This design will be implemented in DX+ Ultra.

The new busbar design is expected to have similar or better MHD performance as compared to DX+ industrial cells. Collector bar and cathode busbar current distribution were analyzed in detail. Mathematical model results for MHD analysis show improvement in all MHD parameters for the new design. Maximum vertical magnetic field B_z, specifically at the upstream corner, is reduced by 2.2 mT. Metal deformation is improved with maximum to minimum difference reduced by 3.2 cm. Metal velocities are also slightly reduced by 0.4 cm/s maintaining similar circulation patterns to the ones in DX+ cells.

The new split anode riser design required some change in the cut-in and cut-out concept for the cell. Mathematical models were used to fully analyze and understand the impact of the modified busbar current loading and new busbar temperatures of the stopped cells. The temperatures are acceptable for insulation materials in different locations. The models were also used to evaluate the influence of cell cut-out on the neighboring operating upstream cell and to maintain the current balance of that cell.

The collector bar flexible design provides a further 16 mV reduction in the external voltage drop. The concept involves a conversion from bolted tabs between flexibles and collector bars, which are used in DUBAL technologies, to welded tri-metallic tabs at the collector bars. The flexibles are now bolted to the cathode ring busbar. Detailed thermo-electric models were developed to evaluate the voltage drops and temperatures across the assembly. This is important to maintain acceptable temperatures, especially at the tri-metallic joint. Copper is no longer used which significantly reduces the assembly cost. The new design also allows for optimization of the collector bars outside the shell, contributing to the voltage savings. Moreover, the new arrangement offers a simpler technique for cell changeover.

Cell Performance

Table V shows KPIs of DX+ demonstration cells for different periods at 440 kA. The KPIs improved after the implementation of the voltage drop initiatives. DUBAL's commitment to performance improvement has taken DX+ demonstration cells even further, to higher amperage. Table VI shows the performance of the DX+ demonstration cells operating now at 450 kA. At this stage, ACD was decreased once again in order to further reduce energy consumption. Note that for clarity, the transition period from 440 kA to 450 kA (29 April to 20 May 2013) is not included in Tables V and VI. At 450 kA, cell KPIs remain excellent.

Conclusions

Tremendous progress has been made on the voltage drop initiatives in DUBAL. The initiatives implemented so far give an equivalent voltage reduction of 150 mV out of the 345 mV for all initiatives planned. The reduction so far gives specific energy saving of 0.47 kWh/kg Al, out of 1.08 kWh/kg Al total for all initiatives, at 95 % current efficiency. Another 70 mV reduction is expected in EMAL Potline-3. The remaining 125 mV will be demonstrated on DX+ Ultra cells.

The validity of the mathematical modeling capabilities has been repeatedly proven and provides DUBAL the confidence on all R&D developments. Modeling is being used extensively for the design and optimization of all DUBAL technologies.

Copper insert trials confirm large cathode voltage drop reduction as predicted by models and the voltage drops in all copper insert cells are constant over time. Busbar redesign will also offer significant energy savings along with expected improved cell stability. Generally, all benefits from the voltage drop initiatives would lead to significant OPEX and CAPEX savings.

KPIs of DX+ demonstration cells improved after the implementation of the voltage drop initiatives.

Table V: KPIs of DX+ demonstration cells at 440 kA after implementation of voltage drop initiatives.

DX+ Demonstration Cells	Base, 440 kA	After impl., 440 kA	Full period, 440 kA
Amperage (kA)	439.8	440.0	439.8
Current Eff. (%)	94.64	95.24	94.96
Start date	20/02/2012	24/02/2013	20/02/2012
End date	3/12/2012	28/04/2013	28/04/2013
Specific Energy DC (kWh/kg Al)	13.58	13.29	13.50
Specific Energy DC @ 95% CE (kWh/kg Al)	13.53	13.32	13.48
Cell Voltage (V)	4.31	4.25	4.30
Net Carbon (kg C/t Al)	402	398	400
Anode Effect Freq. (AE/day)	0.065	0.066	0.065
Anode Effect duration (s)	9.8	5.0	9.3
PFC Emissions CO2 (Computed) (CO_2kg/t Al)	11	6	11

Table VI: KPIs of DX+ demonstration cells at 450 kA after implementation of voltage drop initiatives.

DX+ Demonstration Cells	Final period, 450 kA	Full period, 450 kA
Amperage (kA)	449.1	449.4
Current Eff. (%)	95.13	95.01
Start date	18/07/2013	20/05/2013
End date	20/10/2013	20/10/2013
Specific Energy DC (kWh/kg Al)	13.37	13.40
Specific Energy DC @ 95% CE (kWh/kg Al)	13.37	13.39
Cell Voltage (V)	4.26	4.27
Net Carbon (kg C/t Al)	410	408
Anode Effect Freq. (AE/day)	0.069	0.074
Anode Effect duration (s)	9.78	9.5
PFC Emissions CO2 (Computed) (CO_2kg/t Al)	12	13

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