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DEVELOPMENT HISTORY AND PERFORMANCE OF DUBAL DX+ DEMONSTRATION CELLS

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Abstract

Five DX+ demonstration cells were started up during July-August 2010 in Dubai Aluminium (DUBAL) Eagle demonstration section and were shutdown in January 2014 in order to provide space for five DX+ Ultra low energy demonstration cells. This paper describes the characteristics and performance of DX+ cells during the entire period of their operation from starting cell amperage of 420 kA to 460 kA at shutdown. A new cell control system based on standard PLC (Programmable Logic Controller) was developed on these demonstration cells and successfully transferred to the industrial DX+ cells in EMAL Potline 3. During the whole period of operation, the cell metal production was increased by 228 kg/cell-day and the specific energy consumption was reduced by 0.29 kWh/kg Al while the current efficiency was maintained at 95 %. This was achieved through process optimization, revised work practices coupled with cell control strategies and anode design changes. After shutdown, autopsies were carried out to predict life expectancy of these cells.

Introduction

DUBAL has developed proprietary DX and DX+ technologies [1-3]. DX cells operate in DUBAL Potline 8 and in EMAL Potlines 1 and 2. Five DX+ demonstration cells were started in July and August 2010 in DUBAL Eagle Section at 420 kA and cell amperage was increased in stages with long time operation at 440 kA and 450 kA and a very short time operation at 460 kA before cells were shut-down in January 2014. An industrial scale full potline comprising 444 DX+ cells was started up between September 2013 and June 2014 at 440 – 444 kA at EMAL [4].

Figure 1. DX+ cells in the DUBAL Eagle section.

DUBAL DX+ cells (Figure 1) are designed to operate at much higher amperage than DX cells. At the start-up and during early operation of DX+ cells, many control and cell operation parameters had to be adjusted for higher amperage from previously proven DX cells. This was carried out in the period from the first cell start-up in July 2010 to the end of October 2010. December 2010 was the first month of steady and stable operation in all five DX+ Eagle demonstration cells. This was the beginning of the performance evaluation of the DX+ technology.

The amperage increase started in July 2011. By this time good performance at base design amperage of 420 kA had been proven. Amperage increased in four steps as new booster rectifiers were cut in, but remaining at each amperage long enough to establish the new thermal equilibrium and confirm that the cell performance did not suffer from the amperage increase. In hindsight, an amperage increase of 20 kA in just seven months with excellent performance at each step has to be considered a great success. Detailed monitoring and remarkable cell stability ensured the current efficiency and other performance data were reliable.

After more than a year of successful operation at 440 kA, DX+ Eagle cell amperage was increased to 450 kA between 29 April and 19 May 2013. The rate of amperage increase was constrained by the need to establish stability in the booster rectifier system that needed to be synchronized with the other operating potlines. The cells operated at 450 kA until 12 January 2014. At this time, amperage was further increased to reach 460 kA on 14 January 2014. This was a short three-day trial at 460 kA prior to the cut out of the first cell in the section.

Integral with the cell practice development, the new DUBAL cell control system based on Programmable Logic Controller (PLC) was successfully developed in the DX+ demonstration cells and prepared for transfer to EMAL Potline 3 DX+ cells. The software was developed in a short time, having been initiated in the first quarter of 2011 and implemented in November 2011.

Anode Design Changes

The cells were started with an anode length of 1760 mm and a height of 680 mm with a flat top profile and three-stub yoke assembly. The anode design was revised to reduce current density, bubble resistance, gross carbon consumption, anode voltage drop and to improve anode covering quality. The anode width remained the same at all times.

The anode length was increased from 1760 to 1820 mm in two steps. The anode top profile was changed from flat to one step chamfer to improve anode coverage and reduce gross carbon consumption without compromising the metal purity. In addition, the slot depth was increased to reduce bubble resistance. The three stub anode yoke was replaced with a new in line four-stub anode yoke on 6 December 2011 in order to reduce anode voltage drop.

PLC Based Cell Control System

Originally the DX+ cells were equipped with the DUBAL Cell Control Unit (DCCU). DCCU is a DUBAL in-house developed cell control system, initially introduced for D20 cell technology in Potline 7 in 2005. Since then, several generations of the system have been developed and installed in different Potlines at DUBAL and EMAL. A project to develop a cell control system based on Programmable Logic Controller (PLC) was started in 2007. The new system was partially tested on D20 cells and then on DX cells, however it was not implemented on an industrial scale.

In DX+ demonstration cells, the PLC system was installed in parallel with the DCCU in order to continue the automatic control of the cells without interruption. PLC based cell control system is the most advanced DUBAL cell control system. It offers high flexibility, reliability, use of standard automation components and much better Human-Machine Interface (HMI) than DCCU.

Both the PLC and DCCU systems could monitor cells simultaneously, but control functions were with one of them at a time. Switching over of control functionality was quick, taking only a few minutes, so there was a good possibility to test different control logics of PLC without any disturbance to the cells.

The most intensive online PLC tests started in mid-2011 after some improvements of the system hardware were made in order to reach required accuracy of measurements. The system functionality was tested logic by logic over several months, and then in December 2011 the cells were switched to PLC control on a permanent basis. From then onwards, the DCCU remained as a live redundant system for the PLC, but up until the removal of the DX+ cells from the Eagle section in January 2014 it was never re-used due to the reliability of the PLC system.

The initial set of control logics in PLC was copied from DCCU. It covered only the most important requirements, however the PLC based system could give much smarter and powerful control of the cells along with a user friendly interface for the operators. The PLC development team took this as an opportunity to benchmark functionality and performance of the control system. The tasks were:

- Provide precise alumina feeding to minimize anode effects and reduce background PFC emissions.
- Diagnose deviations in cell conditions and equipment and give clear recommendations to operators.
- Minimize necessity of manual interventions in the cell control during any cell abnormalities.
- Provide a full set of data for all control actions and operations on cells for further analysis.

New methods of the voltage signal processing and underfeed triggers, early anode effect detection (Near anode effect logic) and automatic adjustment of feeding rates gave very good results in terms of anode effect frequency and duration reduction. New logic and HMI interfaces were developed to assist auxiliary routine operations on cells such as anode adjustments, anode dressing and redressing, bath level correction, etc. The introduction of new calculations of low and high frequency voltage fluctuations, which identify MHD and anode noise, improved noise control and helped identifying anode problems.

The team also revised the rules to set cell control parameters. Special templates to calculate alumina feeding parameters and different voltage adders were developed. Fine tuning of the control parameters on the five DX+ demonstration cells helped the PLC based cell control system to be ready for implementation on the EMAL Potline 3 DX+ cells. The system was successfully installed and commissioned on the 444 EMAL Potline 3 cells [4].

Strategy of Amperage Increase

Amperage was increased from 420 to 460 kA successfully during life of the DX+ cells [3]. Cell operation and control parameters for each step of amperage increase were calculated with mathematical models according to the principles of energy and mass balance [5]. All processes participating in energy generation, absorption or loss were included. The base value of enthalpy for alumina reduction and metal re-oxidation reactions were modified accordingly for internal heat and heat loss calculations.

The following parameters were adjusted to maintain thermal balance and achieve stable cell operation:

- Anode length increased from 1760 to 1820 mm in steps.
- Anode cover thickness decreased from 14 to 9 cm in steps.
- Anode yoke changed from 3 to 4 stubs.
- Cell voltage decreased from 4.35 to 4.27 volts.

Cell Performance

DX+ key performance indicators exceeded expectations. Cell KPIs and graphs from 1 December 2010 (when stability and good performance were established in all five cells) to shut down in January 2014 are shown in Table I and Figure 2 - 13. Note that the industrial version of DX+ cells, built in EMAL Potline 3, has larger busbar and cathode collector bar cross-sections than the demonstration cells, which gives the opportunity to reduce the cell voltage by 70 mV at 440 kA and correspondingly reduce specific energy consumption by 0.22 kWh/kg Al.

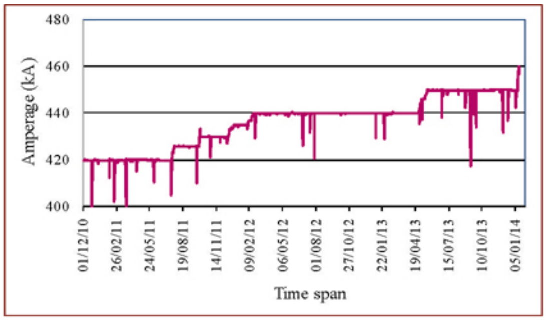

Figure 2. Potline amperage.

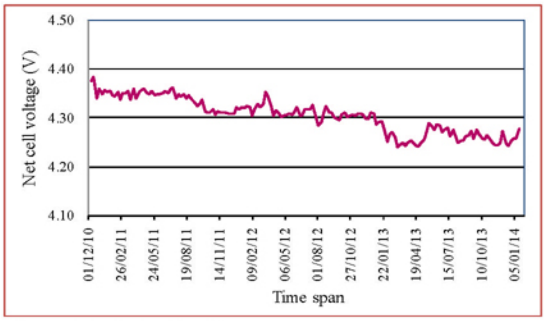

Figure 3. Net cell voltage.

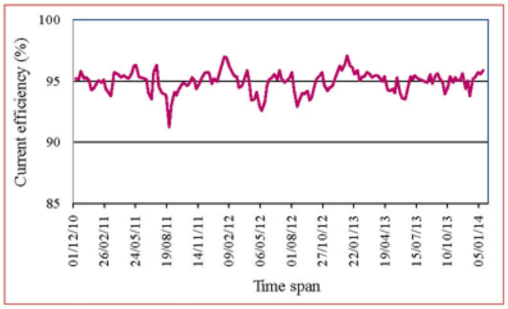

Figure 4. Current efficiency.

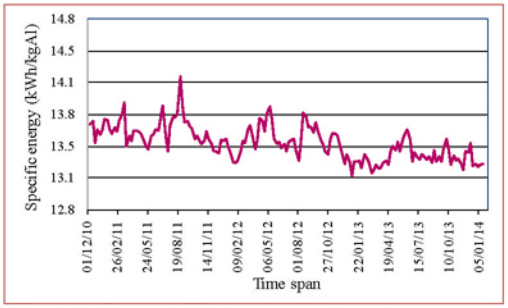

Figure 5. Net specific energy consumption.

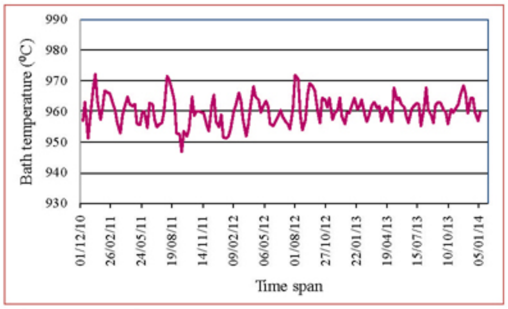

Figure 6. Bath temperature.

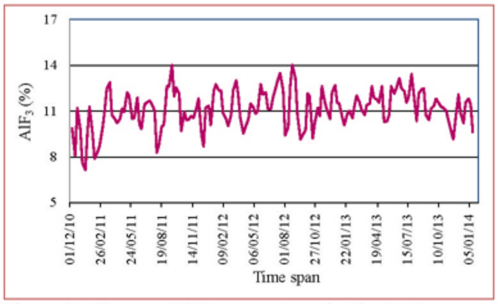

Figure 7. Excess AlF_3 percentage in the bath.

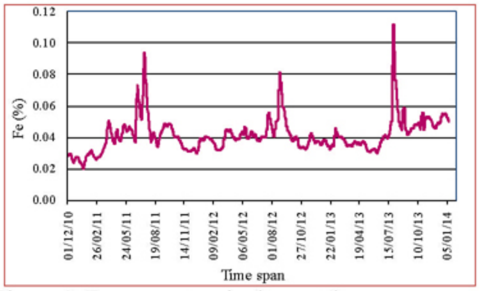

Figure 8. Fe percentage in the metal.

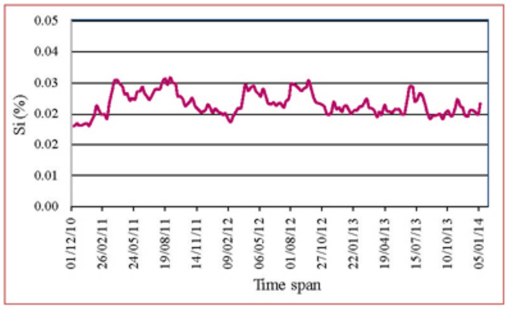

Figure 9. Si percentage in the metal.

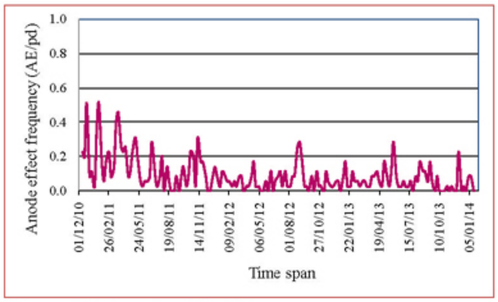

Figure 10. Anode effect frequency.

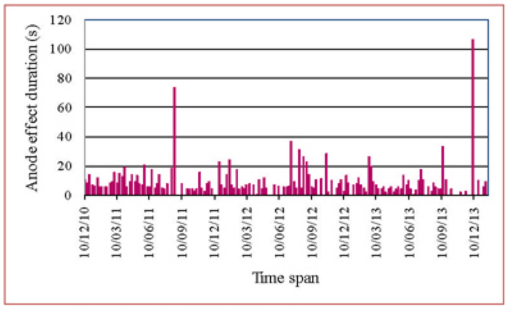

Figure 11. Anode effect duration.

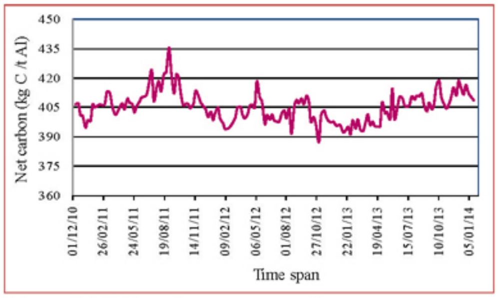

Figure 12. Net carbon consumption.

Figure 13. Gross carbon consumption.

Table I: DX+ Eagle cells-key performance indicators.

KPI	Units	1.12.2010 to 19.7.2011	20.7.2011 to 19.2.2011
Amperage	kA	419.561	429.768
Current efficiency	%	95.12	94.92
Metal production	kg/pot day	3215	3286
Cell voltage	V	4.35	4.32
DC specific energy consumption	kWh/kg Al	13.63	13.57
Gross carbon consumption	kg C/t Al	520	529
Net carbon consumption	kg C/t Al	407	409
Bath temperature	°C	960	958
Excess AlF_3	%	10.4	11.1
Fe	%	0.039	0.040
Si	%	0.027	0.029
AE frequency	AE/pot-day	0.190	0.091
AE duration	s	9.6	10.7
PFC Emission CO_2 Equivalent*	kg/t Al	33	18

Table I (continue): DX+ Eagle cells-key performance indicators.

KPI	Units	20.2.2012 to 28.4.2013	29.4.2013 to 12.1.2014
Amperage	kA	439.829	449.049
Current efficiency	%	94.95	94.92
Metal production	kg/pot day	3364	3433
Cell voltage	V	4.30	4.26
DC specific energy consumption	kWh/kg Al	13.48	13.38
Gross carbon consumption	kg C/t Al	509	526
Net carbon consumption	kg C/t Al	400	409
Bath temperature	°C	961	961
Excess AlF_3	%	11.4	11.4
Fe	%	0.041	0.048
Si	%	0.028	0.026
AE frequency	AE/pot-day	0.064	0.064
AE duration	s	9.0	14.5
PFC emission CO_2 Equivalent*	kg/t Al	10	17

*Calculated with the method described in [2].

Net and Gross Carbon Consumption [6]

DX+ cells had excellent anode carbon performance throughout the cell operation, and the net carbon consumption was between 400 - 409 kg C/t Al at various amperages ranging from 420 – 450 kA. Figure 12 shows net carbon consumption for the whole period. The lowest value of net carbon consumption of 396 kg C/t Al was achieved during five months of cell operation at 440 kA. The average net carbon consumption over the whole period of DX+ cell operation was 405 kg C/t Al. Gross carbon consumption for the whole period of cell operation is shown in Figure 13. It was between 509 – 529 kg C/t Al.

These excellent figures were the result of improvements in anode design and process optimisation, accompanied with continuous extensive measurements of spent anodes and anode properties. The measurements consisted of new anode weight, butt dimensions and butt weight. For the anode butts, measurement took place after cleaning off the material deposited on them. Butt measurements were done on 75 % of the total anodes used in the five DX+ demonstration cells. A displaced dual step (one on each side of the cell) anode setting pattern was found to be most beneficial for good anode cover, dressing, redressing and low carbon consumption.

Anode Effect Performance and PFC Emissions

DX+ cells showed excellent PFC emissions data throughout cell operation. Table I summarizes the anode effect performance and equivalent CO_2 from PFC emissions of the five DX+ Eagle cells from December 2010 to January 2014.

PFC emissions and CO_2 equivalent were calculated according to the Tier 2 method, which uses site specific anode effect data but industry average coefficients, using equations presented in [2]. Low voltage PFC emissions are not included in Table I [7].

Metal Purity

DX+ cells yielded excellent metal purity during the whole period of operation. Overall average metal purity was 99.93 %. Average iron and silicon content for the five DX+ cells evolved over the time as shown in Figures 8 and 9, respectively. An increase in iron content above 0.06 % four times (Figure 8) coincides with anode stub wash on one anode in one cell on those dates.

Altogether there were only four stub washes during the entire cell operation period. Iron content in the affected cell during stub wash increased to 0.1 – 0.4 %, bringing the average of five cells to a maximum of 0.072 - 0.117 % on those days. After each stub wash it took approximately 20 days before the iron concentration in the affected cell decreased to less than 0.06 %. Si content was also very low, 0.020 % to 0.036 %, principally coming from raw materials used. The small concentration of Si also shows that the cell side and end walls were well protected by freeze most of the time.

Experimental Evaluation

Experimental evaluation was done for all five DX+ demonstration cells. Measurements of cell thermal balance, electrical balance, magnetic field and cell stability were carried out at various stages of amperage increase. Analysed data from these measurements was extremely useful for mathematical model validation [8] and sensitivity analysis at higher amperage cell operation.

The following sets of measurements were undertaken for DX+ demonstration cells:

- Freeze profile on side and end walls.
- Cathode block erosion.
- Gas exhaust rate and anode cover thickness.
- Potshell temperature and deformation.
- Cathode, anode and external voltage drop.
- Collector bar current distribution.
- Anode current distribution and anode current pickup after anode change.

- Cell stability limit.
- Busbar temperature distribution and busbar current.
- Magnetic field.
- Metal velocities.

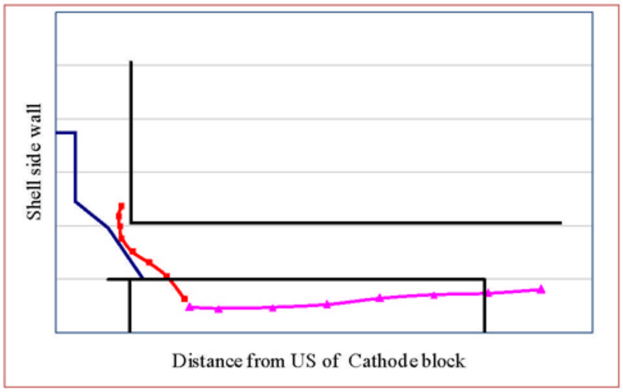

Figure 14. DX+ Eagle cell sidewall avg. freeze and cathode surface erosion profile at 450 kA.

Design validation data was used to fine tune the cell parameters and was very useful for maintaining stable and efficient cell operation. One of the key findings in almost each design validation campaign was excellent freeze coverage of the side and end walls (Figure 14), which was essential for cell lining protection from bath erosion. This also kept the potshell sidewall temperatures below a safe operating limit of lower than 500 °C [8].

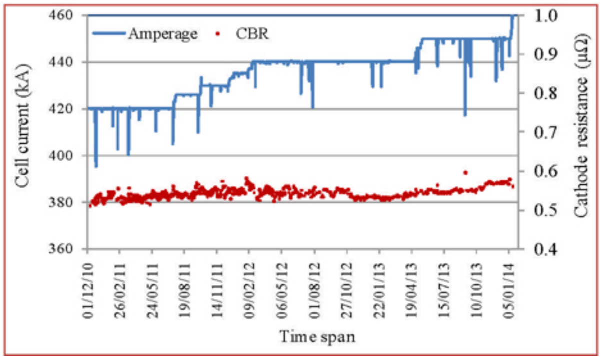

Figure 15. DX+ Eagle middle cell amperage and cathode block resistance (CBR) history.

Another important finding was excellent performance of the graphitized cathode blocks throughout the cell life. As an electrical current carrying system, all cathode blocks worked very well throughout the life of all five cells. Cathode block resistance variation over the whole period of cell operation was very small (Figure 15). Excellent performance of the cathode blocks also reaffirms very good cathode rodding practice at DUBAL.

Cell Autopsies

After the shutdown of the DX+ demonstration cells in January 2014, autopsies were carried out on all five cells for the purpose of examining the general state of the cell lining and predict the cell life from the cathode erosion rate. Full autopsies were conducted on two cells, whilst partial autopsies were conducted on the other three cells. Results are shown in Table II and Figures 16 – 18.

The following sets of measurements were undertaken for DX+ demonstration cells autopsies:

- Cathode surface topography and erosion profile.
- Cathode block core samples at deepest erosion.
- Cathode block and collector bar heaving.
- Side, end and bottom lining thicknesses.
- Sodium penetration on bottom and side lining.
- Potshell and deckplate horizontal and vertical distortion.

Table II: Cathode life expectancy for all five cells.

Cell	Cell cut-out age (days)	Max. erosion rate (mm/y)	Avg. current all life (kA)	Max. erosion rate at 450 kA (mm/y)	Remai-ning life at 450 kA (days)	Life expec-tancy (days)
273	1292	66.4	433.6	68.9	450	1742
274	1295	59.2	433.6	61.4	654	1949
275	1305	48.9	433.4	50.8	1041	2346
276	1281	59.8	433.9	62.1	647	1928
277	1261	66.0	434.3	68.4	491	1752
Ave		**60.1**	**433.8**	**62.3**	**657**	**1943**

Figure 16.Cathode block surface topography and side lining.

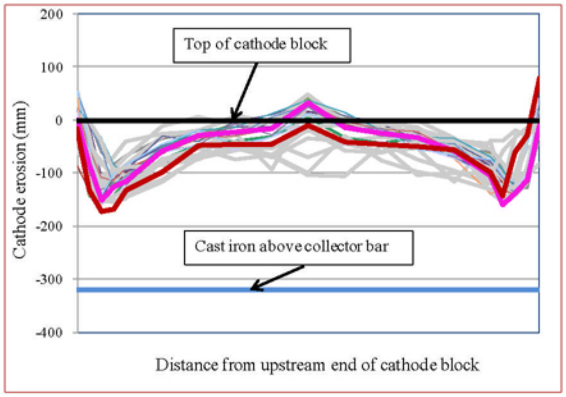

Figure 17. Erosion profiles of cathode block surfaces for DX+ Eagle middle cell (red and pink thicker lines represent two most eroded cathode blocks).

Figure 16 shows cathode surface and sidewall topography. In all five cells, the condition of the cathode surfaces was good and had W-shape erosion profile, typical for graphitized cathode blocks. Figure 17 shows the measured cathode surface profiles of the DX+ middle cell for all the blocks with respect to nominal cathode top surface. The erosion from block to block was relatively equal, except for one block at each end which had less erosion, undoubtedly due to prolonged freeze coverage on them.

There were no potholes in any of the five cells, but a few surface cracks were observed. Cell lining was in good condition all around the side and end walls in all five cells.

Figure 18. DX+ Sidewall SiC blocks and potshell.

SiC blocks were in excellent condition and had no bath erosion, but there was some sodium penetration which appeared darker in colour (Figure 18). Sidewall inserts were in good condition but had some bath erosion at the top. At the bottom, the reaction zone was limited to the bottom of the firebrick layers located below the cathode blocks. Low and high density vermiculite insulation was not reacted. All this confirms the fact that all five cells had good side and end wall freeze coverage throughout the cell operation as discussed in the experimental evaluation paragraph above.

The average cathode erosion rate for all five cells at an average lifetime amperage of 433.8 kA, was 60.1 mm/year. It was determined by the deepest cathode erosion and the minimum carbon left above the cast iron around collector bars. Cathode erosion for all five cells is presented in Table II. Based on average cathode erosion and amperage pro-rated to 450 kA for the rest of the cell life, the average life expectancy for the DX+ demonstration cells was estimated to be 1943 days.

The potshells in all five cells were also in excellent condition with practically no corrosion on the inside or outside around the collector bars and had small permanent deformation. Deckplates showed minimal corrosion and the sealing cement below was not damaged.

Conclusions

All five DX+ Eagle demonstration cells had excellent performance at all amperage levels from 420 – 450 kA. Cell control and cell operation practices were developed for large scale industrial implementation, now operating in EMAL Potline 3. The short test at 460 kA showed that DX+ cell technology has potential for amperage increase beyond 450 kA, which is expected to happen in EMAL Potline 3, designed for 460 kA. EMAL DX+ cells are the same as the prototype cells except for minor changes which reduce cathode and external voltage drop.

Current efficiency was excellent at approximately 95 % throughout the life. In spite of amperage increase, net specific energy was decreased from 13.63 kWh/kg Al at 420 kA to 13.35 kWh/kg Al at 450 kA. EMAL Potline 3 can have a 0.22 kWh/kg Al lower specific energy consumption than the DX+ demonstration cells because of larger busbar and cathode collector bar cross-sections.

Net carbon consumption was excellent from 400 – 409 kg C/t Al for different stages of amperage increase with an overall average of 405 kg C/t Al. Gross carbon consumption was 509 – 529 kg C/t Al.

All five DX+ demonstration cells had good freeze coverage throughout their life, which protected the side and end wall lining from bath erosion. Potshell temperatures throughout the cell operation were also within safe operating limits.

Based on cathode erosion, estimated average cell life for DX+ demonstration cells would be 1943 days, had they not been stopped on purpose.

Acknowledgement

Throughout the development, demonstration and industrial implementation of DX+ technology, there have been many people who are not mentioned in the author list, but who made valuable contributions to the success of these projects. Special thanks go to Prof. Barry Welch, Dr. Vinko Potocnik and Jeffrey Keniry for their continuous input and advice during the design and performance enhancement programme throughout this project.

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