LOW ENERGY CONSUMPTION CELL DESIGNS INVOLVING COPPER INSERTS AND AN INNOVATIVE BUSBAR NETWORK LAYOUT

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Abstract

Two innovations presented by the authors recently at ICSOBA conferences allow to very significantly reducing both the cathode and the busbar voltage drop [1,2].

This paper combines the usage of those two innovations with the usage on the new anode stub hole design presented at the Aluminiun of Siberia conference [3] to come up with a very low energy consumption cell design.

Introduction

The author has been involved in the modeling of aluminium reduction cells for the last 30 years. In 1988, he designed the cathode of the Alcan A310 prototype cell, the first cell to operate above 300 kA in 1989. The thermo-electric cathode slice model he developed was presented at the 1991 ANSYS conference [4]. The Figure 6 of that paper, reproduced in Figure 1 shows the model mesh highlighting the cell lining and potshell design.

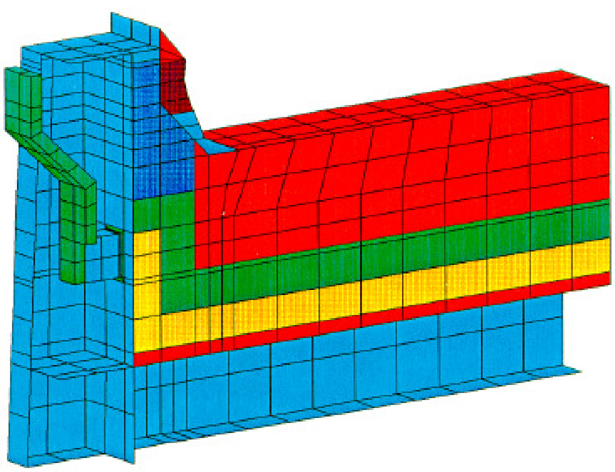

Figure 1: Alcan A310 cathode side slice model mesh

A few years later as an independent consultant, the author developed a similar demonstration model strongly inspired by the VAW CA300 cell design presented in JOM in 1994 [5]. The resulting thermo-electric cathode slice model that was first presented in Figure 12 of the 1997 CQRDA aluminium electrolysis course [6] is reproduced in Figure 2.

The A310 and the CA300 cells were designed at about the same time and operated at about the same amperage. Both designers clearly respected similar design guidelines for the choice of the type of cathode blocks and side blocks, the thickness of that side block, the size of the anode to side wall distance (ASD), the location of the anode shadow, etc.

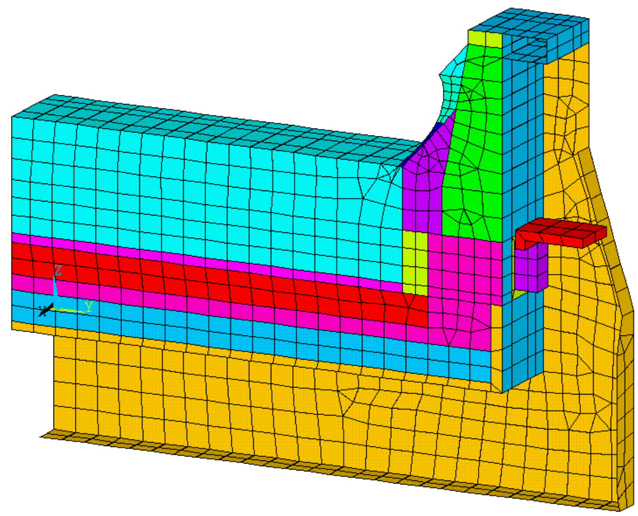

Figure 2: VAW CA300 inspired cathode side slice model mesh

That 300 kA demonstration model typical of the early 1990's state of the art in cell design became the starting point or base case for two styles of retrofit studies, the first one aiming at minimizing the cell energy consumption presented in [6] and the second one aiming at maximizing the cell productivity presented at the TMS 2000 conference [7]. Part of the Table II for a subsequent article presented in the magazine ALUMINIUM in 2005 [8] presenting the key design parameters and predicted operational results of those two cell retrofits is reproduced in Table I.

The key design changes that are allowing either the reduction of the cell energy consumption to 12 kWh/kg or the increase of the cell productivity by 17% are the change of the type of cathode material from 30% to 100% graphitic carbon block, the reduction of the anode to cathode distance (ACD) from 5 to 4 cm and a change of the bath chemistry (and alumina feed control logic) increasing the current efficiency. Other changes are required to obtain an appropriate ledge thickness at a very different level of heat dissipation. Per example, the known strategy to increase the cell productivity is to increase the anode length, decrease the ASD and use thin silicon carbide side walls. In addition, anode stud diameter and collector bar size can be increased while the anode cover thickness can be decreased.

The design strategy to decrease the cell energy consumption to 12 kWh/kg is the opposite, anode stud diameter and collector bar size can be decreased while the anode cover thickness can be increased. What is a lot more significant is that the cell productivity must be decreased by 12%, which explains why so far the industry have not move in that direction despite the fact that operation at that level of power efficiency have been reported as soon as the early 80's [9,10].

Table I: Design and predicted operational data, part of Table II in [8]

	Base case		
Amperage	300 kA	265 kA	350 kA
Nb. of anodes	32	32	32
Anode size	1.6 m X 0.8 m	1.6 m X 0.8 m	1.7 m X 0.8 m
Nb. of anode studs	3 per anode	3 per anode	3 per anode
Anode stud diameter	18 cm	16 cm	19 cm
Anode cover thickness	16 cm	17.5 cm	10 cm
Nb. of cathode blocks	18	18	18
Cathode block length	3.47 m	3.43 m	3.67 m
Type of cathode block	HC3	HC10	HC10
Collector bar size	20 cm X 10 cm	18 cm X 10 cm	20 cm X 10 cm
Type of side block	HC3	Anthracite	SiC
Side block thickness	15 cm +	15 cm +	10 cm +
ASD	35 cm	35 cm	30 cm
Calcium silicate thickness	3.5 cm	6.0 cm	3.5 cm
Inside potshell size	14.4 X 4.35 m	14.4 X 4.35 m	14.4 X 4.35 m
ACD	5 cm	4.15 cm	4 cm
Excess AlF_3	10.90%	13.50%	13.50%
Anode drop	303 mV	273 mV	323 mV
Cathode drop	285 mV	213mV	292 mV
Anode panel heat loss	240 kW	183 kW	284 kW
Cathode bottom heat loss	176 kW	132 kW	202 kW
Operating temperature	973.2 °C	956.1 °C	960.4 °C
Liquidus superheat	6.7 °C	2.4 °C	6.7 °C
Bath ledge thickness	8.66 cm	23.5 cm	9.09 cm
Metal ledge thickness	4.12 cm	9.01 cm	4.42 cm
Current efficiency	94.00%	95.70%	96.10%
Internal heat	628 kW	422 kW	713 kW
Energy consumption	13.72 kWh/kg	11.93 kWh/kg	13.43 kWh/kg

Clearly, a cell designer cannot at the same time aim at maximizing the cell productivity and minimizing the cell energy consumption. This is why Rio Tinto per example has developed and is offering both the AP60 and the APXe cells based on the same basic platform [11].

Yet, new choice of materials and new and innovative design ideas can always be put to contribution in order to further increase the cell productivity or decrease the cell energy consumption. Another tendency is to continue to increase the cell size in order to keep reducing both the cell OPEX and CAPEX. It is in that context that the AP60 platform replaced the AP30 platform that itself replaced the AP18 platform [12] per example.

For one, the author have been advocating that, despite the difficulties that have always been limiting the rate of increase of the cells size since the beginning of the industry, he could foresee no technical limitation that could limit further increase of cell size in the future. It is in that context that the author presented a 500 kA cell design in 2003 in [13] and a 740 kA cell design in 2005 in [8].

In yet another cell retrofit demonstration study paper in 2011 [14] the author took advantage of new design innovations like collector bar copper inserts, anode slots and a new type of anode stub hole design [3] to retrofit the 500 kA cell presented in [13] into a more productive 600 kA cell operating at about the same power efficiency. As an intermediary step not quite optimized in term of thermal conditions, a 500 kA cell operating at 12.1 kWh/kg was also developed. Table II presents detailed data of that study.

Table II: Design and predicted operational data, original work presented in [14]

	Base case		
Amperage	500 kA	500 kA	600 kA
Nb. of anodes	40	48	48
Anode size	1.95 m X 0.8 m	1.95m X .665m	2.0m X .665m
Nb. of anode studs	3 per anode	4 per anode	4 per anode
Anode stud diameter	20.5 cm	17.5 cm	17.5 cm
Anode cover thickness	10 cm	10 cm	10 cm
Nb. of cathode blocks	24	24	24
Cathode block length	4.17 m	4.17 m	4.17 m
Type of cathode block	HC10	HC10	HC10
Collector bar size	20 cm X 10 cm	20 cm X 10 cm	20 cm X 10 cm
Type of side block	SiC	SiC	SiC
Side block thickness	10 cm +	10 cm +	7 cm +
ASD	30 cm	30 cm	28 cm
Calcium silicate thickness	3.5 cm	3.5 cm	3.5 cm
Inside potshell size	17.8 X 4.85 m	17.8 X 4.85 m	17.8 X 4.85 m
ACD	4 cm	3.5 cm	3.5 cm
Excess AlF_3	13.50%	12.00%	12.00%
Anode drop	354 mV	265 mV	318 mV
Cathode drop	314 mV	87 mV	104 mV
Anode panel heat loss	409 kW	420 kW	449 kW
Cathode bottom heat loss	273 kW	238 kW	240 kW
Operating temperature	963.1 °C	955.6 °C	964.8 °C
Liquidus superheat	9.4 °C	2.6 °C	11.8 °C
Bath ledge thickness	6.15 cm	29 cm	4.76 cm
Metal ledge thickness	2.42 cm	26 cm	1.07 cm
Current efficiency	95.90%	96.50%	96.40%
Internal heat	1043 kW	760 kW	1140 kW
Energy consumption	13.61 kWh/kg	12.1 kWh/kg	13.26 kWh/kg

New retrofit study aiming at minimizing cell energy consumption even further

In the past 30 years, the market conditions of high metal value and the existence of regions of the world offering inexpensive electrical power were favorable for new cell designs maximizing cell productivity while maintaining power efficiency in the 13-13.5 kWh/kg range.

The market conditions have evolved recently to a much lower metal value and far less availability of inexpensive electrical power. In that context, the metal production cost is getting quite close to the metal market value and a reduction of the energy consumption can make the difference between operating at profit or at loss.

Technically, 12-12.5 kWh/kg have been achieved multiple times and as for operation at 13-13.5 kWh/kg range, under the current market conditions it might well become the preferable operational range. The next question is technically, regardless of market conditions, how much lower can we manage to go?

Reducing the cell energy consumption means reducing the cell voltage drop which in turn means reducing the cell ohmic resistance. This statement assumed that at 95-96% current efficiency, we cannot expect significant gain to come from that factor. Leaving aside the bath ohmic resistance for now, this leaves three distinct ohmic resistances to work with: the anode, cathode and busbar resistances.

Cathode design with copper collector bars

As presented in Table II, the intermediary cell operating at 500 kA presented in [14] was operating at 87 mV at cathode drop by using the copper collector bars design presented in Figure 3.

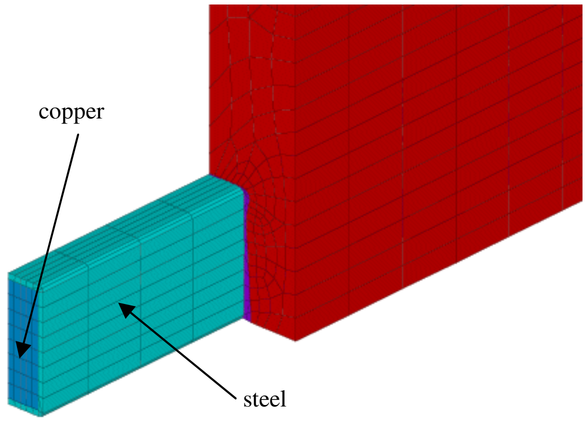

Figure 3: Copper collector bar design originally proposed in [14]

At the time, it was speculative that such a collector bar design could be actually build, but it is no longer the case today after Storvik AS presentation at the ISCOBA 2015 conference [15]. Furthermore, at the TMS 2016 conference KAN-NAK advocated that copper collector bars don't even need to be protected by a shell of steel [16].

As first presented in [2], what the author did not realized in 2011 is that with the usage of copper collector bars, 100% of the cell current can be extracted on the downstream side without generating excessive horizontal current in the metal pad or producing excessive cathode voltage drop.

The results presented in [14] and in [2] are for a 20 cm x 10 cm copper collector bar size. When the current is extracted all on the downstream side of that cell running at 500 kA, the current density in the bar doubles, and the cathode voltage drop increases from 87 mV to 174 mV as presented in [2].

New results for a bigger 25 cm x 16 cm copper collector bar are presented here. As can be seen in Figure 4, the cathode voltage drop is reduced back to 130 mV.

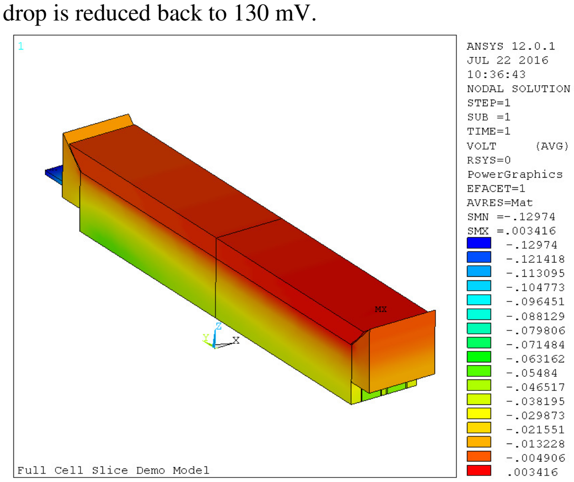

Figure 4: Cathode voltage drop

Figure 5 presents the horizontal currents in the metal pad. They have been reduced as compared to those presented in Figure 2 of [2]. Unfortunately, the center channel creates a gap that prevents the total elimination of a horizontal component in the metal pad current regardless of the size of the copper collector bars used.

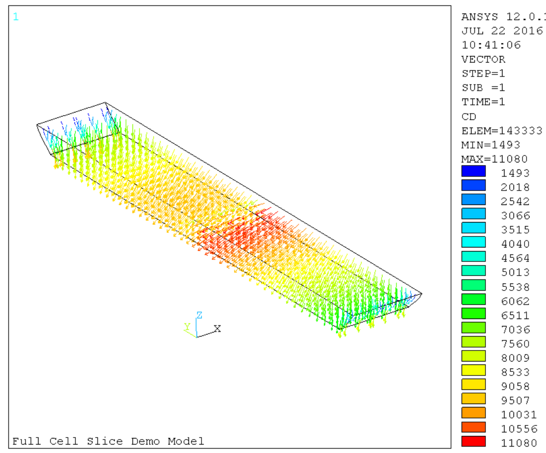

Figure 5: Metal pad current density

External compensation current (ECC) busbar network design

As presented in [2], the idea of taking advantage of copper collector bars to extract 100% of the cell current on its downstream side came to the author as a way to reduce of busbar weight of its own reversed compensation current (RCC) busbar configuration.

It happens that the same idea is easily applicable to existing ECC busbar configurations. In that case, the busbar network is reduced to only the anode risers so it is the preferable busbar configuration if the main goal is to minimize the busbar voltage drop in order to minimize the cell energy consumption.

Figure 6 presents the busbar network and the calculated busbar drop of 134 mV. The busbar current density is quite low but this is consistent with a business scenario where the metal cost is low and the energy cost is high. Figure 7 is presenting the vertical component of the magnetic field (B_z) obtained while using this busbar configuration (see [2] for more results).

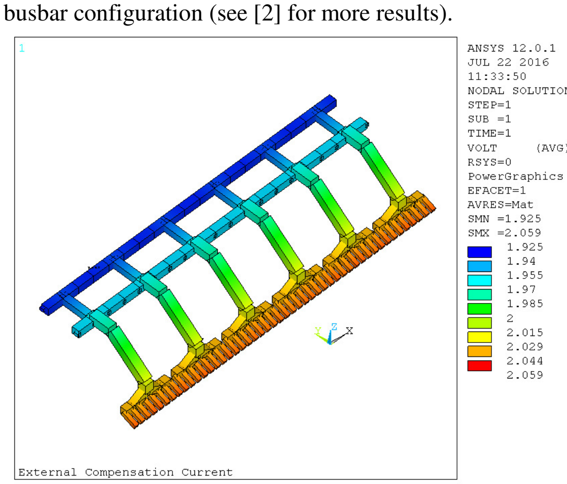

Figure 6: Busbar drop of the ECC busbar network concept with 100% downstream side current exit

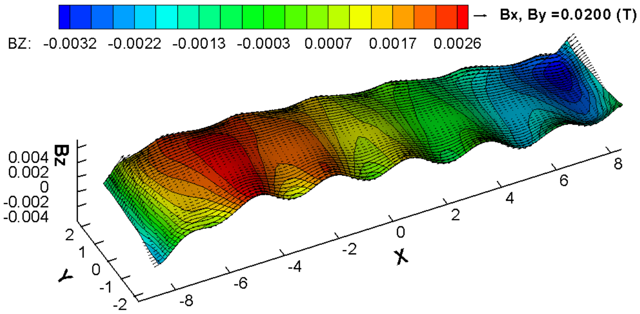

Figure 7: Vertical component of the magnetic field (B_z), Figure 10 in [2]

Anode design with innovative stub hole conception

As presented in [14] and in Table II, when operating the cell at 500 kA using 48 anodes of 1.95 m x 0.665 m, the predicted voltage drop is 265 mV. This already very low anode drop is in great part due to the usage of an innovative stub hole conception. That innovative conception was tested in a thermo-electro-mechanical (TEM) model presented in [17]. Figure 4 of [14] is showing the voltage drop prediction from that TEM model but not the new stub hole design investigated.

That design has been presented for the first time in [3]. Figure 8 is presenting the original ANSYS voltage drop figure of the TEM model testing that new stub hole design concept.

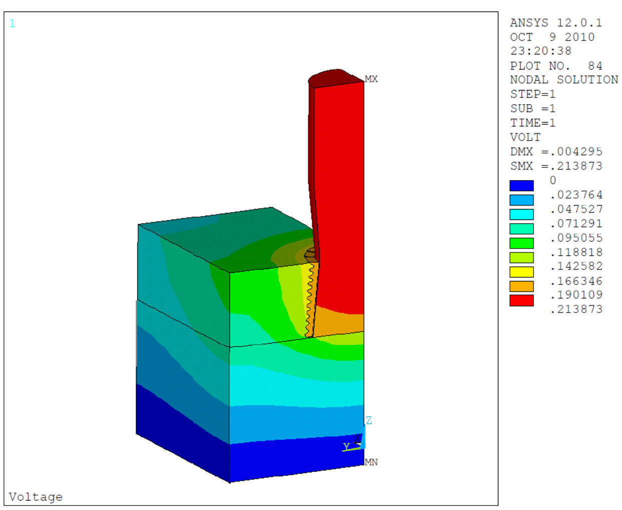

Figure 8: Anode voltage drop from the TEM model

As discussed in [3], the aim of the new design is to get a good contact pressure between the stub bottom horizontal face and the anode stub hole bottom horizontal face. This is achieved by locking the stub vertical thermal expansion. As presented in [3], there is more that one way to achieve this, the final optimized shape presented in [3] is less costly to implement, but was developed after [14] was written.

From that starting point, the author tried to further reduce that anode voltage drop for this study. The option to add copper insert like the one presented in [15] was investigated but the gains were disappointing. It turned out that the best way to achieve more mV saving was to improved the anode aspect ratio.

Figure 9 is presenting the current anode aspect ratio, each stub is feeding a rectangular carbon section of 0.4875 m x 0.665 m, and ideally, each stub should be feeding a square section of carbon. This is important since with 4 fairly big stubs and the new stub hole design, the biggest resistance is now in the carbon section of the anode.

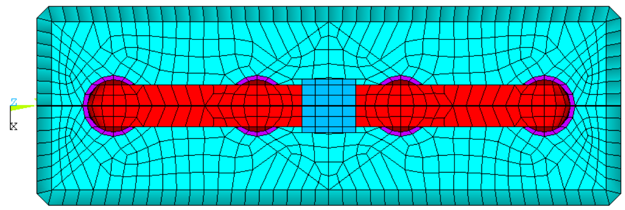

Figure 9: One of the 48 1.95 m x 0.665 m anode

For that reason, the 48 1.95 m x 0.665 m anodes have been replaced with 64 1.95 m x 0.5 m anodes keeping the exact same stub diameter and stub hole design in order to avoid to go back running the TEM model. Figure 10 presents the new anode aspect ratio.

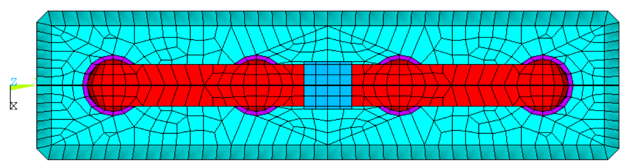

Figure 10: One of the 64 1.95 m x 0.5 m anode

With a parametric model at your disposal, the half anode model can be modified in no time. The same is true for the full anode panel model. Figure 11 is presenting the initial 48 anodes panel layout while Figure 12 is presenting the new 64 anodes panel layout.

The resulting anode voltage drop is presented in Figure 13, simply by changing the anode aspect ratio and by increasing the number of anodes from 48 to 64, the anode voltage drop has been reduced from 265 mV to 224 mV.

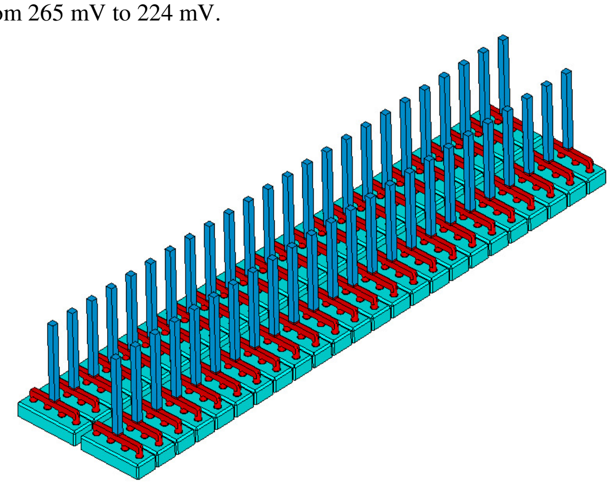

Figure 11: 48 anodes panel layout

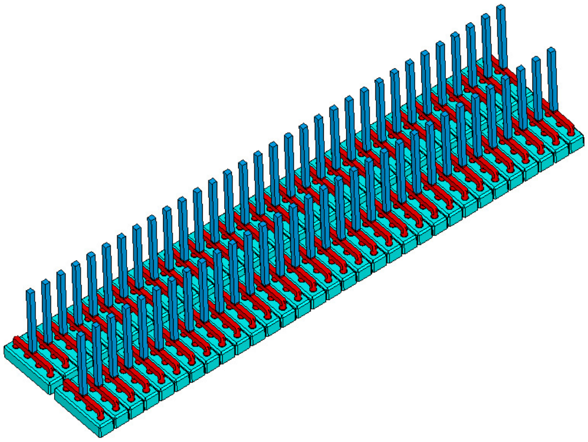

Figure 12: 64 anodes panel layout

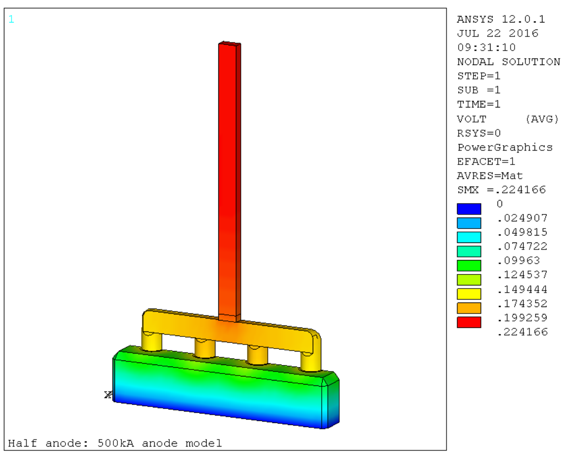

Figure 13: Anode voltage drop from the TE model

Calculation of the resulting cell energy consumption

Several modeling tools could be used to calculate the cell energy consumption from the above results. In [14] the author used Dyna/Marc [18] which also predicts the cell superheat and corresponding ledge thickness.

So far no effort has been made to adjust the cell lining design to the new cell operating conditions so a simple cell voltage break down tool like Peter Entner's CellVolt [19] was used instead. Table III presents the results obtained for the operation at 500 kA corresponding to running at 0.8 A/cm^2 of anode current density.

As in [2], the calculation was done using 3.2 cm of ACD instead of 3.5 cm used in [14] as since 2011, indications are that ACD have been reduced further more in low energy consumption cell prototypes. At 3.2 cm ACD, the predicted cell energy consumption is calculated to be 11.2 kWh/kg.

More significantly, the cell internal heat is calculated to be only 699 kW while the cell lining was designed to comfortably dissipate 1140 kW with 20 cm x 10 cm size collector bars and 192 anode stubs. Clearly a very serious cell lining redesign work needs to be performed as the next step. New insulating materials like the ceramic fire board extensively used in [20] will certainly need to be added to the list of lining materials.

Table III: Design and predicted cell energy consumption

	Base case		
Amperage	500 kA	500 kA	400 kA
Nb. of anodes	48	64	64
Anode size	1.95m X .665m	1.95m X .5m	1.95m X .5m
Nb. of anode studs	4 per anode	4 per anode	4 per anode
Anode stud diameter	17.5 cm	17.5 cm	17.5 cm
Anode cover thickness	10 cm	10 cm	10 cm
Nb. of cathode blocks	24	24	24
Cathode block length	4.17 m	4.17 m	4.17 m
Type of cathode block	HC10	HC10	HC10
Collector bar size	20 cm X 10 cm	25 cm X 16 cm	25 cm X 16 cm
Type of side block	SiC	SiC	SiC
Side block thickness	10 cm +	10 cm +	10 cm +
ASD	30 cm	30 cm	30 cm
Calcium silicate thickness	3.5 cm	3.5 cm	3.5 cm
Inside potshell size	17.8 X 4.85 m	17.8 X 4.85 m	17.8 X 4.85 m
ACD	3.5 cm	3.2 cm	3.2 cm
Excess AlF_3	12.00%	12.00%	12.00%
Anode drop	265 mV	224 mV	179 mV
Cathode drop	87 mV	130 mV	104 mV
Busbar drop	310 mV	134 mV	107 mV
Cell voltage	3.89 V	3.59 V	3.20 V
Current efficiency	95.90%	95.90%	95.90%
Internal heat	758 kW	699 kW	414 kW
Energy consumption	12.1 kWh/kg	11.2 kWh/kg	9.95 kWh/kg

In order to make the new cell lining design work even more challenging and the cell energy savings even more impressive, Table III also reports results for an operation at 400 kA corresponding to running at only 0.64 A/cm^2 of anode current density. At that current density and still at 3.2 ACD, the cell is expected to produce metal using only 9.95 kWh/kg.

The corresponding cell internal heat is calculated to be reduced to 414 kW which is only 36% of the 1140 kW dissipated by the same cell "platform" running at 600 kA and 13.26 kWh/kg.

Conclusions

Two innovations presented by the authors recently at ICSOBA conferences allow to very significantly reducing both the cathode and the busbar voltage drop:

- cathode design with copper collector bars extracting 100% of the cell current on its downstream side
- the usage of modified external compensation current (ECC) busbar configuration made only of anode risers;

are combined with a third innovation presented at the Aluminiun of Siberia conference:

- the usage of a new anode stub hole design.

As a result, a cell operating at 500 kA, 0.8 A/cm^2 of anode current density and 3.2 cm ACD is predicted to have an energy consumption of about 11.2 kWh/kg.

The same cell platform operating at 400 kA, 0.64 A/cm^2 of anode current density and 3.2 cm ACD is predicted to have an energy consumption of about 9.95 kWh/kg.

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