# First attempt to break the 10 kWh/kg aluminium barrier using a wide cell design

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**In his last year ALUMINIUM article [1], the author selected breaking the 11 kWh/kg cell energy consumption barrier as short-term design goal, as a step toward ultimately breaking the 10 kWh/kg cell energy consumption barrier. In the study presented in that article last year, the lowest value of 10.85 kWh/kg Al was obtained using the 100% downstream side current extraction cell design. In his upcoming TMS 2019 paper [2], the author continues working exclusively on that 100% downstream side current extraction cell design, and this time he reached 10.44 kWh/kg Al. In the present study, the author this time shifted to working exclusively on the wide cell design, as presented in an ALUMINIUM article two years ago [3], in this first attempt to break the 10 kWh/kg cell energy consumption barrier.**

The modeling and design work presented in this article is part of a continuing effort to design a cell operating at the lowest possible cell energy consumption. The initial results were first reported in a TMS 2017 paper [4] and were then reported in [1], [5] and soon in [2].

As discussed in the section *Comparison of the two very low energy consumption cell design options* in [5], at the same ACD and anode current density, the 100% downstream side current extraction cell will operate at a lower cell voltage than the wide cell. That could be considered as an advantage to produce the lowest possible cell energy consumption cell design.

Yet, as first reported in [3], the wide cell reduced the heat loss per unit production. So at a given cell ACD, anodic current density and corresponding cell internal heat per unit production, the wide cell design will systematically produce a cell operating at the highest cell superheat for the same lining design.

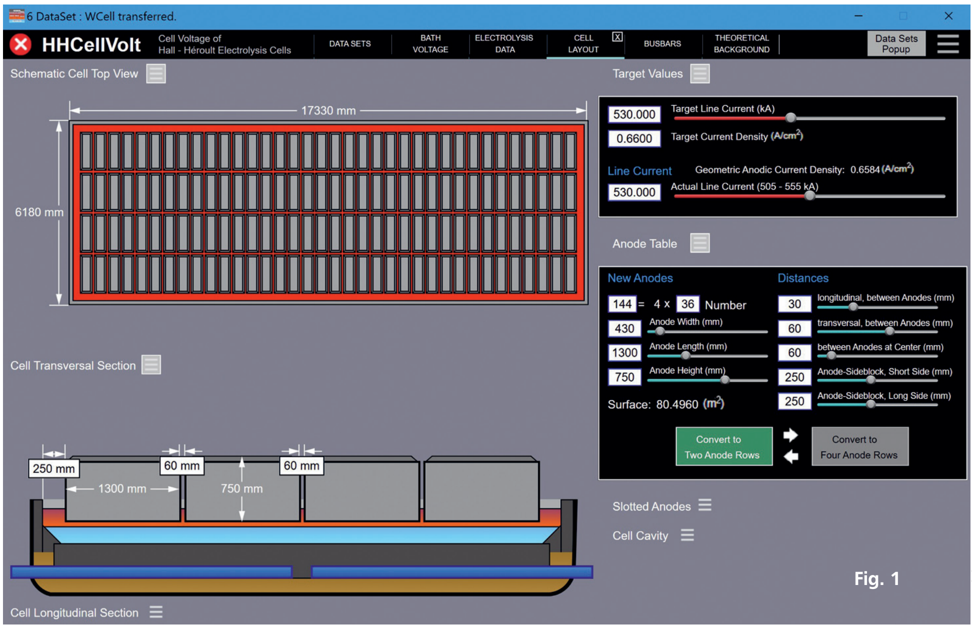
Technically, there is nothing preventing the reduction of the anode current density that would correspond on a cell operating at 10 kWh/kg. Using the 100% downstream side current extraction cell presented in [4], that anode current density was calculated to be about 0.64 A/cm$^2$.

On the other hand, there is definitively a limit on the lowest possible cell superheat a cell can be operated at. Not surprisingly, it turned out that this cell operation parameter is one of the key parameters limiting the reduction of the cell energy consumption. In that context, the wide cell is the better of the two cell design options to attempt to break the 10 kWh/kg cell energy consumption barrier.

## Modelling and design methodology

Since the very beginning of this effort to design a cell operating at the lowest possible energy consumption, and even before that, the author relied on four different modelling tools: HHCellvolt, Dyna/Marc, MHD-Valdis and 3D ANSYS based thermo-electric anode and cathode models to perform his studies.

HHCellVolt developed and commercialized by Peter Entner [6] is the best modelling tool available to very quickly produce a cell layout, such as the one presented in Fig. 1 for the current wide cell design. HHCellVolt is also the perfect tool to calculate directly from enthalpy data how much more energy is



530.000 Target Line Current (kA)
0.6600 Target Current Density (A/cm$^2$)
Geometric Anodic Current Density: 0.6584 (A/cm$^2$)
530.000 Actual Line Current (505 - 555 kA)

144 = 4 x 36 Number
430 Anode Width (mm)
1300 Anode Length (mm)
750 Anode Height (mm)
Surface: 80.4960 (m$^2$)

30 longitudinal, between Anodes (mm)
60 transversal, between Anodes (mm)
60 between Anodes at Center (mm)
250 Anode-Sideblock, Short Side (mm)
250 Anode-Sideblock, Long Side (mm)

Fig. 1

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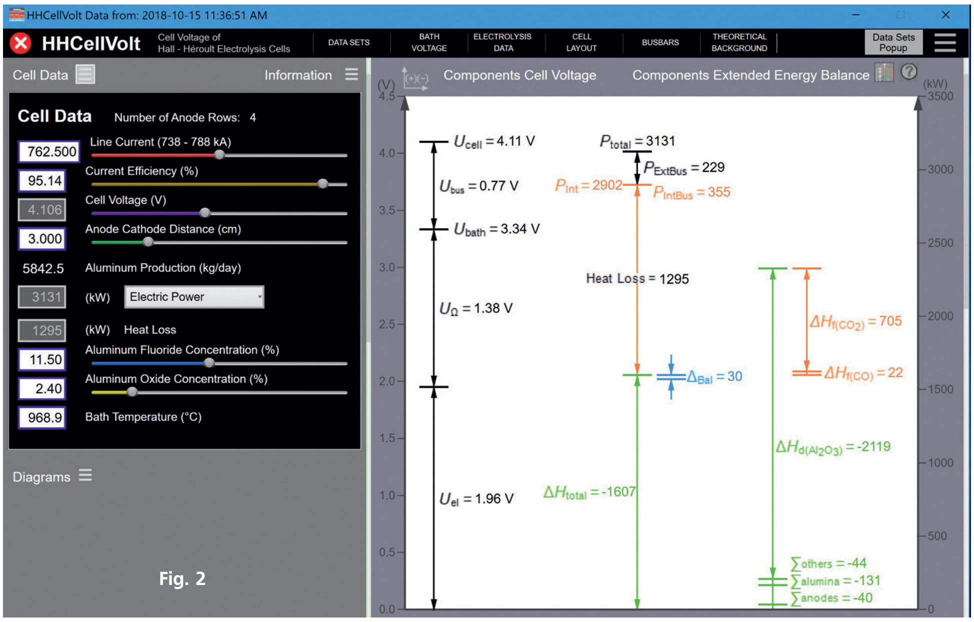

HHCellVolt Data from: 2018-10-15 11:36:51 AM

Cell Data Number of Anode Rows: 4
762.500 Line Current (738 - 788 kA)
95.14 Current Efficiency (%)
4.106 Cell Voltage (V)
3.000 Anode Cathode Distance (cm)
5842.5 Aluminum Production (kg/day)
3131 (kW) Electric Power
1295 (kW) Heat Loss
11.50 Aluminum Fluoride Concentration (%)
2.40 Aluminum Oxide Concentration (%)
968.9 Bath Temperature (°C)

Fig. 2

required to operate the cell compared with the minimum energy required to produce the metal. That subject was recently covered in [7], and will be discussed again in [2]. HHCellVolt is also the most up-to-date tool to compute the cell voltage, based on inputs for the anode, cathode and busbar ohmic resistances, and on the choice of ACD, bath chemistry, bubble model and cell amperage. HHCellVolt finally computes the cell internal heat, based on the calculated cell voltage and energy requirement to operate the cell. It reports this numerically and graphically, generating a Haupin Diagram such as the one presented in Fig. 2 for the initial wide cell design operating at 762.5 kA [3].

The next tool required is the steady state part of the Dyna/Marc cell simulator, developed and commercialized by the author [8]. Dyna/Marc is for solving the cell heat balance. It is based on additional inputs including: the anode panel heat loss, the cathode bottom heat loss, the bath and metal level, some lining material thickness and thermal conductivity. From these, Dyna/Marc will calculate the cell superheat as well as the bath and the metal ledge thickness.

3D ANSYS-based thermo-electric anode and cathode models developed and commercialized by the author [9] are used to compute the anode and cathode voltage drop and the anode and cathode heat losses. The 3D ANSYS-based thermo-electric cathode model also calculates more accurately than the Dyna/Marc the cell ledge profile using the user-defined cell superheat.

Finally, MHD-Valdis, the MHD cell stability solver (developed by Valdis Bojarevics from Greenwich University and commercially available through the author) is used to design the cell busbar and to analyze the corresponding cell stability. MHD-Valdis will directly compute the busbar voltage drop, but the busbar network generated by MHD-Valdis can also be converted into an ANSYS model to compute the busbar voltage drop.

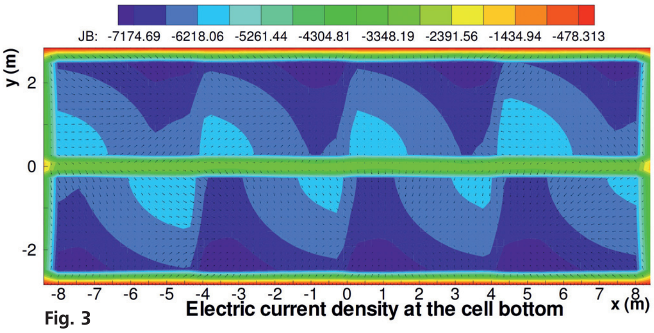

Fig. 3

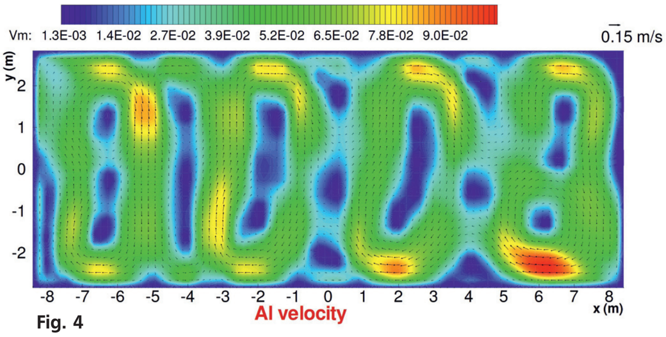

Fig. 4

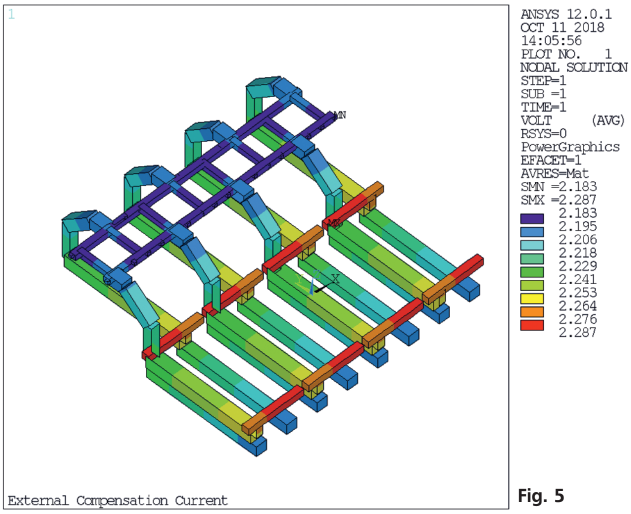

Fig. 5

### Reducing the metal pad thickness from 20 to 10 cm

It is quite well known that reducing the metal pad thickness is a very efficient way to reduce the cell heat loss at a constant cell superheat. Because the initial wide cell design was operating at a quite high anode current density, a typical value of 20 cm was selected for the metal pad thickness. All the 3D ANSYS-based thermo-electric runs and MHD-Valdis cell stability runs up to now were done using that metal pad thickness value.

It is also well known that reducing the metal pad thickness reduces the cell stability because it increases the metal pad horizontal current. Yet, since there is a need to reduce that cathode side wall heat loss without further reducing the cell superheat, we decided to investigate the effect of reducing the metal pad thickness from 20 to 10 cm. By using huge copper collector bars there is essentially no horizontal current in the metal pad, and so there is a minimum risk of destabilizing the cell by reducing the metal pad thickness, but this of course must be confirmed by an MHD-Valdis cell stability analysis.

### MHD-Valdis cell stability analysis at 570 kA and 10 cm ofmetal pad thickness

At 762.5 kA, the amperage selected for the initial wide cell design two years ago, the anode current density is 0.93 A/cm$^2$. At 650 kA, the amperage selected last year, the anode current density is 0.81 A/cm$^2$ and the cell energy consumption is at 11.0 kWh/kg Al. It is clear that further decreasing the cell energy consumption requires further decreasing the cell amperage. To run the MHD-Valdis cell stability with 10 cm of metal pad thickness, we selected a cell amperage of 570 kA which corresponds to an anode current density of 0.71 A/cm$^2$.

The resulting metal pad horizontal currents are presented in Fig. 3, and the corresponding metal pad flow field in Fig. 4. The busbar drop is calculated to be 112 mV.

### 3D ANSYS-based thermo-electric results at 570 kA

On the anode side, the only change to the design was a refinement that limits the anode stubs heat loss. This feature will be revealed in the author’s TMS 2019 paper [2] but not in this article. Using that anode design at 570 kA, together with the new boundary of the cell described in [2], the model predicts an internal anode drop of 207 mV and an external anode drop of 78 mV. The heat loss of the internal part of the anode is predicted to be 221 kW.

On the cathode side, three changes were made: the metal pad thickness was decreased to 10 cm; the ramming slope was decreased accordingly; and the design feature that is limiting the collector bars heat loss was also refined. Using that cathode design at 570 kA, and with the new boundary of the cell, the model predicts an internal cathode drop of 97 mV and an external cathode drop of 49 mV. The heat loss of the internal part of the cathode, at 7 °C of cell superheat, is predicted to be 417 kW.

### Dyna/Marc global analysis of the wide cell design at 570 kA

Using many of the above results as inputs, Dyna/Marc is used to calculate the steady-state cell conditions at 570 kA and 2.8 cm ACD. Table I presents the Dyna/Marc results summary. This predicts the cell voltage to be 3.36 V, the cell internal heat (using Haupin's equation to calculate the equivalent voltage to make the metal) is 613 kW at the calculated current efficiency of 94.4%, and the cell superheat is predicted to be 7.5 °C. Finally, the cell power consumption is calculated to be 10.61 kWh/kg, still quite far from 10 kWh/kg!

### MHD-Valdis cell stability analysis at 530 kA and 10 cm ofmetal pad thickness

The good news is that, when compared with the solution at 650 kA presented in [1], the reduction of the metal pad thickness decreased the cell internal heat from 804 to 613 kW, while maintaining about the same cell superheat around 7.5 °C. Assuming that it is possible to operate the cell at 5.0 °C of cell superheat, the next step is to simply reduce the cell amperage until we reach that value of cell superheat. That cell amperage turned out to be about 530 kA, which corresponds to 0.66 A/cm$^2$ of anode current density. Fig. 5 shows that the busbar drop at 530 kA is calculated to be 104 mV. There is no need to report the rest of the MHD-Valdis cell stability results, as an operation at 530 kA would be more stable that an operation at 570 kA, unless the ledge toe growth gets problematic, which is not the case.

### 3D ANSYS-based thermo-electric results at 530 kA

Using exactly the same anode design at 530 kA, the internal anode drop is predicted to be 191 mV and the external anode drop, which includes the studs outside the crust, the yoke and the rod is predicted to be 72 mV. The internal anode heat loss is 218 kW, which includes only the heat loss of the crust surface by convection and radiation, and the heat loss of the studs by conduction where they exit the crust.

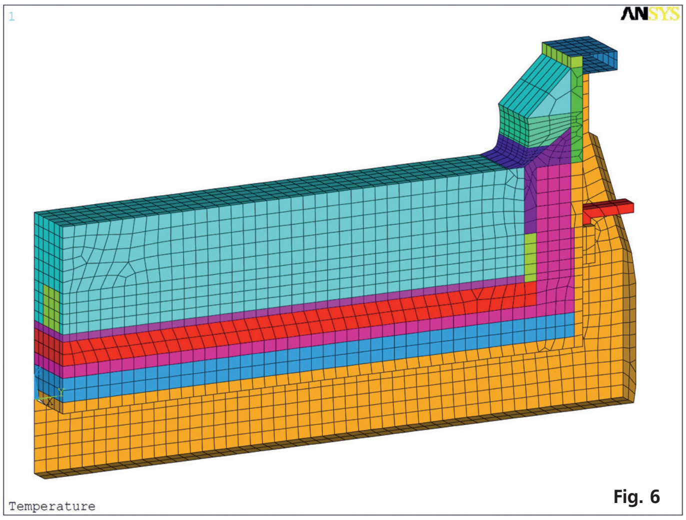

Fig. 6

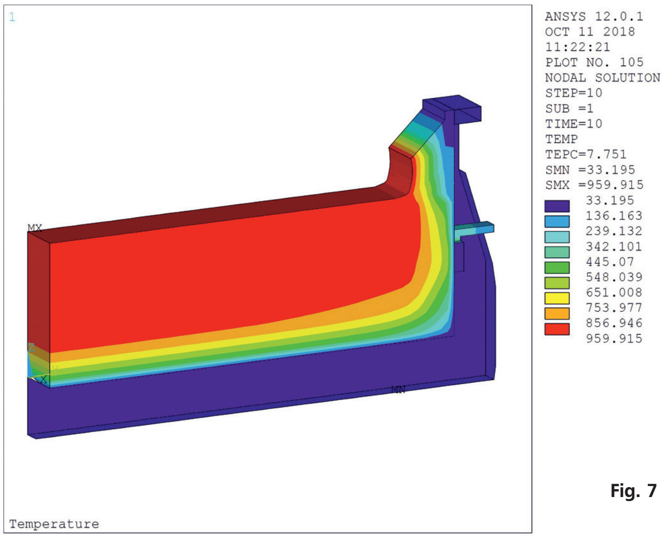

Fig. 7

Table 1

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Steady State Solution
________________________________________________________________
Cell amperage                              570.0 [kA]
Anode to cathode distance                2.80000 [cm]
Operating temperature                    964.064 [C]
Ledge thickness, bath level              8.90003 [cm]
Ledge thickness, metal level             3.19020 [cm]

Bath chemistry:
  Cryolite ratio                          2.20470 [mole/mole]
  Bath ratio                              1.10235 [kg/kg]
  Conc. of excess aluminum fluoride      11.50000 [%]
  Conc. of dissolved alumina              2.80000 [%]
  Conc. of calcium fluoride               6.00000 [%]

Heat balance:
  Superheat                               7.5402 [C]
  Cell energy consumption                10.6072 [kWhr/kg]
  Total heat loss                         612.992 [kW]

Electrical characteristics:
  Current efficiency                      94.3733 [%]
  Anode current density                  0.708110 [A/cm*cm]
  Bath resistivity                       0.454942 [ohm-cm]
  Cell pseudo-resistance                  2.99735 [micro-ohm]
  Bath voltage                            0.94007 [V]
  Electrolysis voltage                    1.87543 [V]
  Cell voltage                            3.35849 [V]
  Voltage to make the metal               2.03522 [V]
```

Table 2

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Steady State Solution
________________________________________________________________
Cell amperage                              530.0 [kA]
Anode to cathode distance                2.80000 [cm]
Operating temperature                    961.560 [C]
Ledge thickness, bath level             15.79983 [cm]
Ledge thickness, metal level             9.99283 [cm]

Bath chemistry:
  Cryolite ratio                          2.20470 [mole/mole]
  Bath ratio                              1.10235 [kg/kg]
  Conc. of excess aluminum fluoride      11.50000 [%]
  Conc. of dissolved alumina              2.80000 [%]
  Conc. of calcium fluoride               6.00000 [%]

Heat balance:
  Superheat                               5.0367 [C]
  Cell energy consumption                10.2313 [kWhr/kg]
  Total heat loss                         516.203 [kW]

Electrical characteristics:
  Current efficiency                      94.3031 [%]
  Anode current density                  0.658418 [A/cm*cm]
  Bath resistivity                       0.456250 [ohm-cm]
  Cell pseudo-resistance                  2.99443 [micro-ohm]
  Bath voltage                            0.87661 [V]
  Electrolysis voltage                    1.85844 [V]
  Cell voltage                            3.23705 [V]
  Voltage to make the metal               2.03346 [V]
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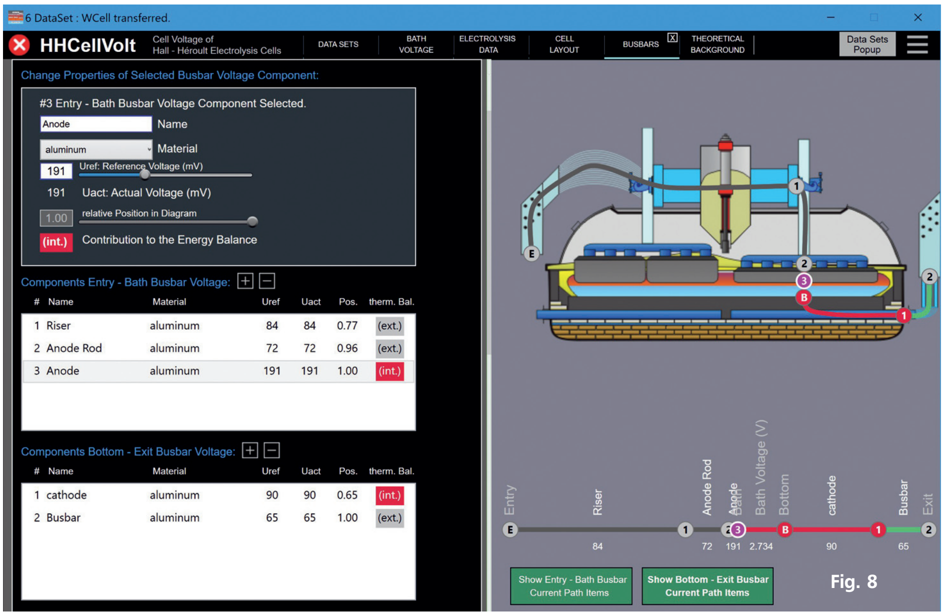


Change Properties of Selected Busbar Voltage Component:

#3 Entry - Bath Busbar Voltage Component Selected.

Name: Anode

Material: aluminum

Uref: Reference Voltage (mV): 191

Uact: Actual Voltage (mV): 191

relative Position in Diagram: 1.00

Contribution to the Energy Balance: (int.)

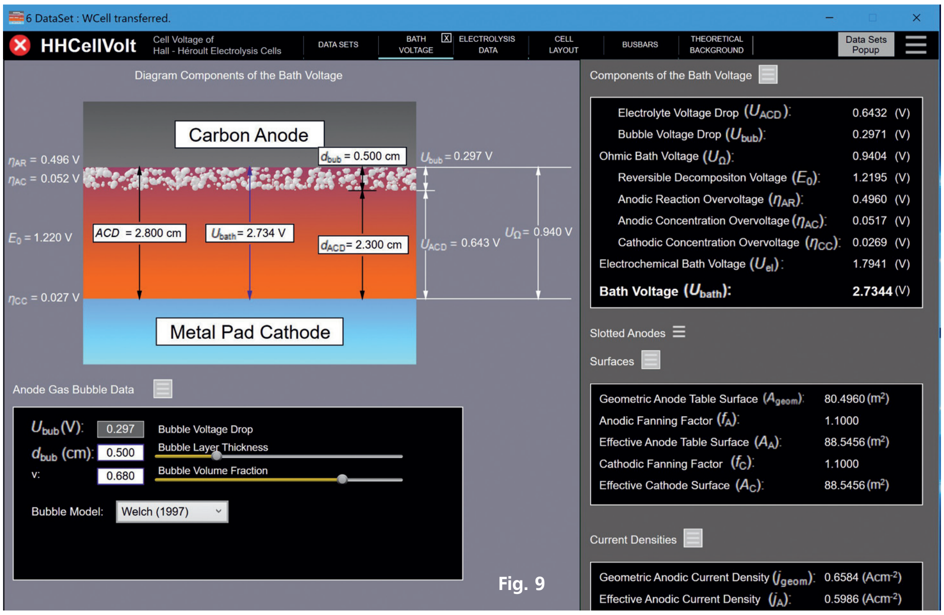
Components Entry - Bath Busbar Voltage:

| # | Name | Material | Uref | Uact | Pos. | therm. Bal. |
|---|---|---|---|---|---|---|
| 1 | Riser | aluminum | 84 | 84 | 0.77 | (ext.) |
| 2 | Anode Rod | aluminum | 72 | 72 | 0.96 | (ext.) |
| 3 | Anode | aluminum | 191 | 191 | 1.00 | (int.) |

Components Bottom - Exit Busbar Voltage:

| # | Name | Material | Uref | Uact | Pos. | therm. Bal. |
|---|---|---|---|---|---|---|
| 1 | cathode | aluminum | 90 | 90 | 0.65 | (int.) |
| 2 | Busbar | aluminum | 65 | 65 | 1.00 | (ext.) |

Fig. 8



Anode Gas Bubble Data

$U_{bub}$ (V): 0.297 Bubble Voltage Drop

$d_{bub}$ (cm): 0.500 Bubble Layer Thickness

v: 0.680 Bubble Volume Fraction

Bubble Model: Welch (1997)

Components of the Bath Voltage

| | | |
|---|---|---|
| Electrolyte Voltage Drop ($U_{ACD}$): | 0.6432 | (V) |
| Bubble Voltage Drop ($U_{bub}$): | 0.2971 | (V) |
| Ohmic Bath Voltage ($U_{\Omega}$): | 0.9404 | (V) |
| Reversible Decompositon Voltage ($E_0$): | 1.2195 | (V) |
| Anodic Reaction Overvoltage ($\eta_{AR}$): | 0.4960 | (V) |
| Anodic Concentration Overvoltage ($\eta_{AC}$): | 0.0517 | (V) |
| Cathodic Concentration Overvoltage ($\eta_{CC}$): | 0.0269 | (V) |
| Electrochemical Bath Voltage ($U_{el}$): | 1.7941 | (V) |
| **Bath Voltage ($U_{bath}$):** | **2.7344** | (V) |

Slotted Anodes

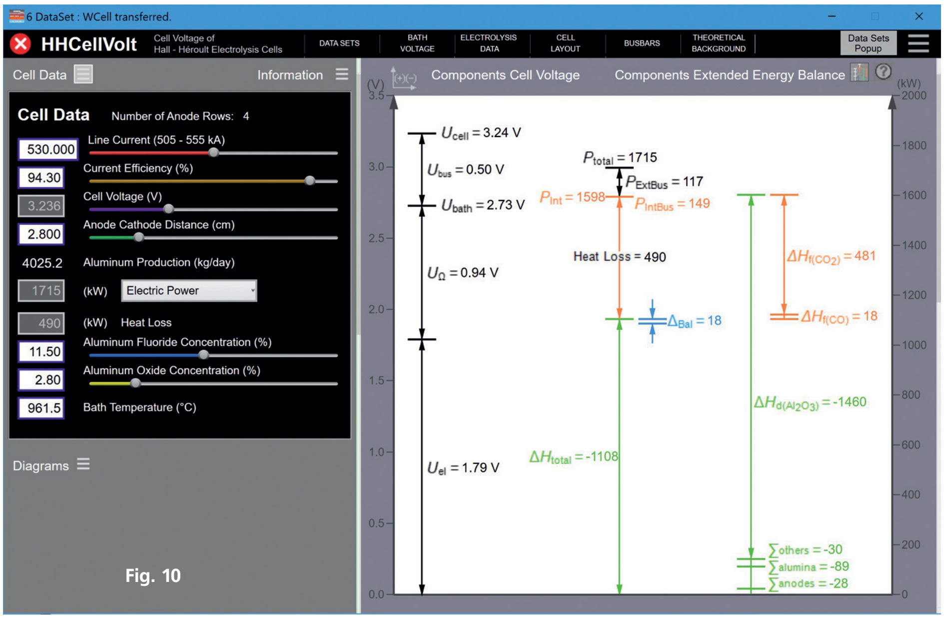
Surfaces

| | |
|---|---|
| Geometric Anode Table Surface ($A_{geom}$): | 80.4960 ($m^2$) |
| Anodic Fanning Factor ($f_A$): | 1.1000 |
| Effective Anode Table Surface ($A_A$): | 88.5456 ($m^2$) |
| Cathodic Fanning Factor ($f_C$): | 1.1000 |
| Effective Cathode Surface ($A_C$): | 88.5456 ($m^2$) |

Current Densities

| | |
|---|---|
| Geometric Anodic Current Density ($j_{geom}$): | 0.6584 ($Acm^{-2}$) |
| Effective Anodic Current Density ($j_A$): | 0.5986 ($Acm^{-2}$) |

Fig. 9



**Cell Data** Number of Anode Rows: 4

530.000 Line Current (505 - 555 kA)

94.30 Current Efficiency (%)

3.236 Cell Voltage (V)

2.800 Anode Cathode Distance (cm)

4025.2 Aluminum Production (kg/day)

1715 (kW) Electric Power

490 (kW) Heat Loss

11.50 Aluminum Fluoride Concentration (%)

2.80 Aluminum Oxide Concentration (%)

961.5 Bath Temperature (°C)

Fig. 10

The cathode design also remained the same. Fig. 6 shows the cathode side slice model mesh with the converged ledge profile at 5 °C of cell superheat, while Fig. 7 shows the corresponding temperature solution. The model predicts an internal cathode drop of 90 mV and an external cathode drop of 45 mV. The heat loss of the internal part of the cathode at 5 °C of cell superheat is 311 kW. About 40% of that cathode heat loss is going through the ledge, 35% escapes by conduction in the collector bars and the remaining 25% is going out down thought the cell lining.

## HHCellVolt model results at 530 kA

At that stage, HHCellvolt can be used to calculate the cell voltage and the cell internal heat, assuming a value for the cell current efficiency. Fig. 8 shows HHCellvolt busbar panel where the user enters the anode, cathode and busbar voltage drop. That figure illustrates clearly the new boundary between the internal voltage drop and the external voltage drop. The external section goes from the site where the collector bars exit the cell to the site where the stubs enter into the anode cover material. Fig. 9 shows the HHCellVolt bath voltage drop results, these employ user inputs for the ACD, the bubble model, and the anodic current density, which is calculated from the anode layout presented in Fig. 1 at 530 kA cell amperage. Finally, the main HHCellVolt panel presented in Fig. 10 shows the global results corresponding to that user-assumed current efficiency.

## Dyna/Marc global analysis of the wide cell design at 530 kA

Finally, using the same inputs (except for the cell current efficiency that is part of the solution), Dyna/Marc calculates the steady-state cell conditions at 530 kA and 2.8 cm ACD. Table II summarizes the Dyna/Marc results: it predicts the cell voltage to be 3.24 V, the cell internal heat (using Haupin's equation to calculate the equivalent voltage to make the metal) to be 516 kW at the calculated current efficiency of 94.3%, and the cell superheat to be 5.0 °C. Finally, the cell power consumption is calculated to be 10.23 kWh/kg, not quite 10 kWh/kg unfortunately!

## Discussion and future work

Table III summarizes the results of the four wide-cell designs presented so far, all using the same wide potshell platform. The cell operating at 530 kA, 0.66 A/cm² and 10.23

kWh/kg dissipates only 39% of the heat dissipated by the cell operating at 762.5 kA, 0.94 A/cm$^2$ and 12.85 kWh/kg. Both HHCellVolt and Dyna/Marc can easily predict the cell amperage needed to operate at 10.0 kWh/kg, assuming no other changes: the answer is 505 kA, 0.63 A/cm$^2$ and 436 kW of cell internal heat. This 436 kW represents only 33% of the heat dissipated by the cell operating at 762.5 kA and 12.85 kWh/kg, and only 84% of the heat dissipated by the cell operating at 530 kA and 10.23 kWh/kg.

This 15% extra reduction of the cell heat loss must be achieved without further reducing the cell superheat. It is also fair to assume that it would not be safe to further reduce the metal pad thickness. Yet, as can be seen in Fig. 6, after the reduction of that metal pad thickness there is now plenty of spare cell cavity. This cavity provides space to increase the thickness of the cell lining below the cathode block, and now new semi-insulating lining materials which resist sodium vapour have also become available. This combination represents an opportunity to design a more insulating cathode lining, and hence to reduce the cathode heat loss at constant cell superheat, with no risk of degrading the cathode lining by exposing it to high temperature and sodium vapour.

## Conclusions

Two extra steps towards the design of a cell operating at 10.0 kWh/kg Al have been presented in this article. The last step is the design of a wide cell operating at 530 kA, 0.66 A/cm$^2$ and 10.23 kWh/kg Al. That cell operates at the assumed lowest ACD of 2.8 cm, the lowest assumed metal pad thickness of 10 cm, and the lowest assumed cell superheat of 5 °C. That cell also operates at 25 cm of anode cover thickness, which may not be the thickest possible, but must be quite close to it. Despite these steps, and together with refined design features to limit the studs and collector bars heat loss (more details on this will be presented in [2]), in the current study it was not possible to design a cell operating at 10.0 kWh/kg Al. Yet this milestone goal is getting more and more accessible, and should be reached quite soon now, still using the wide cell design option.

**Table 3**

| | | | | |
|---|---|---|---|---|
| Amperage | 762.5 kA | 650 kA | 570 kA | 530 kA |
| Nb. of anodes | 48 | 36 | 36 | 36 |
| Anode size | 2.6m X .65m | 2.6m X .86m | 2.6m X .86m | 2.6m X .86m |
| Nb. of anode studs | 4 per anode | 12 per anode | 12 per anode | 12 per anode |
| Anode stud diameter | 21.0 cm | 16.0 cm | 18.0 cm | 18.0 cm |
| Anode cover thickness | 15 cm | 25 cm | 25 cm | 25 cm |
| Nb. of cathode blocks | 24 | 24 | 24 | 24 |
| Cathode block length | 5.37 m | 5.37 m | 5.37 m | 5.37 m |
| Type of cathode block | HC10 | HC10 | HC10 | HC10 |
| Collector bar size | 20 cm X 12 cm | 20 cm X 15 cm | 20 cm X 15 cm | 20 cm X 15 cm |
| Type of side block | HC3 | HC3 | HC3 | HC3 |
| Side block thickness | 7 cm | 7 cm | 7 cm | 7 cm |
| ASD | 25 cm | 25 cm | 25 cm | 25 cm |
| Calcium silicate thickness | 3.5 cm | 6.0 cm | 6.0 cm | 6.0 cm |
| Inside potshell size | 17.02 X 5.88 m | 17.02 X 5.88 m | 17.02 X 5.88 m | 17.02 X 5.88 m |
| ACD | 3.0 cm | 2.8 cm | 2.8 cm | 2.8 cm |
| Anode current density | 0.93 A/cm$^2$ | 0.81 A/cm$^2$ | 0.71 A/cm$^2$ | 0.66 A/cm$^2$ |
| Metal level | 20 cm | 20 cm | 10 cm | 10 cm |
| Excess $AlF_3$ | 11.50% | 11.50% | 11.50% | 11.50% |
| | | | | |
| Anode drop (A) | 347 mV (T) | 252 mV (T) | 207 mV (I) | 191 mV (I) |
| Cathode drop (A) | 118 mV (T) | 109 mV (T) | 91 mV (I) | 90 mV (I) |
| Busbar/External drop (A) | 300 mV (B) | 170 mV (B) | 227 mV (E) | 221 mV (E) |
| Anode panel heat loss (A) | 553 kW (T) | 339 kW (T) | 221 kW (I) | 218 kW (I) |
| Cathode total heat loss (A) | 715 kW (T) | 482 kW (T) | 417 kW (I) | 311 kW (I) |
| Operating temperature (D/M) | 968.9 °C | 966.5 °C | 964.1 °C | 961.6 °C |
| Liquidus superheat (D/M) | 10.0 °C | 7.6 °C | 7.5 °C | 5.0 °C |
| Bath ledge thickness (A) | 6.82 cm | 14.25 cm | 18.36 cm | 21.38 cm |
| Metal ledge thickness (A) | 1.85 cm | 4.58 cm | 6.88 cm | 7.60 cm |
| Current efficiency (D/M) | 95.1% | 94.9% | 94.4% | 94.3% |
| Internal heat (D/M) | 1328 kW | 804 kW | 613 kW | 516 kW |
| Energy consumption | 12.85 kWh/kg | 11.0 kWh/kg | 10.6 kWh/kg | 10.2 kWh/kg |

*A = ANSYS; D/M = Dyna/Marc; T = Total; B = Busbar; I = Internal; E = External*

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## Author

Dr Marc Dupuis is a consultant specialized in the applications of mathematical modelling for the aluminium industry since 1994, the year when he founded his own consulting company GeniSim Inc (www.genisim.com). Before that, he graduated with a Ph.D. in chemical engineering from Laval University in Quebec City in 1984, and then worked ten years as a research engineer for Alcan International. His main research interests are the development of mathematical models of the Hall-Héroult cell dealing with the thermo-electric, thermo-mechanic, electro-magnetic and hydrodynamic aspects of the problem. He was also involved in the design of experimental high amperage cells and with the retrofit of many existing cell technologies.