THERMO-ELECTRIC DESIGN OF A 740 kA CELL, IS THERE A SIZE LIMIT?

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In 2000, before the announcement of the AP50 cell technology, the author presented the thermo-electric design of a 400 kA cell [1]. In 2003, that work was extended in order to present the thermo-electric design of a 500 kA cell [2].

Those papers were trying to demonstrate that with the support of reliable mathematical modeling tools, there is no limit to the size of cells that could be designed as far as the thermal balance aspect of the cell design is concerned.

Yet, in both occasions, the author has been challenged to design an even bigger cell! This time, the thermo-electric design of a 26.2 meters long 740 kA cell is being presented. In addition, a basic geometric surface area to volume ratio analysis reveals that if the same lining design would be extended to a 85.8 meters long cell, it would be in 'comfortable' thermal balance at around 2380 kA.

Base case 300 kA cell design

The assumed base case 300 kA cell presented in this study is not an existing cell design but it has been strongly inspired by the prototype cell design presented by VAW in the early 90's [3].

The 350 kA cell design

The author has already presented in [1] a proposed lining design retrofit that permits to increase the amperage to 350 kA in a way similar to the AP30 cell technology being retrofitted into the AP35 cell technology [4].

The 265 kA cell design

Alternatively, the author had also demonstrated in [5] that the same base case 300 kA cell can be retrofitted into a very energy efficient but not so productive 265 kA cell operating at 11.94 kWh/kg.

Considering that cell prototypes operations between 12.2 and 12.6 kWh/kg have been reported in Japan in the early 80's [6,7], it is only a reminder that it is technically possible to operate very low heat dissipating cells.

One potshell size, but three very different thermal balances

At this point, it is important to point out that depending on the cell lining design selected, cells sharing the same 14.4 m X 4.35 m potshell can be operated in 'comfortable' thermal balance, dissipating as low as 422 kW or as high as 712 kW. This is about a ± 25% variation around the average value, clearly demonstrating that the cell thermal balance related design constraints are not terribly limiting!

The 400 kA cell design

From the 14.4 m X 4.35 m base case potshell size 350 kA cell lining design, a 400 kA cell has been produced by extending the potshell length to 16.1 meters [1]. This proposed change has been analyzed using both the very fast lump parameters model (see Table I) and the more elaborated ANSYS® based 3D full cell slice model (see Table II).

Although there is no substitute for performing retrofit studies using reliable mathematical modeling tools, it is worth noticing that a very similar prediction can be made using only a basic geometric surface area to volume ratio analysis [8].

The initial potshell size being 1.48 m X 14.4 m X 4.35 m, its surface area to volume ratio is 1.95 m^2/m^3. 32 1.7 m X 0.8 m anodes can be fitted in that cell. In order to be able to add 4 extra anodes, the length of the potshell must be increased to 16.1 meters. At that new length, the surface area to volume ratio of the potshell is now 1.935 m^2/m^3. Using only that information, the predicted amperage of the extended cell is:

$$350 \times \frac{36}{32} \times \frac{1.935}{1.95} = 390 \ kA \qquad (1)$$

The prediction is not perfectly accurate because, in order to be able to fix 2 extra cathode blocks in the new potshell, the width of all the cathode blocks have been decreased, which in turn decreased the average current density in the collector bars. Hence, the 400 kA cell lining design is not a pure geometric extension of the 350 kA cell design.

Extrapolation to a 1650 kA cell design

Adding 1.7 m to the potshell length only changed its geometric surface area to volume ratio by 1.5%, but a more drastic extension will have a more significant impact.

If instead of adding only 4 extra anodes, the number of anodes is multiplied by 5, the potshell required to fit those 160 anodes must be 68.8 meters long. For that potshell length, the surface area to volume ratio drops to 1.84 m^2/m^3. This time, the change of aspect ratio will have a sensitive impact on the 'comfortable' cell amperage (see Curve 1 of Figure 1):

$$350 \times \frac{160}{32} \times \frac{1.84}{1.95} = 1650 \ kA \tag{2}$$

This loss of 100 kA or 5.7% due to the change of aspect ratio is not negligible, but remains quite small when compared with the ± 25% due to quite simple lining design changes.

The 500 kA cell design

The 500 kA cell design presented in [2] was obtained using only the lump parameters model (see Table I). The same cell design analysis study has now been repeated using the more elaborate ANSYS® based 3D full cell slice model (see Table II and Figure 2). This design is using a wider 4.85 meters potshell in order to accommodate 40 longer 1.95 meters anodes with bigger studs diameter. For that reason, the basic geometric surface area to volume ratio analysis cannot be used this time.

The 740 kA cell design

But this will not be the case for the 740 kA cell design as it is purely a 50% extension of the above 500 kA cell. This means that this design uses 60 1.95 m X 0.8 m anodes in a 26.2 m X 4.85 m potshell. There are now 36 cathode blocks and this time there was no need to change their width.

The new design has been analyzed using both types of models (see Tables I and II) and both models predict an increase of cell superheat and a loss of ledge thickness indicating that 740 kA is a bit too much current. 735 kA would have been a more 'comfortable' choice, as we will see below.

The better choice of 735 kA for the new cell design amperage is the result of the basic geometric surface area to volume ratio analysis. The aspect ratio of the 1.48 m X 17.8 m X 4.85 m potshell is 1.876 m^2/m^3 while the one of the 1.48 m X 26.2 m X 4.85 m potshell is 1.84 m^2/m^3, which gives:

$$500 \times \frac{60}{40} \times \frac{1.84}{1.876} = 735 \ kA \tag{3}$$

Extrapolation to a 2380 kA cell design

Pushing once again the basic geometric surface area to volume ratio analysis to the limit, a 85.8 m potshell is required in order to be able to put 200 anodes in a single cell. The aspect ratio of that potshell would be 1.787 m^2/m^3, which gives for the predicted 'comfortable' amperage (see Curve 2 of Figure 1):

$$500 \times \frac{200}{40} \times \frac{1.787}{1.876} = 2380 \ kA \tag{4}$$

A new generation thermo-electric model

Very recently, a new generation thermo-electric model has been developed: the ANSYS® based 3D full cell and external busbar model [9] (see Figure 3). When interfaced with an MHD model, this kind of very elaborate thermo-electric model can be used to predict the evolution of the ledge thickness along the perimeter of a cell. While it was not built for that purpose, it is nice to know that it can be used to confirm the heat balance predicted by the two conventional thermo-electric models.

The above analysis clearly demonstrates that if a forced air sidewall cooling system is required in order to be able to operate very high amperage cells [8], it is clearly not because of the impact of the little reduction of the surface area to volume ratio on the cell heat balance. As far as only the cell heat balance design issue is concerned, there is no limit to the size of cells that can be designed.

Of course, as the cell gets longer, it will be more difficult for the fresh air coming from the potroom walls openings to reach the center of the cell. This impact can be analyzed in potroom ventilation models like the one presented in [10]. It would no doubt be a very serious issue for a 85 meters long cell, but that impact on even a 18 m long cell when compared to a 14 m long one should not be that significant.

This leaves only mechanical design considerations to justify the need of forced air sidewall cooling system on a 500 kA cell design.

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Author

Dr. Marc Dupuis is a consultant specialized in the applications of mathematical modeling 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 10 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 the retrofit of many existing cell technologies.

Table I : Results using Dyna/Marc 1.8 modeling tool

	Base case					
Amperage	300 kA	265 kA	350 kA	400 kA	500 kA	740 kA
Nb. of anodes	32	32	32	36	40	60
Anode size	1.6 m X 0.8 m	1.6 m X 0.8 m	1.7 m X 0.8 m	1.7 m X 0.8 m	1.95 m X 0.8 m	1.95 m X 0.8 m
Nb. of anode studs	3 per anode	3 per anode	3 per anode	3 per anode	4 per anode	4 per anode
Anode stud diameter	18 cm	16 cm	19 cm	19 cm	17.5 cm	17.5 cm
Anode cover thickness	16 cm	17.5 cm	10 cm	10 cm	10 cm	10 cm
Nb. of cathode blocks	18	18	18	20	24	36
Cathode block length	3.47 m	3.43 m	3.67 m	3.67 m	4.17 m	4.17 m
Type of cathode block	HC3	HC10	HC10	HC10	HC10	HC10
Collector bar size	20 cm X 10 cm	18 cm X 10 cm	20 cm X 10 cm	20 cm X 10 cm	20 cm X 10 cm	20 cm X 10 cm
Type of side block	HC3	Anthracite	SiC	SiC	SiC	SiC
Side block thickness	15 cm +	15 cm +	10 cm +	10 cm +	10 cm +	10 cm +
ASD	35 cm	35 cm	30 cm	30 cm	30 cm	30 cm
Calcium silicate thickness	3.5 cm	6.0 cm	3.5 cm	3.5 cm	3.5 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	16.1 X 4.35 m	17.8 X 4.85 m	26.2 X 4.85 m
ACD	5 cm	4.15 cm	4 cm	4 cm	4 cm	4 cm
Excess AlF_3	10.9 %	13.5 %	13.5 %	13.5 %	13.5 %	13.5 %
Anode drop	306 mV	280 mV	330 mV	335 mV	320 mV	316 mV
Cathode drop	290 mV	212 mV	293 mV	301 mV	312 mV	308 mV
Anode panel heat loss	239 kW	193 kW	284 kW	311 kW	394 kW	585 kW
Cathode bottom heat loss	166 kW	135 kW	173 kW	193 kW	238 kW	346 kW
Operating temperature	973.3 °C	957.3 °C	961.5 °C	962.7 °C	963.4 °C	963.7 °C
Liquidus superheat	6.8 °C	3.6 °C	7.8 °C	9.0 °C	9.7 °C	10.0 °C
Bath ledge thickness	7.61 cm	17.3 cm	6.69 cm	5.11 cm	4.44 cm	4.16 cm
Metal ledge thickness	2.79 cm	11.4 cm	2.42 cm	0.83 cm	0.17 cm	0.01 cm
Current efficiency	94.0 %	95.6 %	96.0 %	96.0 %	95.9 %	95.8 %
Internal heat	628 kW	422 kW	712 kW	829 kW	1019 kW	1484 kW
Energy consumption	13.75 kWh/kg	11.95 kWh/kg	13.37 kWh/kg	13.49 kWh/kg	13.39 kWh/kg	13.30 kWh/kg

Table II : Results using an ANSYS® based 3D full cell slice modeling tool

	Base case					
Amperage	300 kA	265 kA	350 kA	400 kA	500 kA	740 kA
Nb. of anodes	32	32	32	36	40	60
Anode size	1.6 m X 0.8 m	1.6 m X 0.8 m	1.7 m X 0.8 m	1.7 m X 0.8 m	1.95 m X 0.8 m	1.95 m X 0.8 m
Nb. of anode studs	3 per anode	3 per anode	3 per anode	3 per anode	3 per anode	3 per anode
Anode stud diameter	18 cm	16 cm	19 cm	19 cm	20.5 cm	20.5 cm
Anode cover thickness	16 cm	17.5 cm	10 cm	10 cm	10 cm	10 cm
Nb. of cathode blocks	18	18	18	20	24	36
Cathode block length	3.47 m	3.43 m	3.67 m	3.67 m	4.17 m	4.17 m
Type of cathode block	HC3	HC10	HC10	HC10	HC10	HC10
Collector bar size	20 cm X 10 cm	18 cm X 10 cm	20 cm X 10 cm	20 cm X 10 cm	20 cm X 10 cm	20 cm X 10 cm
Type of side block	HC3	Anthracite	SiC	SiC	SiC	SiC
Side block thickness	15 cm +	15 cm +	10 cm +	10 cm +	10 cm +	10 cm +
ASD	35 cm	35 cm	30 cm	30 cm	30 cm	30 cm
Calcium silicate thickness	3.5 cm	6.0 cm	3.5 cm	3.5 cm	3.5 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	16.1 X 4.35 m	17.8 X 4.85 m	26.2 X 4.85 m
ACD	5 cm	4.15 cm	4 cm	4 cm	4 cm	4 cm
Excess AlF_3	10.9 %	13.5 %	13.5 %	13.5 %	13.5 %	13.5 %
Anode drop	303 mV	273 mV	323 mV	328 mV	354 mV	349 mV
Cathode drop	285 mV	213mV	292 mV	301 mV	314 mV	310 mV
Anode panel heat loss	240 kW	183 kW	284 kW	322 kW	409 kW	611 kW
Cathode bottom heat loss	176 kW	132 kW	202 kW	226 kW	273 kW	395 kW
Operating temperature	973.2 °C	956.1 °C	960.4 °C	961.7 °C	963.1 °C	963.5 °C
Liquidus superheat	6.7 °C	2.4 °C	6.7 °C	8.0 °C	9.4 °C	9.8 °C
Bath ledge thickness	8.66 cm	23.5 cm	9.09 cm	7.32 cm	6.15 cm	5.84 cm
Metal ledge thickness	4.12 cm	9.01 cm	4.42 cm	3.39 cm	2.42 cm	2.15 cm
Current efficiency	94.0 %	95.7 %	96.1 %	96.1 %	95.9 %	95.8 %
Internal heat	628 kW	422 kW	713 kW	832 kW	1043 kW	1518 kW
Energy consumption	13.72 kWh/kg	11.93 kWh/kg	13.43 kWh/kg	13.57 kWh/kg	13.61 kWh/kg	13.51 kWh/kg

Figure 1: Extrapolation of the cell amperage vs the cell aspect ratio for the 350 kA and the 500 kA cell designs

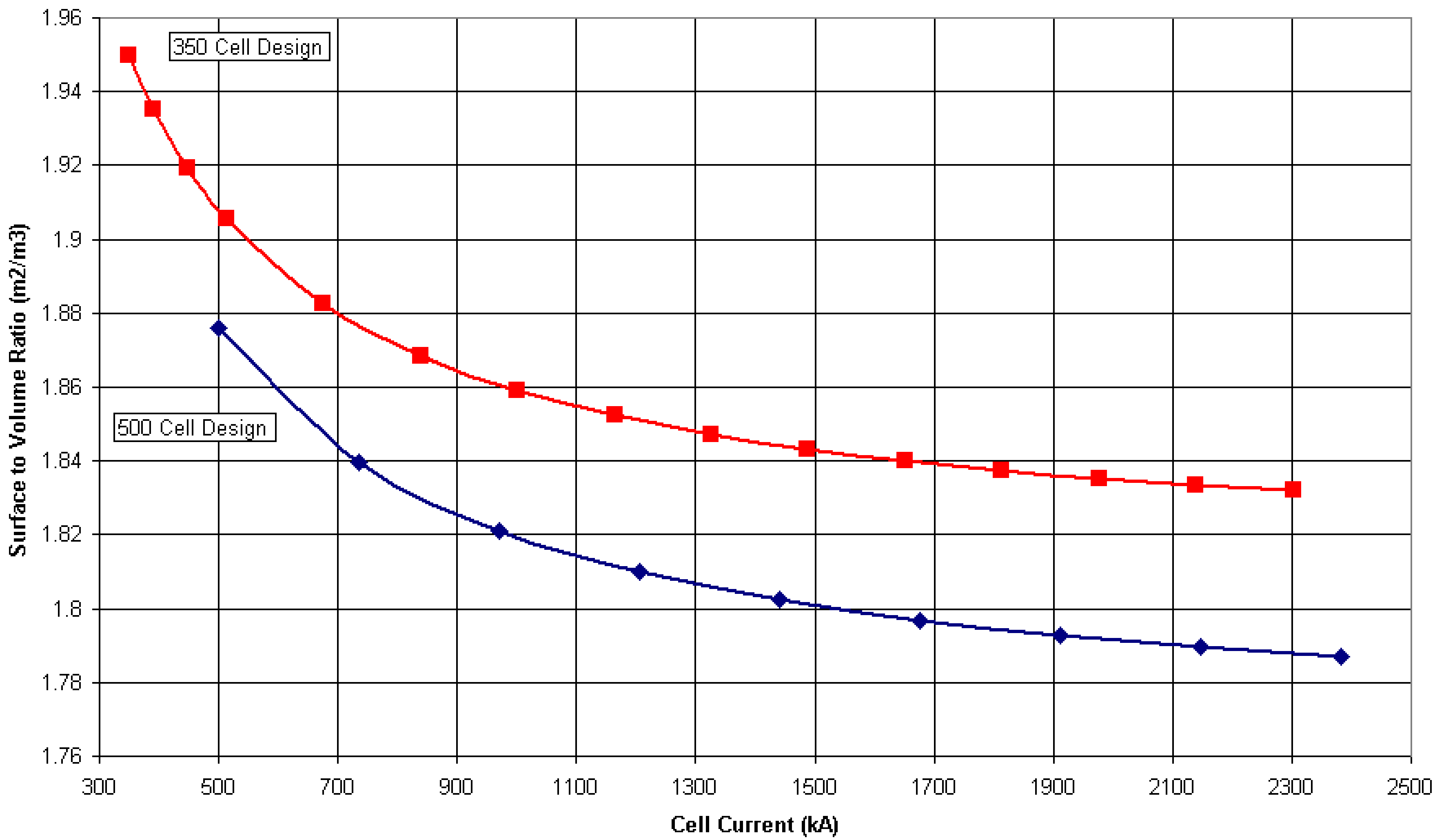
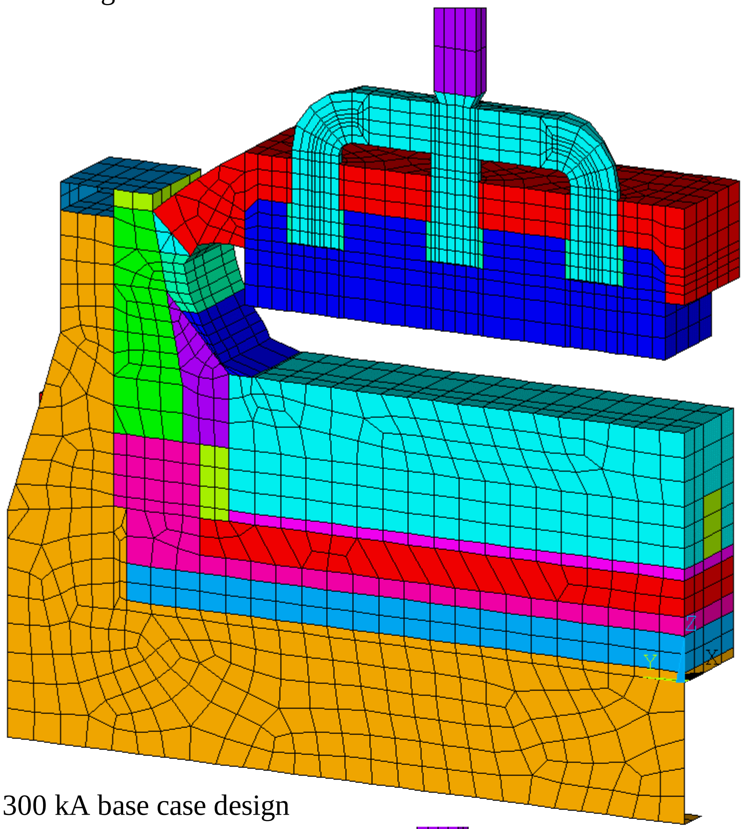
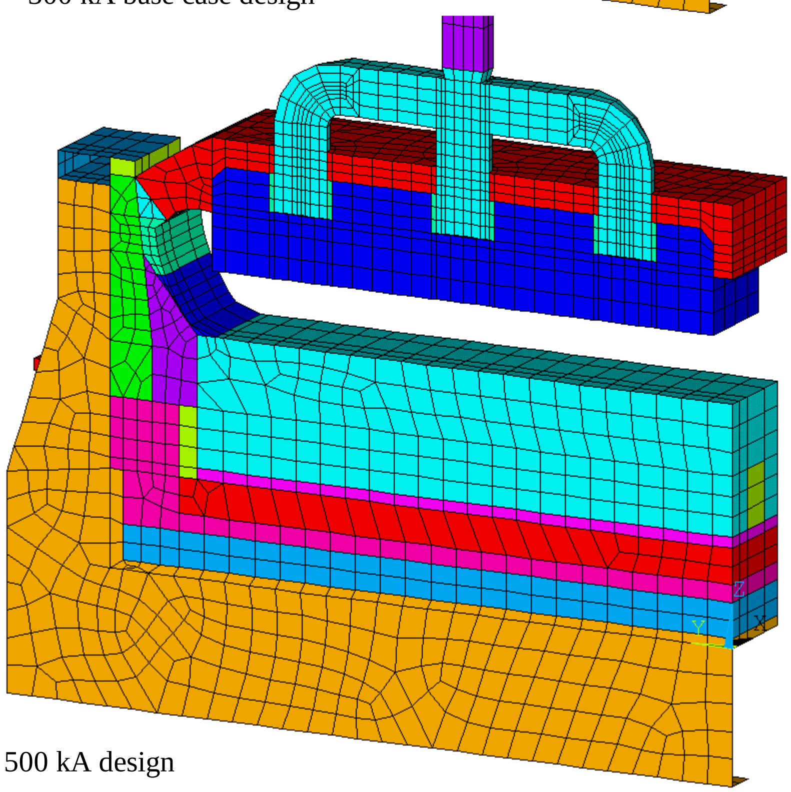


Figure 2: ANSYS® based 3D full cell slice models

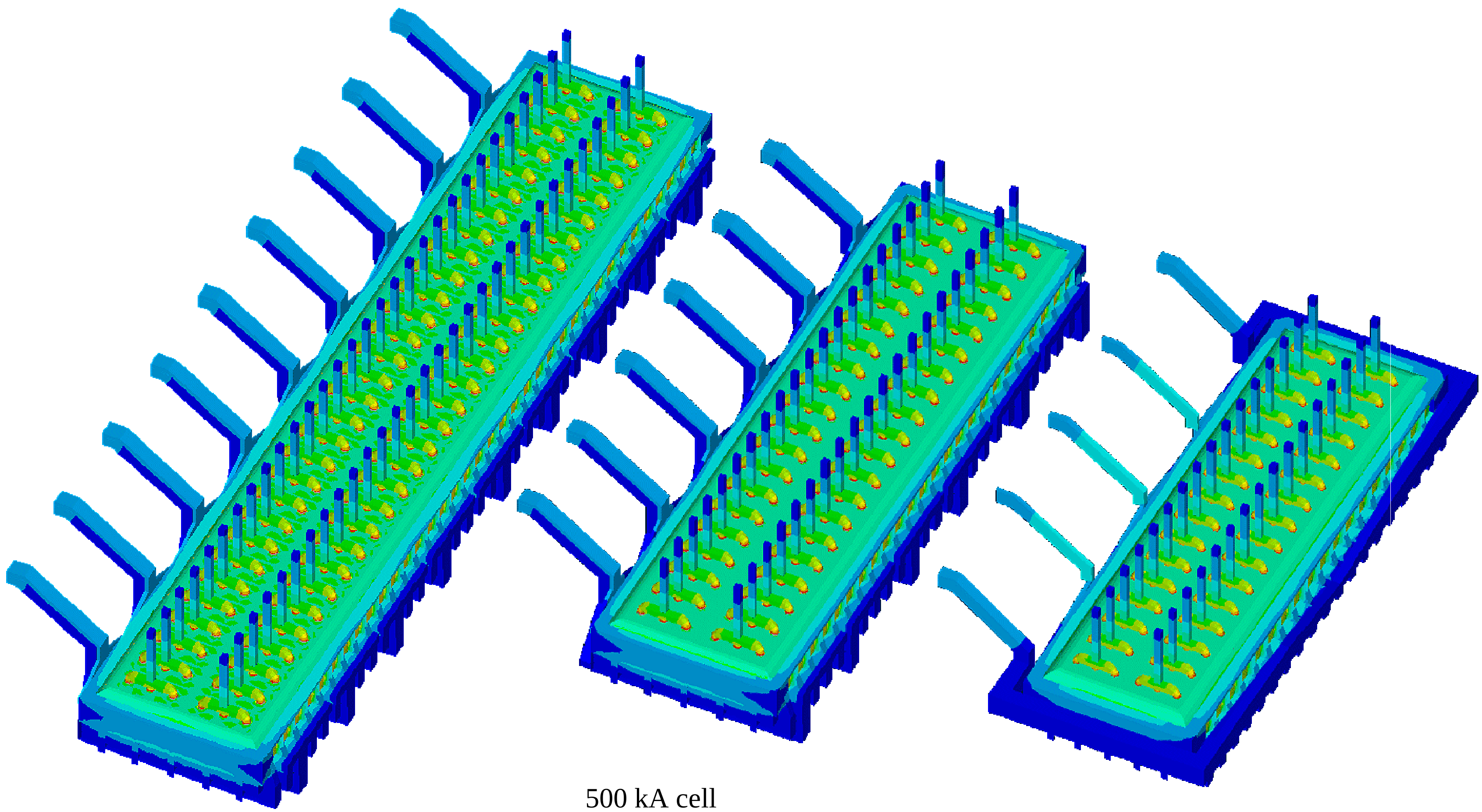


300 kA base case design



500 kA design

Figure 3: ANSYS® based 3D full cell and external busbar model



740 kA cell

500 kA cell

300 kA cell