
Welcome
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Using Mathematical Models to Improve the Thermal Balance of Hall-Héroult Cells

Dr Marc Dupuis

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Plan of the Presentation

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- Retrofitting Existing Cell Designs Using Mathematical Models
- Investing in the Development of Mathematical Models: Financial Risk and Rewards
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- Calibration and Validation of the Mathematical Models
- Examples of Applications of an ANSYS®-based 3D Full Cell Side Slice Thermo-electric Model
- Conclusions

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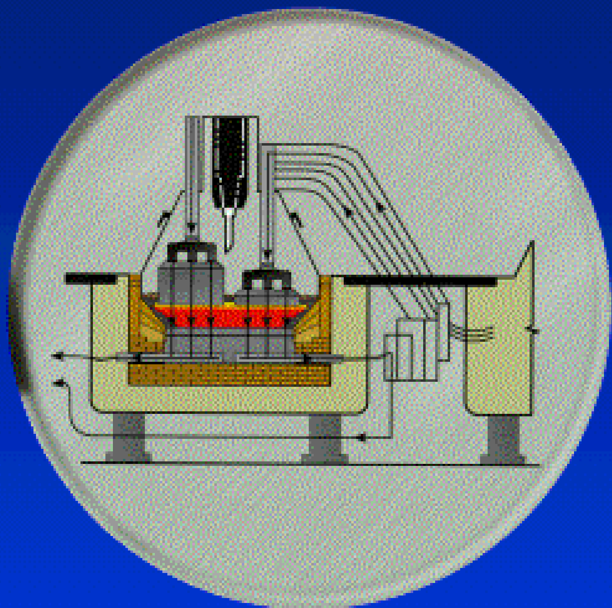
Introduction



The power consumption of the Hall-Héroult cell being one of the major operating costs, the aluminium industry is constantly trying to reduce the specific power consumption of smelters expressed in kWh/kg of aluminium produced.

Today, best results are:

12.9 - 13.0 kWh/kg for high amperage PBF cells
14.0 - 14.5 kWh/kg for best VSS cells

Older smelters still operating at 17 - 18 kWh/kg are feeling an increasing pressure from their more efficient competitors. They have essentially two options:

1) Retrofit their cell design in order to improve their power consumption and hence reduce their production costs
2) Be run out of business

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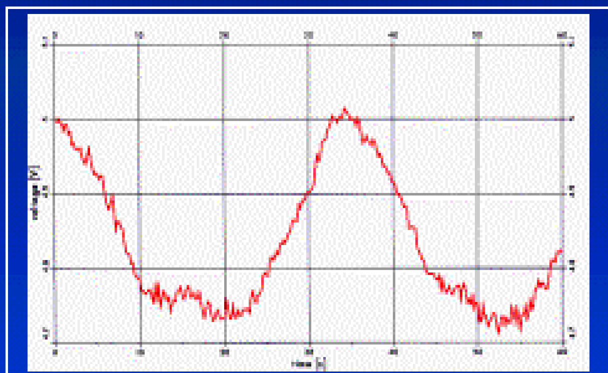
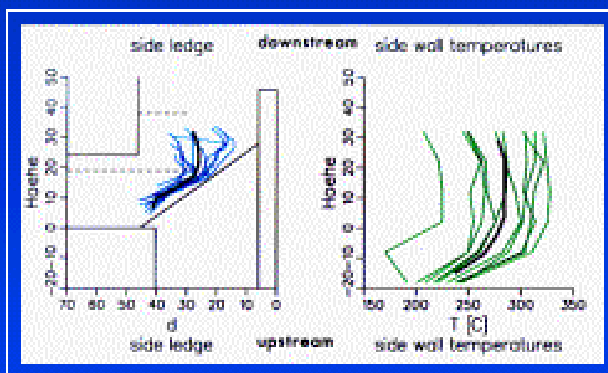
Retrofitting Existing Cell Designs to Improve their Power Consumption

Retrofitting a cell design in order to improve its power consumption typically involves improving the cell thermal balance and the cell MHD stability



MHD Stability



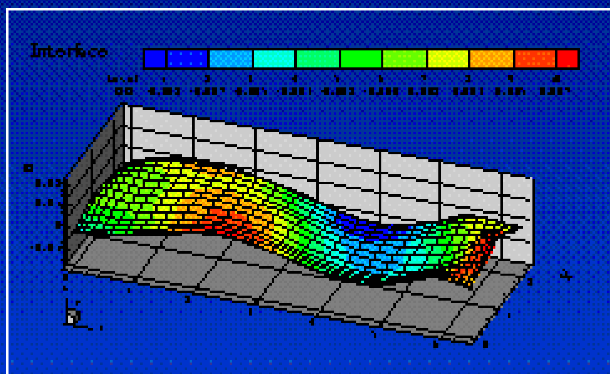
Thermal Balance

Base Case

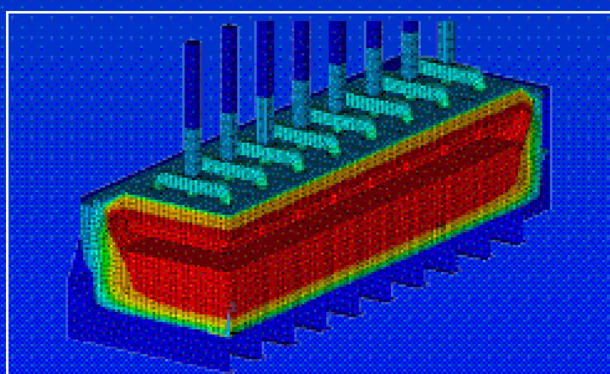
Cell Design

Retrofitting Existing Cell Designs Using Mathematical Models

It is now possible to drastically reduce the number of physical prototyping trial and error design loops by using mathematical models to perform most of that trial and error development work using virtual prototyping instead.



MHD Model



Thermo-electric Model

Retrofitted Cell Design

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Investing in the Development of Mathematical Models: Financial Risk and Rewards

The Hall-Héroult process being so complex on one hand and the measurement of the process behavior being so difficult to perform on the other hand, the development of reliable Hall-Héroult cell mathematical models was, and continues to be a real challenge.

Things basically can go wrong the two opposite ways:

1) The development of a "quick and dirty" model that will not be representative of the real behavior of the process

Example from TMS 2001, p 519

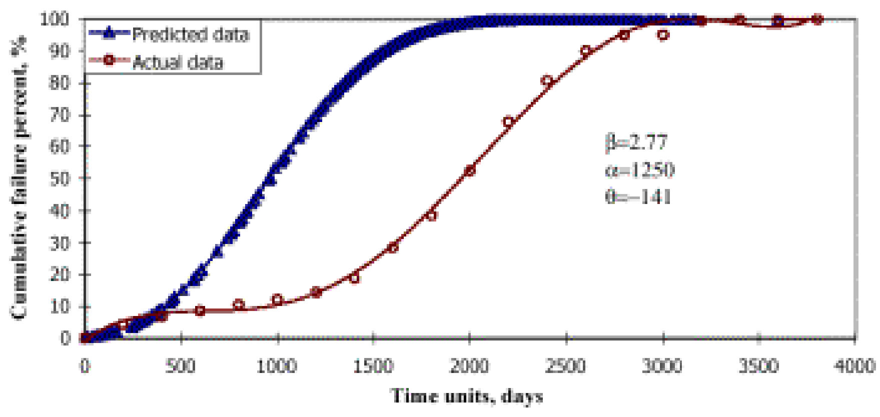
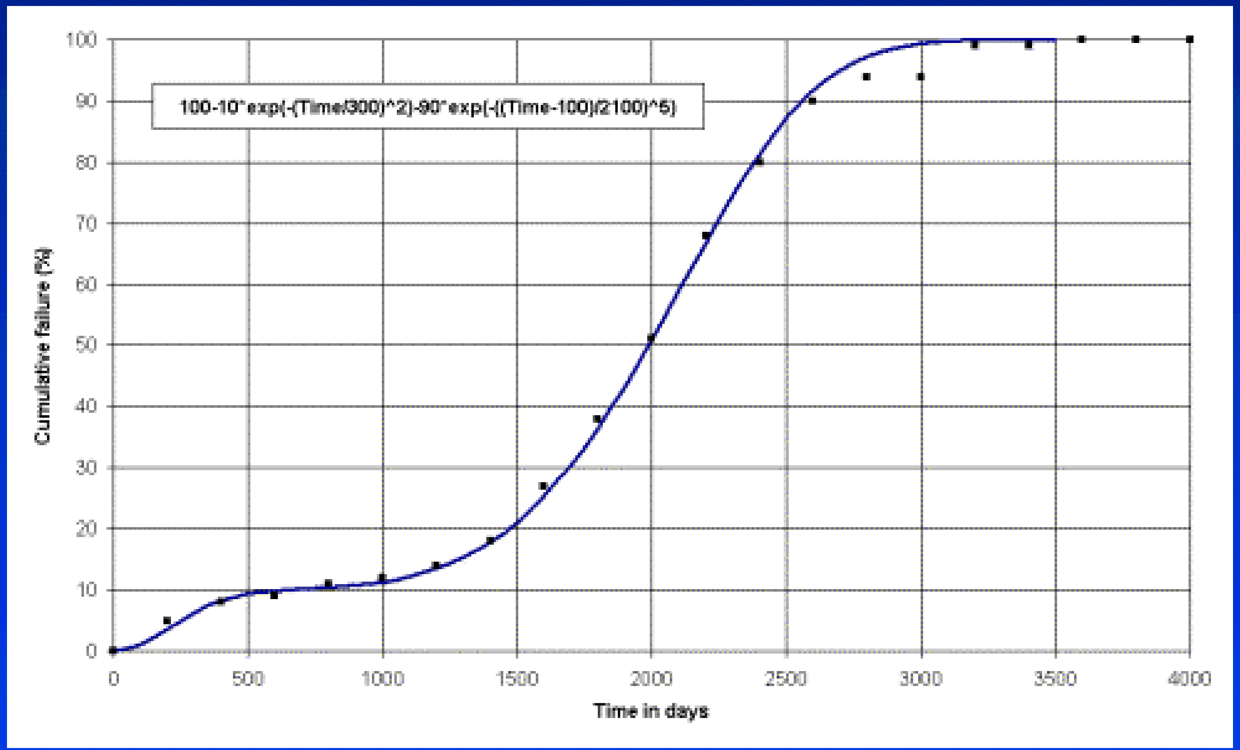


Figure 4: Actual vs. predicted failure pattern based on complete failure data in year's 1989/90 to 1994/95.

Investing in the Development of Mathematical Models: Financial Risk and Rewards

1) The development of a "quick and dirty" model that will not be representative of the real behavior of the process

In the previous example, taking into consideration a second early failure mode in addition to the main failure mode would have been enough to fix the model !



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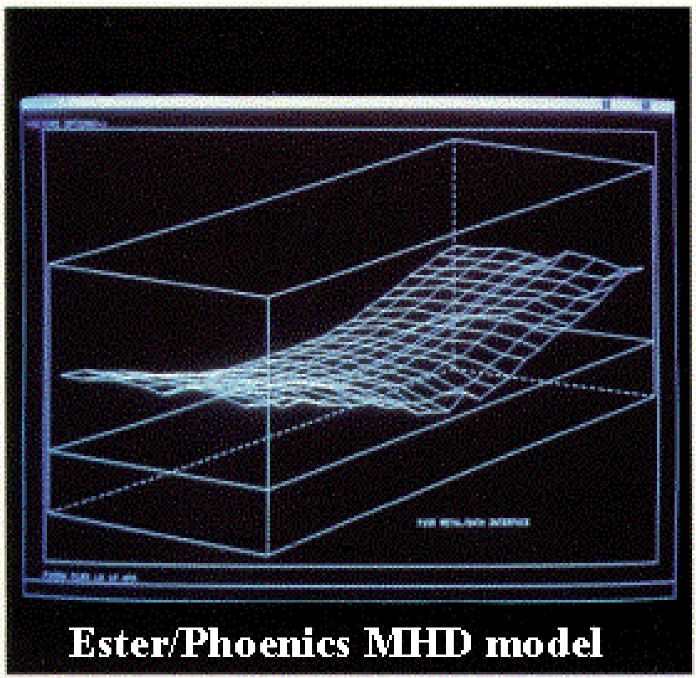
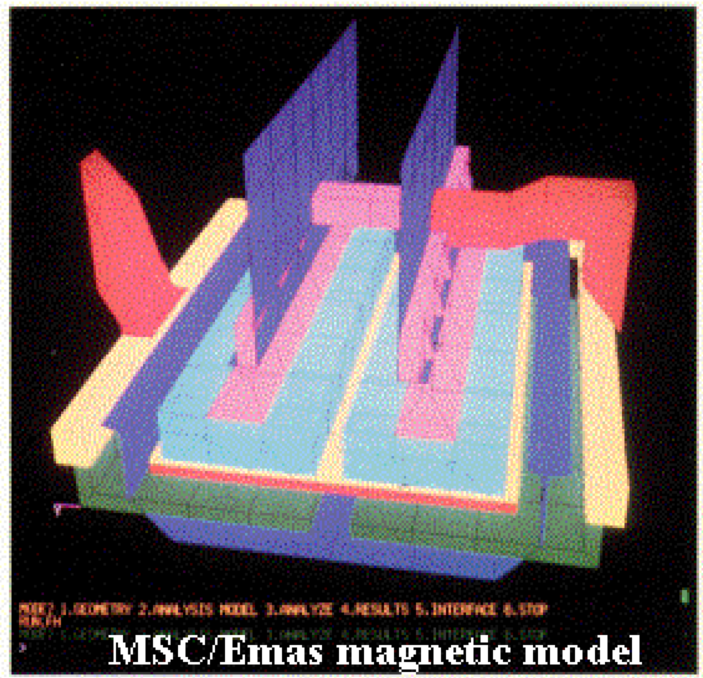
Investing in the Development of Mathematical Models: Financial Risk and Rewards

Things basically can go wrong the two opposite ways:



Ester/Phoenics MHD model



MSC/Emas magnetic model

2) The never-ending development of a "monstrous" unmanageable model that tries to take everything into account

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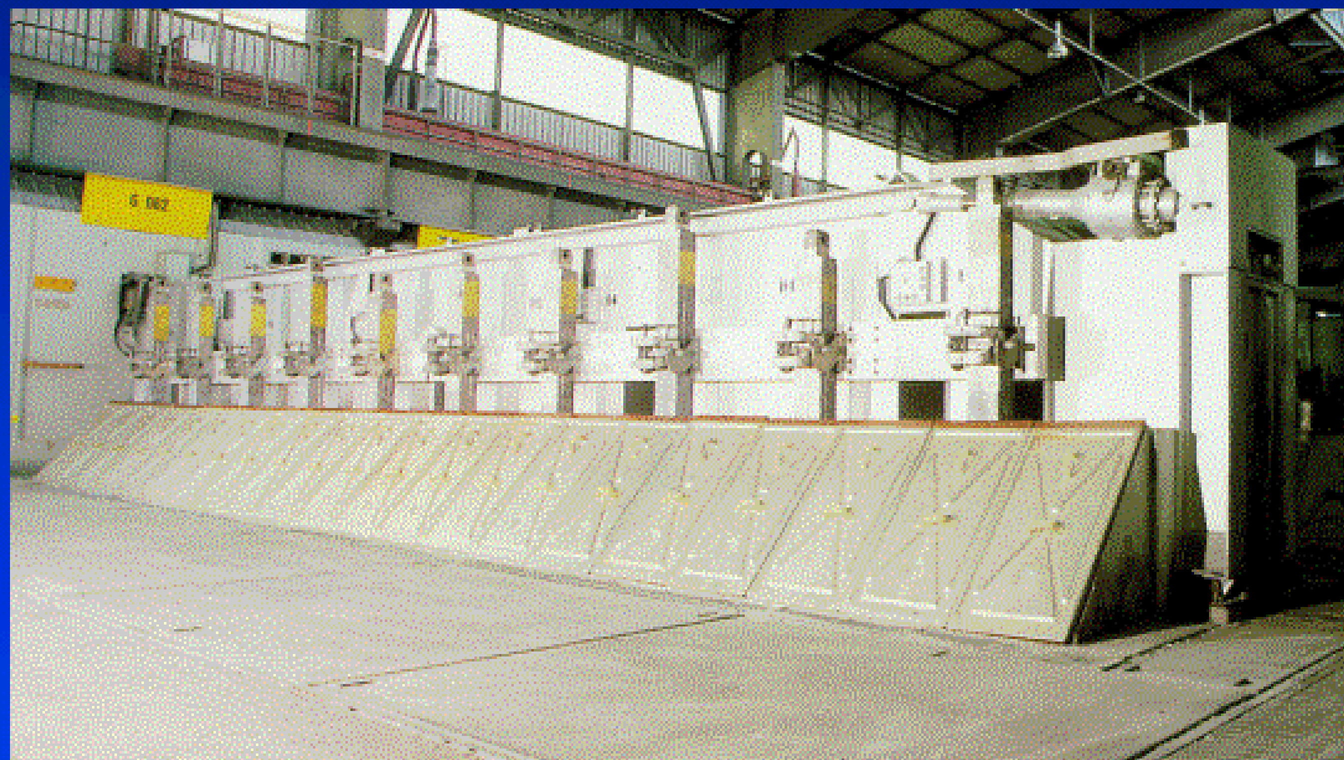
Investing in the Development of Mathematical Models: Financial Risk and Rewards

The “four pillars” of the AP18 and AP30 successful development:

1) Magnetic and MHD models
2) Cell thermo-electric and busbars balance electrical models
3) Potshell/superstructure mechanical models
4) Transient thermo-mechanical cell start-up model



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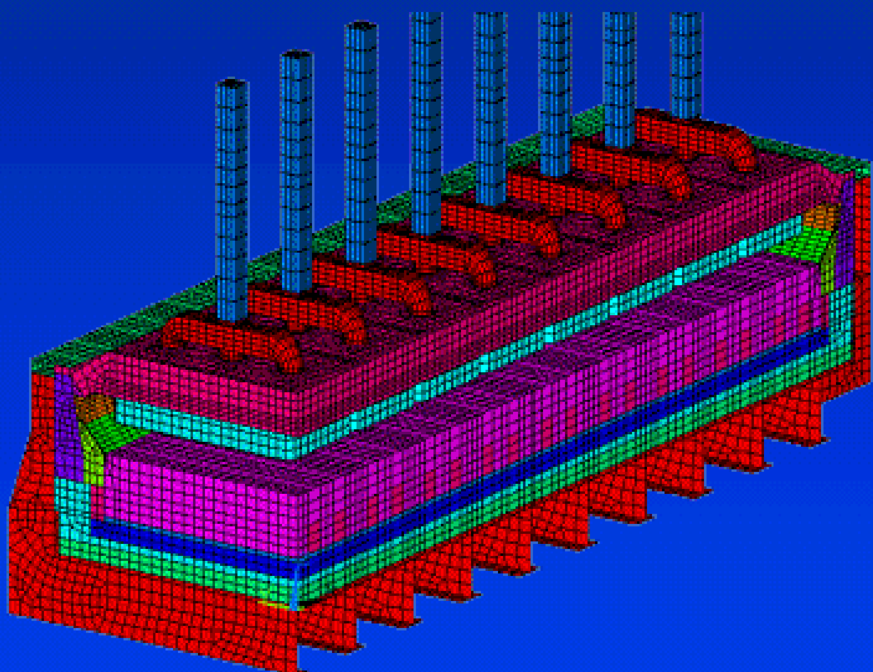
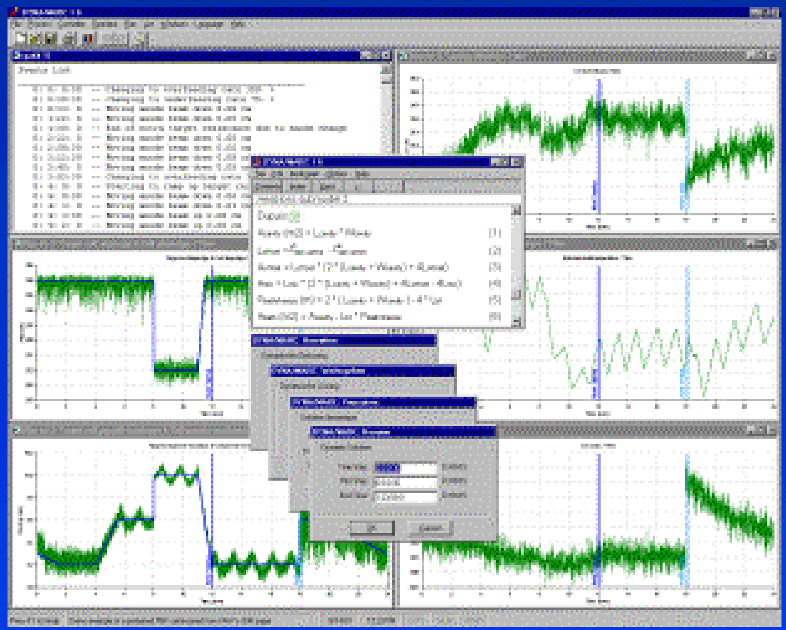
Reducing the Financial Risk and Shortening the Payback Time by Using Well Established Reliable and Commercially Available Mathematical Models

ANSYS®-based 3D steady-state thermo-electric models



Dyna/Marc lump parameters+ model



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Dyna/Marc Lump Parameters+ Model

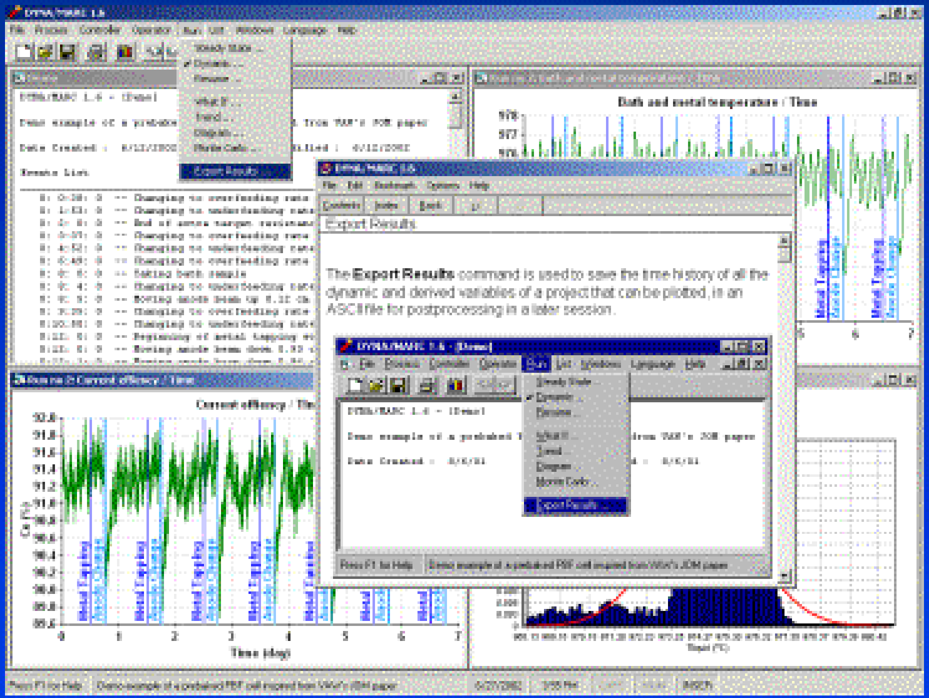
DYNA/MARC (DYNAmic Model of Aluminum Reduction Cells) is a dynamic simulator of the behavior of aluminum reduction cells.

DYNA/MARC is composed of three different models.

The first is the Process model, that solves the heat and mass balance in the cell. It also takes into account the evolution of the ACD (anode to cathode distance) and the line amperage fluctuation.

The second model is the Controller model. This reproduces the plant controller response based on all the programmed algorithms taking into account the current cell state.

Finally, the Operator model allows the software to simulate the actions undertaken by the operator on his schedule or when the controller requires his intervention.



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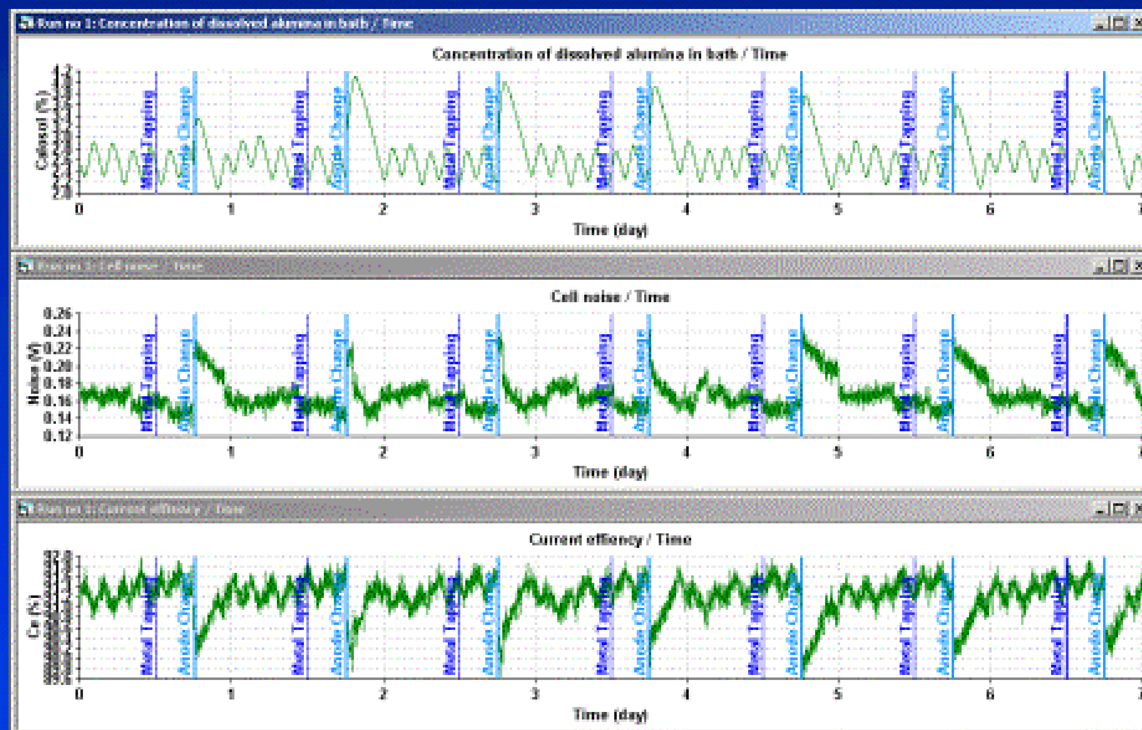
Dyna/Marc Lump Parameters+ Model

Dyna/Marc can be used to illustrate the behavior of the Hall-Héroult process in the context of a general purpose aluminium electrolysis training course.

For example, it can illustrate the impact of undesirable alumina feeding from the cover material during an anode change on the cell current efficiency.



With undesirable alumina feeding

Dyna/Marc Lump Parameters+ Model

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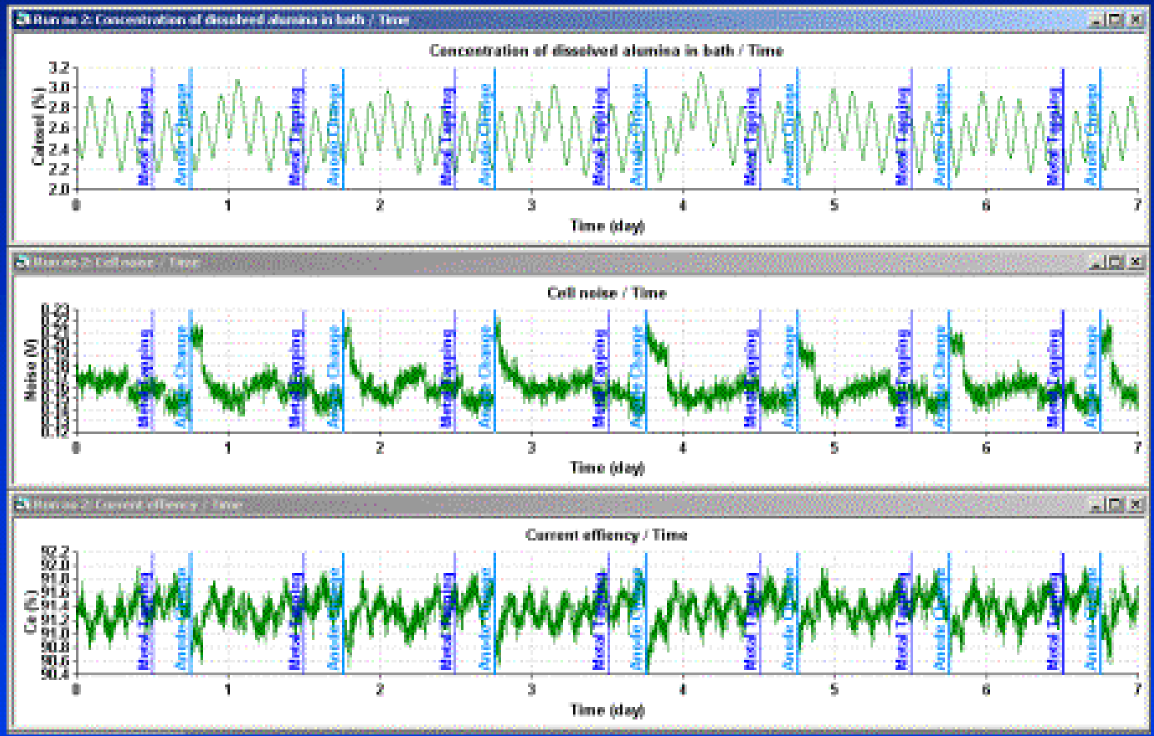

Without undesirable alumina feeding

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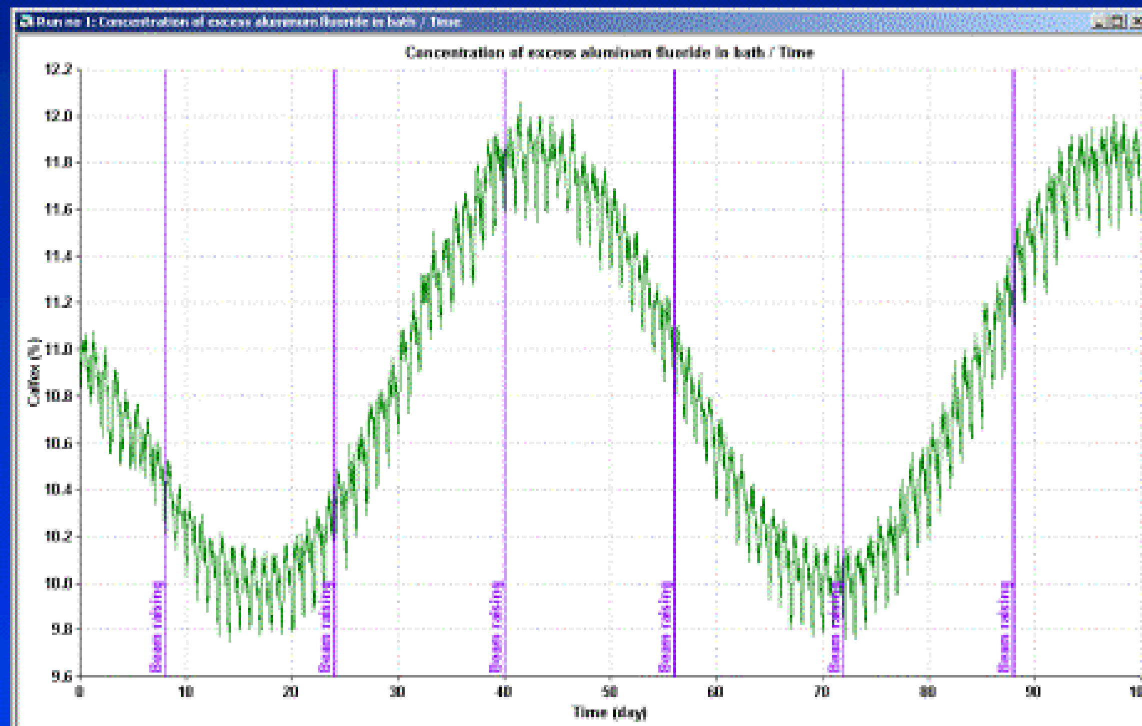
Dyna/Marc Lump Parameters+ Model

Dyna/Marc can also be used to test changes to the cell control logic or to train operators using a cell controller.

For example, it can illustrate the impact of changing the bath sampling frequency and the formula that is used to adjust the amount of AlF_3 added to the cell on the long-term evolution of the bath chemistry.



Operation with bath sampling every day

Dyna/Marc Lump Parameters+ Model

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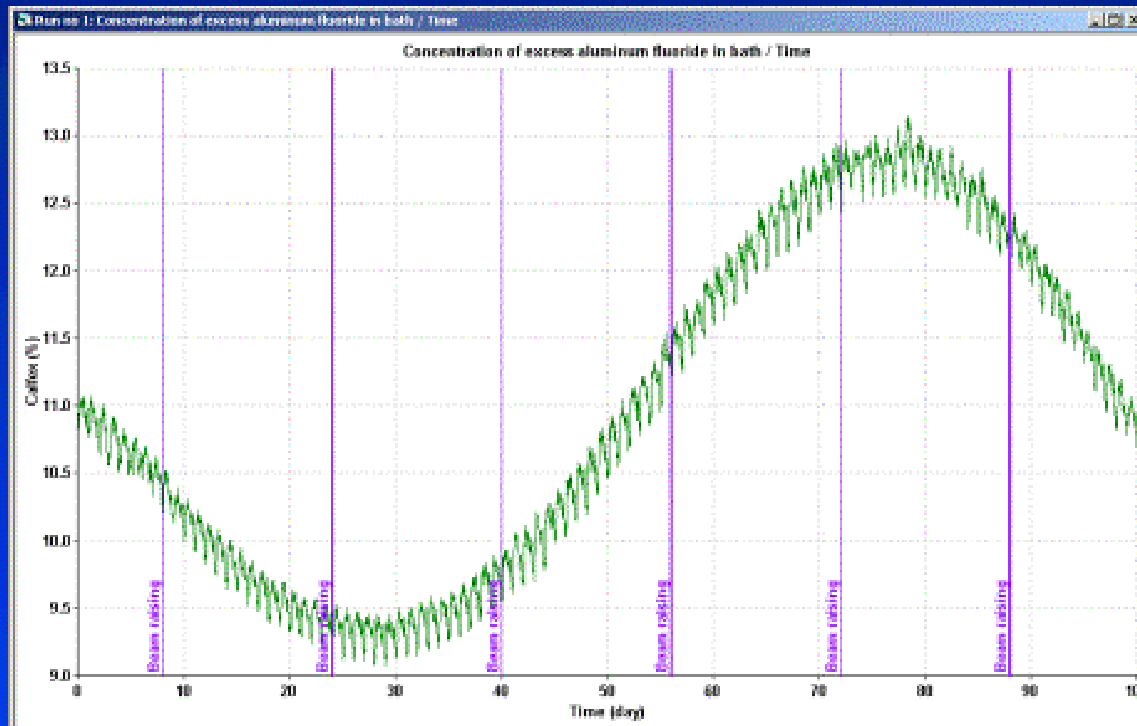
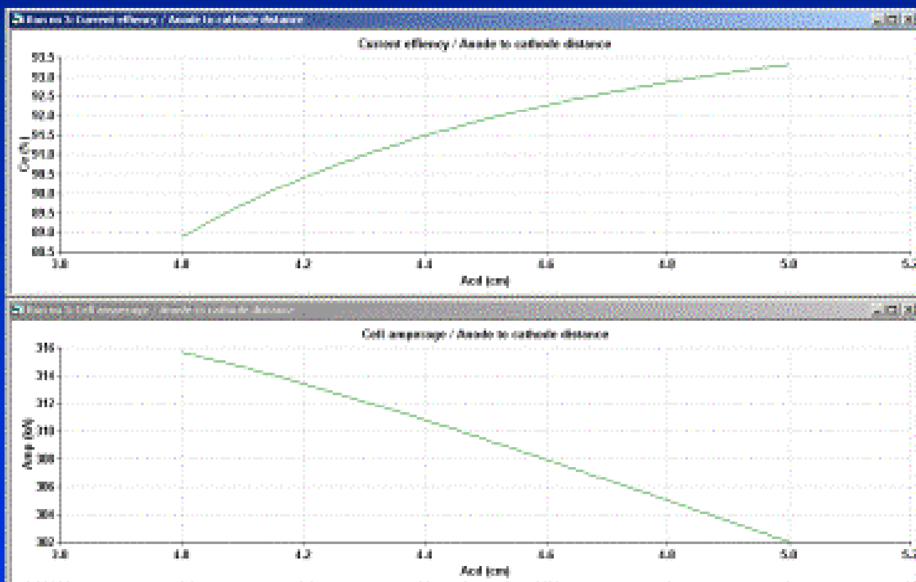


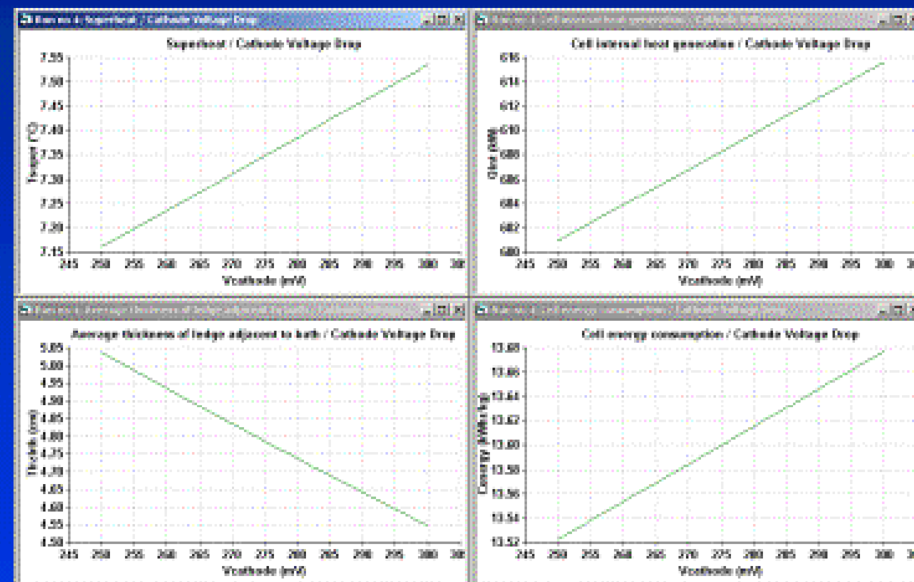
Operation with bath sampling every 3 days

Dyna/Marc Lump Parameters+ Model

As a mathematical tool to improve the cell thermal balance, Dyna/Marc is mostly used in steady-state mode. At the beginning of a retrofit project, it provides fast answers to “what if” questions and can produce trend analysis.



Impact of replacing ACD by Amperage at constant cell internal heat



Impact of reducing cathode voltage drop at constant ACD

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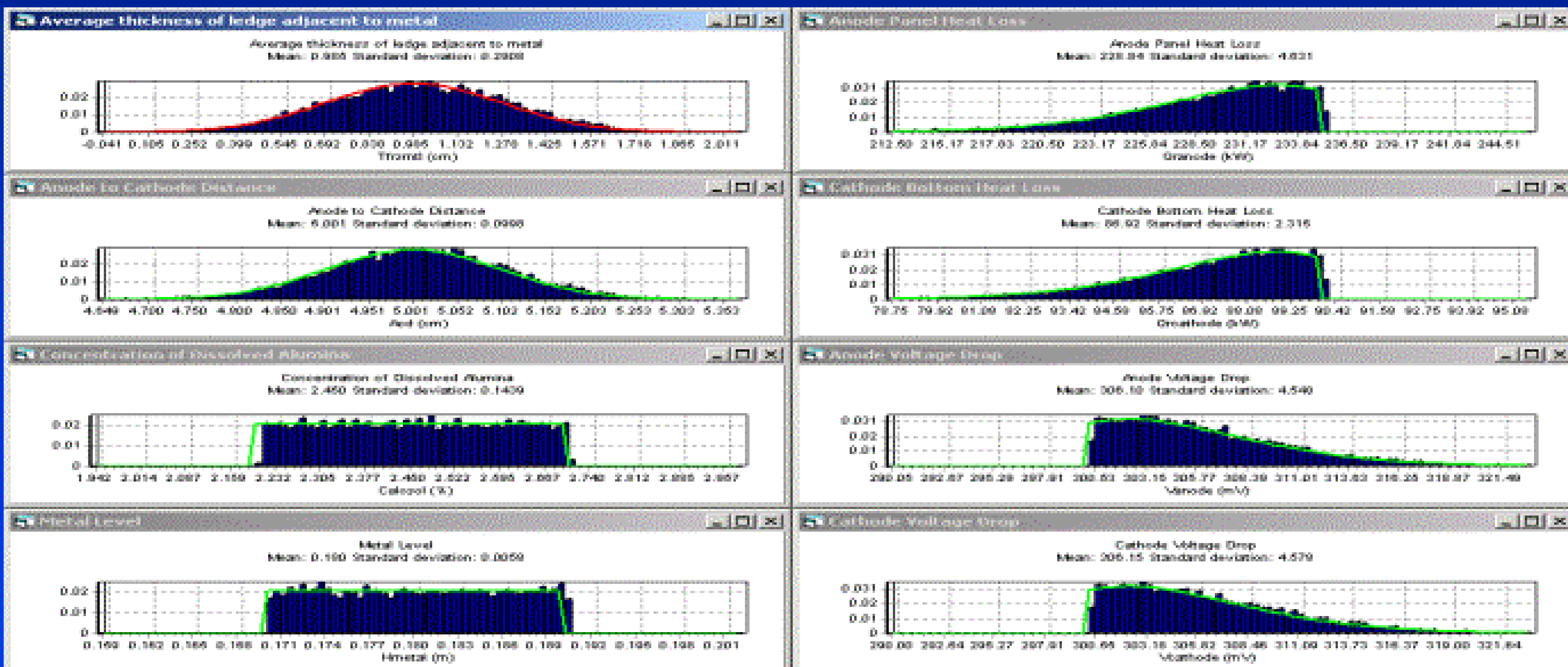
Dyna/Marc Lump Parameters+ Model

Later on, the Monte Carlo statistical tool of Dyna/Marc can be used to perform a risk assessment analysis, which is important because no mathematical model is 100% accurate and often a 5% compound inaccuracy on the main models predictions can translate into a 25% offset between the predicted and prototype measured average thickness of the ledge at the metal level for example.

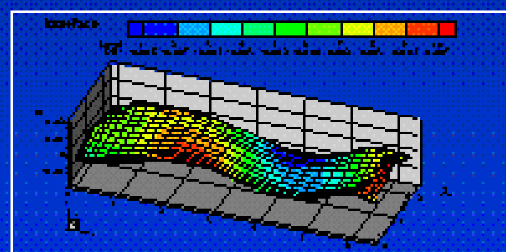


ANSYS®-based Steady-State Finite Element Thermo-Electric Models

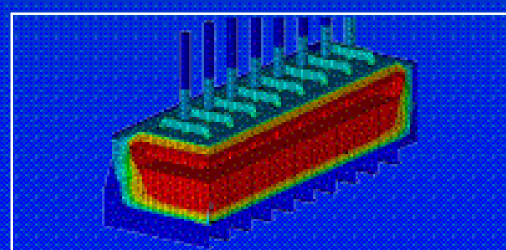
One of the main three pillars of Hall-Héroult cell design

- Stress models which are generally associated with cell shell deformation and cathode heaving issues.

- Magneto-hydro-dynamic (MHD) models which are generally associated with the problem of cell stability.



- Thermal-electric models which are generally associated with the problem of cell heat balance.



Cell Design

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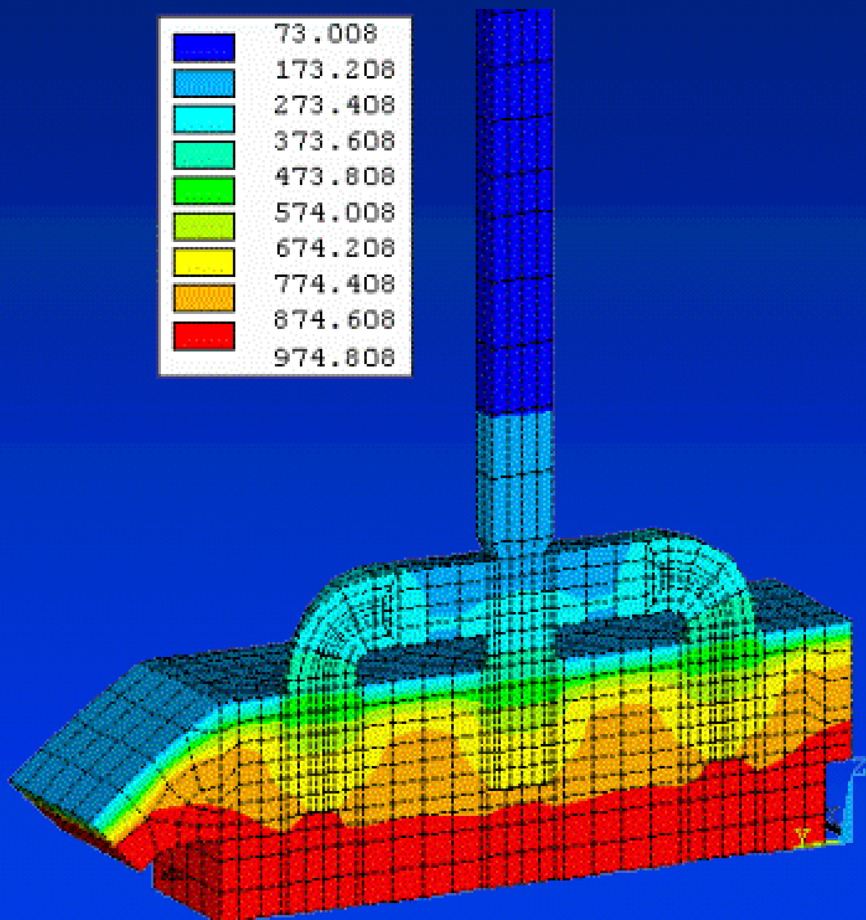
ANSYS®-based Steady-State Finite Element Thermo-Electric Models



Half-anode model

**** HEAT BALANCE TABLE ****
**** Half Anode Model : VAW 300 ****

HEAT INPUT	W	W/m^2	%
Bath to anode carbon	1491.59	1508.61	42.16
Bath to crust	642.57	3161.81	18.16
Joule heat	1403.42		39.67
Total Heat Input	3537.57		100.00

HEAT LOST	W	W/m^2	%
Crust to air	1394.79	1651.42	38.50
Studs to air	1819.48	4067.71	50.22
Aluminum rod to air	408.50	693.78	11.28
Total Heat Lost	3622.77		100.00

Solution Error 2.35 %

ANODE PANEL HEAT LOST	KW	W/m^2	%
Crust to air	89.27	1651.42	38.50
Studs to air	116.45	4067.71	50.22
Aluminum rod to air	26.14	693.78	11.28
Total Anode Panel Heat Lost	231.86		100.00

Avg. Drop at clamp (mV)	Current at anode Surf (Amps)
302.910	4687.500

Targeted cell current: 300000.00 Amps
Obtained cell current: 300000.00 Amps

Solution Error .00 %

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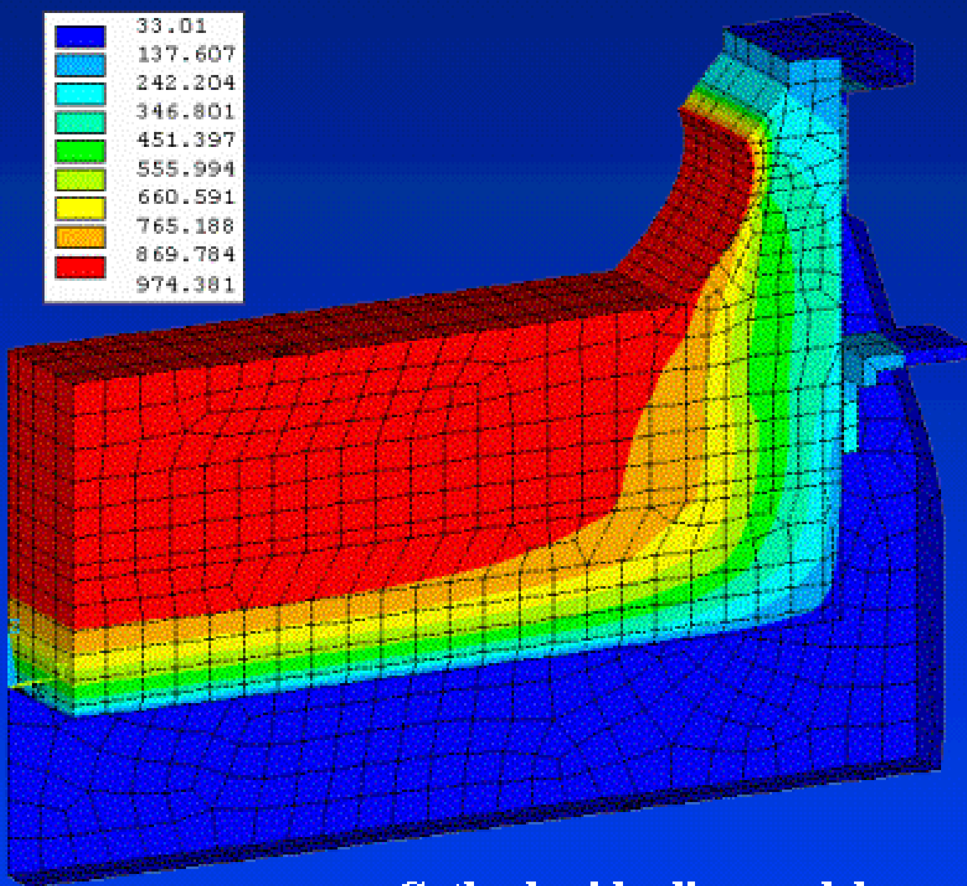
ANSYS®-based Steady-State Finite Element Thermo-Electric Models



Cathode side slice model

**** HEAT BALANCE TABLE ****
**** Side Slice Model : vaw_20 ****
**** Freeze profile stopped ****
**** after 10. iterations ****

MODEL HEAT IN/OUT	W	W/m^2	%
Total Heat Input	4517.31		100.00
Total Heat Lost	4545.21		100.00

Solution Error .61 %

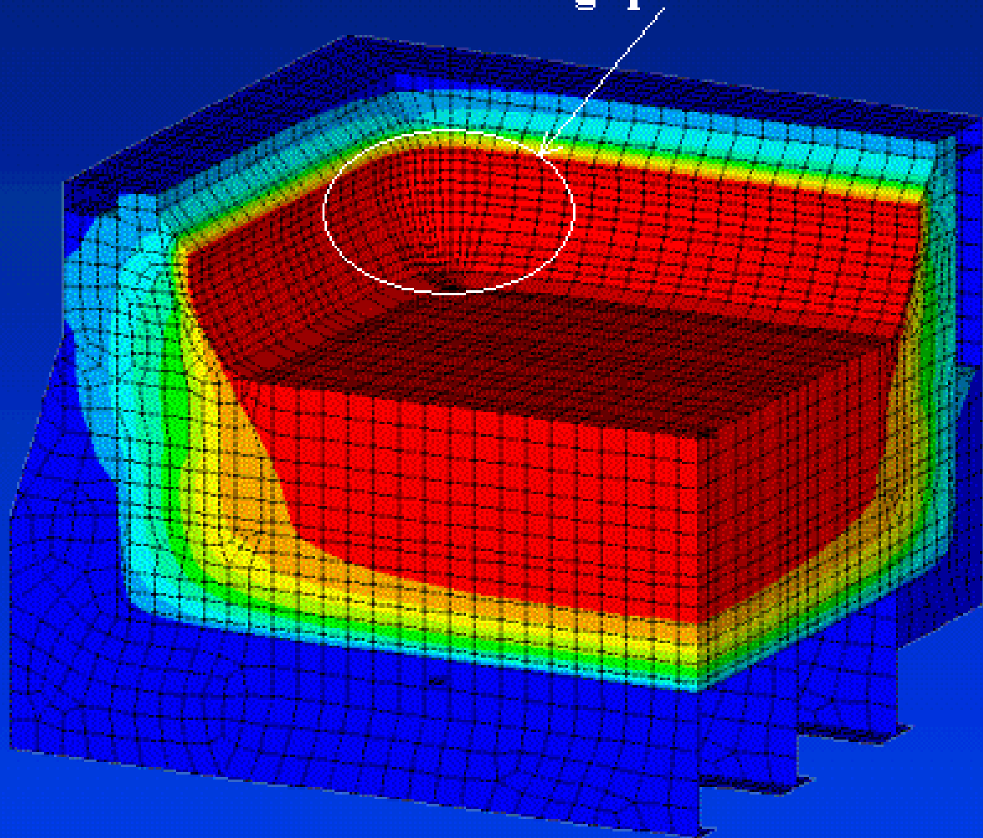
CATHODE HEAT LOST	KW	W/m^2	%
Shell wall above bath level	62.81	1344.21	15.99
Shell wall opposite to bath	40.42	5399.96	10.29
Shell wall opposite to metal	40.61	7220.85	10.34
Shell wall opposite to block	83.88	5797.58	21.36
Shell wall below block	8.91	669.22	2.27
Shell floor	24.02	414.59	6.12
Cradle above bath level	2.67	1585.30	.68
Cradle opposite to bath	9.58	2164.69	2.44
Cradle opposite to metal	6.30	2601.20	1.60
Cradle opposite to block	25.24	927.80	6.43
Cradle opposite to brick	3.74	159.54	.95
Cradle below floor level	14.74	99.09	3.75
Bar and Flex to air	45.23	2653.04	11.52
End of flex to busbar	24.54	40579.69	6.25
Total Cathode Heat Lost	392.71		100.00

Avg. Drop at Bar End (mV)	Average Flex. Drop (mV)	Current at Cathode Surf (Amps)
285.44	7.474	4166.667

Targeted cell current: 300000.00 Amps
Obtained cell current: 300000.00 Amps

Solution Error .00 %

ANSYS®-based Steady-State Finite Element Thermo-Electric Models



Cathode corner model

**** HEAT BALANCE TABLE ****
**** Side Slice Model : vaw_20 ****
**** Freeze profile stopped ****
**** after 5. iterations ****

HEAT INPUT	W	W/m^2	%
Total Heat Input	32208.66		100.00

SIDE HEAT LOST	W	W/m^2	%
Total Side Heat Lost	16161.42		100.00

END HEAT LOST	W	W/m^2	%
Shell wall above bath level	3565.04	1177.54	13.22
Shell wall opposite to bath	2405.54	4724.46	8.49
Shell wall opposite to metal	2392.08	6408.56	8.66
Shell wall opposite to block	4462.34	5318.25	18.10
Shell wall below block	523.08	629.74	2.01
End stiffener above bath level	109.09	587.13	.68
End stiffener opposite to bath	388.02	476.37	2.41
End stiffener opposite to metal	260.99	466.88	1.62
End stiffener opposite to block	1064.37	970.85	6.60
End stiffener opposite to brick	206.19	276.89	1.28
End stiffener below floor level	855.13	108.22	5.30
Total End Heat Lost	16119.37		100.00

Total Heat Lost	32280.79		100.00

Solution Error .22 %

Avg. Drop at Bar End (mV)	Average Flex. Drop (mV)	Current at Cathode Surf (Amps)
280.221	7.355	16666.667

Targeted cell current: 300000.00 Amps
Obtained cell current: 300000.00 Amps

Solution Error .00 %

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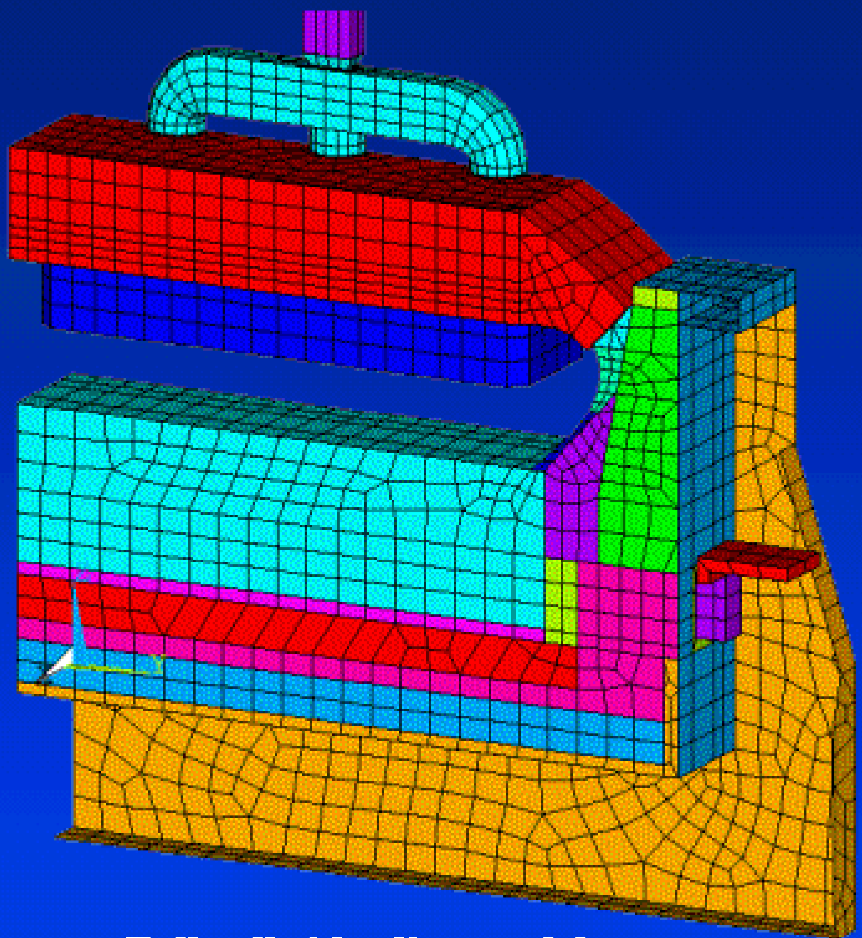
ANSYS®-based Steady-State Finite Element Thermo-Electric Models



Full cell side slice model

HEAT BALANCE SUMMARY
Full slice Model : VAW 300

INTERNAL HEAT CALCULATION	
Operating temperature	972.17 °C
Bath Resistivity	.424563 ohm-cm
Anode Current Density	.732422 A/cm^2
Cathode Current Density	.668449 A/cm^2
Bath Voltage	1.58152 volts
Electrolysis Voltage	1.92456 volts
Total Cell Voltage	4.29380 volts
Equivalent Voltage to Make Metal	2.01837 volts
Current Efficiency	93.2480 %
Internal Heat Generation	622.630 KW

TOTAL HEAT LOST	
Total Anode Panel Heat Loss	237.289 KW
Total Cathode Heat Loss	385.233 KW
Total Cell Heat Loss	622.522 KW

HEAT UNBALANCE .02 %

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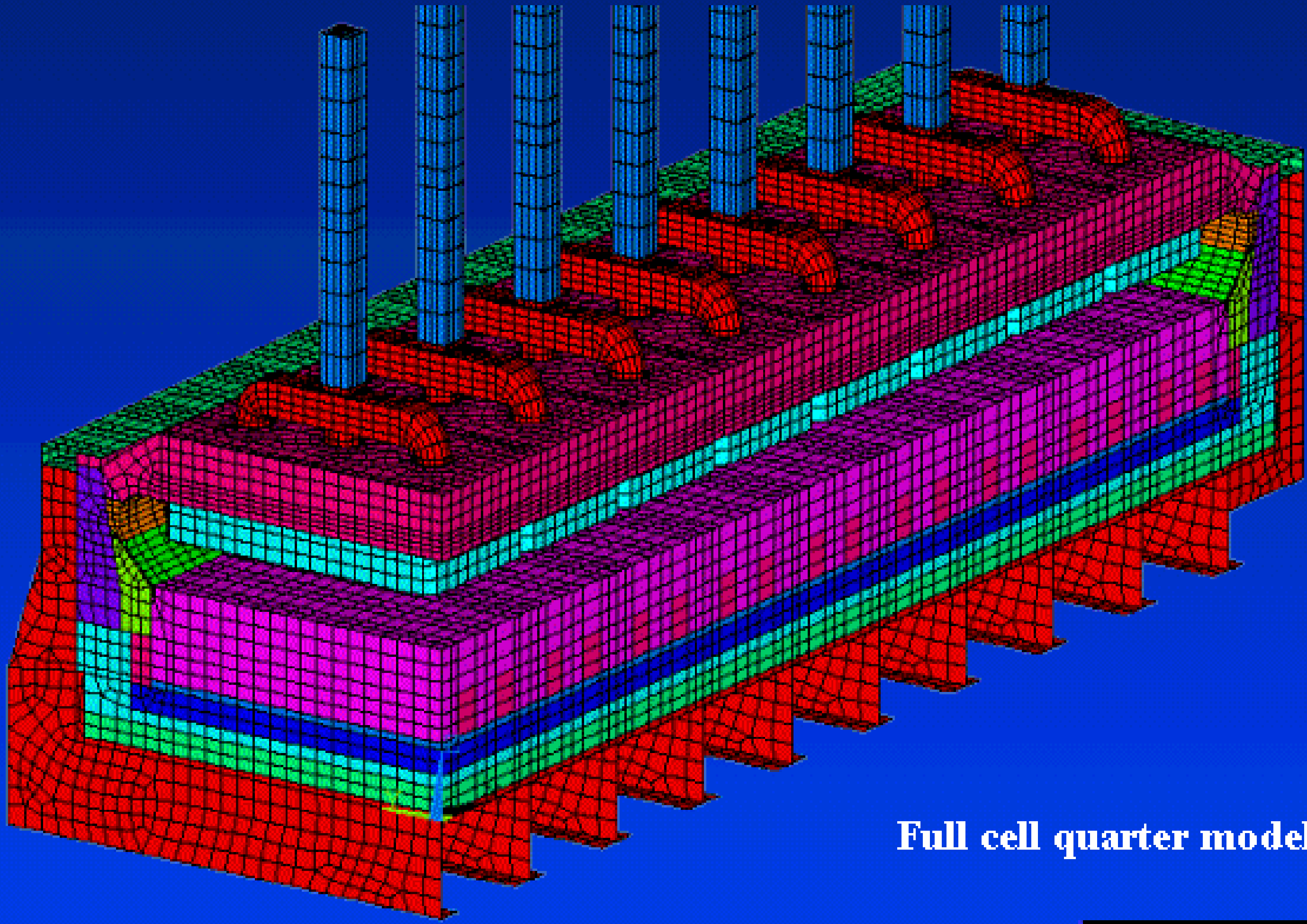
ANSYS®-based Steady-State Finite Element Thermo-Electric Models



Full cell quarter model

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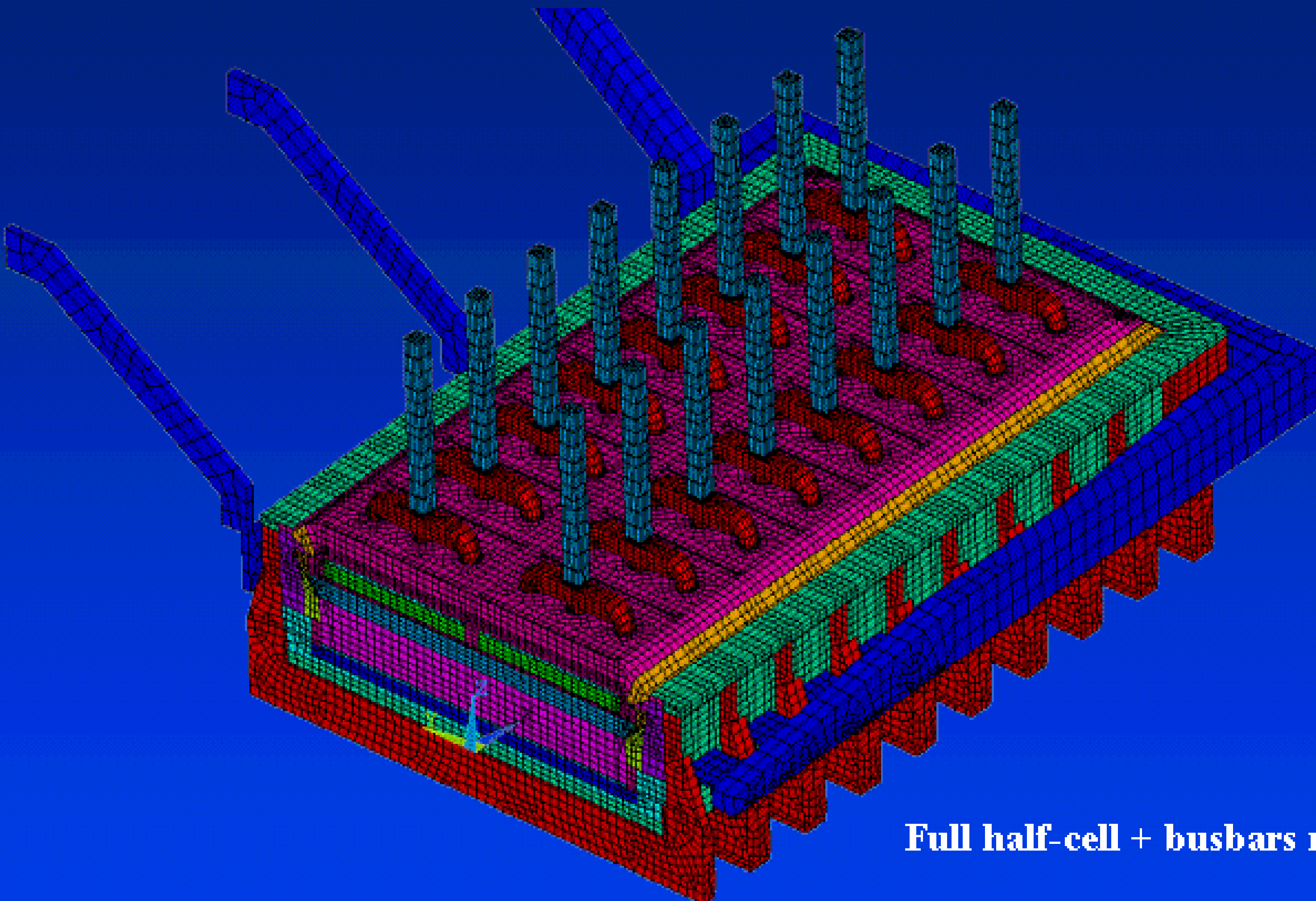
ANSYS®-based Steady-State Finite Element Thermo-Electric Models



Full half-cell + busbars model

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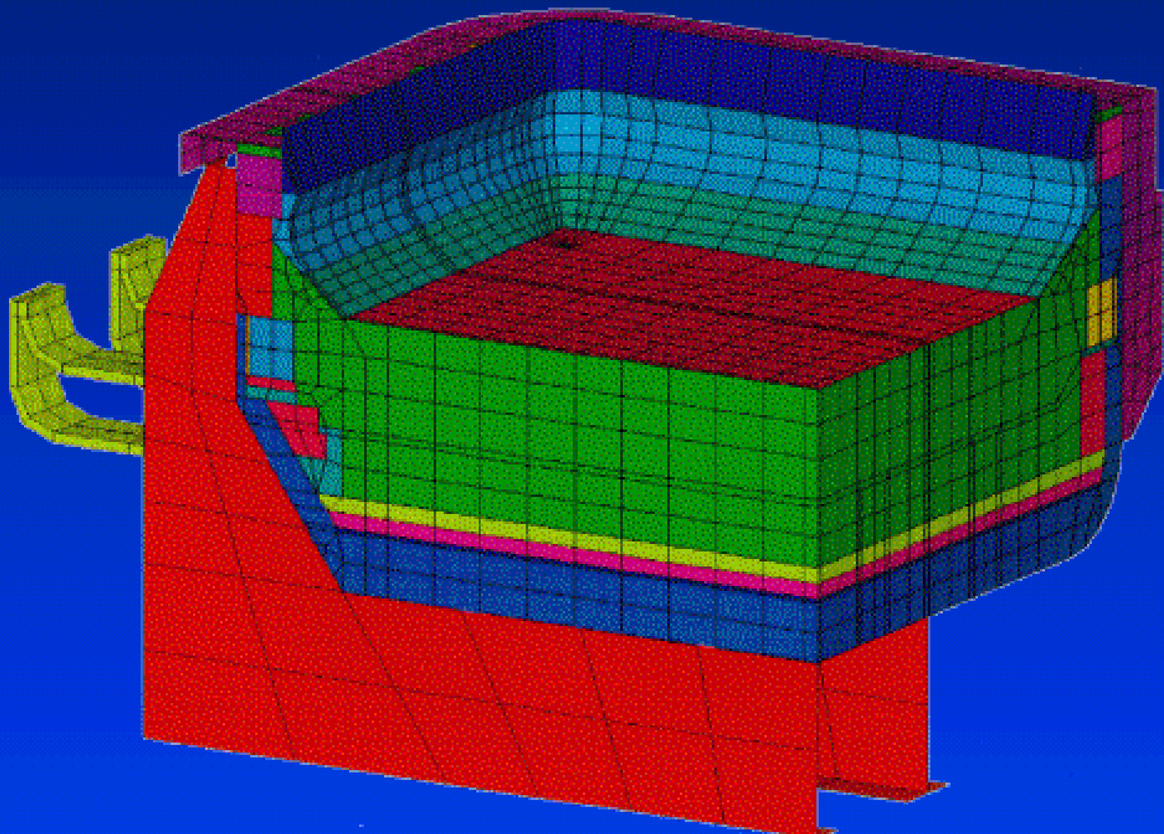
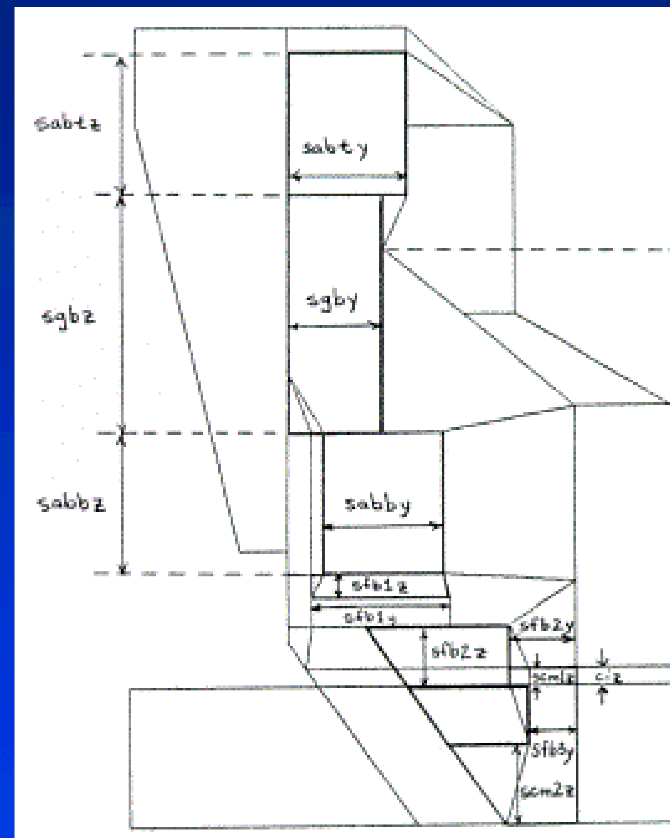
ANSYS®-based Steady-State Finite Element Thermo-Electric Models



Alcoa P-155 corner model



Part of the P-155 model topology

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Calibration and Validation of the Mathematical Models

To be considered validated, a new model must be able to well reproduce the existing cell measured heat balance. Typically, the most difficult part of the model development and validation exercise is obtaining reliable data of a cell heat balance from a thermal blitz campaign.

Thermal blitz heat flux measurements

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Examples of Applications of an ANSYS®-based 3D Full Cell Slice Thermo-Electric Model

	Base Case	Retrofit 1	Retrofit 2
Cell amperage (kA)	300	350	265
Cell internal heat (kW)	628	713	427
Cell kWh/kg	13.75	13.40	11.94

Those two extreme cases clearly demonstrate that as far as the cell thermal balance is concerned, the window of opportunities is quite wide. Only a complimentary technico-economical study can indicate which of the two retrofit scenarios offers the best return on investment (obviously, the outcome of that study will mostly depend on the selected long-term cost of the electrical power).

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Conclusions

- These days, with the support of well established and reliable mathematical models, older smelters operating at 17-18 kWh/kg due to a poor thermal design should be able to come up with successful retrofit design proposal(s) well within a year, test that (those) design proposal(s) in prototypes during a minimum of two years and then be able to proceed to a full implementation phase.
- As far as the thermal balance problem of the cell is concerned, there is no known technical reason that should prevent a significant reduction of their power consumption.

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