# Using Mathematical Models to Improve the Efficiency of Hall-Héroult Cells

Dr Marc Dupuis

GENISIM

# Plan of the Presentation

- GeniSim
- Industry Challenge and a Cell Retrofit Success Story
- Introduction to H.H. Cell Mathematical Models
- ANSYS®-based 3D Steady-state Finite Element Thermo-electric Models
- Description of a 3D Steady-state Cathode Side Slice Model
- Validation of a 3D Steady-state Thermo-electric Model
- Examples of Applications of an ANSYS®-based 3D Full Cell Side Slice Thermo-electric Model
- Conclusions

GENISIM

# GENISIM

a Canadian company 100%
owned by Dr. Marc Dupuis

- Offers independent cell modeling and design expertise
- Distributes licenses of its proprietary aluminium reduction cell modeling technology

GENISIM

# GENISIM

## Dr. Marc Dupuis Experience Building
## T/E Models

With Alcan
1987-1994:

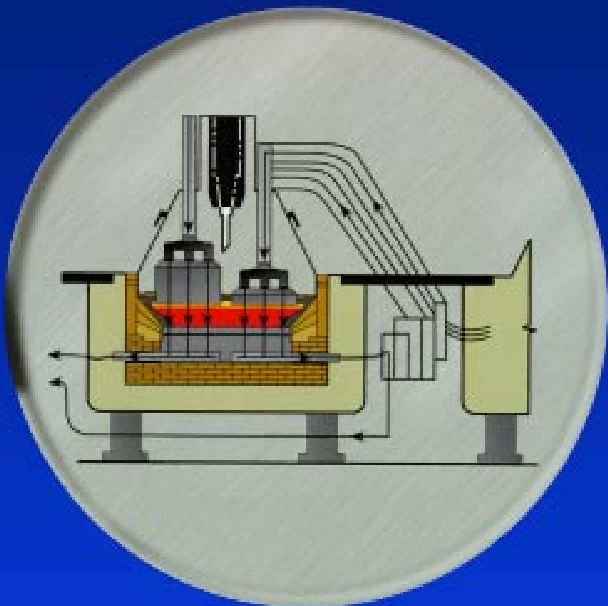
- Alcan prototypes: A275, A265-H, A310
- Alcan prebaked: A70, A140, A165
- Alcan HSS
- Alcoa P155
- Pechiney AP18

With GeniSim
1996-2002:

- Pechiney AP30
- Alcoa: P155, A697
- Reynolds prebaked: P-19, P-20S, P-23S
- Kaiser P69
- Reynolds HSS
- Pechiney HSS
- Alcan VSS

GENISIM

# Industry Challenge



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

# GENISIM

| | START-UP 1992 | LATEST POTS 1998 |
|---|---|---|
| **PRODUCTION :** | | |
| • Production per pot/day (kg) | 2245 | 2486 |
| • Current efficiency (%) | 94.5 | 96 |
| **POWER :** | | |
| • Amperage (kA) | 295 | 319 |
| • Pot voltage (V) | 4.330 | 4.185 |
| • DC kWh/t | 13 650 | 13 000 |
| **CONSUMPTIONS :** | | |
| • Gross carbon (kg/t) | 540 | 493 |
| • Net carbon (kg/t) | 410 | 397 |
| • Anodes cycle-shifts-8 hours | 80 | 90 |
| **METAL PURITY :** | | |
| • Iron (ppm) | --- | 700 |
| • Silicon (ppm) | --- | 240 |
| **POT CONDITION :** | | |
| • Anode effects (pot/day) | 0.40 | 0.20 |

Tableau no. 1 : Lauralco's results

## Success Story

**Lauralco used GeniSim 3D ANSYS® thermo-electric models and Dyna/Marc cell simulator to improve their cell lining design.**

**Lauralco is now considered one of the most efficient smelter in the industry.**

GENISIM

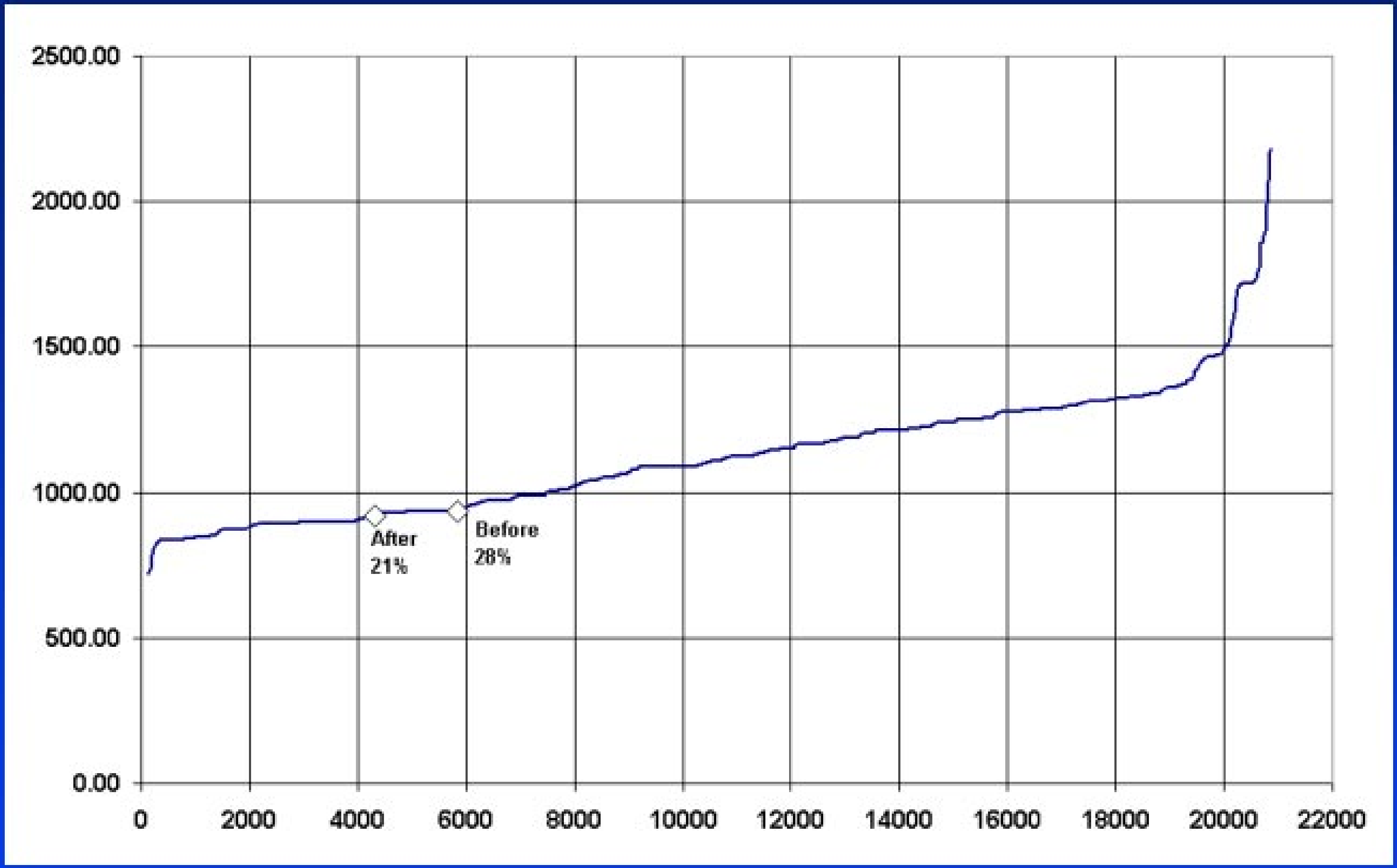
# Lauralco Retrofit Results (based on CRU data)

**1993 Operating Costs**
(contains no depreciation or other charge for capital)
($/ton except where noted)

| | Before | After |
|---|---|---|
| **Smelter** | **Deschambault** | **Deschambault** |
| **Country** | **Canada** | **Canada** |
| **Company** | **Alumax** | **Alumax** |
| **Capacity (tpy)** | 224 | 235 |
| **Electricity usage (kWh/t)** | 13650 | 13000 |
| **Electricity price ($/kWh)** | 0.012 | 0.012 |
| **Total electricity cost:** | 163.03 | 155.27 |
| **Alumina usage (t/t Al)** | 1.92 | 1.92 |
| **Alumina price ($/t Alumina)** | 204.80 | 204.80 |
| **Total alumina cost:** | 393.22 | 393.22 |
| **Other raw materials** | 88.44 | 88.44 |
| **Plant power and fuel** | 7.54 | 7.54 |
| **Consumables** | 38.29 | 38.29 |
| **Maintenance** | 52.93 | 52.93 |
| **Labor** | 82.00 | 78.00 |
| **Freight** | 39.09 | 39.09 |
| **General and administrative** | 67.71 | 67.71 |

GENISIM

# Lauralco Retrofit Results (based on CRU data)



# Introduction to H.H. Cell Models

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

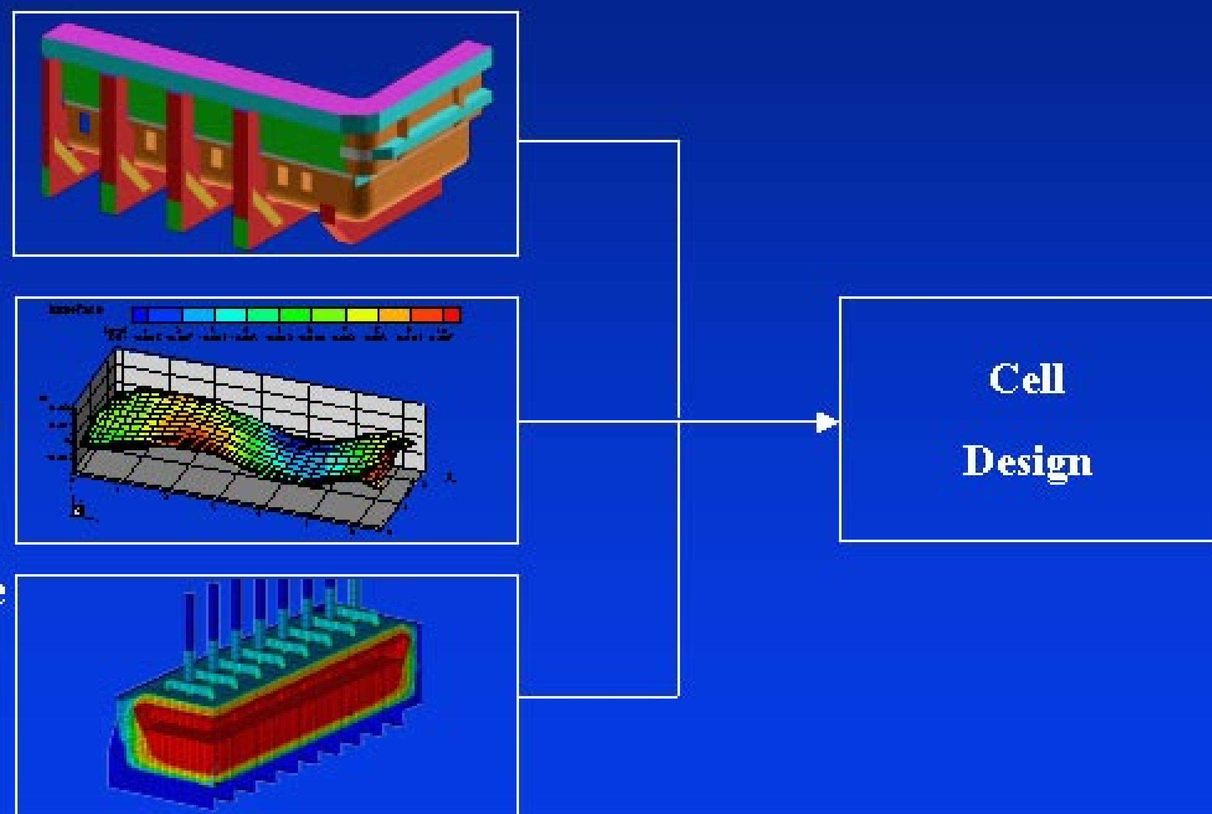
4) Transient thermo-mechanical cell start-up model

GENISIM

# Introduction to H.H. Cell Models

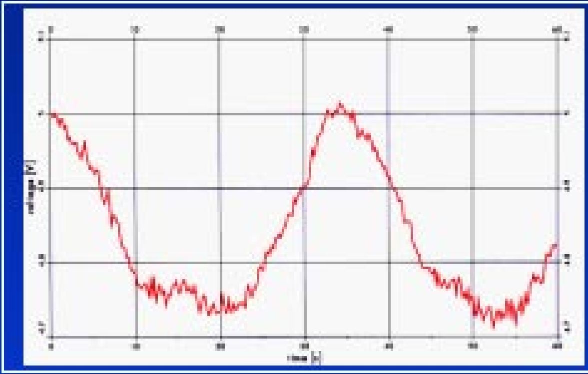
**The main three pillars of Hall-Héroult cell design**

- 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.

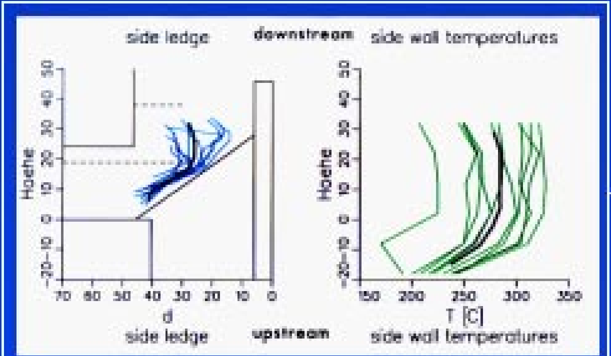


# Introduction to H.H. Cell Models

**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

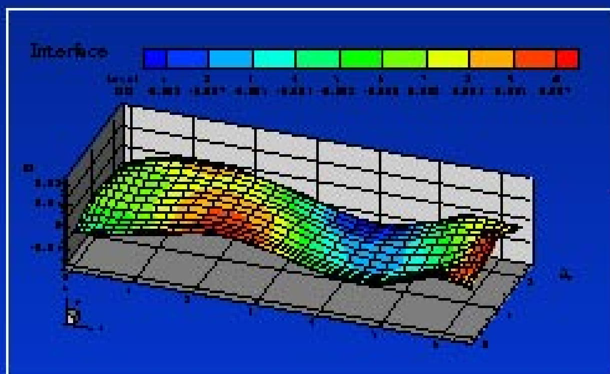
**Base Case**

**Cell Design**

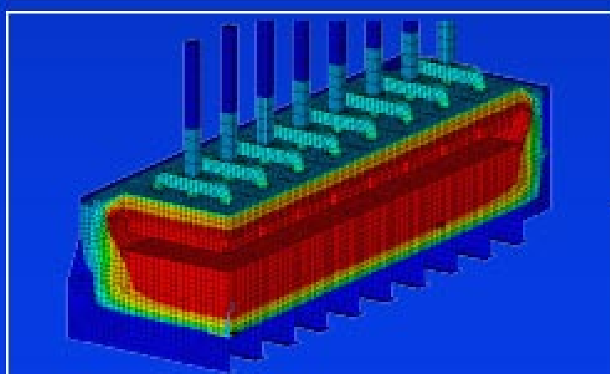
GENISIM

# Introduction to H.H. Cell 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**



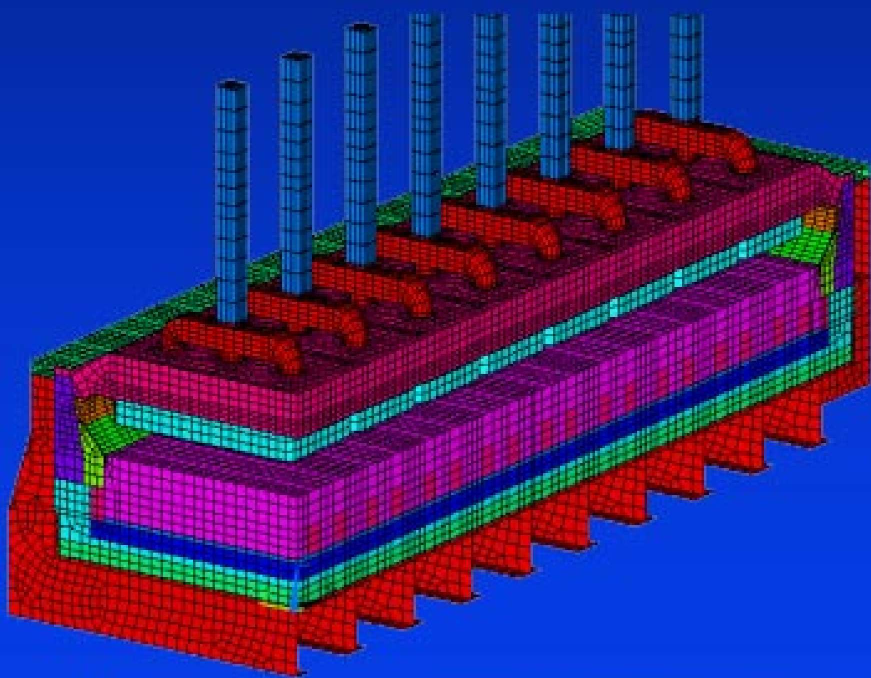
**Thermo-electric Model**

→ **Retrofitted Cell Design**

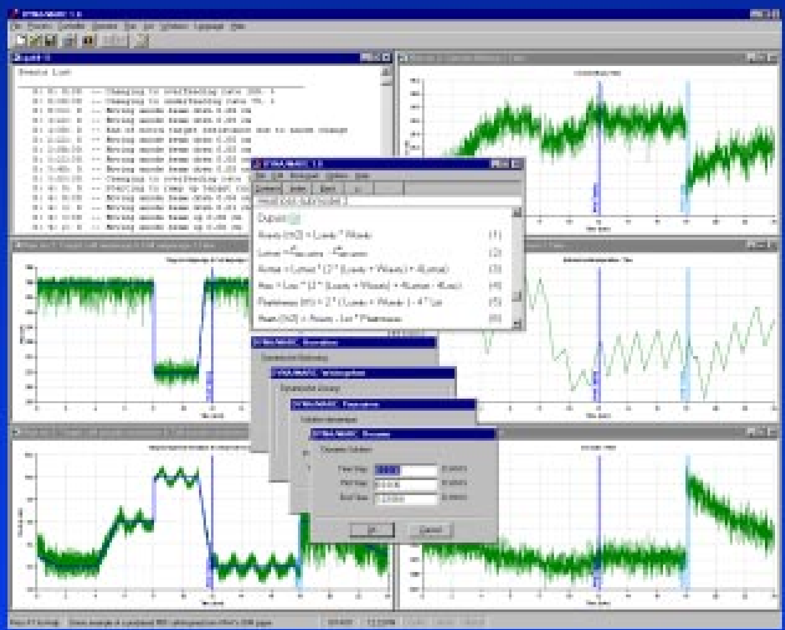
GENISIM

# Introduction to H.H. Cell Models: Thermo-electric Models from GeniSim

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



**Dyna/Marc lump parameters+ model**



GENISIM

# Dyna/Marc Lump Parameters+ Model

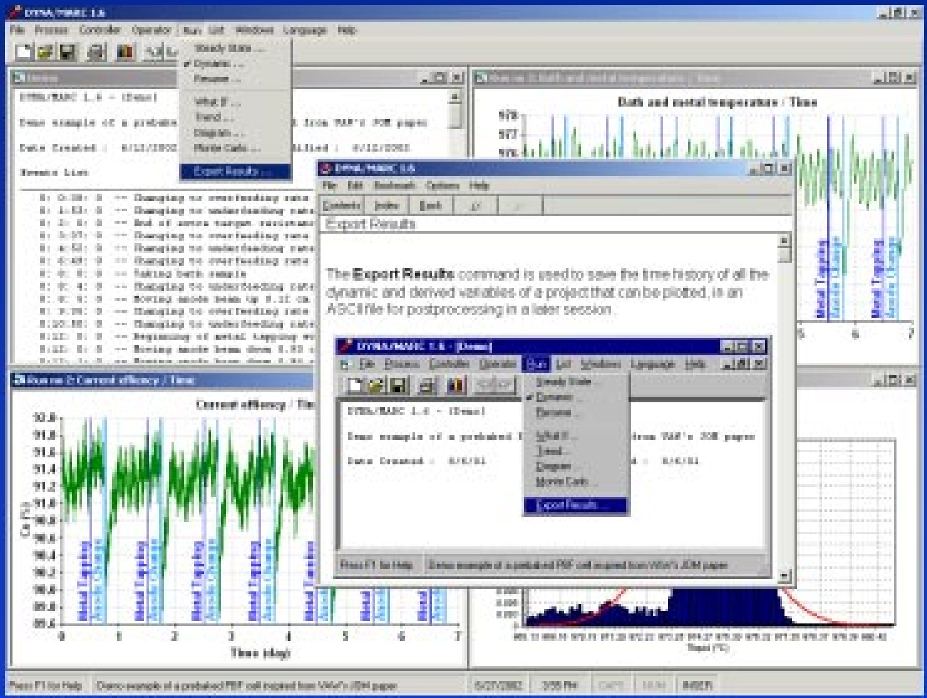
**DYNA/MARC (DYNAmic Model of Aluminum Reduction Cells) is a dynamic simulator of the behavior of aluminum reduction cells.**

**DYNA/MARC is composed of three different models.**

**The first is the <u>Process model</u>, 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.**

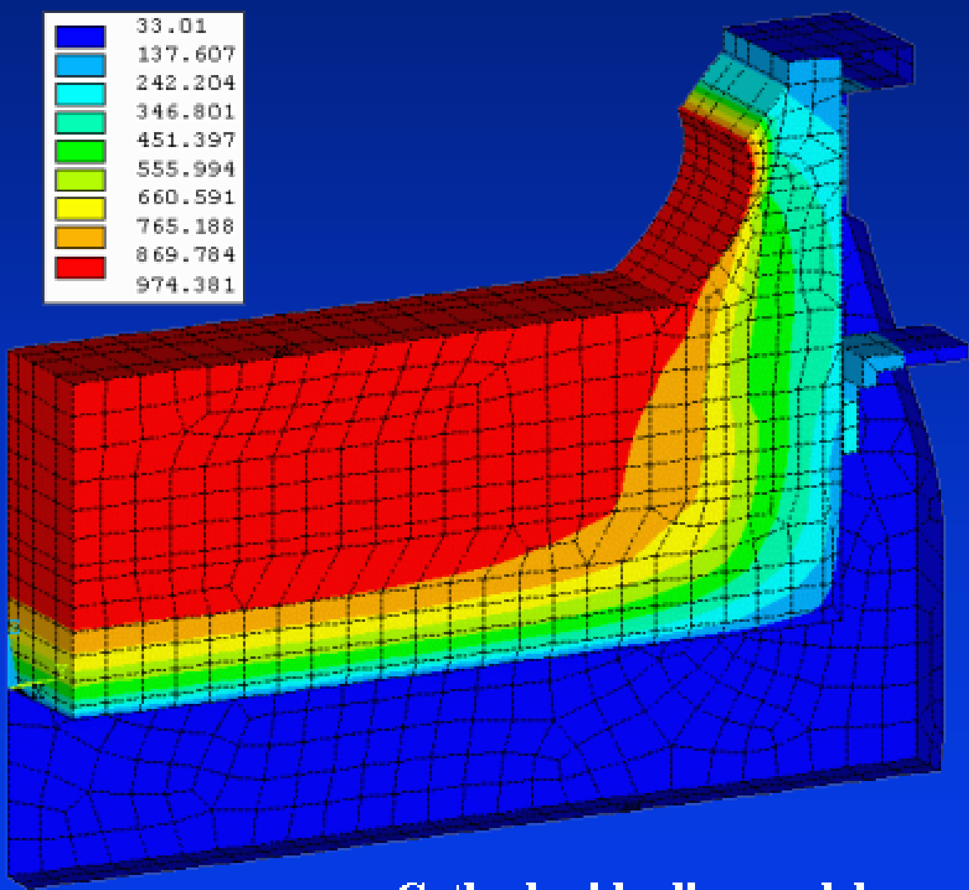
**The second model is the <u>Controller model</u>. This reproduces the plant controller response based on all the programmed algorithms taking into account the current cell state.**

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




GENISIM

# 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 |

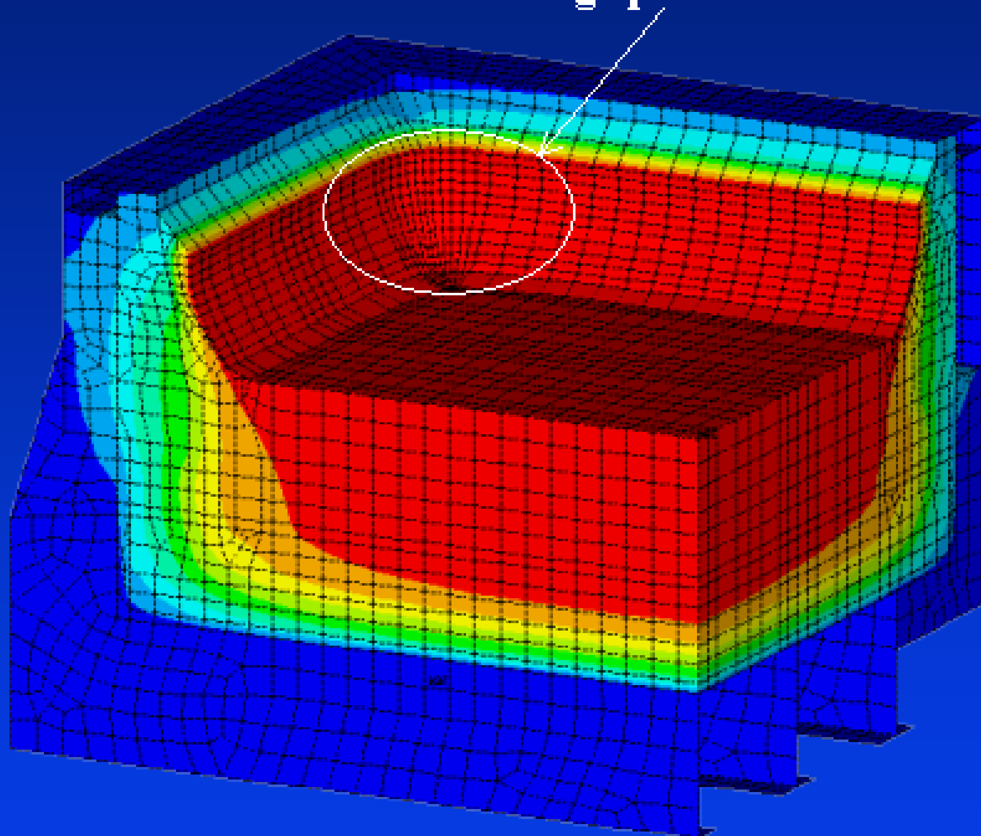
| Avg. Drop at Bar End (mV) | Average Flex. Drop (mV) | Current at Cathode Surf (Amps) |
|---|---|---|
| 285.44 | 7.474 | 4166.667 |

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

Solution Error .00 %

GENISIM

# 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 |

| | W | | % |
|---|---|---|---|
| Total Heat Lost | 32280.79 | | 100.00 |

Solution Error .22 %

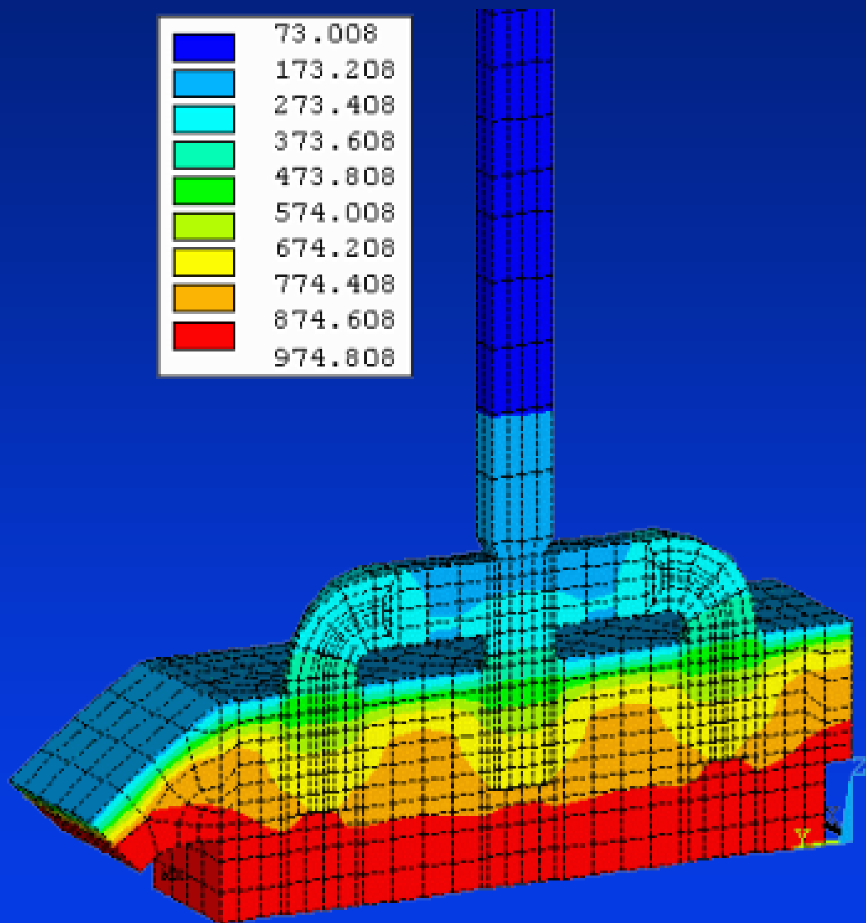
| Avg. Drop at Bar End (mV) | Average Flex. Drop (mV) | Current at Cathode Surf (Amps) |
|---|---|---|
| 280.221 | 7.355 | 16666.667 |

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

Solution Error .00 %

GENISIM

# 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 %

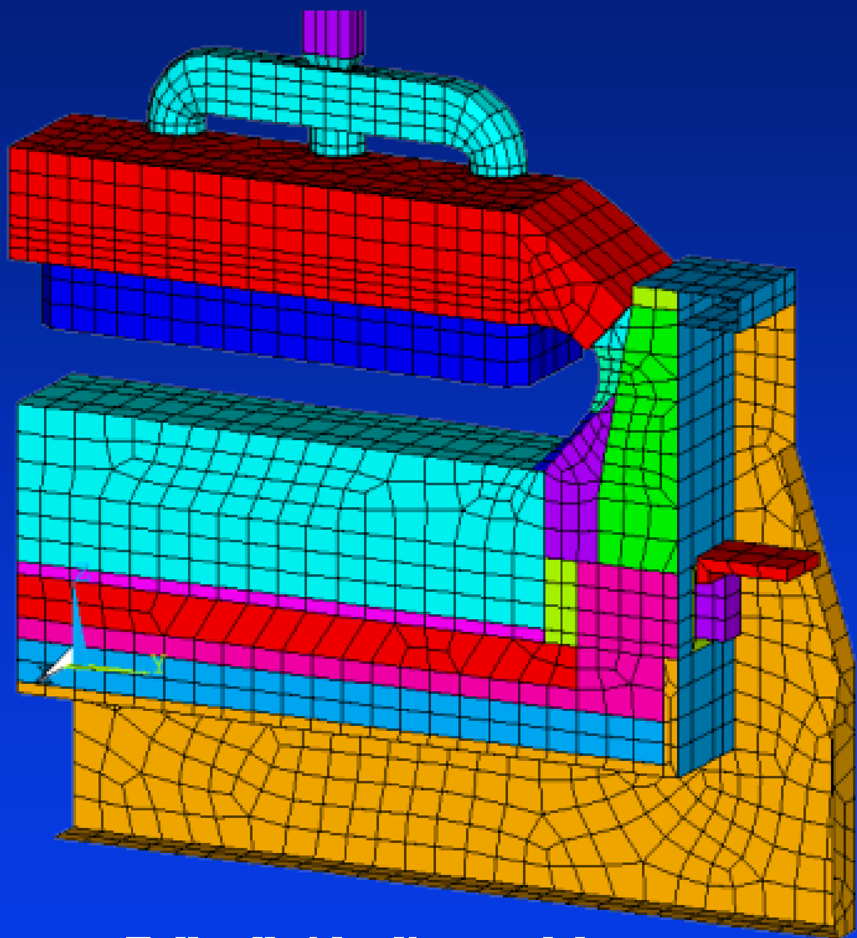
| ANODE PANEL HEAT LOST | KW | W/m^2 | % |
|---|---|---|---|
| Crust to air | 89.27 | 1651.42 | 38.50 |
| Studs to air | 116.45 | 4067.71 | 50.22 |
| Aluminum rod to air | 26.14 | 693.78 | 11.28 |
| Total Anode Panel Heat Lost | 231.86 | | 100.00 |

| 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 %

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



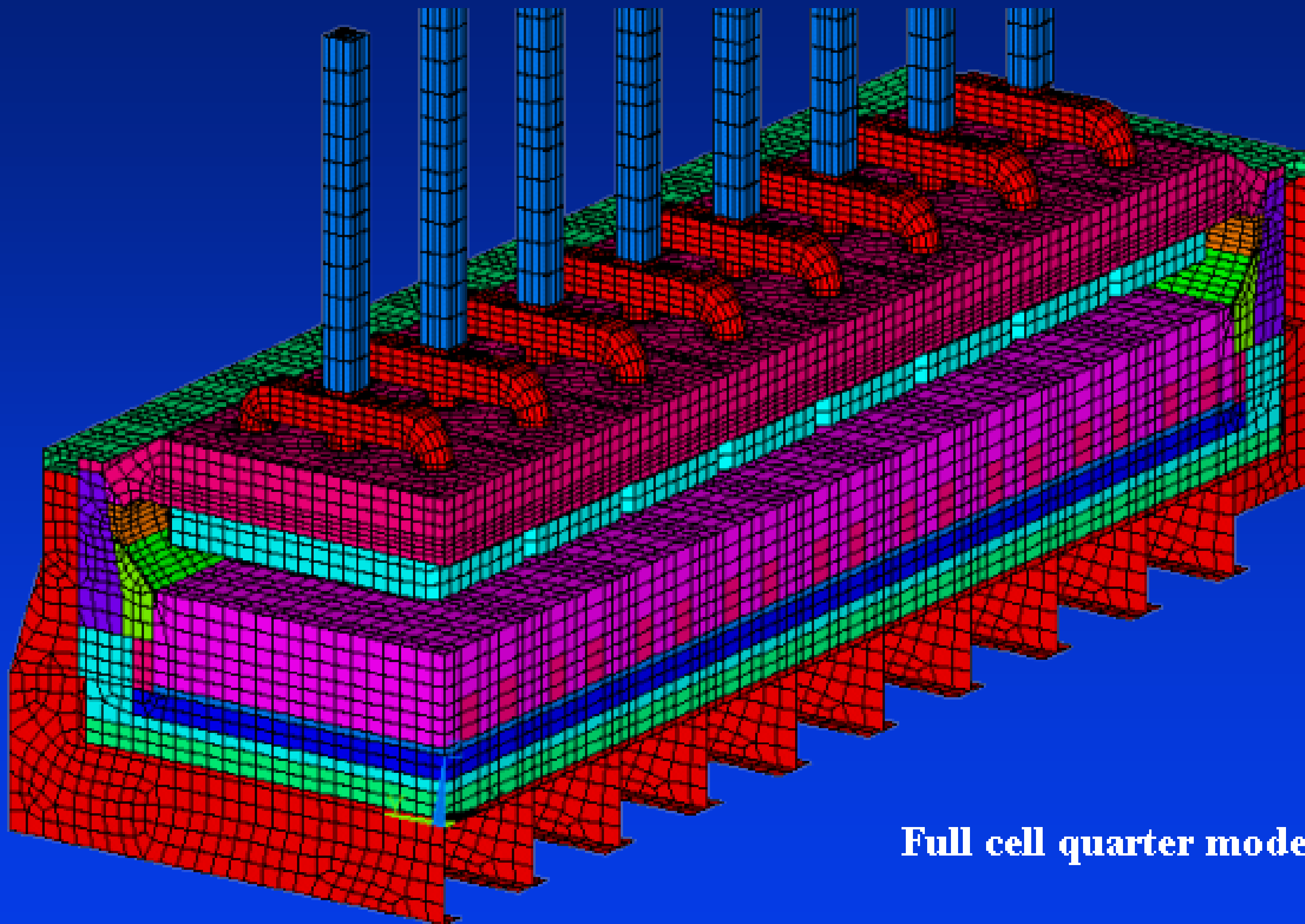
Full cell side slice model

**** 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 % |

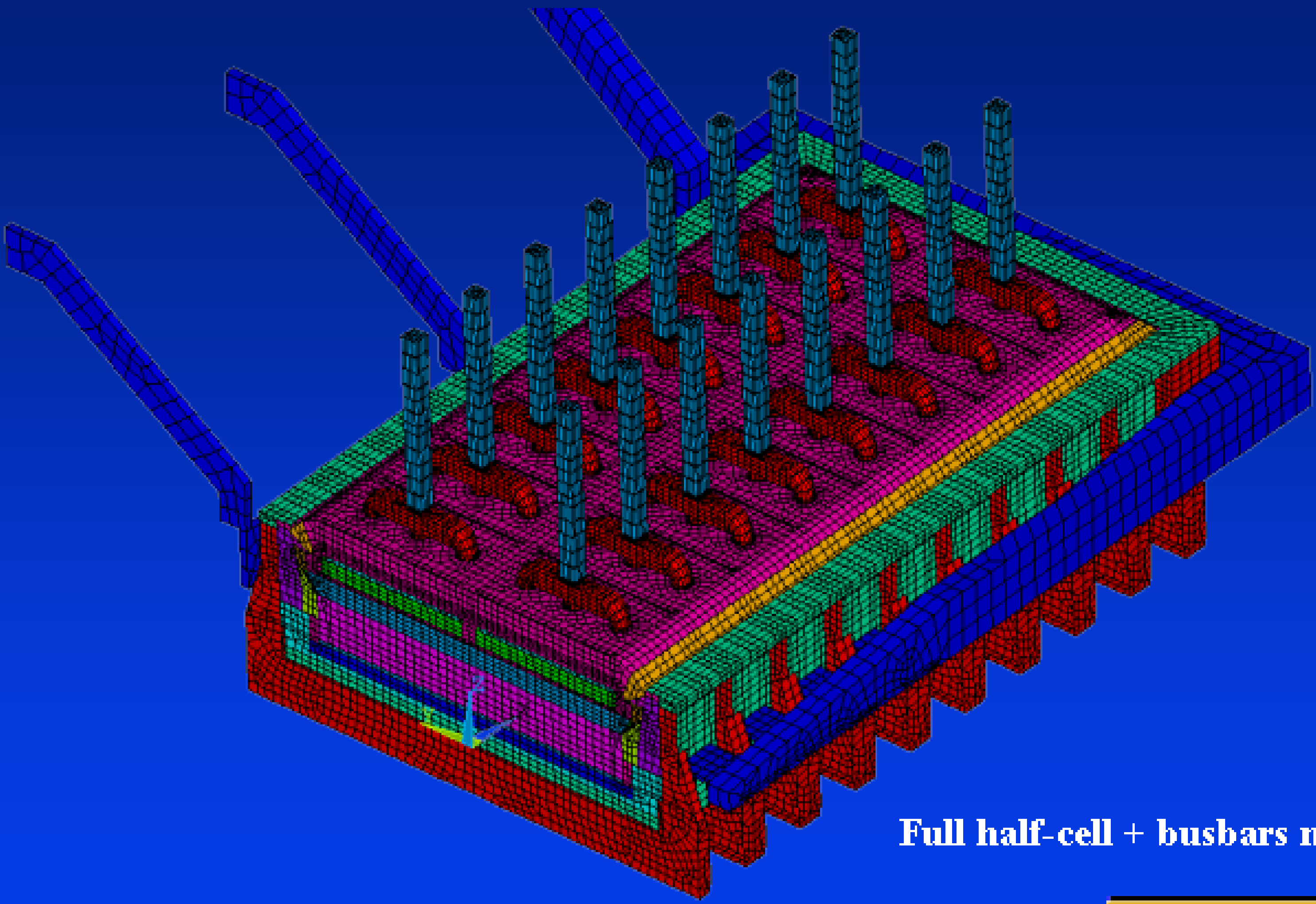
GENISIM

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



Full cell quarter model

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



Full half-cell + busbars model

GENISIM

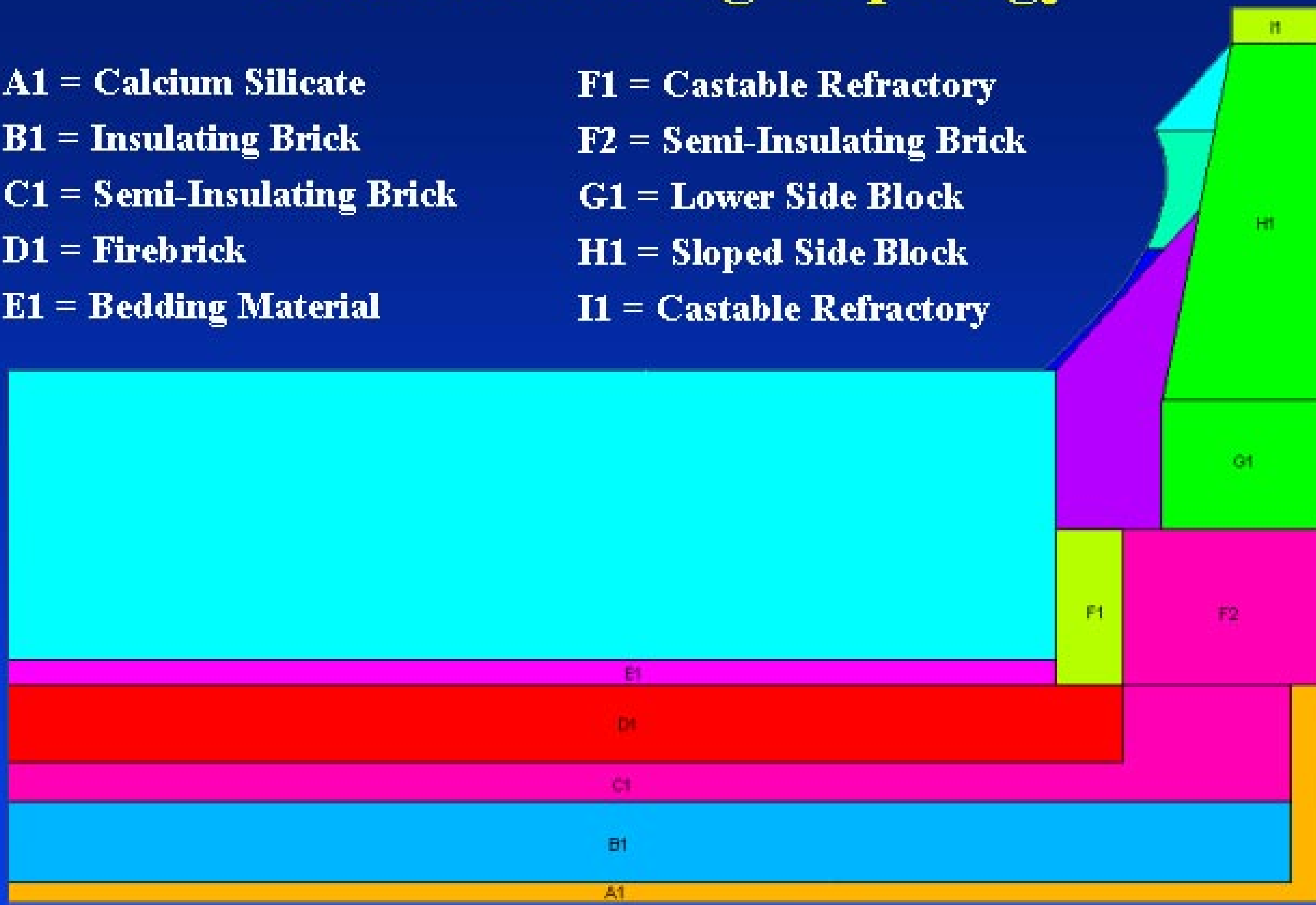
# Description of a 3D Steady-state Cathode Side Slice Model

GENISIM

# Cathode Lining Topology

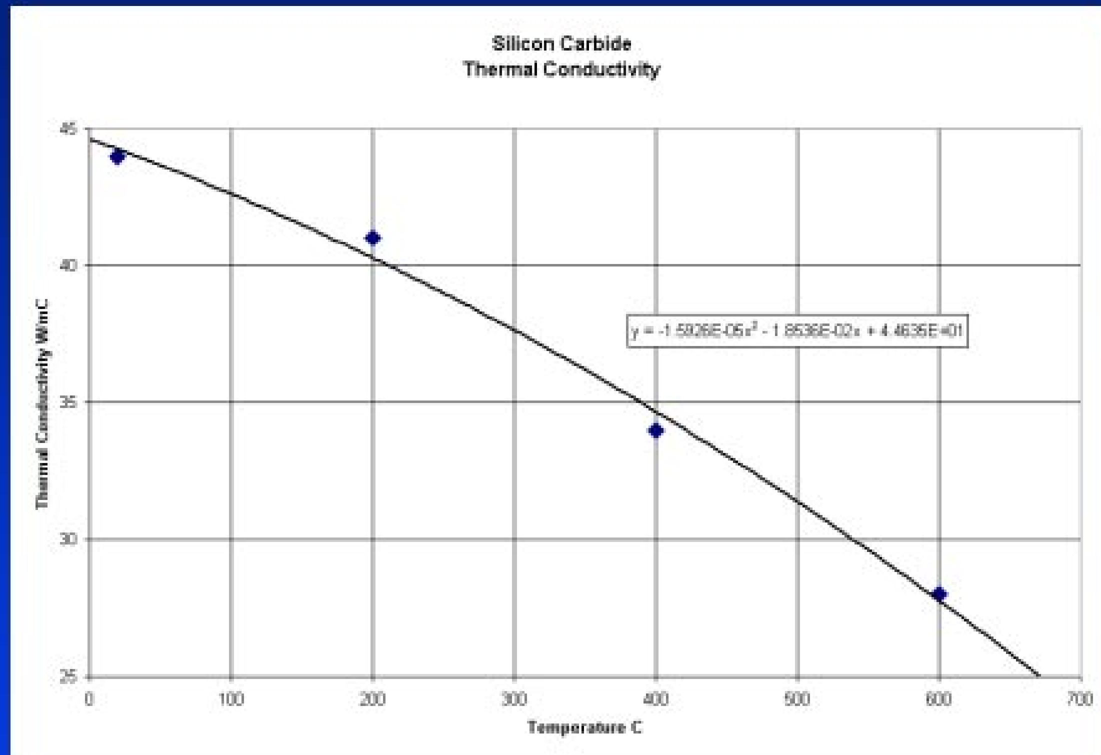
A1 = Calcium Silicate
B1 = Insulating Brick
C1 = Semi-Insulating Brick
D1 = Firebrick
E1 = Bedding Material

F1 = Castable Refractory
F2 = Semi-Insulating Brick
G1 = Lower Side Block
H1 = Sloped Side Block
I1 = Castable Refractory



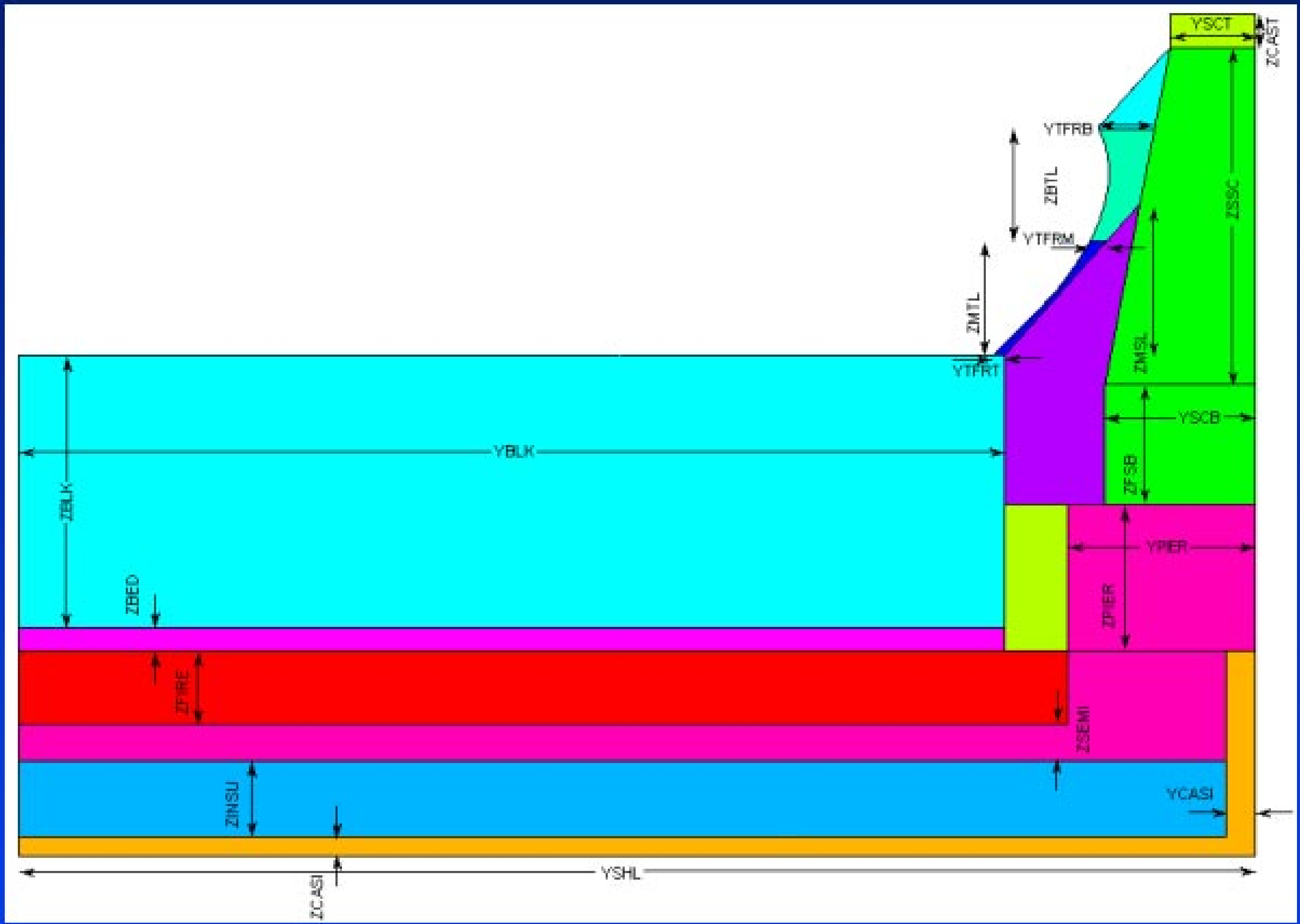
# Non-Linear Material Properties

| Material | Thermal Conductivity (W/m/K) | Specific Heat (J/kg/K) | Density at 25°C (kg/m³) |
|---|---|---|---|
| 1. Steel | 44.3(100°C); 41.4(200°C); 38.5(300°C); 35.6(over 400°C) | 459.8 | 7800 |
| 2. Calciumsilicate | 0.07(200°C); 0.09(400°C); 0.10(over 600°C) | 840 | 245 |
| 3. Glass | 0.83(over25°C) | 752.4 | 2200 |
| 4. Alumina | 0.155(100°C); 0.167(200°C); 0.182(300°C); 0.21(500°C); 0.238(700°C); 0.25(over 800°C) | 850 | 3900 |
| 5. Vermiculite(1) | 0.17(200°C); 0.20(400°C); 0.22(over 600°C) | 800 | 600 |
| 6. Castable | 0.75(over 25°C) | 794 | 2000 |
| 7. Refractory | 1.23(300°C); 1.49(600°C); 1.5 (over 900°C) | | 2150 |
| 8. Vermiculite(2) | 0.105(200°C); 0.13(400°C); 0.15(over 600°C) | 1180 | 375 |
| 9. Ramming Paste | 6(over 30°C) | 1000 | 1500 |
| 10. Sidewall Carbon | 120(over 30°C) | 1200 | 1651 |
| 11. Silicon Carbide | 44(20°C); 41(200°C); 34(400°C); 28(over 600°C) | 710.6 | 2660 |
| 12. Side Crust | 1.36(300°C); 1.5(500°C); 2.03(700°C); 2.94(over 900°C) | 1410 | 1957 |
| 13. Cathode Carbon | M:12(30°C); 13(1000°C); P:10(30°C); 12(1000°C) | 1200 | 1940 |



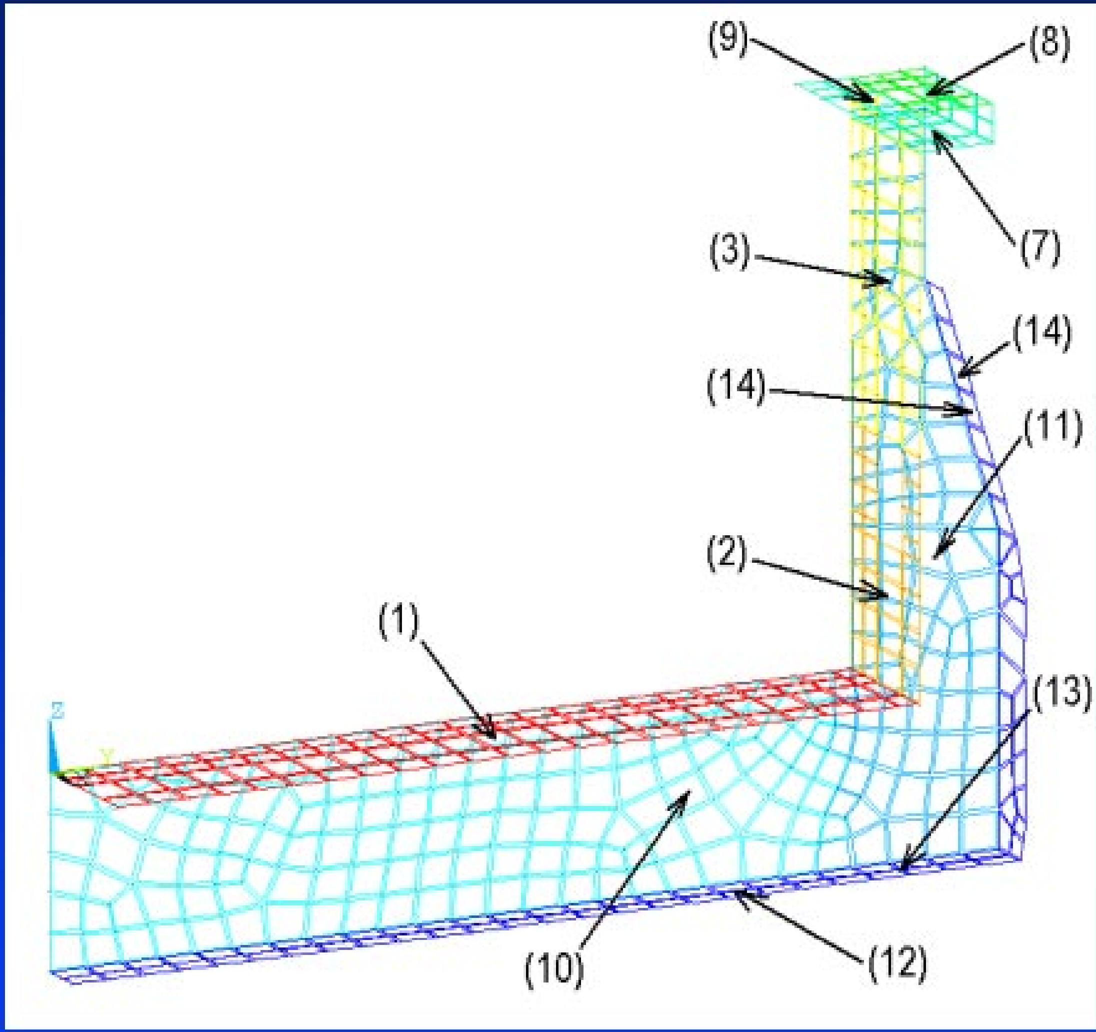

**Sample Properties from Sun and al TMS 2003**

# Size Parameters Definitions



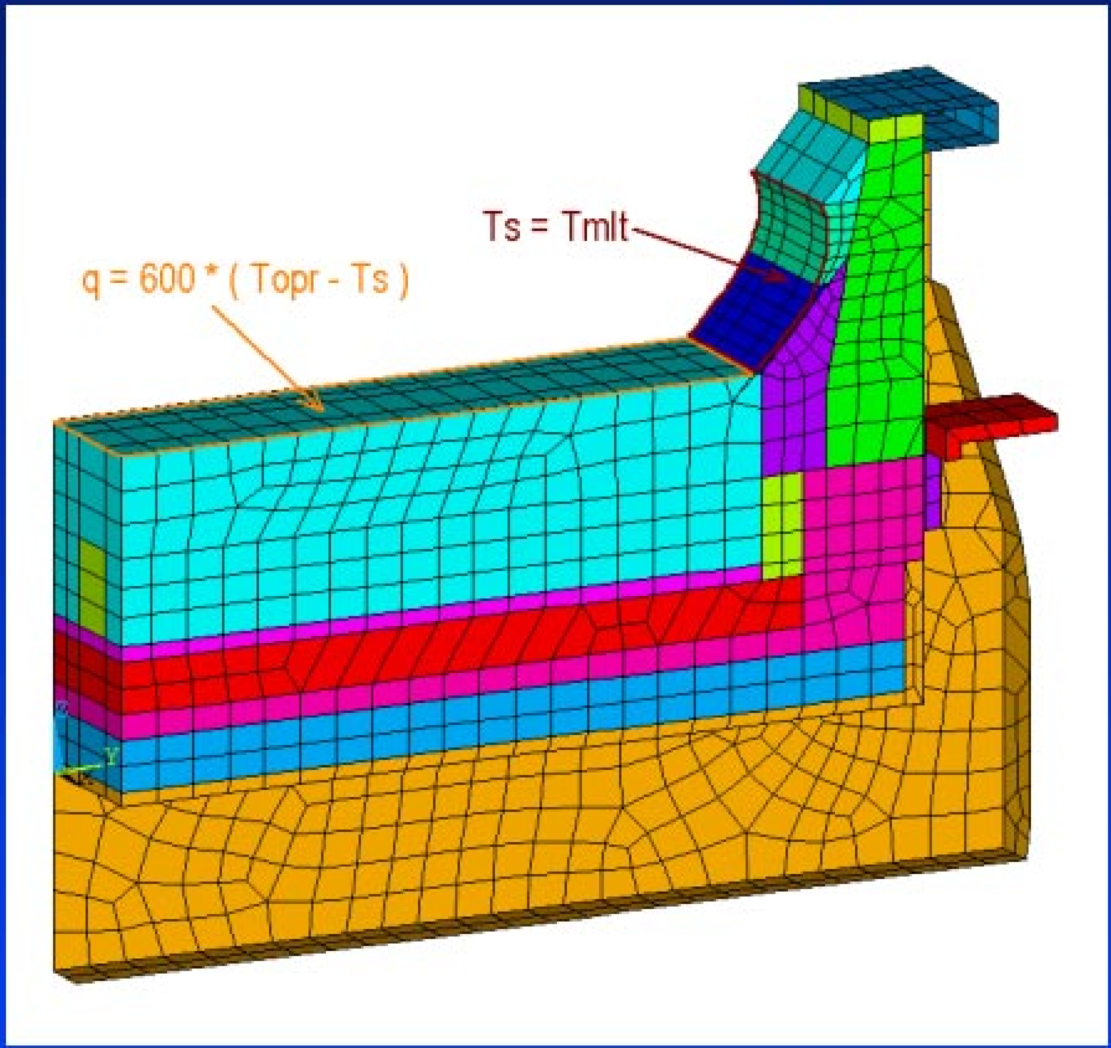

GENISIM

# Steel to Air Boundary Conditions



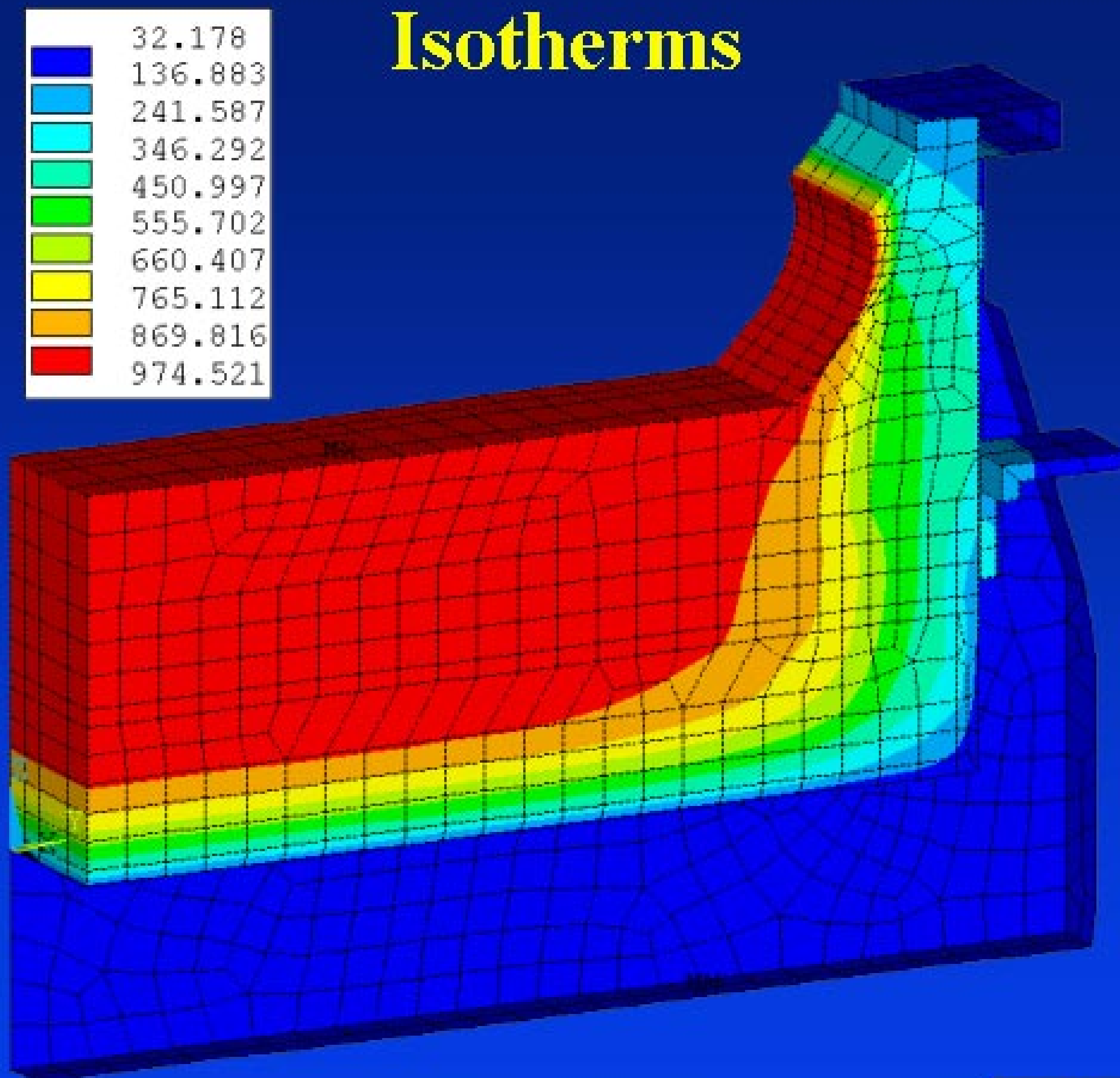

GENISIM

# Internal Thermal Boundary Conditions



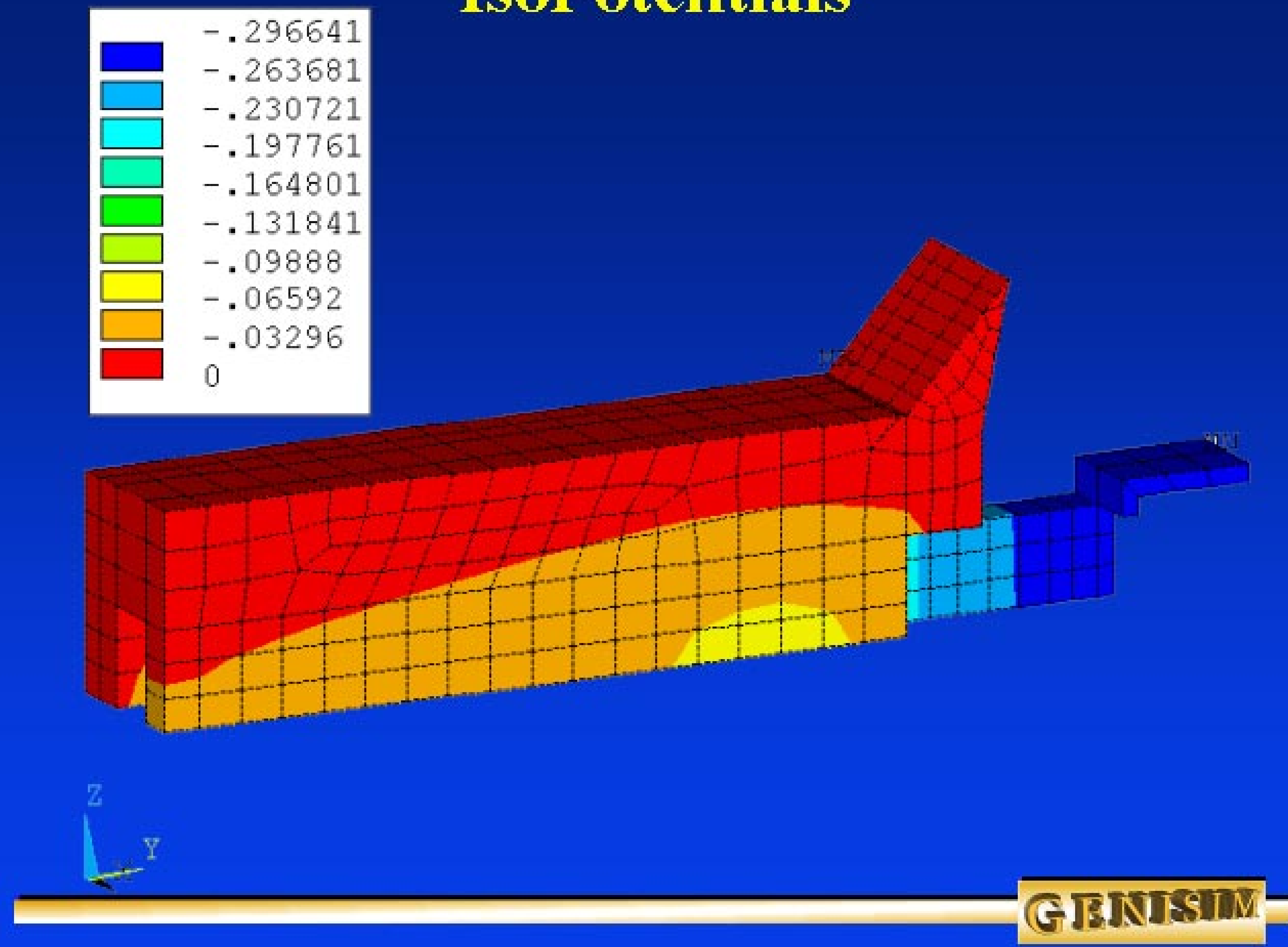

GENISIM

# Isotherms

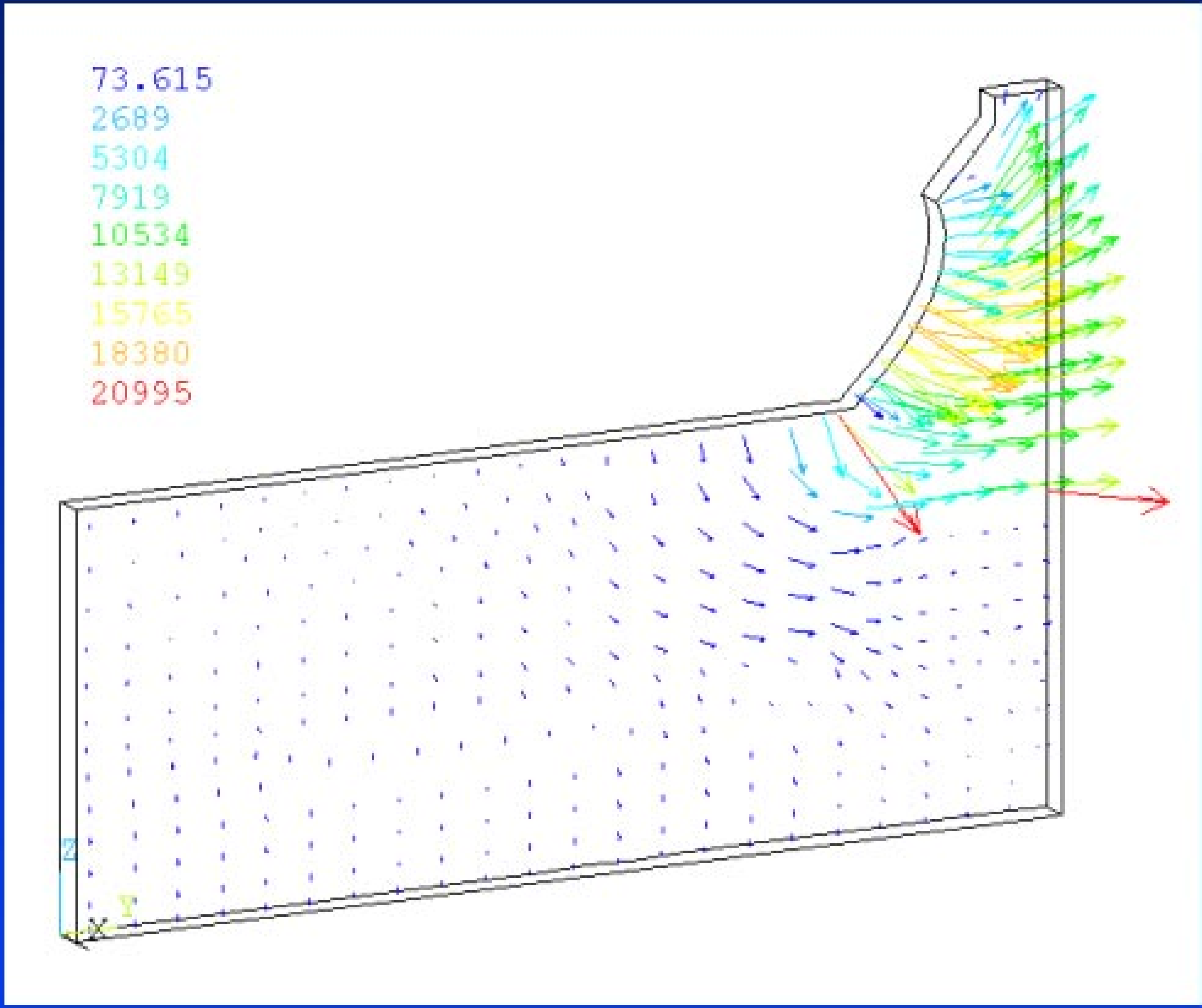



GENISIM

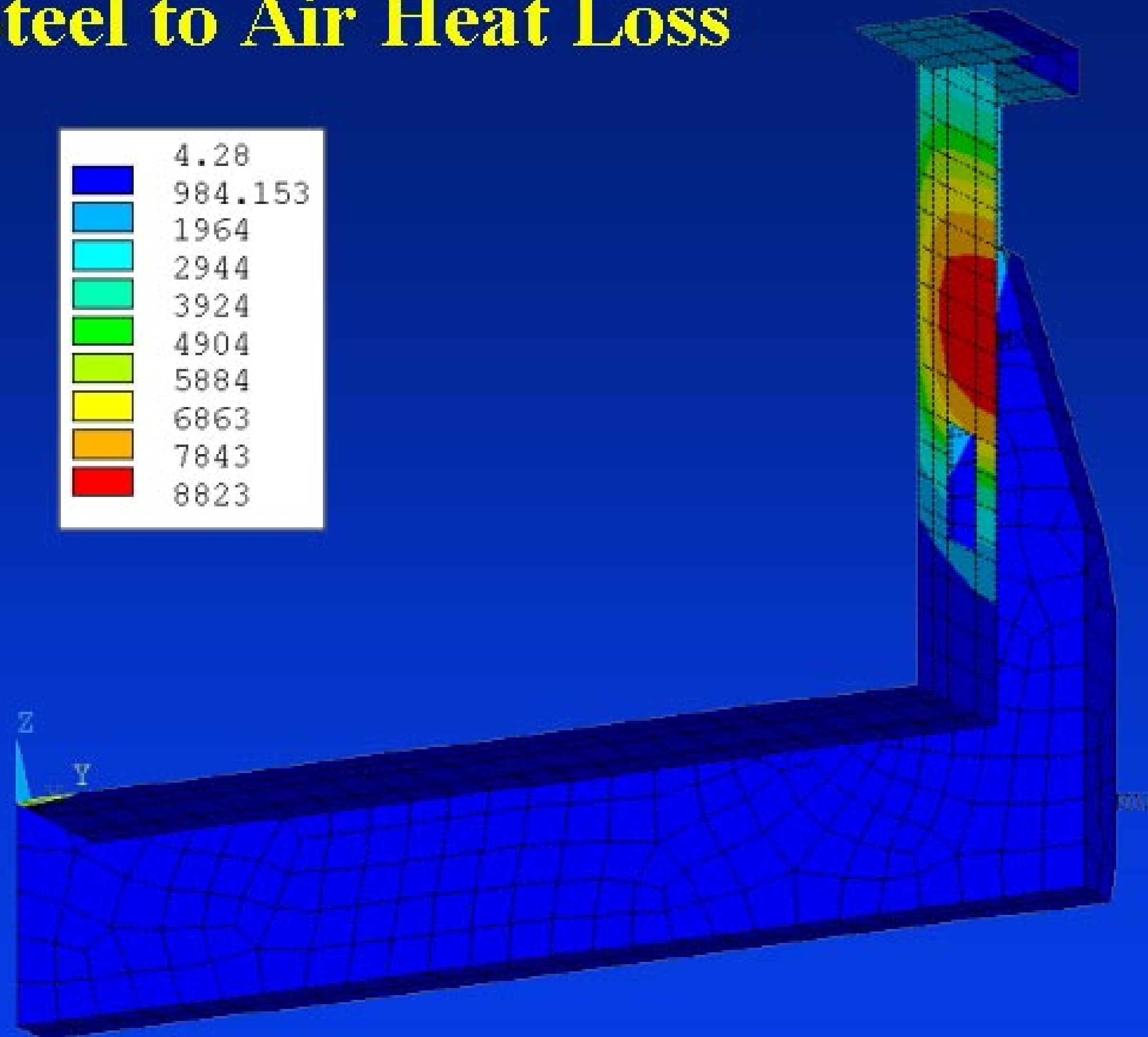
# IsoPotentials



# Heat Flux in Lining



# Steel to Air Heat Loss




GENISIM

# Cathode Heat Balance

| CATHODE HEAT LOST | kW | W/m^2 | % |
|---|---|---|---|
| Shell wall above bath level | 63.85 | 1371.52 | 16.10 |
| Shell wall opposite to bath | 39.78 | 5333.88 | 10.03 |
| Shell wall opposite to metal | 41.06 | 7327.54 | 10.35 |
| Shell wall opposite to block | 86.19 | 5978.86 | 21.73 |
| Shell wall below block | 10.39 | 782.97 | 2.62 |
| Shell floor | 22.39 | 386.36 | 5.64 |
| Cradle above bath level | 2.76 | 1645.46 | .70 |
| Cradle opposite to bath | 9.99 | 2265.24 | 2.52 |
| Cradle opposite to metal | 6.67 | 2762.29 | 1.68 |
| Cradle opposite to block | 26.20 | 966.65 | 6.61 |
| Cradle opposite to brick | 3.67 | 156.96 | .92 |
| Cradle below floor level | 13.72 | 92.25 | 3.46 |
| Bar and Flex to air | 45.91 | 2692.87 | 11.57 |
| End of flex to busbar | 24.09 | 39827.42 | 6.07 |
| Cathode bottom estimate | 176.36 | | 44.46 |
| Total Cathode Heat Lost | 396.67 | | 100.00 |

# Validation of a 3D Steady-state Thermo-electric Model

# Thermal Blitz

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.

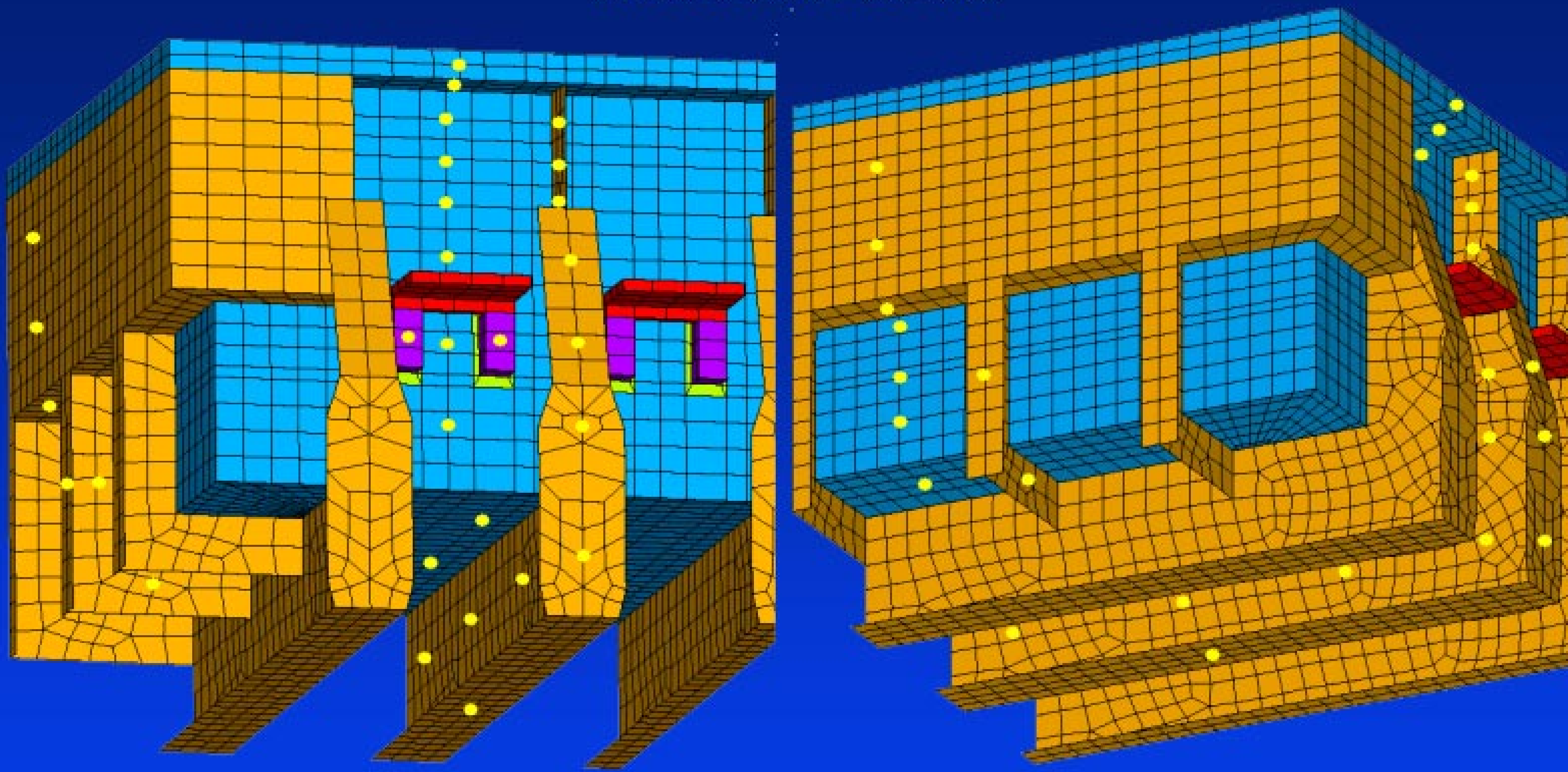
Thermal blitz heat flux measurements

# Thermal Blitz


Heat flow meters and probes used in a thermal blitz

GENISIM

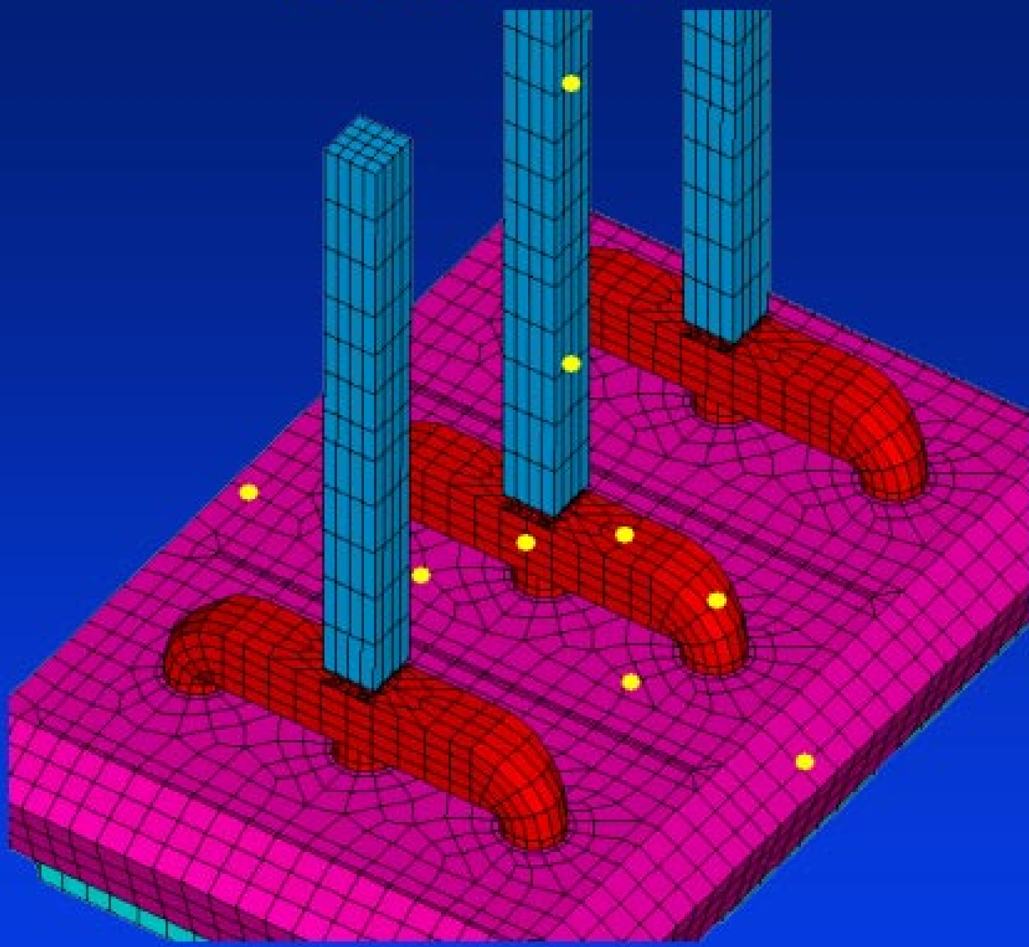
# Thermal Blitz



Up to 200 positions on the cathode shell and cradles are measured

GENISIM

# Thermal Blitz



Up to 60 positions on the anode panel (prebaked example) are also measured

# Thermal Blitz

| Heat Flux Measurements for Cell Heat Balance | | |
|---|---|---|
| date: 11-Aug-03 cell: "VAW" 300 | slice no: A2 | |
| Shell Wall | | |
| Description | Flux | Temp |
| Wall above bath level | 2000 | 150 |
| Wall bath level | 5500 | 230 |
| Wall metal level | 7500 | 250 |
| Wall block level above bar | 6000 | 235 |
| Left collector bar | 3000 | 190 |
| Right collector bar | 3000 | 190 |
| Wall collector bar level | 1500 | 90 |
| Wall brick level | 1000 | 60 |
| Floor near centerline | 500 | 50 |
| Floor at quarter point | 500 | 50 |
| Floor near corner | 500 | 50 |
| Cradle web | | |
| Wall above bath level | 1000 | 100 |
| Wall bath level | 2165 | 130 |
| Wall metal level | 2660 | 140 |
| Wall block level above bar | 955 | 125 |
| Wall collector bar level | 400 | 60 |
| Wall brick level | 155 | 50 |
| In the corner | 100 | 35 |
| Floor near centerline | 100 | 35 |
| Floor at quarter point | 100 | 35 |
| Floor near corner | 100 | 35 |
| Cradle flange | | |
| Wall above bath level | 500 | 65 |
| Wall bath level | 1085 | 80 |
| Wall metal level | 1330 | 90 |
| Wall block level above bar | 475 | 40 |
| Wall collector bar level | 200 | 35 |
| Wall brick level | 50 | 30 |
| Under the floor | 50 | 30 |

| Heat Flux Measurements for Cell Heat Balance | | |
|---|---|---|
| date: 11-Aug-03 cell: "VAW" 300 | duct end | |
| Shell Wall | | |
| Description | flux | temp |
| Wall metal level | 1500 | 90 |
| Wall block level above bar | 3000 | 200 |
| Wall collector bar level | 4000 | 210 |
| Wall brick level | 3000 | 200 |
| Cradle web | | |
| horizontal strip | 1500 | 90 |
| vertical stiffeners | 1000 | 75 |
| horizontal stiffeners | 100 | 35 |
| Cradle flange | | |
| cover plate | 500 | 50 |
| top of the horizontal strip | 1000 | 75 |
| bottom of the horizontal strip | 1000 | 75 |
| vertical stiffeners | 300 | 40 |

Measurements are then transfer into an Excel spreadsheet

6 side slices and 4 end slices measurement are transfer for the cathode part

GENISIM

# Thermal Blitz

| Heat Flux Measurements for Cell Heat Balance | | |
|---|---|---|
| date: 11-Aug-03<br>cell: "VAW" 300 | side slices mean | |
| **Shell Wall** | | |
| Description | Flux | Temp |
| Wall above bath level | 1971.2 | 148.7 |
| Wall bath level | 5459.1 | 229.6 |
| Wall metal level | 7448.1 | 247.1 |
| Wall block level above bar | 5994.5 | 233.7 |
| Left collector bar | 2974.5 | 188.8 |
| Right collector bar | 3009.8 | 190.4 |
| Wall collector bar level | 1511.0 | 90.0 |
| Wall brick level | 977.1 | 59.3 |
| Floor near centerline | 503.7 | 49.7 |
| Floor at quarter point | 503.1 | 50.4 |
| Floor near corner | 491.3 | 49.7 |
| **Cradle web** | | |
| Wall above bath level | 1009.8 | 99.9 |
| Wall bath level | 2141.0 | 131.5 |
| Wall metal level | 2662.2 | 139.7 |
| Wall block level above bar | 958.1 | 125.5 |
| Wall collector bar level | 395.0 | 59.8 |
| Wall brick level | 156.7 | 50.3 |
| In the corner | 100.1 | 35.0 |
| Floor near centerline | 100.7 | 35.0 |
| Floor at quarter point | 99.2 | 34.8 |
| Floor near corner | 101.4 | 35.5 |
| **Cradle flange** | | |
| Wall above bath level | 491.7 | 65.6 |
| Wall bath level | 1088.8 | 79.9 |
| Wall metal level | 1327.0 | 88.8 |
| Wall block level above bar | 474.0 | 39.1 |
| Wall collector bar level | 202.3 | 35.5 |
| Wall brick level | 49.6 | 30.0 |
| Under the floor | 50.3 | 30.4 |

| Heat Flux Measurements for Cell Heat Balance | | |
|---|---|---|
| date: 11-Aug-03<br>cell: "VAW" 300 | ends mean | |
| **Shell Wall** | | |
| Description | Flux | Temp |
| Wall metal level | 1484.3 | 90.1 |
| Wall block level above bar | 2988.2 | 198.4 |
| Wall collector bar level | 4049.5 | 214.2 |
| Wall brick level | 2972.7 | 202.2 |
| **Cradle web** | | |
| horizontal strip | 1490.8 | 88.4 |
| vertical stiffeners | 985.3 | 73.7 |
| horizontal stiffeners | 99.8 | 35.3 |
| **Cradle flange** | | |
| cover plate | 495.6 | 50.4 |
| top of the horizontal strip | 994.1 | 73.5 |
| bottom of the horizontal strip | 1010.2 | 76.7 |
| vertical stiffeners | 298.2 | 40.3 |

The Excel spreadsheet is used to perform heat flux averaging

GENISIM

# Thermal Blitz

basic informations on cell dimensions

| | | |
|---|---|---|
| inside shell length | (m) | 14.4 |
| inside shell width | (m) | 4.35 |
| anode length | (m) | 1.6 |
| number of anodes | (-) | 32 |
| width of the anode rod | (m) | 0.16 |
| thickness of the anode rod | (m) | 0.16 |
| height of anode rod | (m) | 1.8 |
| height of anode rod outside hood | (m) | 1 |
| studs diameter | (m) | 0.18 |
| number of studs per anode | (-) | 3 |
| studs height outside anode carbon | (m) | 0.24 |
| height of the anode yoke | (m) | 0.18 |
| thickness of the anode yoke | (m) | 0.18 |
| total length of the anode yoke | (m) | 1 |
| thickness of the crust cover | (m) | 0.16 |
| width of the side channels up to coverplate | (m) | 0.35 |
| width of the center channel | (m) | 0.15 |
| height of insulation layers under blocks | (m) | 0.4 |
| height of cathode blocks | (m) | 0.48 |
| metal height | (m) | 0.2 |
| bath height | (m) | 0.2 |
| inside shell height | (m) | 1.48 |
| height of collector bars | (m) | 0.2 |
| width of collector bars | (m) | 0.1 |
| length of collector bars stickout | (m) | 0.1 |
| number of collector bars in cell | (-) | 72 |
| height of cradles web under the shell | (m) | 0.5 |
| width of cradles web on the side walls | (m) | 0.35 |
| width of the cradles flange | (m) | 0.2 |
| number of cradles | (-) | 19 |
| width of end cover plate | (m) | 0.35 |
| height of the end wall horizontal strip | (m) | 0.6 |
| lenght of the end wall horizontal strip | (m) | 8 |
| length of the vertical stiffeners in the ends | (m) | 0.75 |
| length of horizontal stiffeners in the ends | (m) | 0.3 |
| width of the vertical stiffeners flange | (m) | 0.2 |
| number of end wall vertical stiffeners | (m) | 5 |

computed surfaces using basic information

| | | |
|---|---|---|
| surface of shell side wall above bath level | (m2) | 5.76 |
| surface of shell side wall at bath level | (m2) | 5.76 |
| surface of shell side wall at metal level | (m2) | 5.76 |
| surface of shell side wall at bar level | (m2) | 4.32 |
| surface shell side wall block level above bar | (m2) | 8.06 |
| surface shell side wall at insulation level | (m2) | 11.52 |
| surface of collector bar stickout | (m2) | 5.76 |
| surface of perimeter section of shell floor | (m2) | 25.09 |
| surface of in between section of shell floor | (m2) | 20.88 |
| surface of center section of shell floor | (m2) | 16.68 |
| surface of cradle web above bath level | (m2) | 5.32 |
| surface of cradle web at bath level | (m2) | 5.32 |
| surface of cradle web at metal level | (m2) | 5.32 |
| surface of cradle web at collector bar level | (m2) | 5.32 |
| surface of cradle web block level above bar | (m2) | 7.45 |
| surface of cradle web at insulation level | (m2) | 10.64 |
| surface of cradle web in corner | (m2) | 13.30 |
| 1/3 surface of cradle web under shell floor | (m2) | 27.55 |
| surface of cradle flange above bath level | (m2) | 1.52 |
| surface of cradle flange at bath level | (m2) | 1.52 |
| surface of cradle flange at metal level | (m2) | 1.52 |
| surface of cradle flange at bar level | (m2) | 1.52 |
| surface cradle flange block level above bar | (m2) | 2.13 |
| surface of cradle flange at insulation level | (m2) | 3.04 |
| surface cradle horizontal flange under floor | (m2) | 3.80 |
| surface of shell end wall at metal level | (m2) | 1.74 |
| surface of shell end wall at bar level | (m2) | 1.74 |
| surface shell end wall block level above bar | (m2) | 2.44 |
| surface shell end wall at insulation level | (m2) | 3.48 |
| surface of shell end wall coverplate | (m2) | 3.05 |
| surface of the end wall horizontal strip | (m2) | 9.60 |
| surface of the end wall horizontal strip web | (m2) | 5.60 |
| surface of vertical stiffeners web in the ends | (m2) | 5.25 |
| surface of horizontal stiffeners web in the ends | (m2) | 4.50 |
| surface of vertical stiffeners flange in the ends | (m2) | 1.5 |
| surface of ASD and AED channels | (m2) | 12.64 |
| surface of crust above center channel | (m2) | 2.06 |
| surface of crust above anodes | (m2) | 45.51 |
| surface of studs exposed to air | (m2) | 6.79 |
| surface of anode yokes | (m2) | 23.04 |
| surface of anode rods inside hood | (m2) | 16.38 |
| surface of anode rod outside hood | (m2) | 20.48 |

Another part of the spreadsheet computes the area of the different surfaces of the cell

GENISIM

# Thermal Blitz

Heat Balance Results

date: 12-Aug-03 Cell: "VAW" 300

| Cathode Heat Losses | W / m2 | kW | % |
|---|---|---|---|
| Shell side wall above bath level | 2002 | 11.53 | 1.83 |
| Shell side wall opposite to bath | 5616 | 32.35 | 5.14 |
| Shell side wall opposite to metal | 7617 | 43.87 | 6.97 |
| Shell side wall opposite to block above bar | 6041 | 48.71 | 7.74 |
| Shell side wall opposite to block between bars | 1505 | 6.50 | 1.03 |
| Collector bars to air | 3035 | 17.48 | 2.78 |
| Collector bars to flexible | | 57.42 | 9.12 |
| Shell side wall opposite to brick | 990 | 11.40 | 1.81 |
| Shell floor close to corner | 504 | 12.65 | 2.01 |
| Shell floor quarter point region | 499 | 10.42 | 1.65 |
| Shell floor centerline region | 498 | 8.31 | 1.32 |
| Cradle above bath level | 882 | 6.04 | 0.96 |
| Cradle opposite to bath | 1906 | 13.04 | 2.07 |
| Cradle opposite to metal | 2360 | 16.14 | 2.56 |
| Cradle opposite to block above bar | 854 | 8.18 | 1.30 |
| Cradle opposite to block between bars | 355 | 2.43 | 0.39 |
| Cradle opposite to brick | 130 | 1.78 | 0.28 |
| Cradle corner | 89 | 1.53 | 0.24 |
| Cradle below floor close to corner | 100 | 2.75 | 0.44 |
| Cradle below floor quarter point region | 101 | 2.77 | 0.44 |
| Cradle below floor centerline region | 102 | 2.80 | 0.45 |
| Shell end wall opposite to metal | 1503 | 2.62 | 0.42 |
| Shell end wall opposite to block above bar | 3050 | 7.43 | 1.18 |
| Shell end wall opposite to block below top of bar | 4034 | 7.02 | 1.11 |
| Shell end wall opposite to brick | 2931 | 10.20 | 1.62 |
| Shell coverplate in the ends | 490 | 1.49 | 0.24 |
| Shell horizontal strip in the ends | 1112 | 27.59 | 4.38 |
| Shell vertical stiffeners in the ends | 837 | 5.65 | 0.90 |
| Shell horizontal stiffeners in the ends | 100 | 0.45 | 0.07 |
| **Total for the cathode part** | | **380.56** | **60.43** |
| **Anode Heat Losses** | | | |
| Crust in side channels | 1713 | 21.65 | 3.44 |
| Crust above anodes | 1798 | 81.80 | 12.99 |
| Crust in center channel | 1740 | 3.58 | 0.57 |
| Studs | 4002 | 27.16 | 4.31 |
| Yoke | 3682 | 84.83 | 13.47 |
| Aluminum rod | 818 | 30.14 | 4.79 |
| **Total for the anode part** | | **249.2** | **39.57** |
| **Total for the cell** | | **629.7** | **100.00** |

**For each surfaces, the average heat flux is multiply by the surface area in order to obtain the surface heat loss.**

**The summation of all the surfaces heat losses gives the total cell heat loss.**

**By using a spreadsheet, the blitz results are available as soon as the measurements are transferred into it.**

GENISIM

# Thermal Blitz

| | |
|---|---|
| g | 1.05 |
| ce | 94 |
| tliquid | 973.5 |
| amp | 300 |
| vcell | 4.333 |
| vext | 0.2 |
| CaF2 | 3 |
| Al2O3 | 2.475 |
| AlF3 | 11 |
| caloeut | 6.8655279 |
| teu | 944.00742 |
| superheat | 29.492579 |
| tliq | 966.35243 |
| superheat | 7.1475703 |
| co | 13.333333 |
| co2 | 86.666667 |
| umetal | 2.0312133 |
| qbath | 2.85 |
| qin | 627.68602 |
| qout | 629.67361 |
| closing | 100.32% |

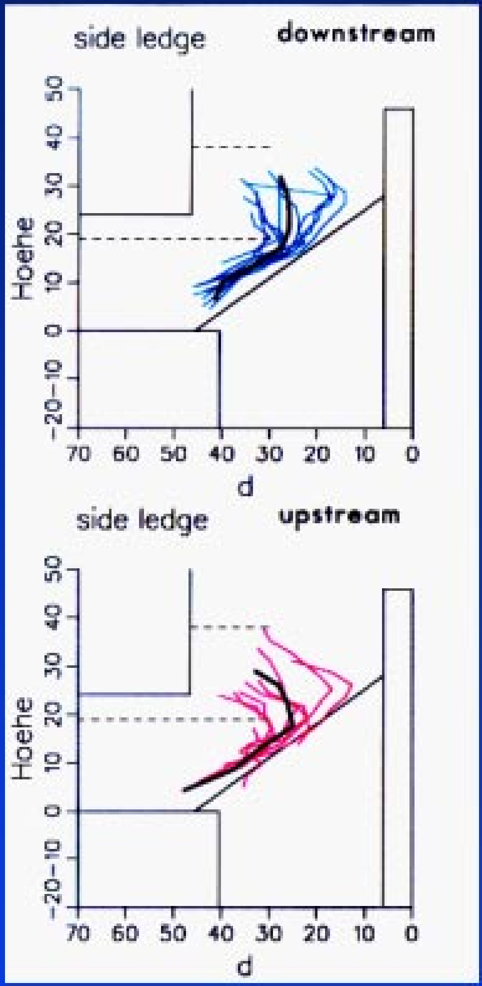
Measurement of the complete heat balance requires that all heat losses be measured such that the sum of the measurements is equal to what is called the theoretical heat loss. The theoretical heat loss is calculated from the voltages and line current. The heat balance closure, then, is defined as the % of the theoretical heat that is actually measured:

$$\%\ \text{Closure} = \frac{Q_{measured}}{\left(V_{pot} - E_{\Delta H} - V_{ext}\right) \bullet I} (100\%)$$

Thorough and careful measurements usually close the heat balance between 93% and 105% of the theoretical heat loss.

**To be judge reliable, the cell heat loss measured in a thermal blitz must be comparable with the assessment of the cell internal heat.**

# Thermal Blitz




In order to support the model calibration exercise, it is also quite important to measure during the thermal blitz the following:

- Collectors bar to flex heat loss
- Voltage break down
- Freeze profiles
- Operating temperature
- Bath chemistry
- Cell superheat (Cry-O-Therm)
- Temperature in the basement
- Average anode crust height
- Temperature under the hood
- Temperature in the potroom

GENISIM

# Model Calibration

Assuming that your are using the best material properties available and that you have a good estimate of the boundary conditions, the key items that may need to be calibrated because they are very hard to assess and have a big influence on the model behavior are:

- Freeze profiles (freeze thickness)
- Calcium silicate/insulating brick  degradation temperature
- Cast iron/cathode block  contact resistance
- Anode crust thickness
- Anode crust densification temperature
- Cast iron/anode block contact resistance

GENISIM

# 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 |

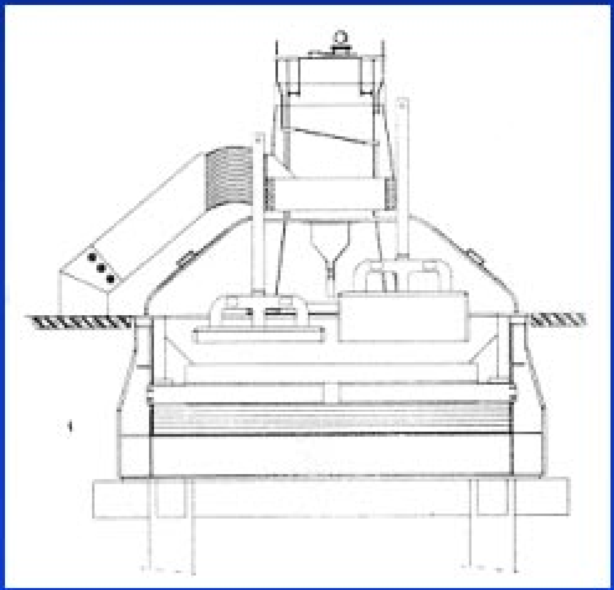
**Those two extreme cases clearly demonstrate that as far as the cell thermal balance is concerned, the window of opportunities is quite wide. Only a complimentary technico-economical study can indicate which of the two retrofit scenarios offers the best return on investment (obviously, the outcome of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

GENISIM

# Retrofit Study No: 1
# Step by Step

GENISIM

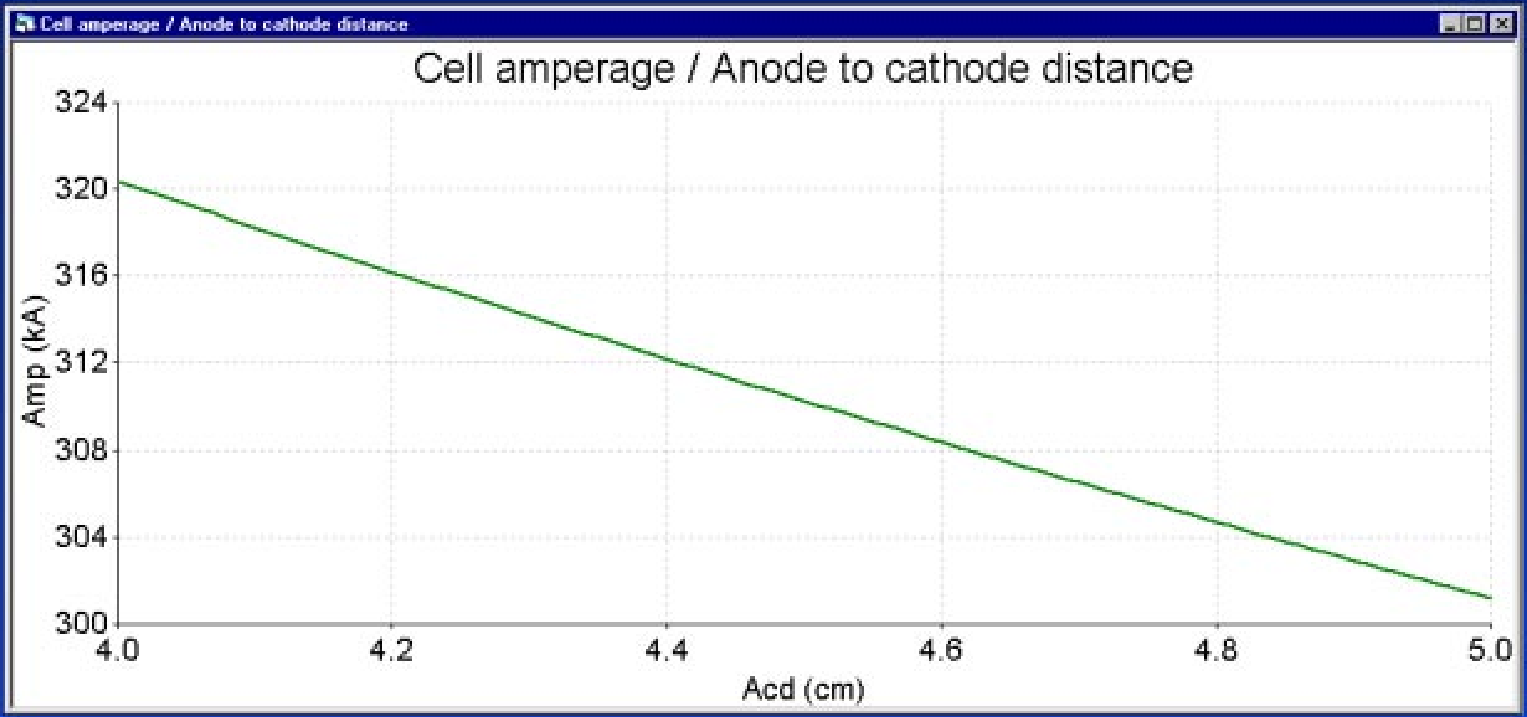
# Validated Base Case Model Results



| | |
|---|---|
| Amperage | 300 kA |
| Nb. of anodes | 32 |
| Anode size | 1.6 m X 0.8 m |
| Nb. of anode studs | 3 per anode |
| Anode stud diameter | 18 cm |
| Anode cover thickness | 16 cm |
| Nb. of cathode blocks | 18 |
| Cathode block length | 3.47 m |
| Type of cathode block | 30 % graphitic |
| Type of side block | 30 % graphitic |
| Side block thickness | 15 cm + |
| ASD and AED | 35 cm |
| Inside potshell size | 14.4 m X 4.35 m |
| ACD | 5 cm |
| Excess $AlF_3$ | 10.9 % |
| Operating temperature | 973.3 °C |
| Liquidus superheat | 6.8 °C |
| Current efficiency | 94.0 % |
| Internal heat | 628 kW |
| Energy consumption | 13.75 kWh/kg |

GENISIM

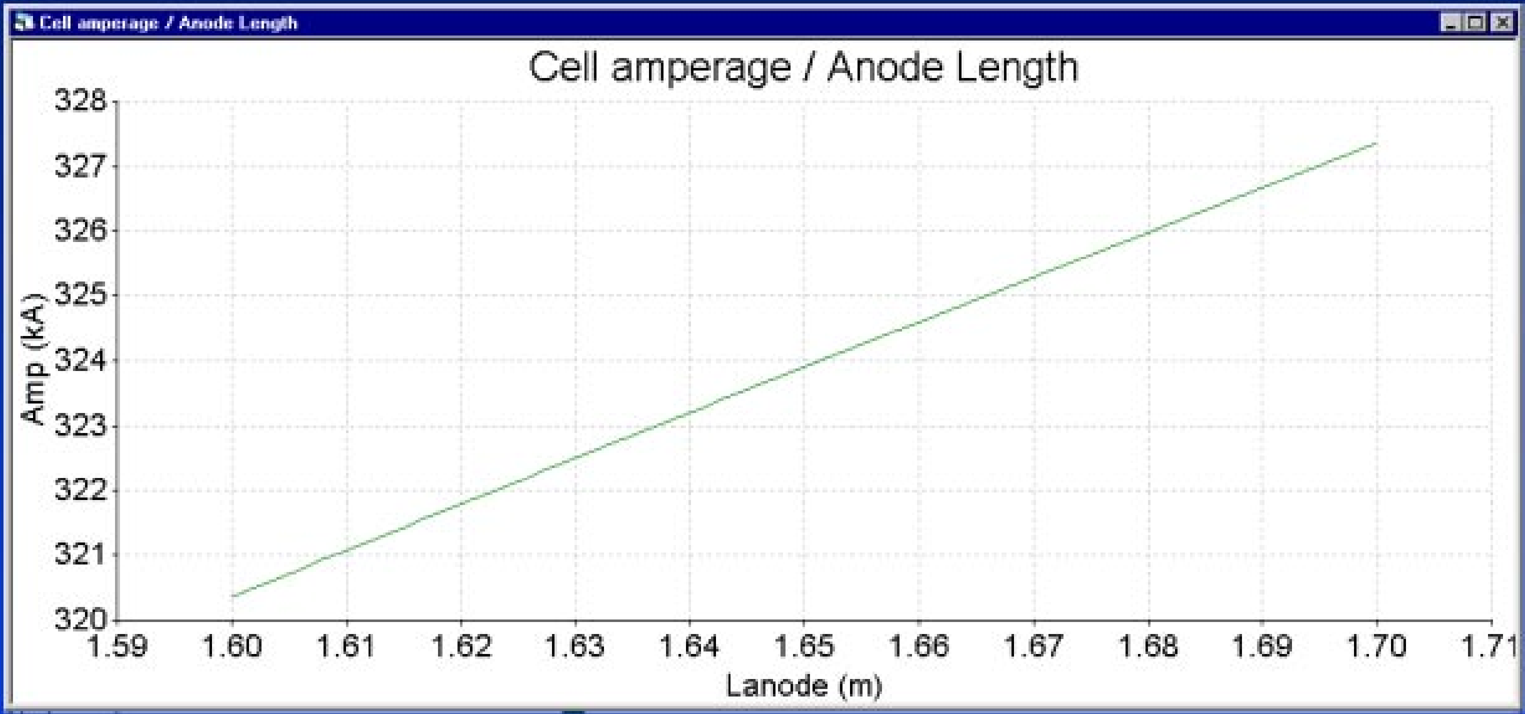
# Step-by-Step Retrofit Study




- **Process model's trend analysis: Exchanging ACD for amperage**

GENISIM

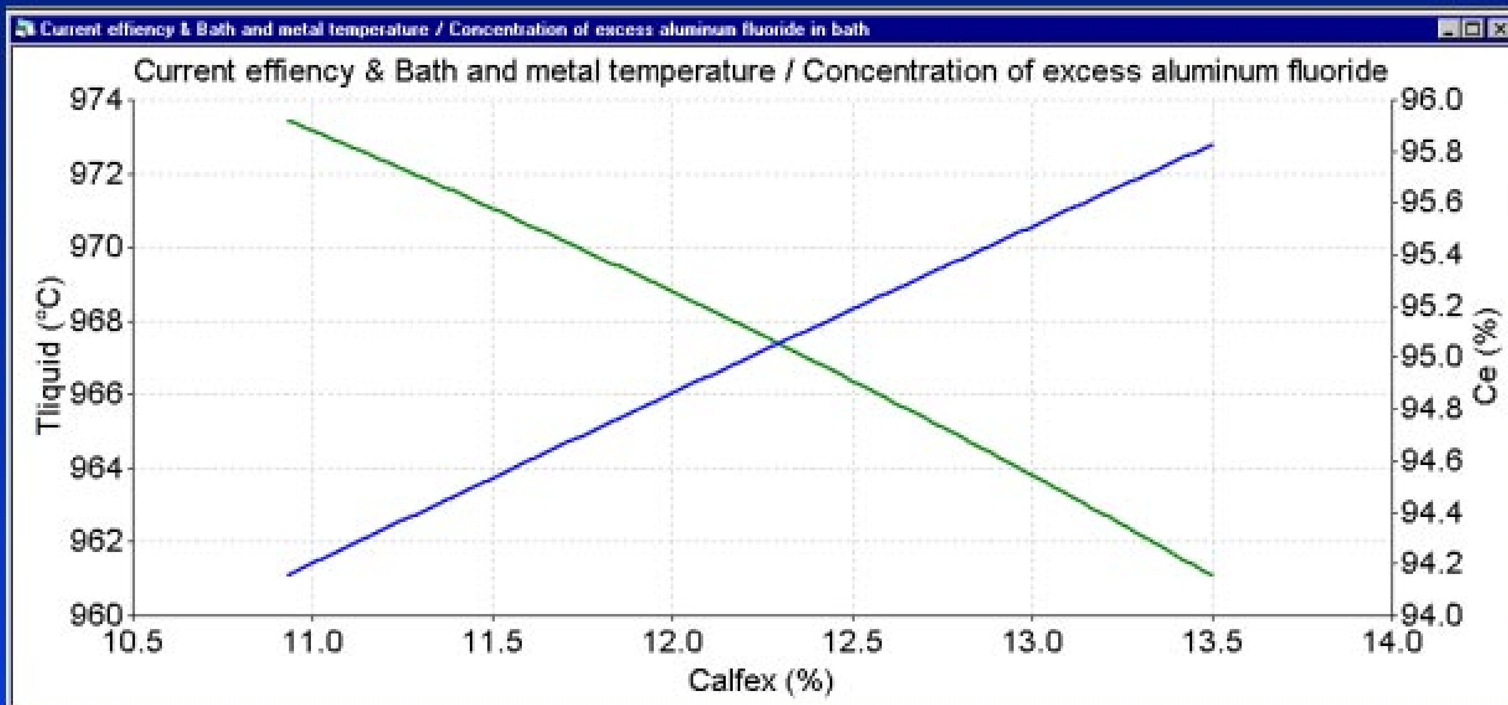
# Step-by-Step Retrofit Study




- Trend analysis: More amperage using longer anodes

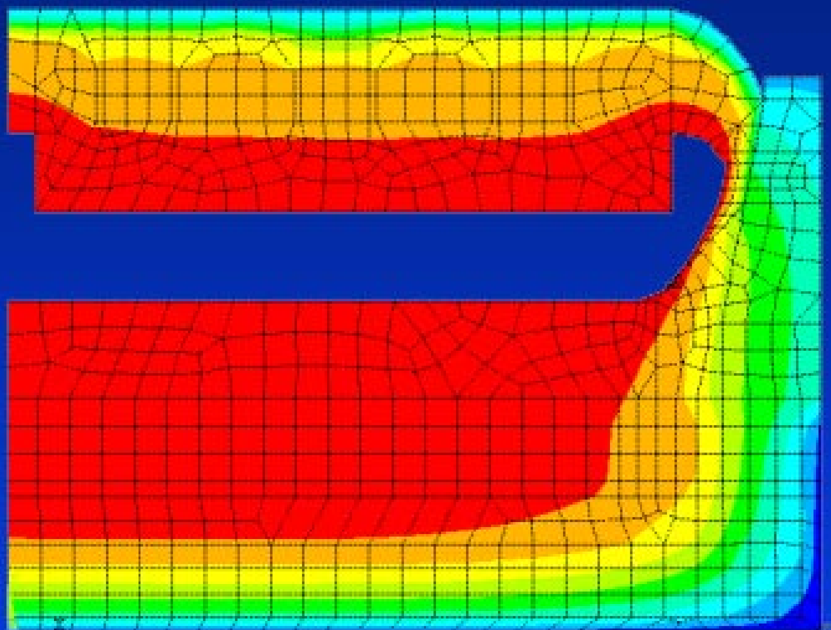
GENISIM

# Step-by-Step Retrofit Study




- Trend analysis: Effect of adding excess $AlF_3$ on CE

# Step-by-Step Retrofit Study

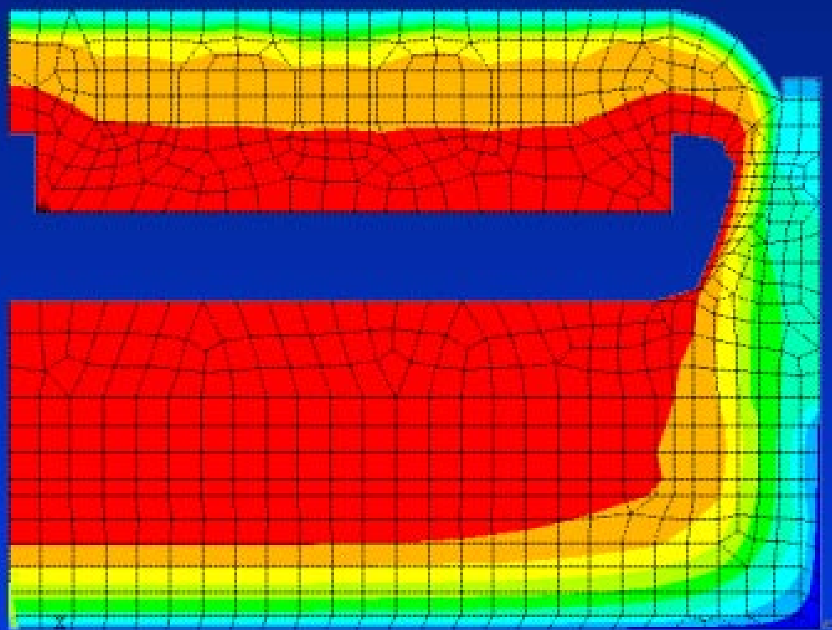


- **Confirmation of results using 2D+ model**

| | |
|---|---|
| Amperage | 327 kA |
| Nb. of anodes | 32 |
| Anode size | 1.7 m X 0.8 m |
| Nb. of anode studs | 3 per anode |
| Anode stud diameter | 18 cm |
| Anode cover thickness | 16 cm |
| Nb. of cathode blocks | 18 |
| Cathode block length | 3.47 m |
| Type of cathode block | 30 % graphitic |
| Type of side block | 30 % graphitic |
| Side block thickness | 15 cm + |
| ASD | 25 cm |
| Inside potshell size | 14.4 m X 4.35 m |
| ACD | 4 cm |
| Excess $AlF_3$ | 13.5 % |
| Operating temperature | 960.8 °C |
| Liquidus superheat | 7.1 °C |
| Current efficiency | 95.8 % |
| Internal heat | 639 kW |
| Energy consumption | 13.09 kWh/kg |

GENISIM

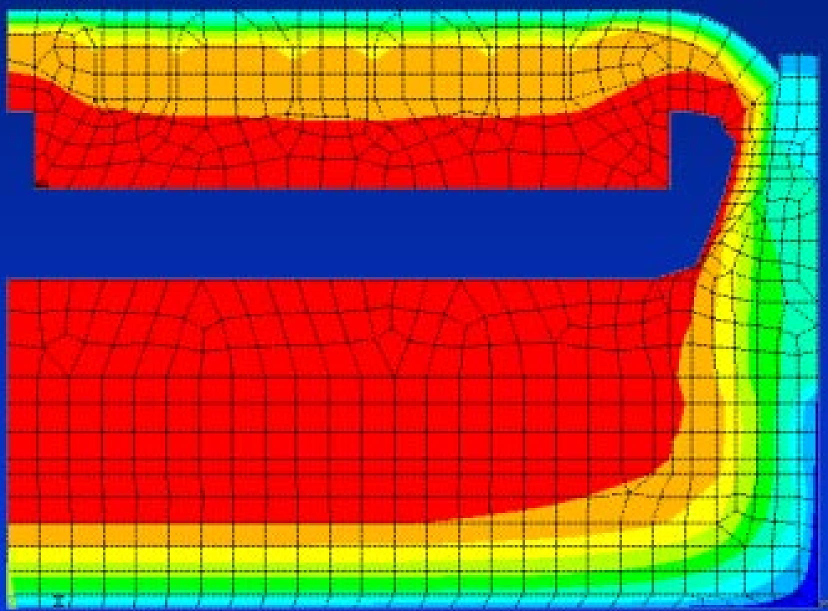
# Step-by-Step Retrofit Study



- **Modifying cathode and side wall blocks**

| | |
|---|---|
| Amperage | 327 kA |
| Nb. of anodes | 32 |
| Anode size | 1.7 m X 0.8 m |
| Nb. of anode studs | 3 per anode |
| Anode stud diameter | 18 cm |
| Anode cover thickness | 16 cm |
| Nb. of cathode blocks | 18 |
| Cathode block length | 3.67 m |
| Type of cathode block | 100 % graphitized |
| Type of side block | Silicon carbide |
| Side block thickness | 10 cm + |
| ASD | 30 cm |
| Inside potshell size | 14.4 m X 4.35 m |
| ACD | 4 cm |
| Excess $AlF_3$ | 13.5 % |
| Operating temperature | 958.9 °C |
| Liquidus superheat | 5.2 °C |
| Current efficiency | 96.0 % |
| Internal heat | 624 kW |
| Energy consumption | 12.95 kWh/kg |

# Step-by-Step Retrofit Study

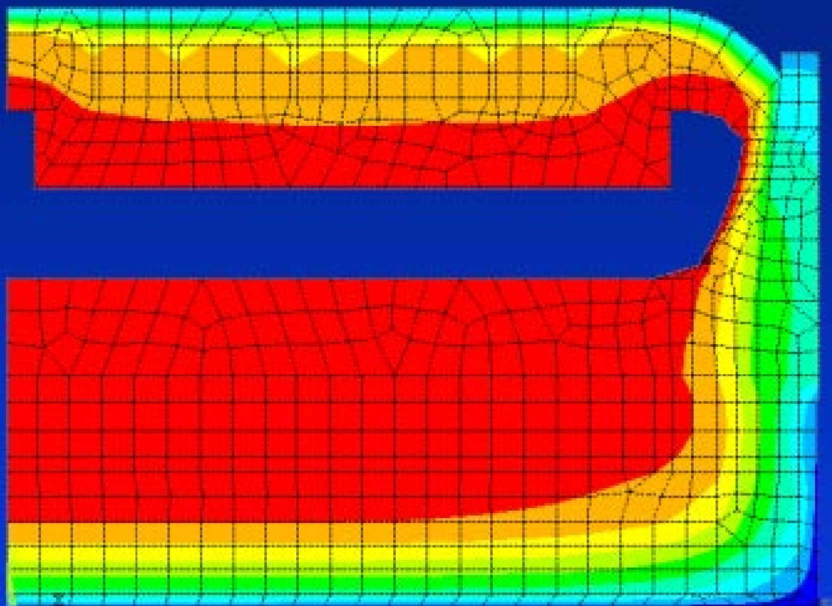


| | |
|---|---|
| Amperage | 335 kA |
| Nb. of anodes | 32 |
| Anode size | 1.7 m X 0.8 m |
| Nb. of anode studs | 3 per anode |
| Anode stud diameter | 18 cm |
| Anode cover thickness | 10 cm |
| Nb. of cathode blocks | 18 |
| Cathode block length | 3.67 m |
| Type of cathode block | 100 % graphitized |
| Type of side block | Silicon carbide |
| Side block thickness | 10 cm + |
| ASD | 30 cm |
| Inside potshell size | 14.4 m X 4.35 m |
| ACD | 4 cm |
| Excess $AlF_3$ | 13.5 % |
| Operating temperature | 959.2 °C |
| Liquidus superheat | 5.5 °C |
| Current efficiency | 96.0 % |
| Internal heat | 657 kW |
| Energy consumption | 13.2 kWh/kg |

- **Decreasing anode cover to 10 cm and increasing amperage to 335 kA**

GENISIM

# Step-by-Step Retrofit Study

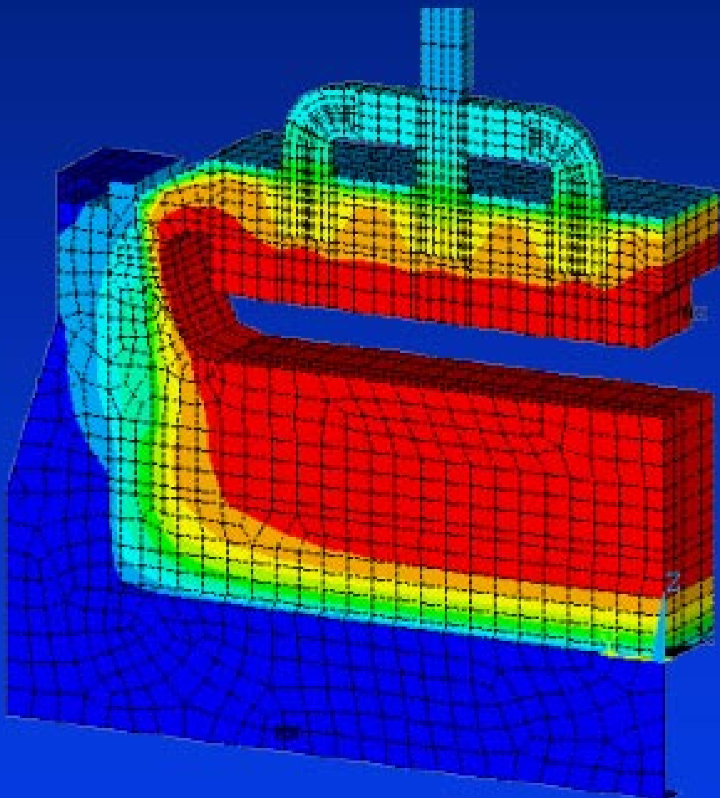


- **Increasing stud diameter to 19 cm and increasing amperage to 345 kA**

| | |
|---|---|
| Amperage | 345 kA |
| Nb. of anodes | 32 |
| Anode size | 1.7 m X 0.8 m |
| Nb. of anode studs | 3 per anode |
| Anode stud diameter | 19 cm |
| Anode cover thickness | 10 cm |
| Nb. of cathode blocks | 18 |
| Cathode block length | 3.67 m |
| Type of cathode block | 100 % graphitized |
| Type of side block | Silicon carbide |
| Side block thickness | 10 cm + |
| ASD | 30 cm |
| Inside potshell size | 14.4 m X 4.35 m |
| ACD | 4 cm |
| Excess $AlF_3$ | 13.5 % |
| Operating temperature | 960.3 °C |
| Liquidus superheat | 6.6 °C |
| Current efficiency | 96.0 % |
| Internal heat | 695 kW |
| Energy consumption | 13.35 kWh/kg |

GENISIM

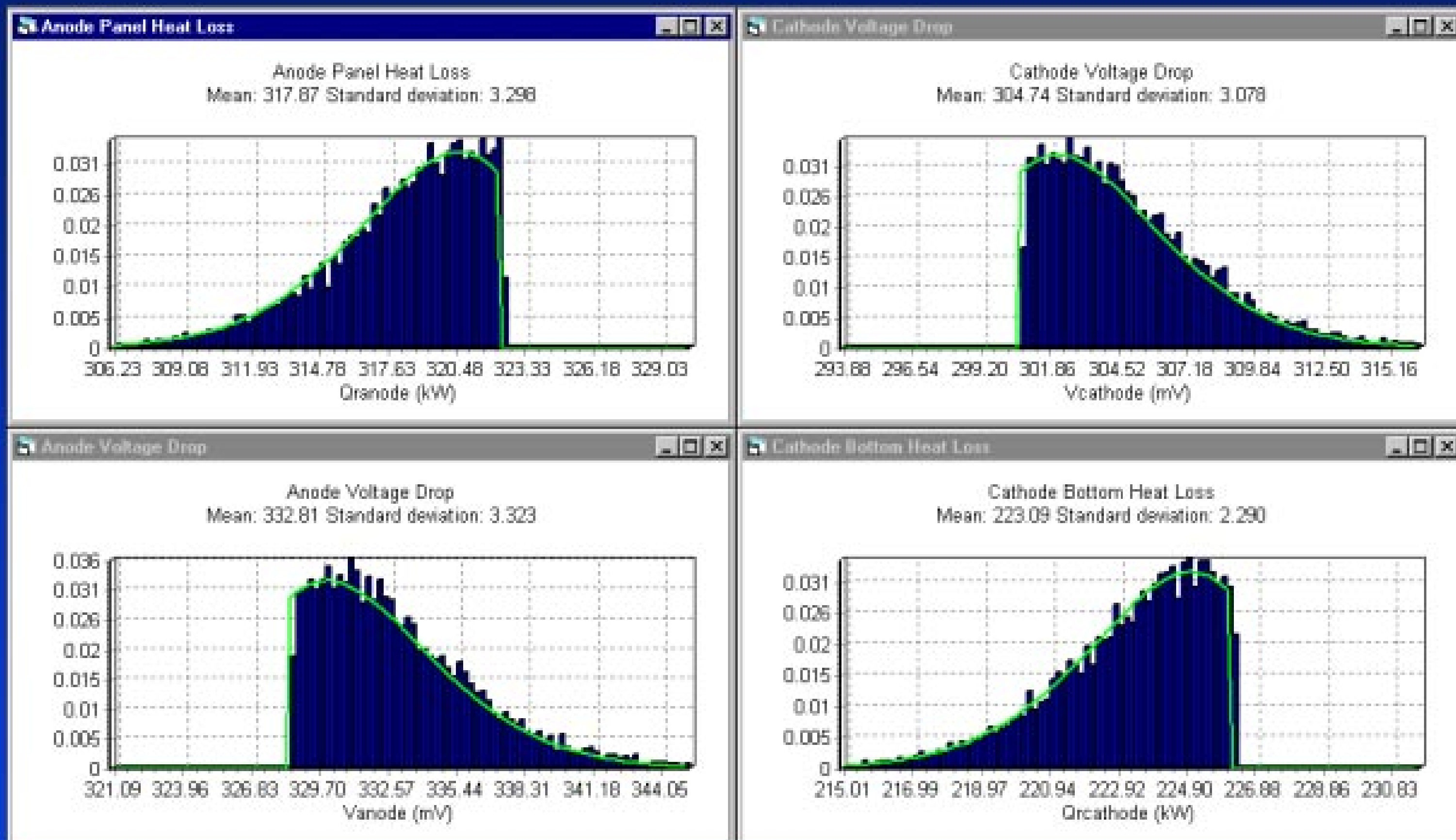
# Step-by-Step Retrofit Study



| Amperage | 350 kA |
|---|---|
| Nb. of anodes | 32 |
| Anode size | 1.7 m X 0.8 m |
| Nb. of anode studs | 3 per anode |
| Anode stud diameter | 19 cm |
| Anode cover thickness | 10 cm |
| Nb. of cathode blocks | 18 |
| Cathode block length | 3.67 m |
| Type of cathode block | 100 % graphitized |
| Type of side block | Silicon carbide |
| Side block thickness | 10 cm + |
| ASD | 30 cm |
| Inside potshell size | 14.4 m X 4.35 m |
| ACD | 4 cm |
| Excess $AlF_3$ | 13.5 % |
| Operating temperature | 960.4 °C |
| Liquidus superheat | 6.7 °C |
| Current efficiency | 96.1 % |
| Internal heat | 713 kW |
| Energy consumption | 13.4 kWh/kg |

- **Increasing amperage to 350 kA**

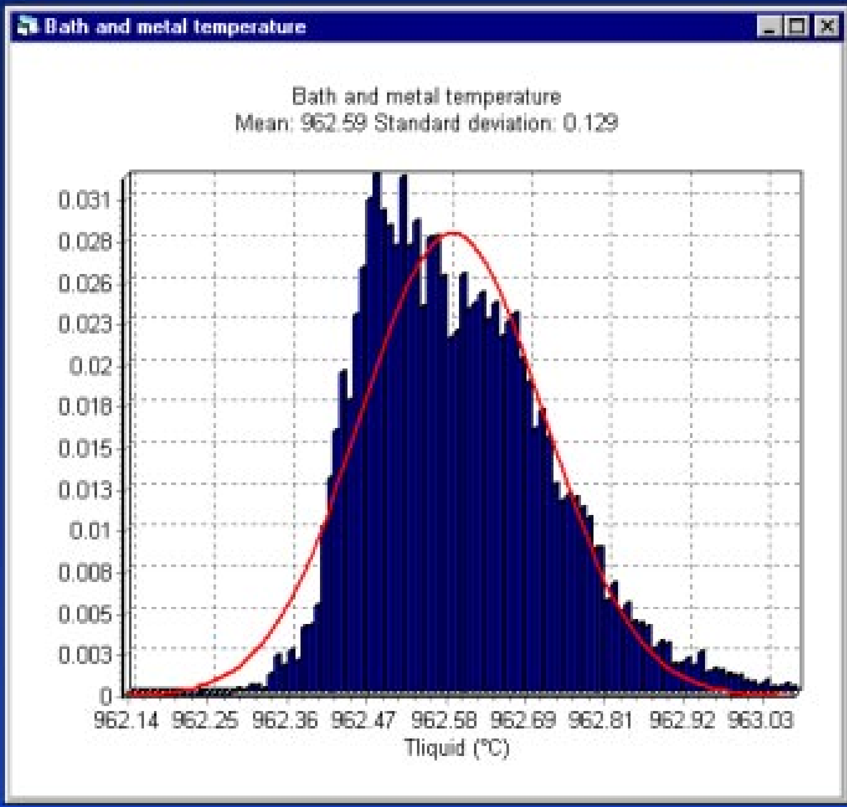
# Model Accuracy Risk Assessment Analysis

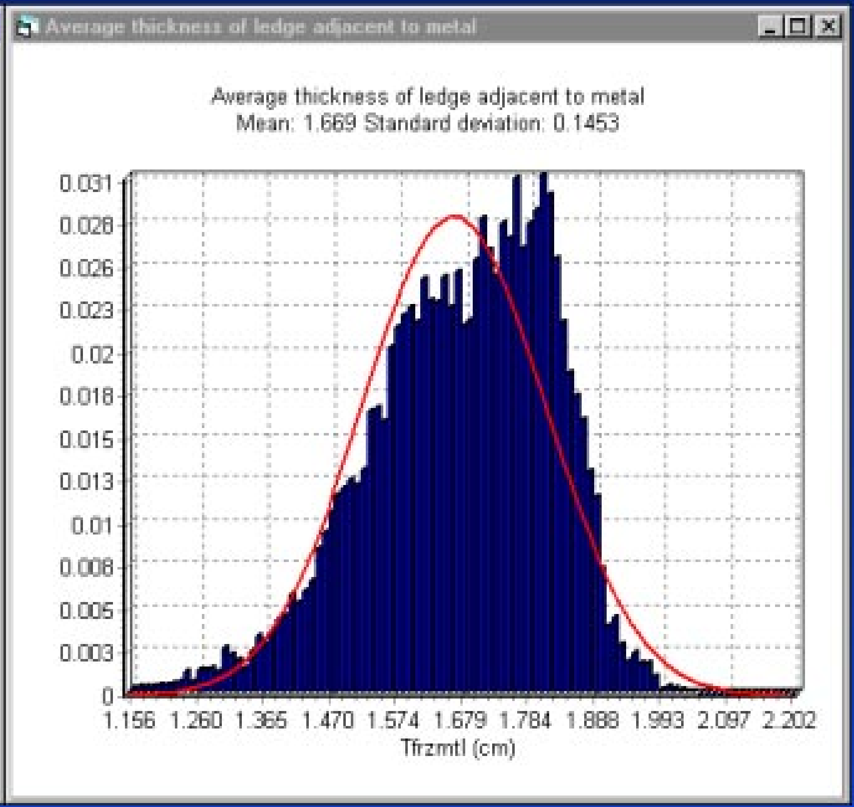



- Monte Carlo risk assessment analysis: Input distributions

GENISIM

# Model Accuracy Risk Assessment Analysis

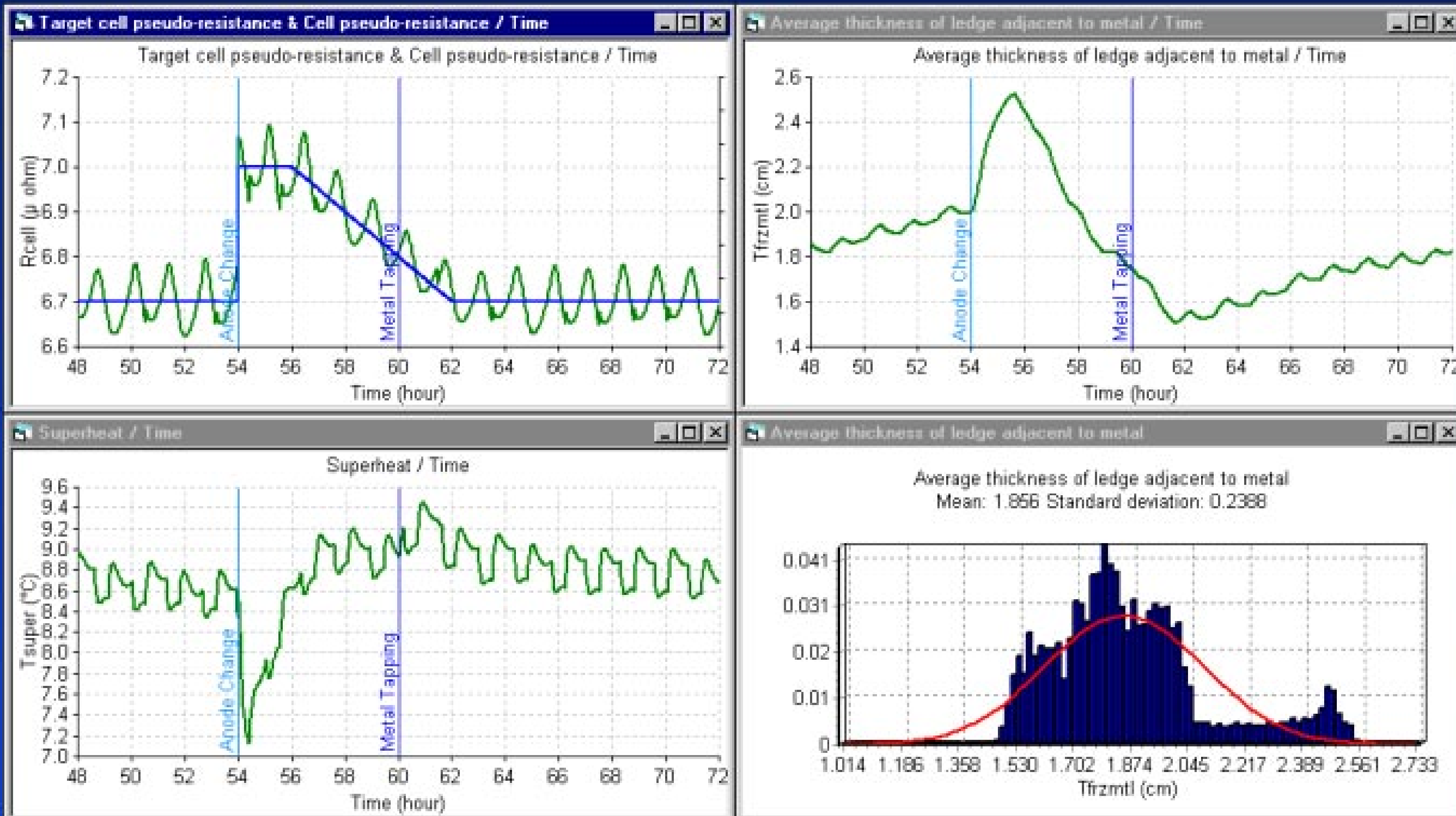



- Monte Carlo risk assessment analysis: Output distributions

GENISIM

# Operational Range Dynamic Analysis




GENISIM

# 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.