Industrial Aluminum Electrolysis

Marc Dupuis Process Simulation

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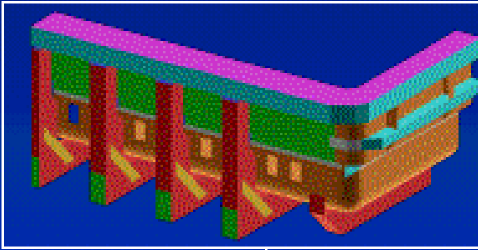
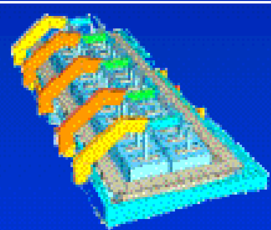
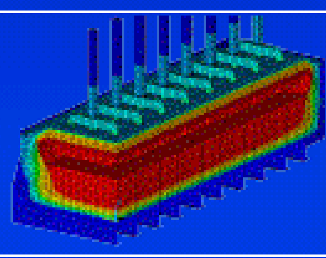
Categories of Hall-Héroult Mathematical Models

Superstructure Design



Point Breaker Feeder Design





Cell Design

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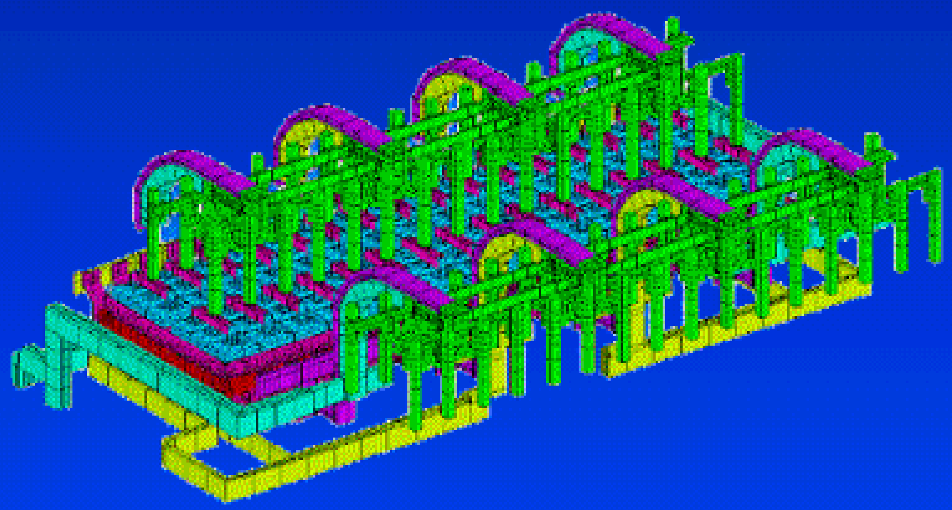
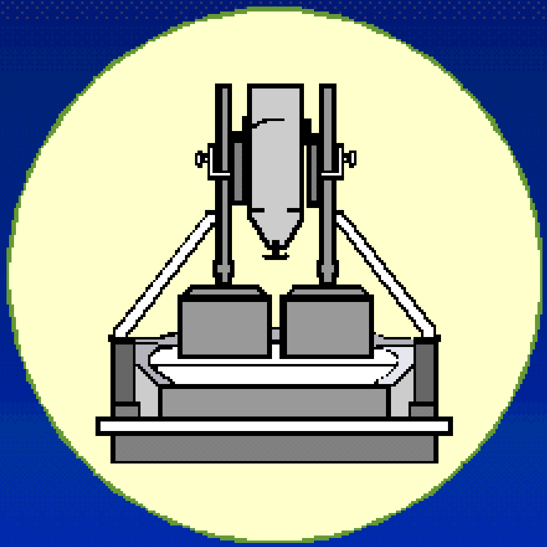
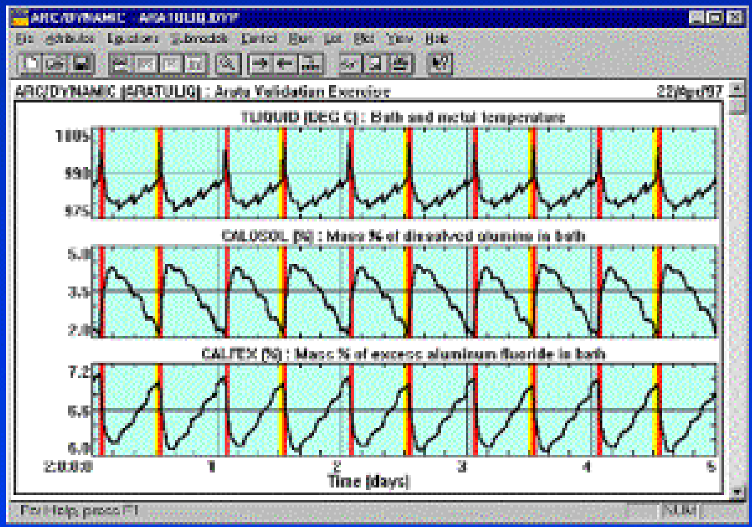
3D
Steady-State
Models





1D
Dynamic
Models



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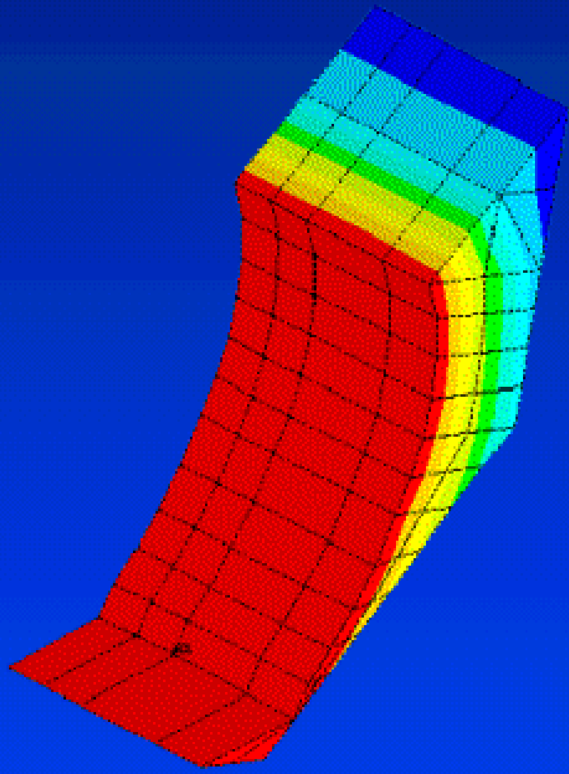
The Goals of 3D Steady-State Thermal-Electric Models are to Calculate the:

- Global Cell Heat Dissipation
- Cathode Lining Drop
- Ledge Profile
- Anode Drop



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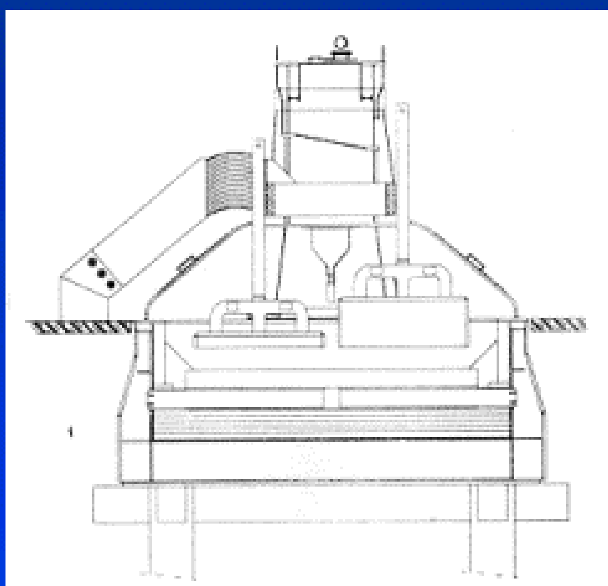
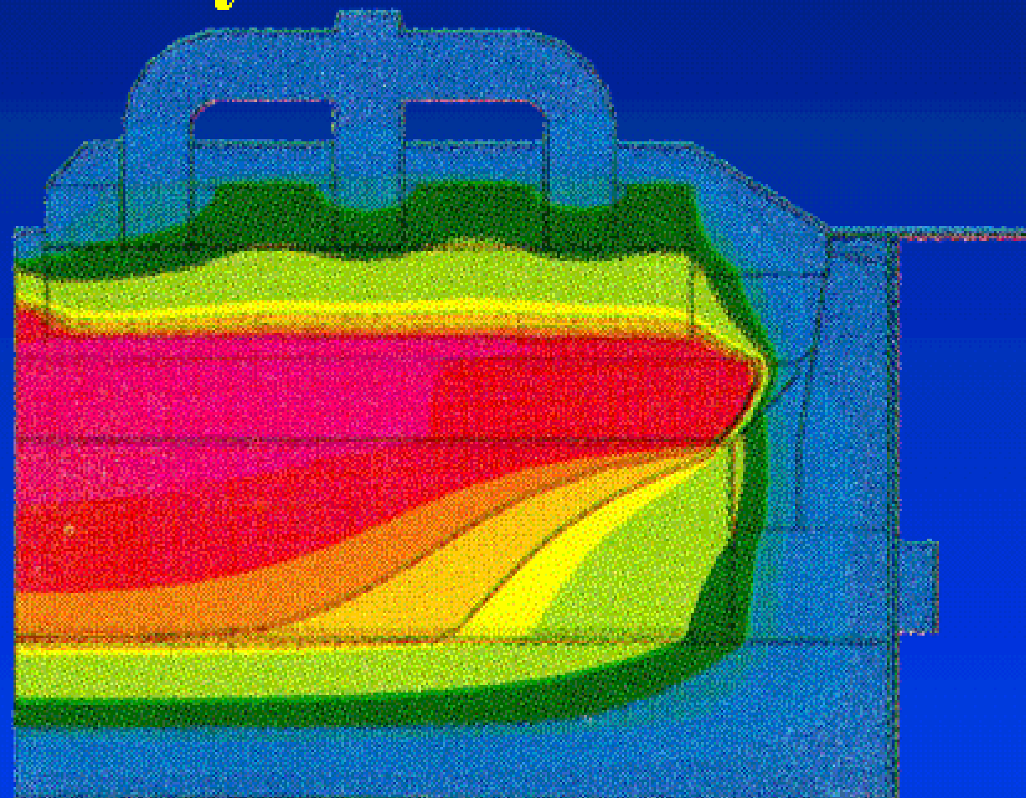
Demonstration Models Inspired from the VAW's JOM Paper of February 1994





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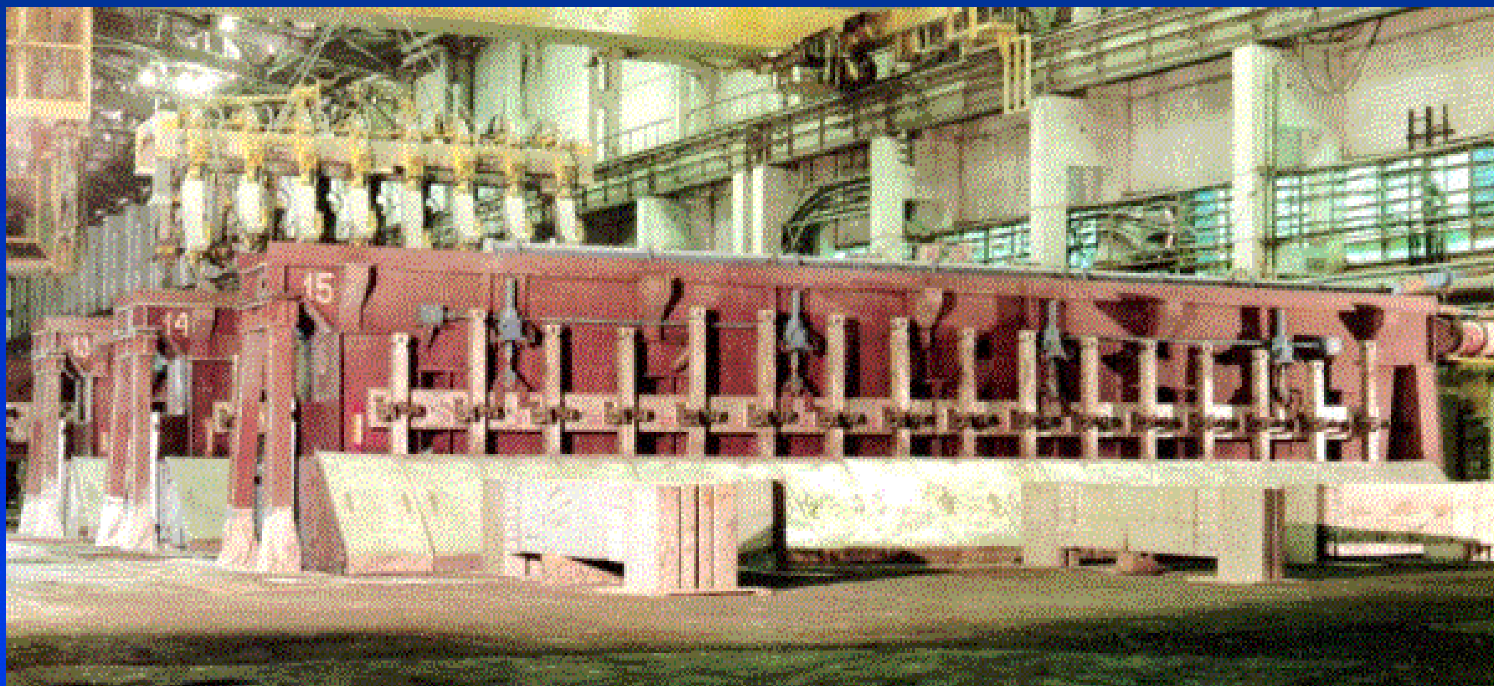
I used the Information Available and Guessed the Rest, so it is a Realistic but *Imaginary* Cell Design



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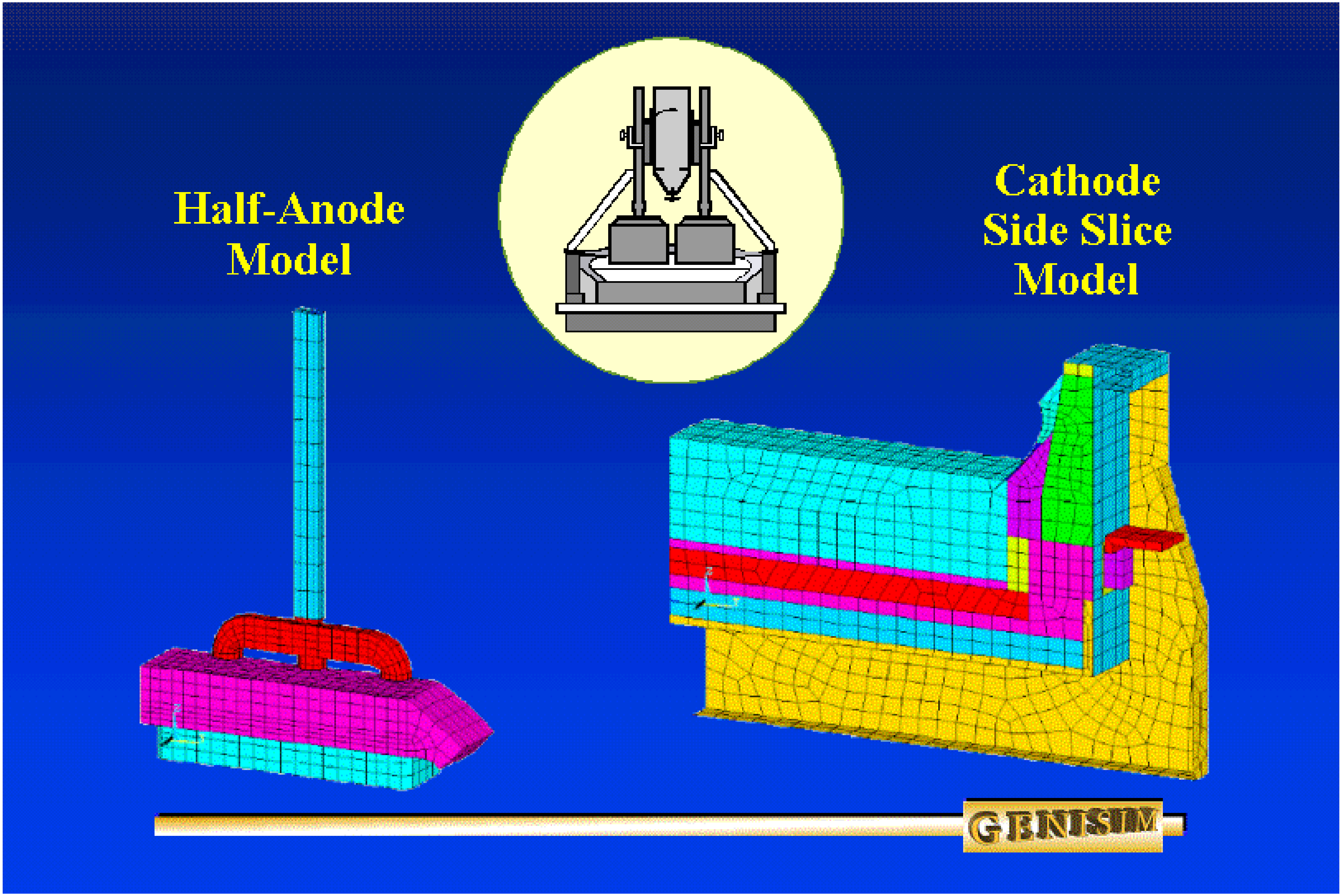
Half-Anode
Model
Cathode
Side Slice
Model
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Thermal Blitz

Heat Flux Measurements for Cell Heat Balance

date: 8-Sep-97 slice no: A2
cell: 'SOAR' 300

Description	Flux	Temp
Shell Wall		
Wall above bath level	2000	130
Wall bath level	5500	230
Wall metal level	7500	230
Wall block level above bar	6000	235
Left collector bar	3000	190
Right collector bar	3000	190
Wall collector bar level	1500	50
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
Floor extension	0	0
In the corner	100	35
Wall extension wide section	0	0
Wall extension narrow section	0	0
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	1550	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 Balance Results

date: 8-Sep-97 Cell: 'SOAR' 300

Cathode Heat Losses	W/m2	kW	%
Shell side wall above bath level	1000	11.51	1.86
Shell side wall opposite to bath	5500	71.68	5.11
Shell side wall opposite to metal	7500	47.10	6.97
Shell side wall opposite to block above bar	6000	48.78	7.80
Shell side wall opposite to block between bars	1500	6.48	1.05
Collector bars to air	1000	17.38	2.79
Collector bars to flexible		60	9.68
Shell side wall opposite to brick	1000	11.51	1.86
Shell floor close to corner	500	12.54	2.02
Shell floor quarter point region	500	10.44	1.68
Shell floor centerline region	500	8.74	1.74
Cradle above bath level	889	6.08	0.98
Cradle opposite to bath	1915	17.17	2.12
Cradle opposite to metal	2164	16.17	2.61
Cradle opposite to block above bar	848	8.12	1.22
Cradle opposite to block between bars	756	2.47	0.29
Cradle opposite to brick	122	1.80	0.29
Cradle corner	51	1.51	0.25
Cradle below floor close to corner	100	2.76	0.44
Cradle below floor quarter point region	100	2.76	0.44
Cradle below floor centerline region	100	2.76	0.44
Shell end wall opposite to metal	1500	2.61	0.42
Shell end wall opposite to block above bar	1000	7.22	1.28
Shell end wall opposite to block below top of bar	4000	6.96	1.12
Shell end wall opposite to brick	1000	10.44	1.68
Shell coverplate in the ends	500	1.51	0.25
Shell horizontal strip in the ends	1184	18.00	2.90
Shell vertical stiffeners in the ends	898	5.51	0.89
Shell horizontal stiffeners in the ends	100	0.45	0.07
Total for the cathode part		371.76	59.95

Anode Heat Losses	W/m2	kW	%
Crust in side channels	1700	21.48	3.46
Crust above anodes	1800	81.91	13.21
Crust in center channel	1750	7.60	0.58
Studs	4000	27.14	4.78
Yoke	7640	82.87	17.57
Aluminum rod	822	30.11	4.89
Total for the anode part		248.3	40.05
Total for the cell		610.1	100.00

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Instrumented Anode Setup

Half-Anode Model
Base Case Results

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

HEAT INPUT	W	W/m^2	%
Bath to anode carbon	1501.54	1510.60	42.06
Bath to crust	611.64	3304.00	10.01
Joule heat	1396.94		39.13
Total Heat Input	3510.13		100.00

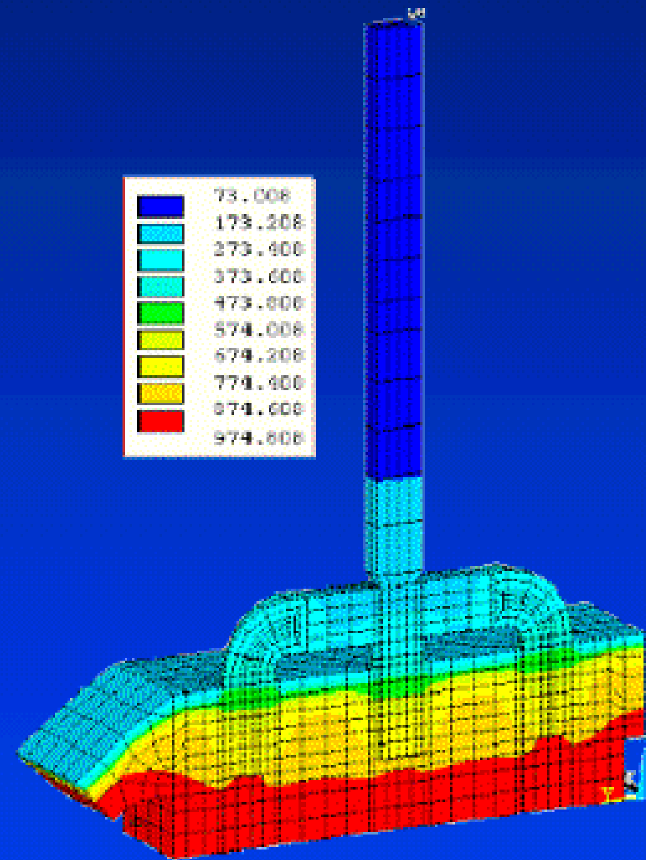
HEAT LOST	W	W/m^2	%
Crust to air	1433.63	1691.41	39.15
Stub to air	1019.63	4060.04	49.69
Aluminum rod to air	400.50	693.10	11.16
Total Heat Lost	3661.16		100.00

Solution Error 2.50 %

ANODIC PANEL HEAT LOST	kW	W/m^2	%
Crust to air	91.15	1691.41	39.15
Stub to air	116.46	4060.04	49.69
Aluminum rod to air	26.14	693.10	11.16
Total Anode Panel Heat Lost	234.35		100.00

Avg. Drop at clamp (mV)	Current at anode Surf (Amps)
302.103	4601.500

Targeted cell current: 300000.00 Amps
Obtained cell current: 300000.00 Amps
Solution Error 0.00 %



Cathode Side Slice Model
Base Case Results

**** Heat Balance Table ****
**** Side Slice Model : 'VAW' 300 ****
**** freeze profile converged ****
**** after 7. iterations ****

Heat input	W	W/m^2	%
bath to freeze	765.88	8888.80	17.24
metal to freeze	1471.68	14988.86	33.19
metal to carbon	1002.48	1007.15	22.57
Joule heat	1201.75		27.05
total heat input	4441.81		100.00

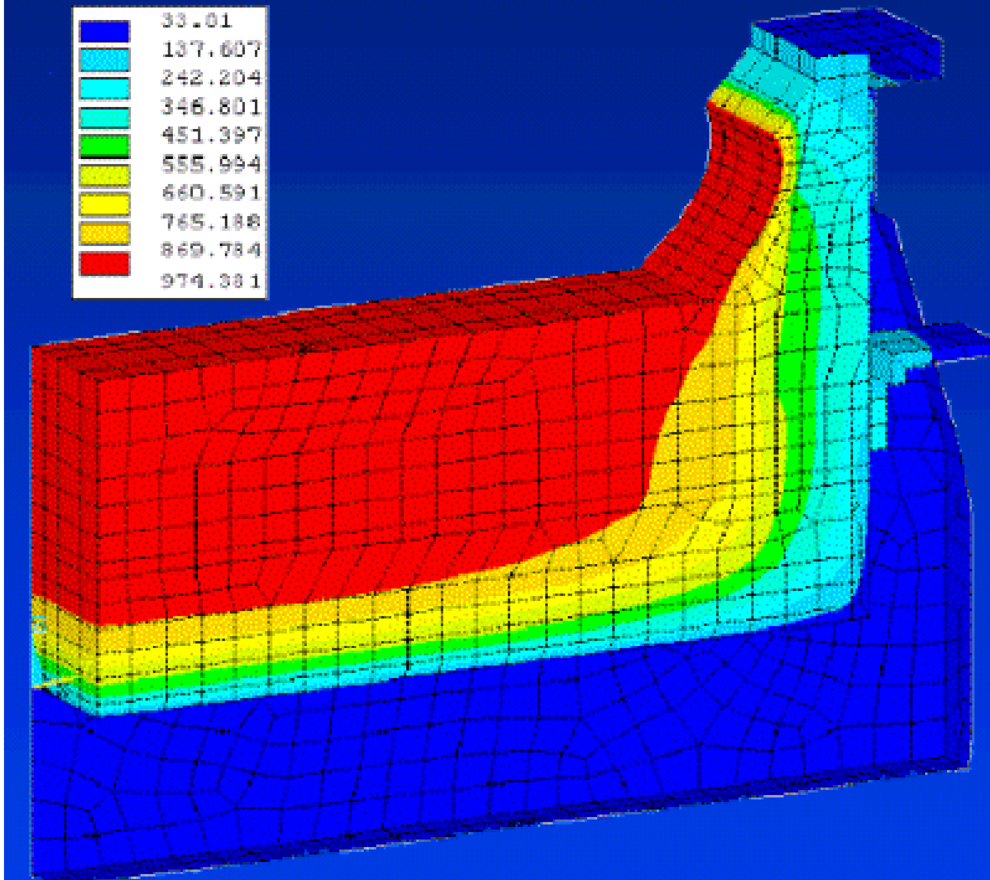
Heat lost	W	W/m^2	%
Shell wall above bath level	641.76	1204.80	14.98
Shell wall opposite to bath	412.86	5161.22	8.26
Shell wall opposite to metal	422.58	7628.48	8.48
Shell wall opposite to block	885.01	5722.22	18.84
Shell wall below block	84.77	665.54	2.19
Shell floor	333.18	414.62	7.47
Cradle above bath level	26.21	1514.97	0.58
Cradle opposite to bath	101.09	2075.57	2.27
Cradle opposite to metal	66.45	2546.87	1.48
Cradle opposite to block	261.89	828.84	5.87
Cradle opposite to brick	49.64	159.86	0.88
Cradle below floor level	202.55	88.29	4.54
Bar and flex to air	627.98	2648.40	14.07
End of flex to busbar	340.92	40514.19	7.69
total heat lost	4458.68		100.00

Solution error 0.40 %

Total Cathode heat lost 385.92 100.00

Avg. drop at bar end (mV)	Average flex. drop (mV)	Current at Cathode surf (Amps)
285.268	7.479	4166.667

Targeted cell current: 300000.00 Amps
Obtained cell current: 300000.00 Amps
Solution error 0.00 %



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Comparison Against Cell Internal Heat

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      ****         HEAT BALANCE SUMMARY          ****
      ****    Full slice  Model : "VAW" 300      ****

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INTERNAL HEAT CALCULATION
--------------------------------------------------------------
Bath Resistivity                          0.423211 ohm-cm
Anode Current Density                     0.732422 A/cm^2
Cathode Current Density                   0.668449 A/cm^2
Bath Voltage                               1.57648 volts
Electrolysis Voltage                       1.92441 volts
Total Cell Voltage                         4.28826 volts
Equivalent Voltage to Make Metal           2.01347 volts
Current Efficiency                         92.9152 %
--------------------------------------------------------------
Internal Heat Generation                   622.435 kW
==============================================================

TOTAL HEAT LOST
--------------------------------------------------------------
Total Anode Panel Heat Loss                234.350 kW
Total Cathode Heat Loss                    385.320 kW
--------------------------------------------------------------
Total Cell Heat Loss                       619.670 kW
==============================================================

HEAT UNBALANCE                                0.45 %
==============================================================
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- Bath resistivity using Wang's equation
- Bath voltage using Haupin's equation
- Electrolysis voltage using Haupin's equation
- Equivalent voltage to make metal using Haupin's equation
- Cell current efficiency using Solli's equation

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Base Case Data from my CQRDA's Retrofit Study Example

- **Base case basic input data:**
  - amperage — 300 kA
  - operating temperature — 975 °C
- **Base case models results:**
  - cathode lining drop — 284 mV
  - anode drop — 303 mV
  - anode panel heat losses — 234 kW
  - cathode shell heat losses — 385 kW
- **Base case operational results:**
  - cell voltage — 4.28 V
  - internal heat — 622.4 kW
  - current efficiency — 92.91 %
  - energy consumption — 13.75 kWh / kg

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Retrofitted Data from my CQRDA's Retrofit Study Example

- Retrofitted basic input data:
  - amperage 265 kA
  - operating temperature 950 °C
- Retrofitted models results:
  - cathode lining drop 213 mV
  - anode drop 276 mV
  - anode panel heat losses 183 kW
  - cathode shell heat losses 245 kW
- Retrofitted operational results:
  - cell voltage 3.85 V
  - internal heat 427 kW
  - current efficiency 96.0 %
  - energy consumption 11.94 kWh / kg

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Sensitivity Study
Results Summary

- Anode cover reduced from 16 cm to 13 cm
- Model response: anode panel heat losses increased from 235.35 kW to 247.57 kW
- Operating temperature reduced from 975 °C to 973.75 °C
- Model response: cathode shell heat losses reduced from 385.32 kW to 374.62 kW

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Verification that the New Thermal Balance have been Found

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--------------------------------------------------------------

     ****          HEAT BALANCE SUMMARY            ****
     ****      Full slice  Model : "VAW" 300       ****

--------------------------------------------------------------

INTERNAL HEAT CALCULATION
--------------------------------------------------------------
Bath Resistivity                           0.423211 ohm-cm
Anode Current Density                      0.732422 A/cm^2
Cathode Current Density                    0.668449 A/cm^2
Bath Voltage                                1.57648 volts
Electrolysis Voltage                        1.92441 volts
Total Cell Voltage                          4.28645 volts
Equivalent Voltage to Make Metal            2.01347 volts
Current Efficiency                          92.9152 %
--------------------------------------------------------------
Internal Heat Generation                    621.893 kW
--------------------------------------------------------------

TOTAL HEAT LOST
--------------------------------------------------------------
Total Anode Panel Heat Loss                 247.570 kW
Total Cathode Heat Loss                     374.620 kW
--------------------------------------------------------------
Total Cell Heat Loss                        622.190 kW
--------------------------------------------------------------

HEAT UNBALANCE                                 0.05 %
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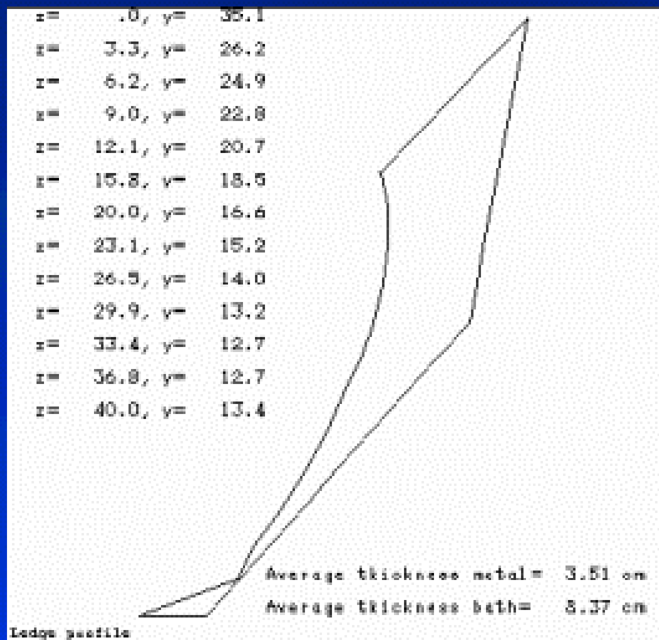
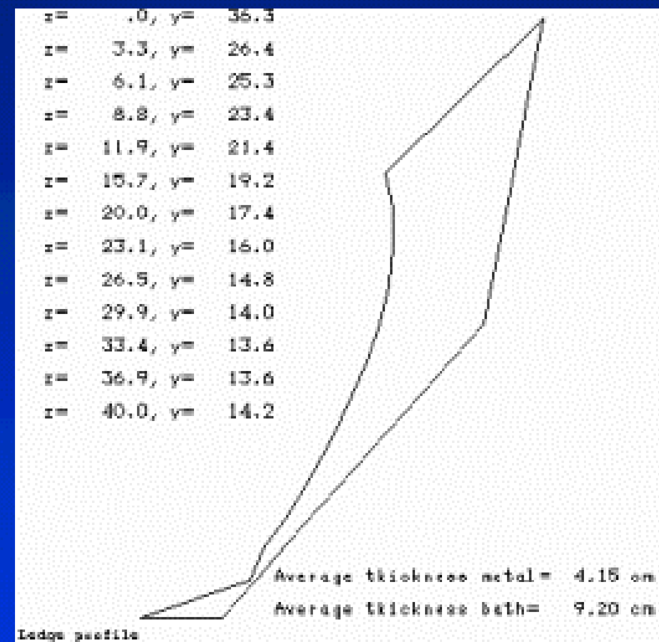
- With the separated 3D half-anode and 3D cathode side slice models approach, it is up to the user to find the new steady-state operating temperature after having changed the alumina cover thickness
- This can be done by trial and error or by doing some simple "back of the envelope" calculations

Interpretation of the Results



20 °C of cell eutectic superheat



18.75 °C of cell eutectic superheat

- When we remove 3 cm of alumina cover, the cell reacts by increasing the ledge thickness by an average of 0.72 cm

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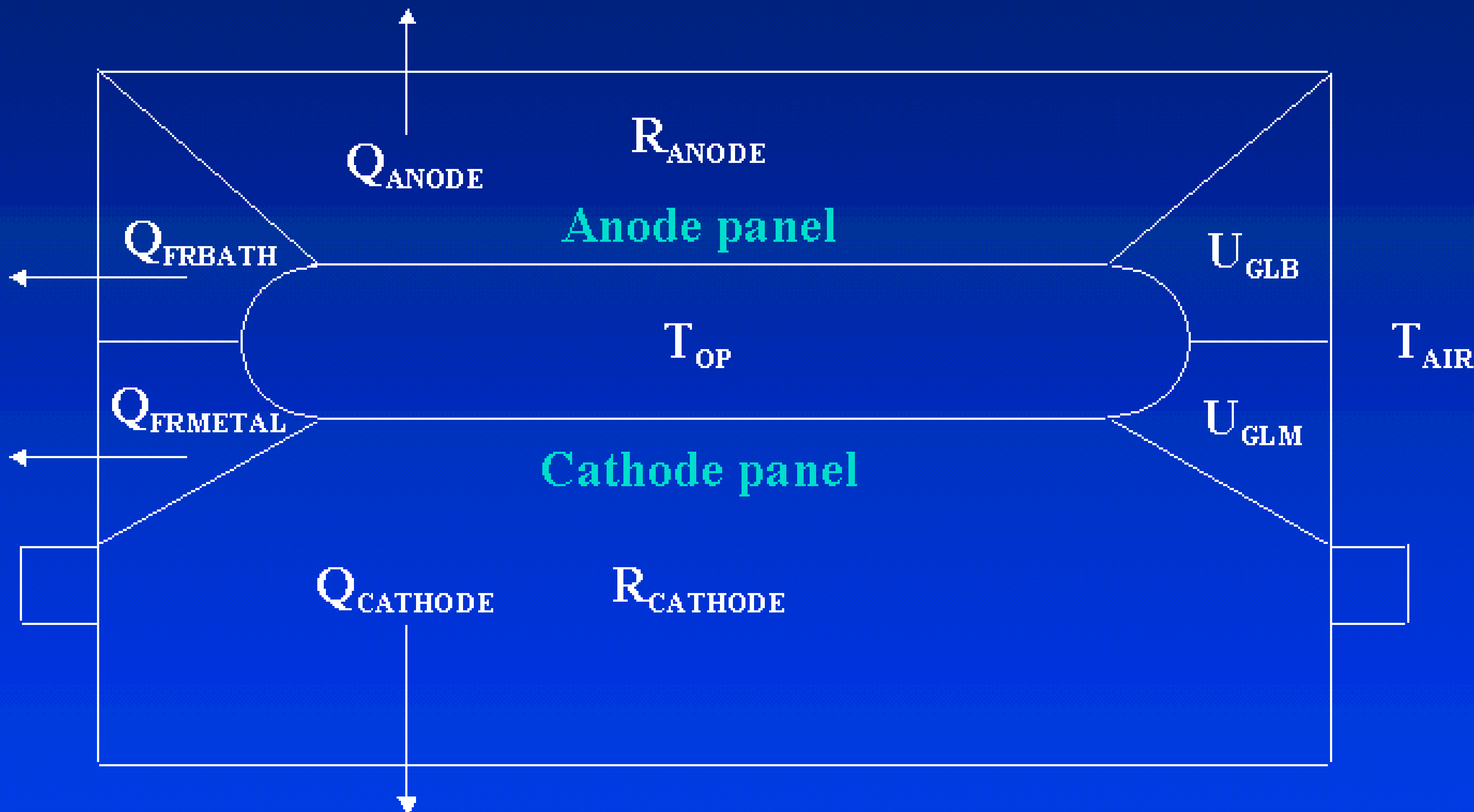
1D Thermal Model Concept



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1D Thermal Model Equations

$$Q_{ANODE} = R_{ANODE} * (T_{OP} - T_{AIR})$$

$$Q_{CATHODE} = R_{CATHODE} * (T_{OP} - T_{AIR})$$

$$Q_{FRBATH} = h_{FRB} * A_{BATH/LEDGE} * (T_{OP} - T_{MLT}) = U_{GLB} * A_{BATH/LEDGE} * (T_{OP} - T_{AIR})$$

$$Q_{FRMETAL} = h_{FRM} * A_{METAL/LEDGE} * (T_{OP} - T_{MLT}) = U_{GLM} * A_{METAL/LEDGE} * (T_{OP} - T_{AIR})$$

$$U_{GLB} = \frac{1}{\left(\frac{1}{U_{FIXB}} + \frac{1}{U_{FRB}}\right)}$$

$$U_{GLM} = \frac{1}{\left(\frac{1}{U_{FIXM}} + \frac{1}{U_{FRM}}\right)}$$

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Using the 3D Models Results to Define the Parameters of the 1D Thermal Model

Q_{ANODE} = 234.35 kW

$Q_{CATHODE}$ = 175.87 kW

R_{ANODE} = 0.2467 kW/°C

$R_{CATHODE}$ = 0.1851 kW/°C

Q_{FRBATH} = 72.31 kW

$Q_{FRMETAL}$ = 137.14 kW

U_{GLB} = 10.53 W/m^2°C

U_{GLM} = 15.16 W/m^2°C

U_{FIXB} = 29.43 W/m^2°C

U_{FIXM} = 21.70 W/m^2°C

U_{FRB} = 16.39 W/m^2°C

U_{FRM} = 50.26 W/m^2°C

L_{BF} = 8.26 cm

L_{MF} = 3.70 cm

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From the 1D Thermal Model Concept to a 1D Thermal Steady-State Model

```
--------------------------------------------------------------

     ****          HEAT BALANCE SUMMARY            ****
     ****     Full slice  Model : "VAR" 300        ****

--------------------------------------------------------------

INTERNAL HEAT CALCULATION
--------------------------------------------------------------
Bath Resistivity                              0.421029 ohm-cm
Anode Current Density                         0.732422 A/cm^2
Cathode Current Density                       0.668449 A/cm^2
Bath Voltage                                   1.56835 volts
Electrolysis Voltage                           1.92431 volts
Total Cell Voltage                             4.28004 volts
Equivalent Voltage to Make Metal               2.01206 volts
Current Efficiency                             92.8436 %
--------------------------------------------------------------
Internal Heat Generation                       620.394 kW
--------------------------------------------------------------

TOTAL HEAT LOST
--------------------------------------------------------------
Total Anode Panel Heat Loss                    234.114 kW
Total Cathode Panel Heat Loss                  175.693 kW
Heat Loss Through Ledge at Bath Level           72.702 kW
Heat Loss Through Ledge at Metal Level         137.886 kW
--------------------------------------------------------------
Total Cell Heat Loss                           620.395 kW
--------------------------------------------------------------

HEAT UNBALANCE                                    0.00 %
==============================================================
```

```
Ledge thickness, bath level (cm)             8.60843
Ledge thickness, metal level (cm)            4.04444
Bath chemistry:
  Cryolite ratio                             2.50691
  Bath ratio                                 1.25345
  Modified conc. of diss. alumina (%)        1.23832
  Conc. of diss. alumina at eutect. (%)      7.48812
  Conc. of saturated diss. alumina (%)       8.53723
  Conc. of cryolite (%)                     87.70000
Heat balance:
  Superheat (C)                              19.4736
  Cell energy consumption (kWh/kg)           13.7405
  Total side resis. bath level (W/m^2C)       10.260
  Total side resis. met. level (W/m^2C)       14.774
  Total heat loss (kW)                       620.395
  Total electrical input energy (kW)         1224.01
  Internal heat generation (kW)              620.394
Electrical characteristics:
  Current efficiency (%)                     92.8436
  Cathode current density (A/cm^2)          0.732422
  Cathode current density (A/cm^2)          0.668449
  Bath resistivity (ohm-cm)                 0.421029
  Cell pseudo-resistance (micro-ohm)         8.76679
  Bath voltage (V)                           1.56835
  Electrolysis voltage (V)                   1.92431
  Cell voltage (V)                           4.28004
  Voltage to make the metal (V)              2.01206
Geometric variables:
  Area of anodes (m^2)                       40.9600
  Perimeter of ledge, bath level (m)         35.5557
  Perimeter of ledge, metal level (m)        35.1222
```

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Prediction of the 1D Steady-State Model for the Sensitivity Study

• Thickness of anode cover:	16 cm	13 cm
• Anode panel heat loss at 975 °C :	234.35 kW	247.57 kW
• Converged operating temperature:	974.05 °C	972.89 °C
• Converged cell eutectic superheat:	19.47 °C	18.32 °C
• Converged bath's ledge thickness:	8.61 cm	9.45 cm
• Converged metal's ledge thickness:	4.04 cm	4.88 cm

- Conclusion of the study: an average of 0.84 cm extra ledge thickness

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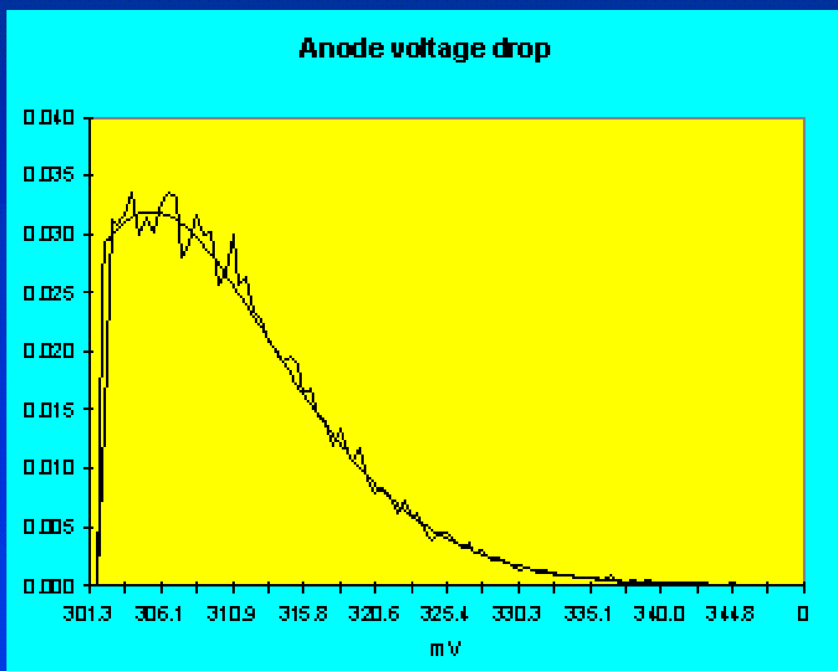
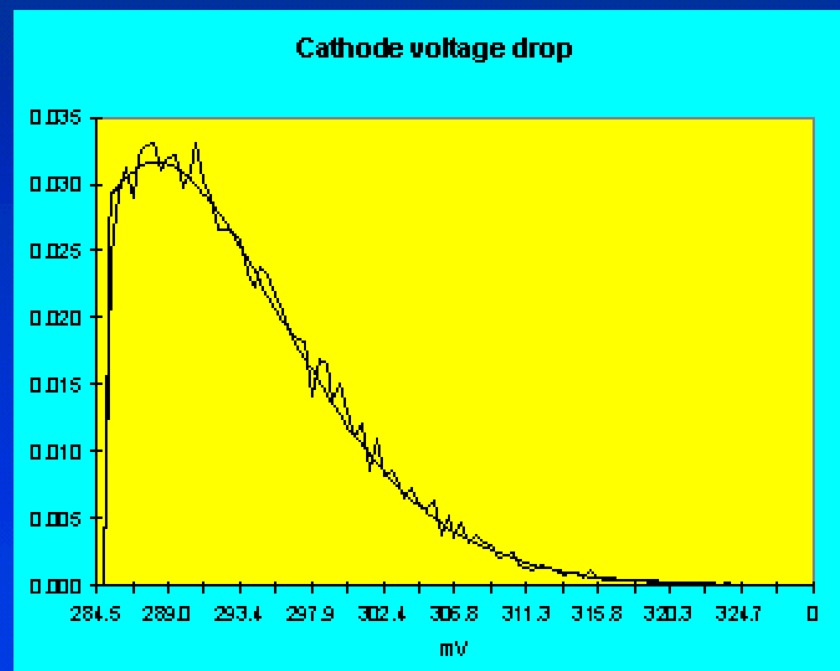
Monte Carlo Sensitivity Study: Replace Definite Results Obtained by 3D Models by Probability Distributions





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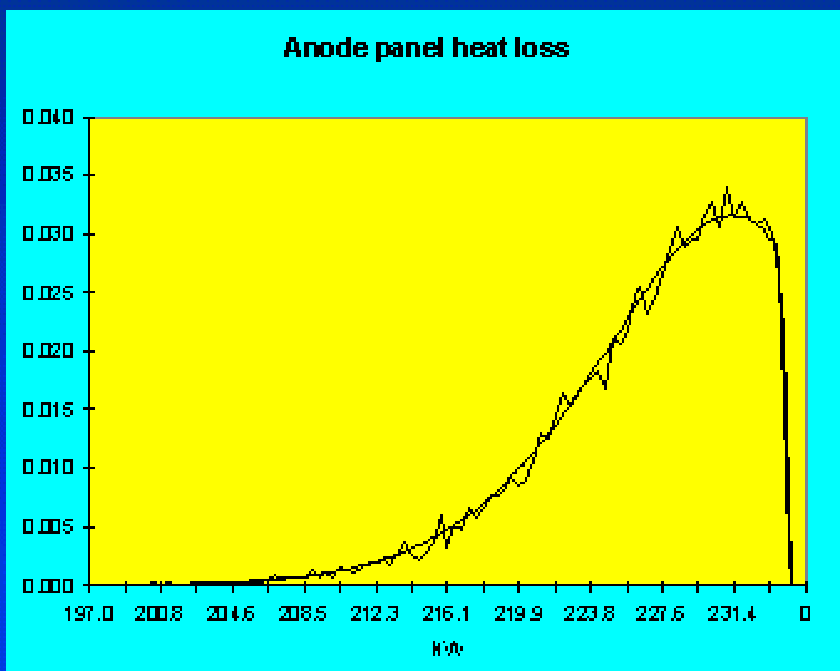
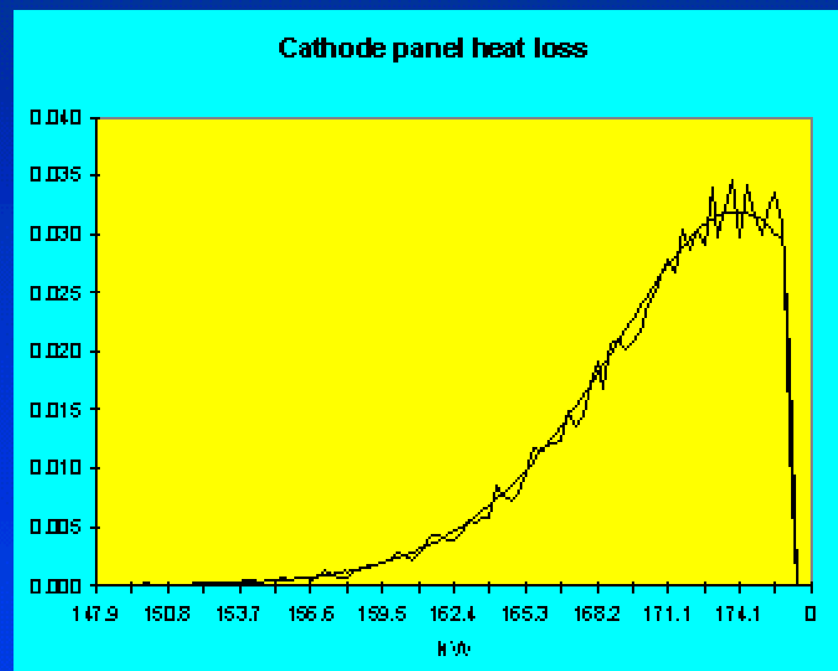
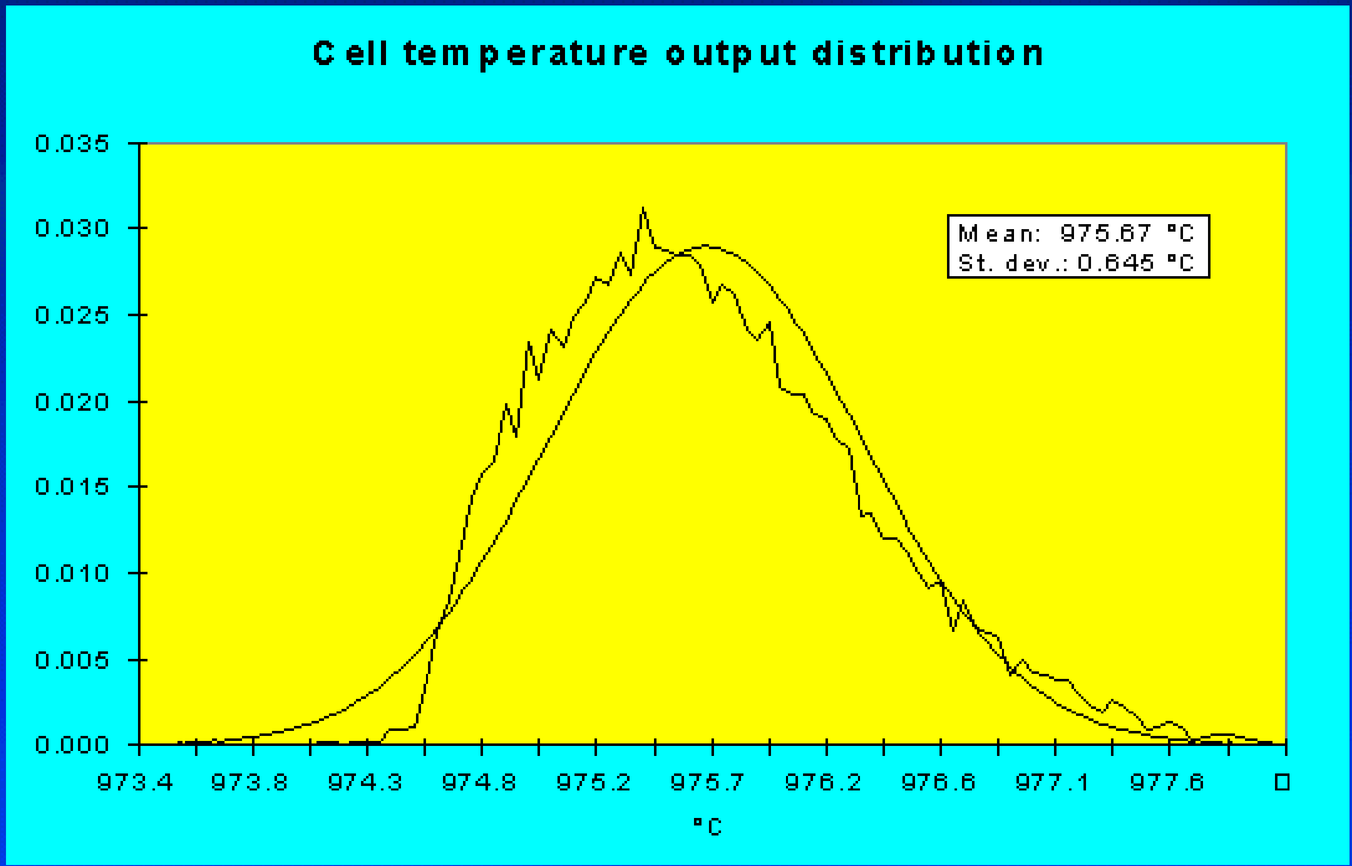
Monte Carlo Sensitivity Study: Replace Definite Results Obtained by 3D Models by Probability Distributions

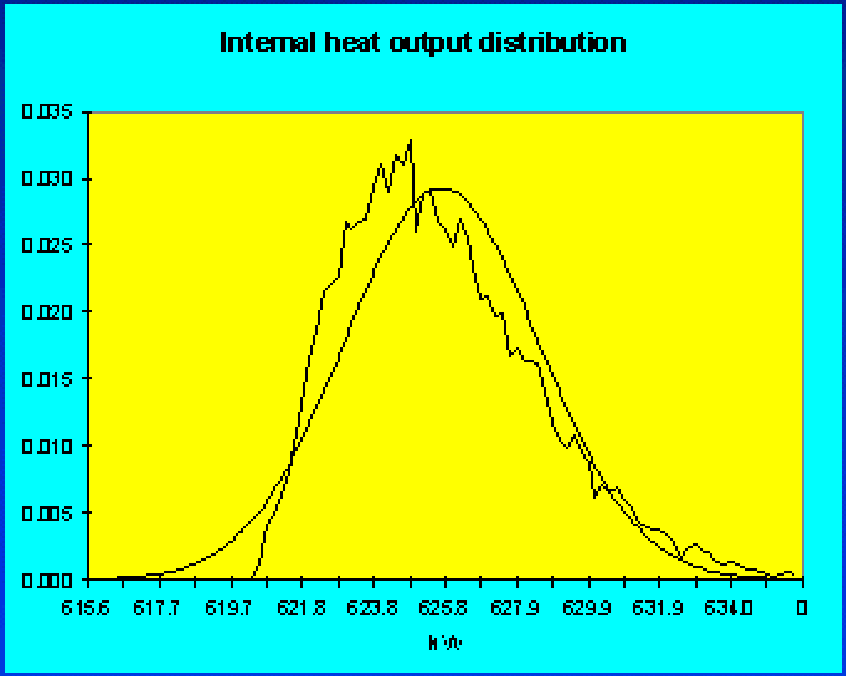


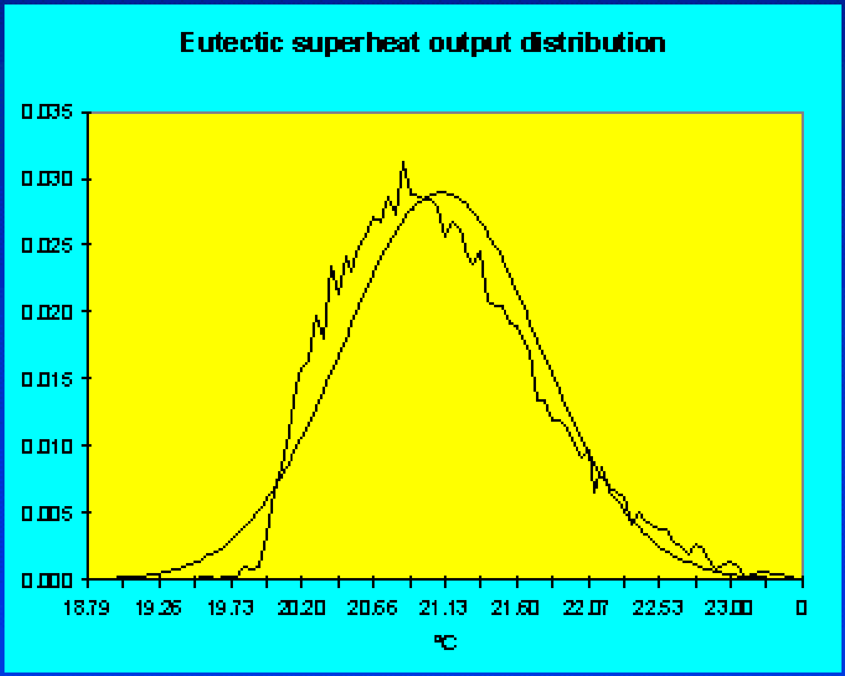


Main Output Distribution of the Monte Carlo Study



Indirect Output Variable Distributions from the Monte Carlo Study





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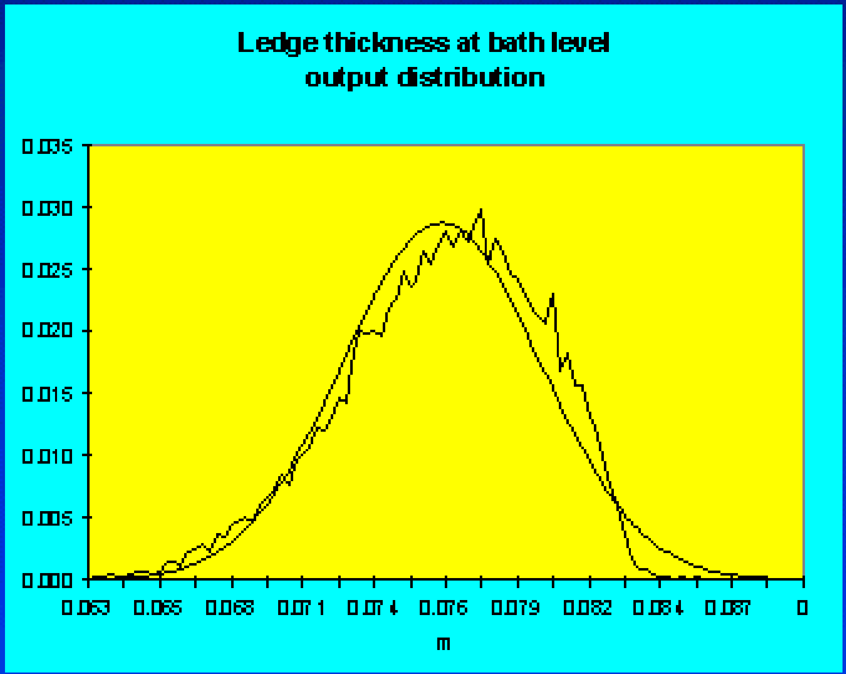
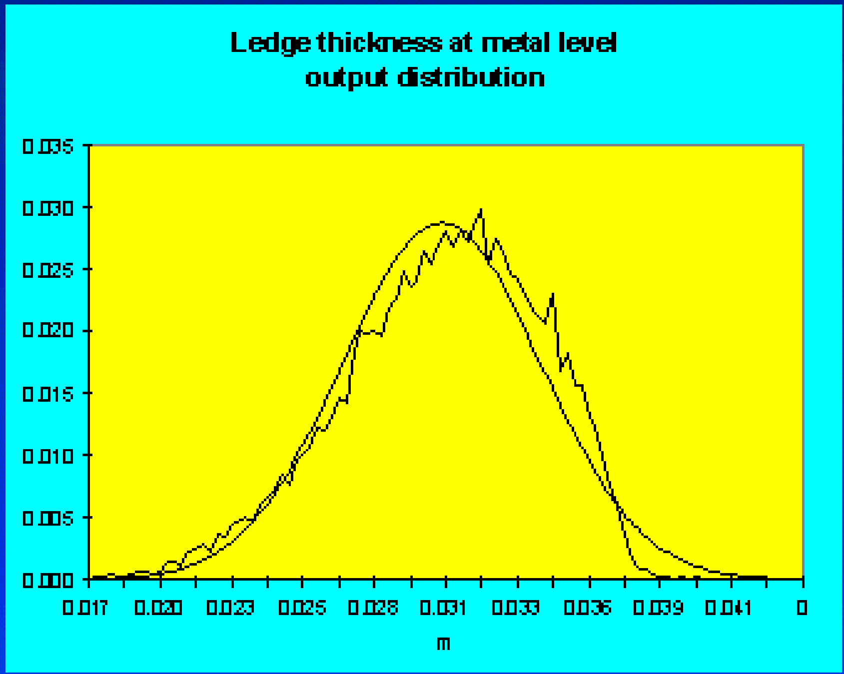
Indirect Output Variable Distributions from the Monte Carlo Study





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Extending from a 1D Steady-State Model to a 1D Dynamic Model

Adding to the Process Model

- Mass balance equations of all the constituents of the bath, the dispersed alumina, the sludge and the metal
- Kinetic equations of the alumina dissolution, sludge formation, back feeding and metal production reaction
- Kinetic equation of the ledge formation and melting, and equations that follow the dynamic ledge thickness evolution both at bath and metal level
- Kinetic equation of the fluoride evaporation
- Equation that follows the ACD dynamic evolution

Extending from a 1D Steady-State Model to a 1D Dynamic Model

Additions to the Heat Balance Equation

- Splitting of the energy required to make metal terms into 3 components:
  - the energy required to heat-up to bath temperature and dissolve the alumina
  - the energy required to heat-up to bath temperature the anode carbon block
  - the energy required by the chemical reaction itself
- Adding terms to account for the heat required to heat-up and to dissolve all additives fed to the cell. For the alumina, the heat required to dissolve it is coupled to its rate of dissolution.

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Extending from a 1D Steady-State Model to a 1D Dynamic Model

Additions to the Heat Balance Equation

- Adding a term to account for the heat required to heat-up newly set anodes including a kinetic equation for its heating rate
- Adding a term to account for the heat of fusion of the ledge that is coupled to its forming/melting rate
- Adding a term for the latent heat of the bath, metal, dispersed alumina and sludge

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Extending from a 1D Steady-State Model to a 1D Dynamic Model

Adding a Control Model

- Cell alumina feeding and cell resistance control algorithm
- Anode effect quenching control algorithm
- Bath ratio control logic
- Metal tapping policy
- Anode change schedule

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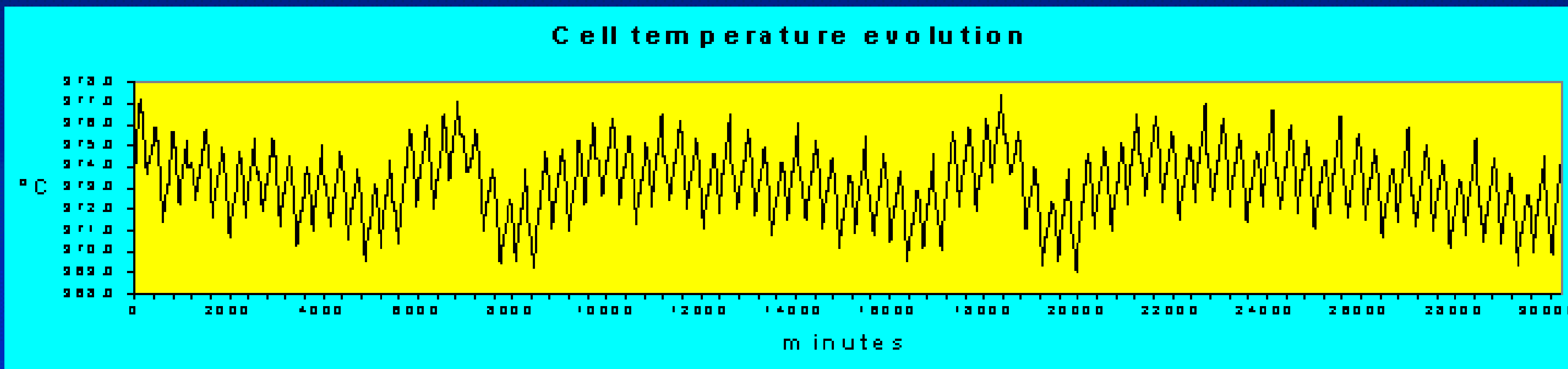
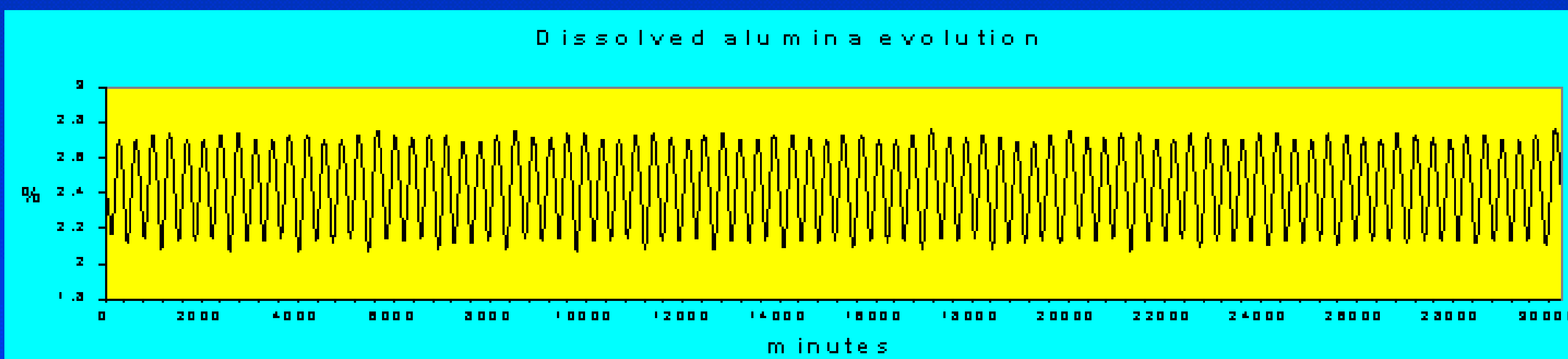
1D Dynamic Model Application
3 Weeks of Stable Operation





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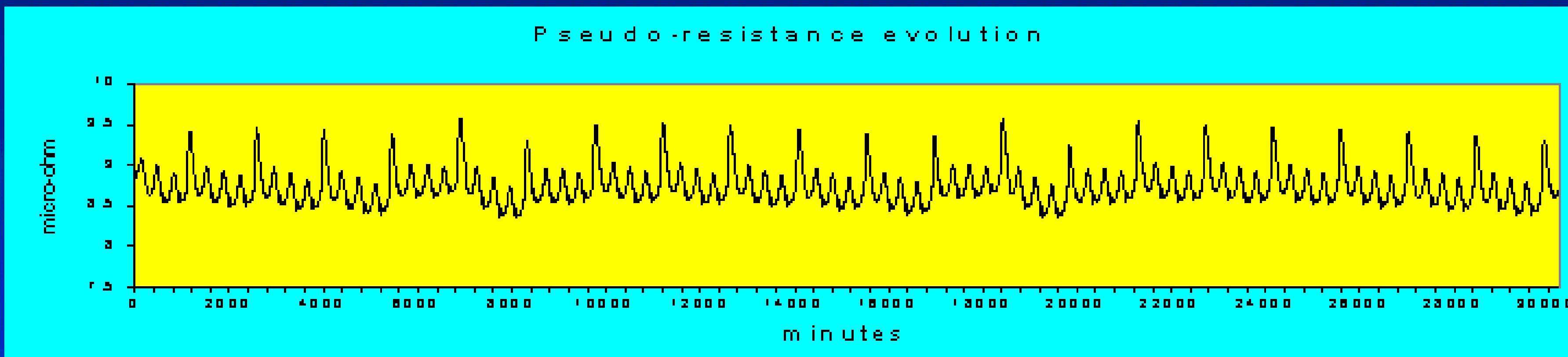
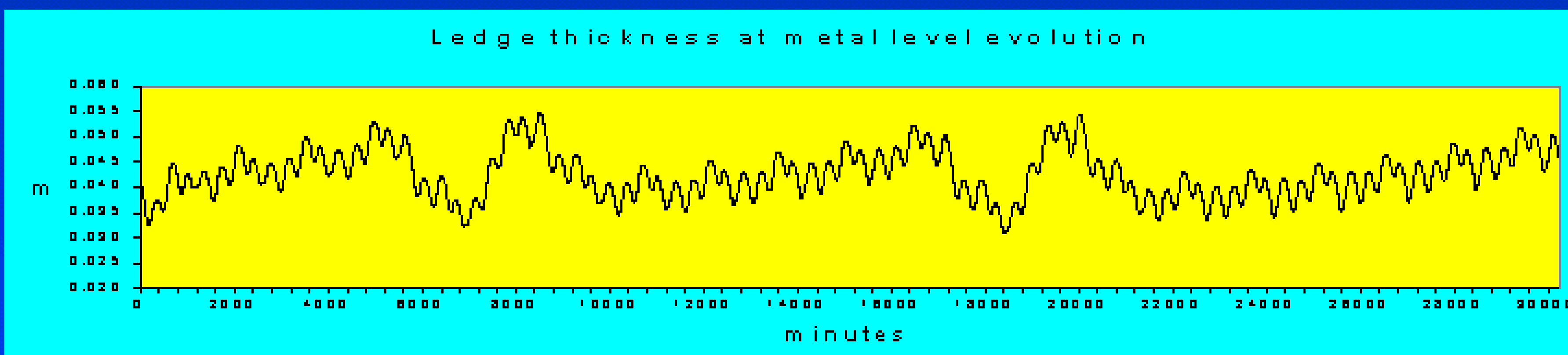
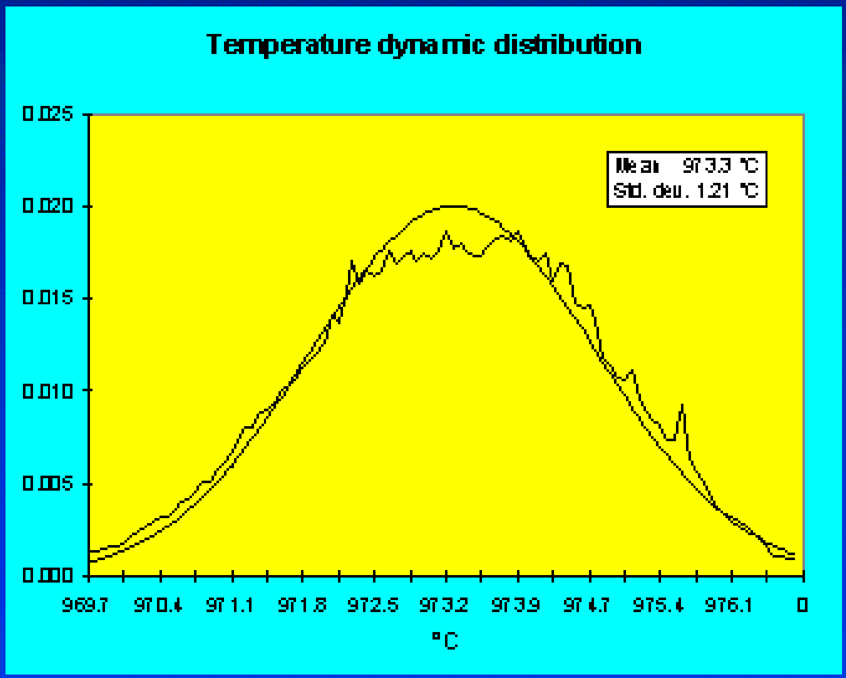
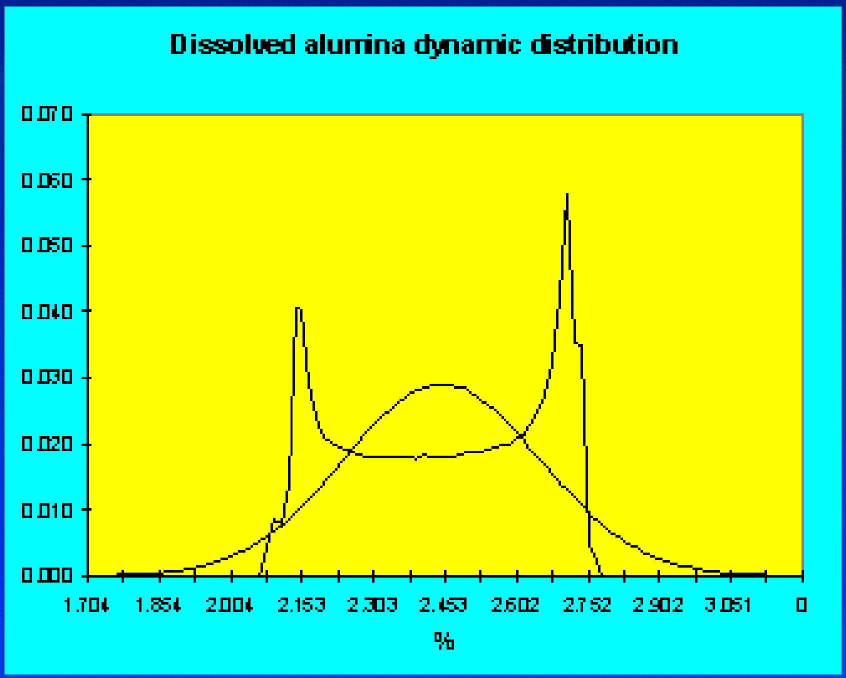
3 Weeks of Stable Operation





Histograms from the Dynamic Model for Stable Cell Operation





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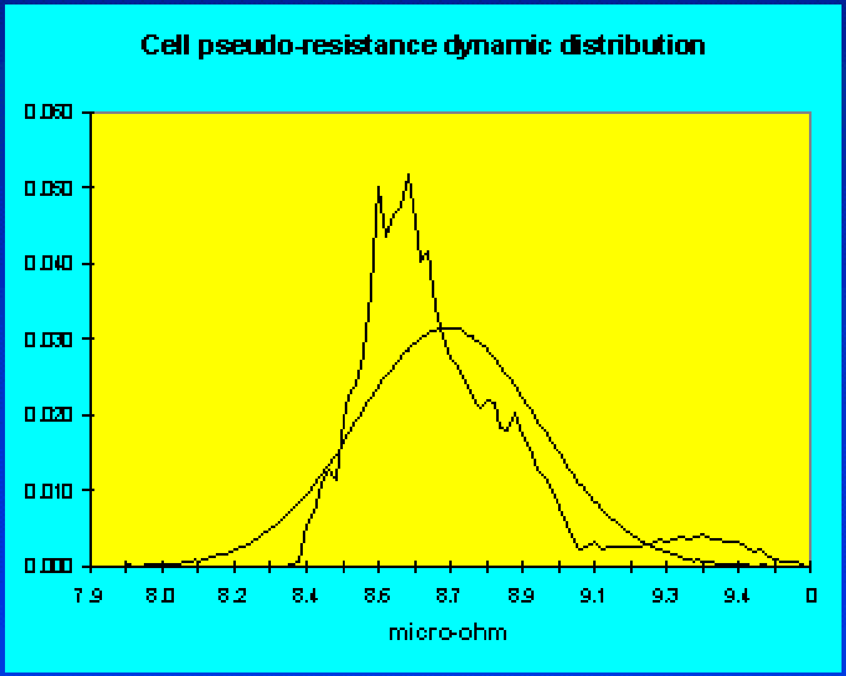
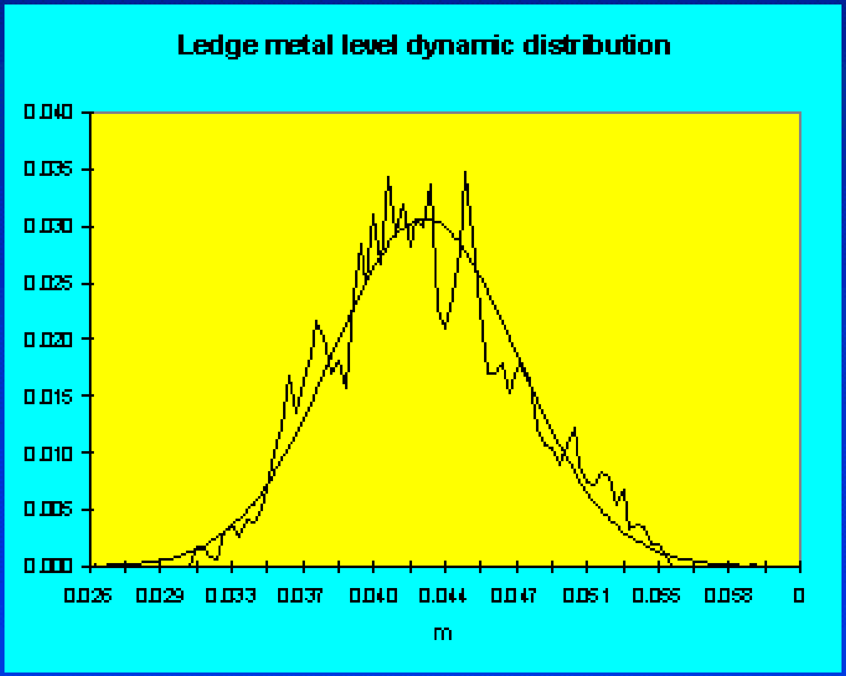
Histograms from the Dynamic Model for Stable Cell Operation





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Conclusions from the Monte Carlo and Dynamic Study

By designing a cell to have 4 cm of ledge in the 3D steady-state model, we have a fair amount of chance to end up with a cell having only 2 cm of ledge left in its normal "low tide" conditions!

Knowing that, it is up to the design team to decide if 4 cm of ledge at the metal level is a safe target for the 3D steady-state model "Optimal Design Solution"

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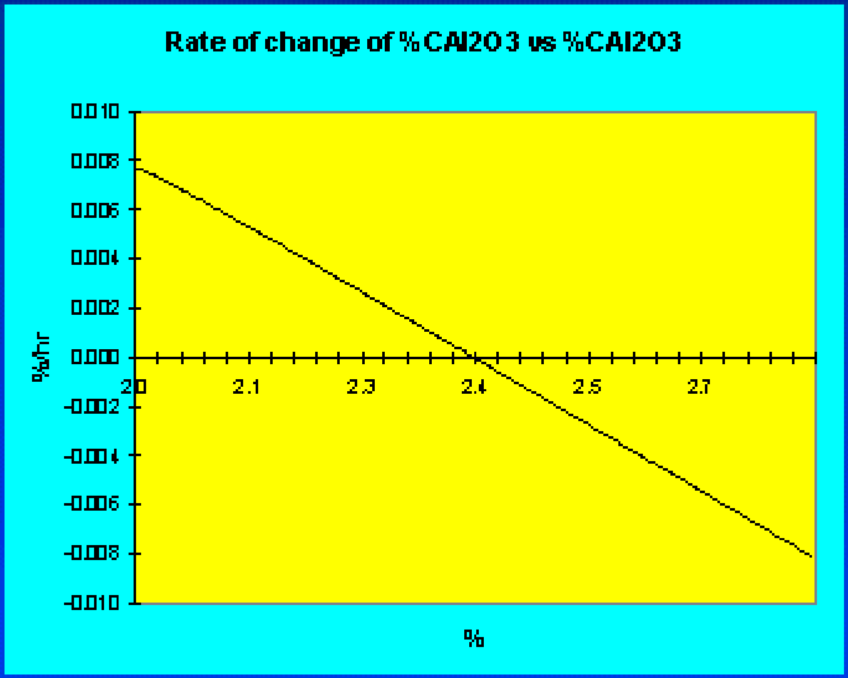
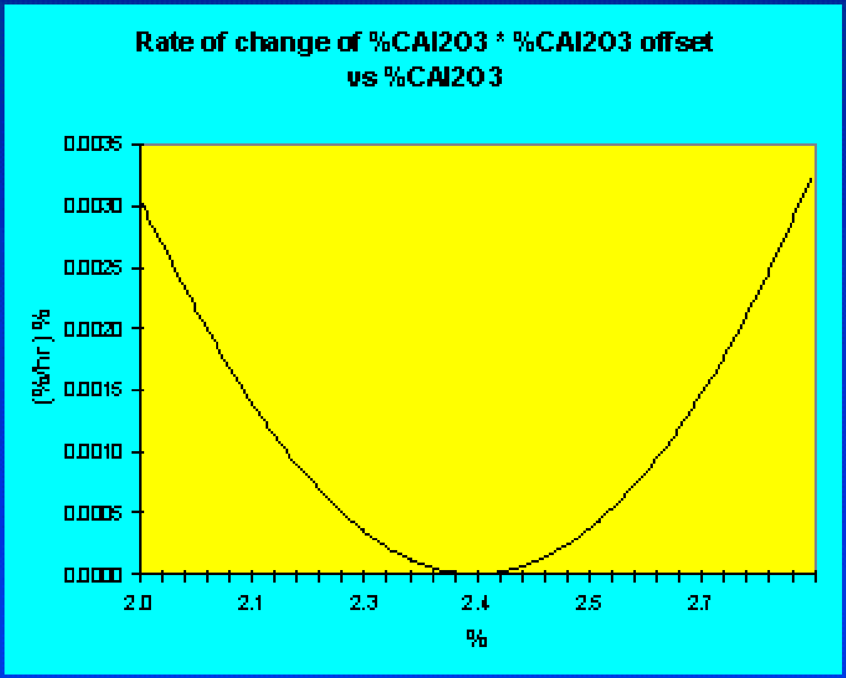
Using a 1D Dynamic Model to Assist in the Development of Cell Control Logic

Theory A: Positive CE vs. %Al_2O_3 Slope





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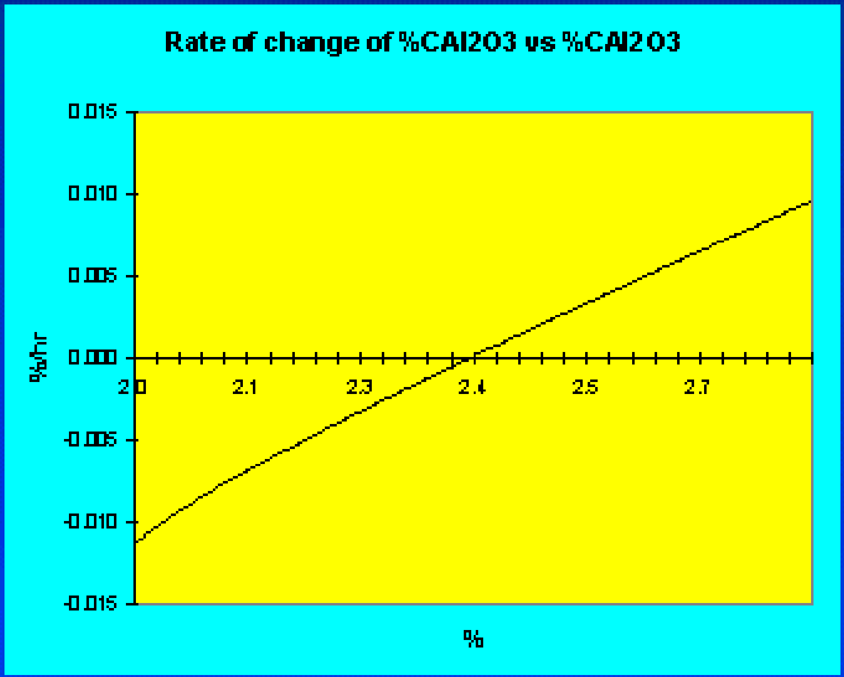
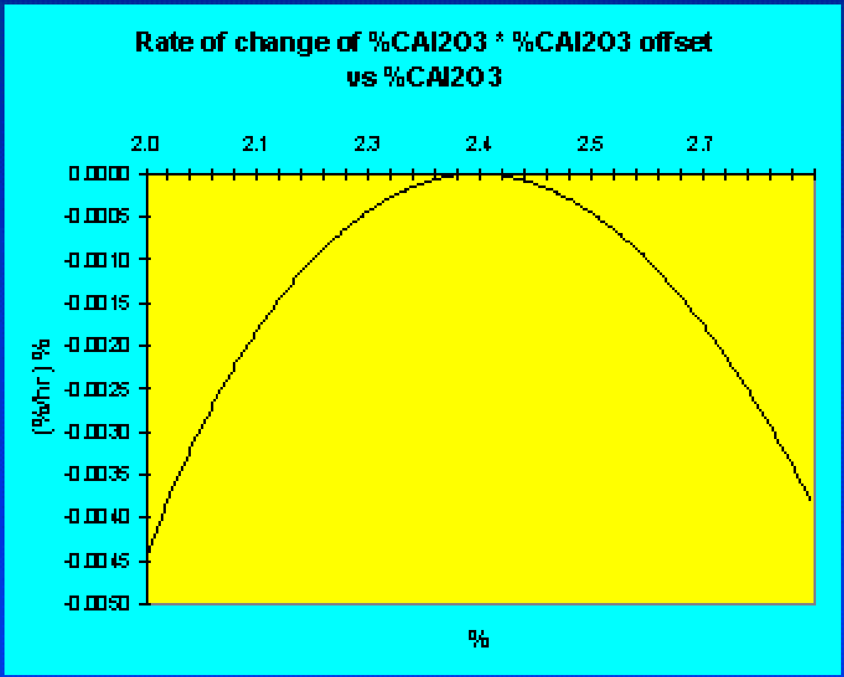
Using a 1D Dynamic Model to Assist in the Development of Cell Control Logic

Theory B: Negative CE vs. %Al_2O_3 Slope





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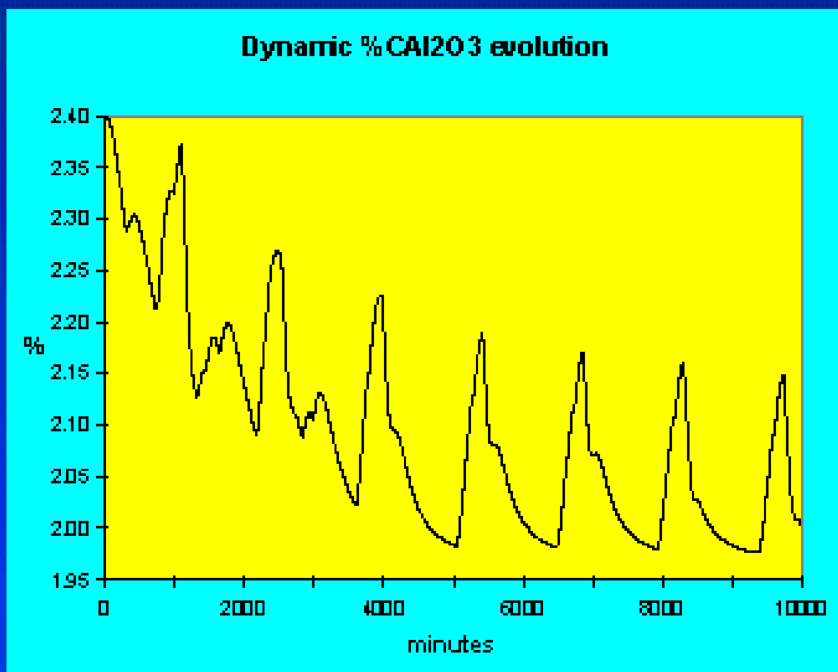
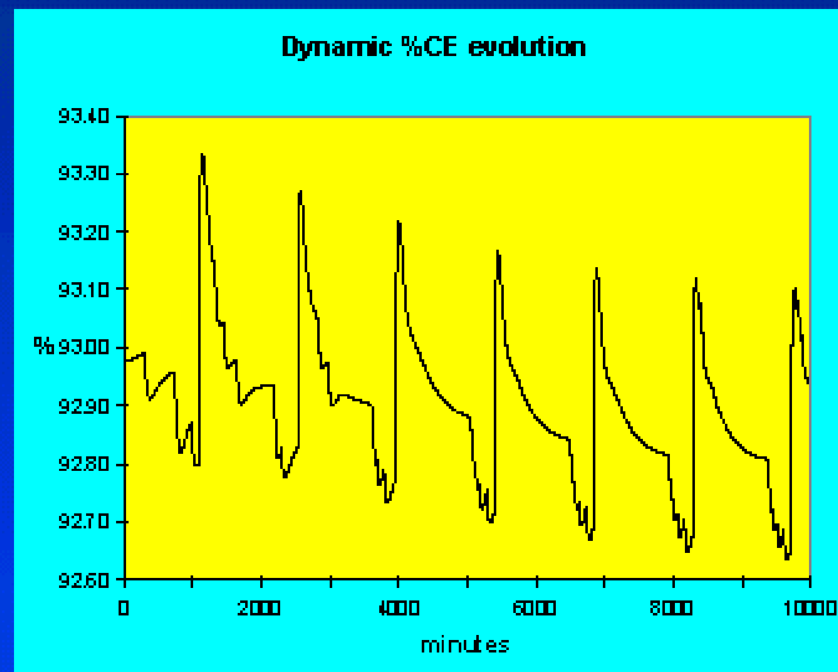
Using a 1D Dynamic Model to Assist in the Development of Cell Control Logic

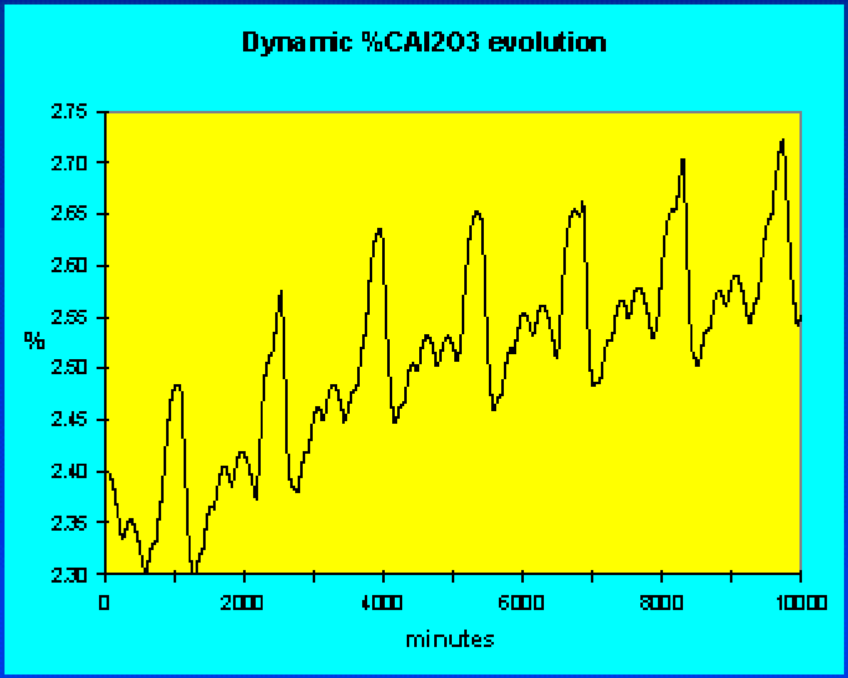
Theory A: Nominal Feeding at 179.5 kg/hr

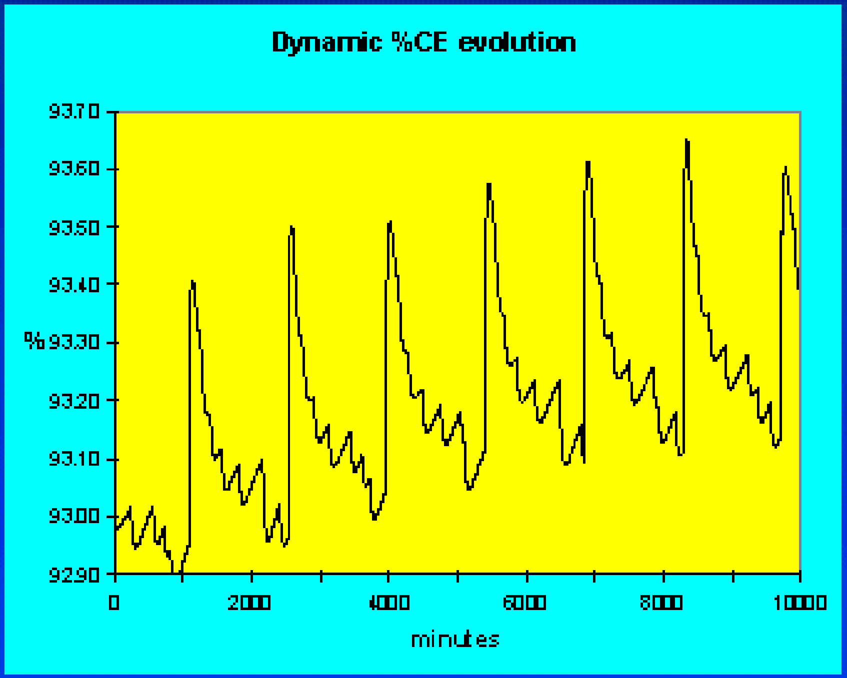




Using a 1D Dynamic Model to Assist in the Development of Cell Control Logic

Theory A: Nominal Feeding at 180.5 kg/hr





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Using a 1D Dynamic Model to Assist in the Development of Cell Control Logic

Nominal feeding logic is perfectly adapted to the case where the slope of the CE vs. Al_2O_3 is positive because:

- It is advantageous to operate constantly the cell at a nominal rate that corresponds to an alumina concentration of around 3.5 % maximizing both the current efficiency and the power efficiency
- The cell is "self-compensating" small fluctuations in the targeted feeding rate

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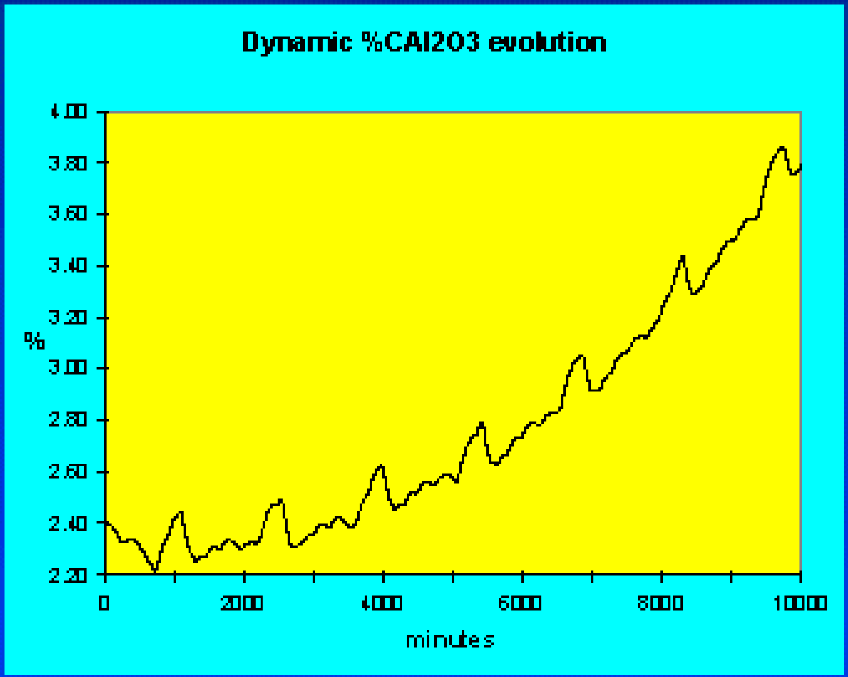
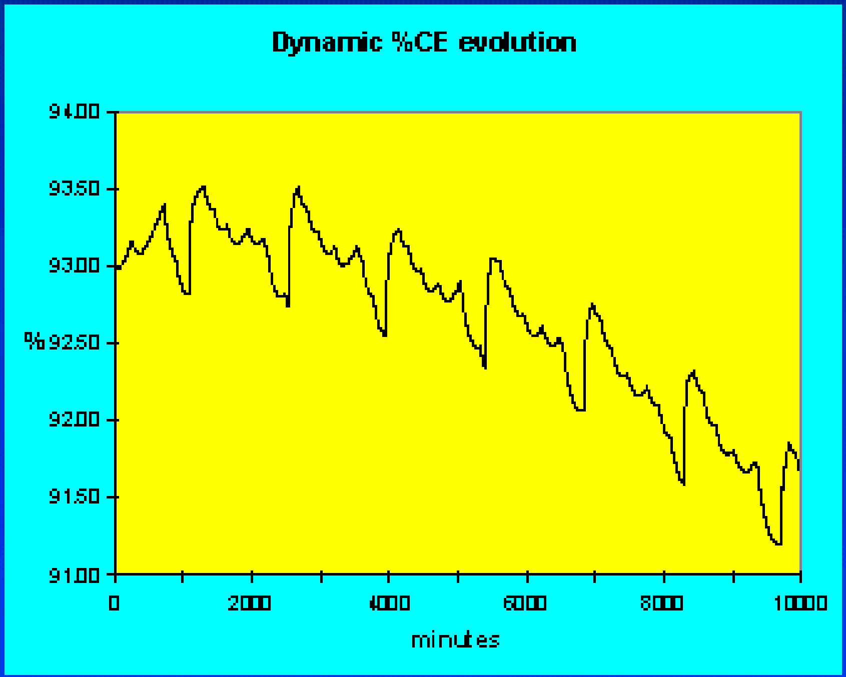
Using a 1D Dynamic Model to Assist in the Development of Cell Control Logic

Theory B: Nominal Feeding at 180.5 kg/hr





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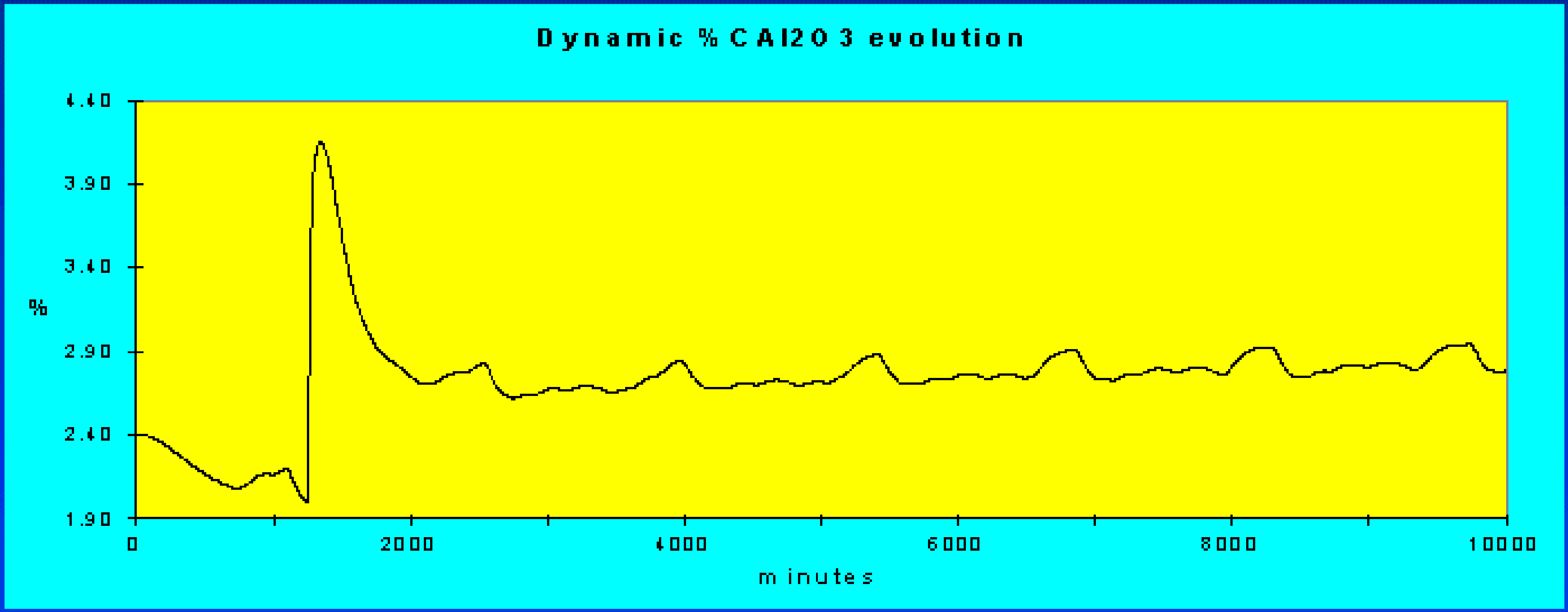
Using a 1D Dynamic Model to Assist in the Development of Cell Control Logic

Theory B: Nominal Feeding at 179.5 kg/hr



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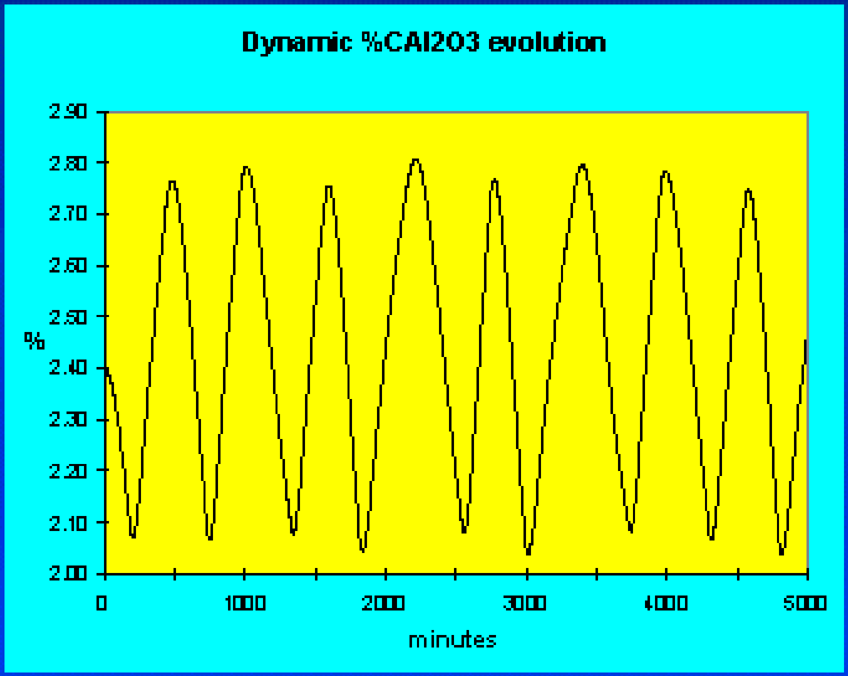
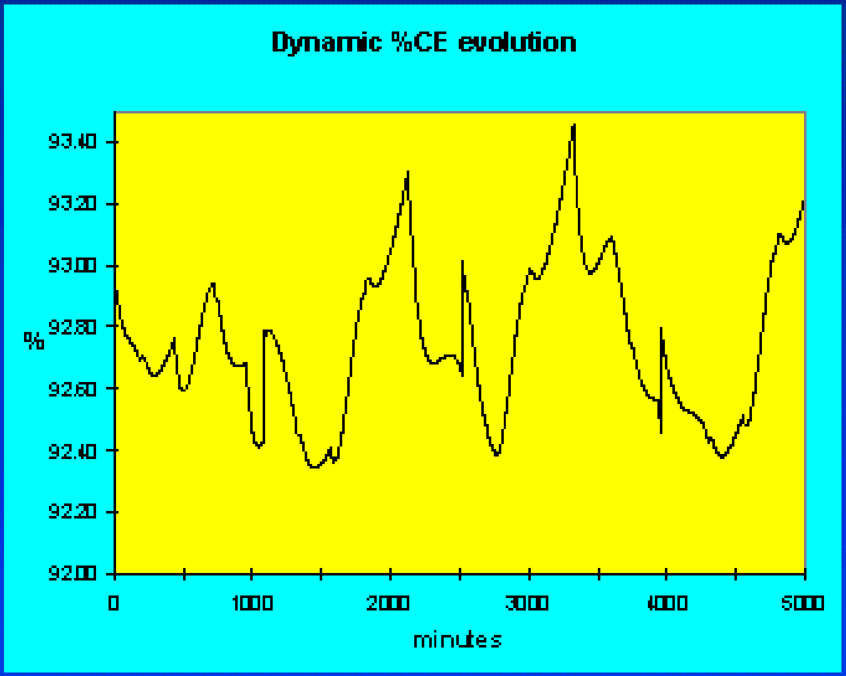
Using a 1D Dynamic Model to Assist in the Development of Cell Control Logic

Theory B: Continuous Tracking





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Using a 1D Dynamic Model to Assist in the Development of Cell Control Logic

Continuous tracking feeding logic is perfectly adapted to the case where the slope of the CE vs. Al_2O_3 is negative because:

- Knowing that a steady-state nominal feeding rate does not exist, it instead maintains a continuous balancing act by shifting between strong over and under-feeding rate
- It maintains the alumina concentration at its minimum in order to maximize the cell current efficiency and at the same time takes advantage of the cell resistance increased toward the anode effect to evaluate when it is time to change the alumina feeding rate.

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Conclusions

In general conclusion, I hope I was able to convince you of the value of using process simulation models to assist you in your work, since I strongly believe that they offer tremendous opportunities to improve the productivity of all of the smelters in operation today

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