Modeling Aluminum Reduction Cell since 1980 and Beyond

Marc Dupuis GENISIM

Plan of the presentation

- Introduction
- Past developments
    - 1984, 2D in-house potroom ventilation model
    - 1984, 3D ANSYS based thermo-electric half anode model
    - 1986, 3D ANSYS based thermo-electric cathode side slice and cathode corner model
    - 1988, 3D ANSYS based cathode potshell plastic deformation mechanical model
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Plan of the presentation

- Past developments

  2001, 3D CFX-4 based potroom ventilation model

  2002, 3D ANSYS based thermo-electric half cathode and external busbar model

  2003, 3D ANSYS based thermo-electric full cathode and external busbar model

  2004, 3D ANSYS based thermo-electric full cell and external busbar model

  2004, 3D ANSYS based full cell and external busbar erosion model

- Future developments

  Weakly coupled 3D thermo-electric full cell and external busbar and MHD model

  3D fully coupled thermo-electro-magneto-hydro-dynamic full cell and external busbar model

  3D fully coupled thermo-electro-magneto-mechanico-hydro-dynamic full cell and external busbar model

  3D fully coupled thermo-electro-magneto-mechanico-hydro-dynamic full cell and external busbar model weakly coupled with a 3D potroom ventilation model

- Conclusions

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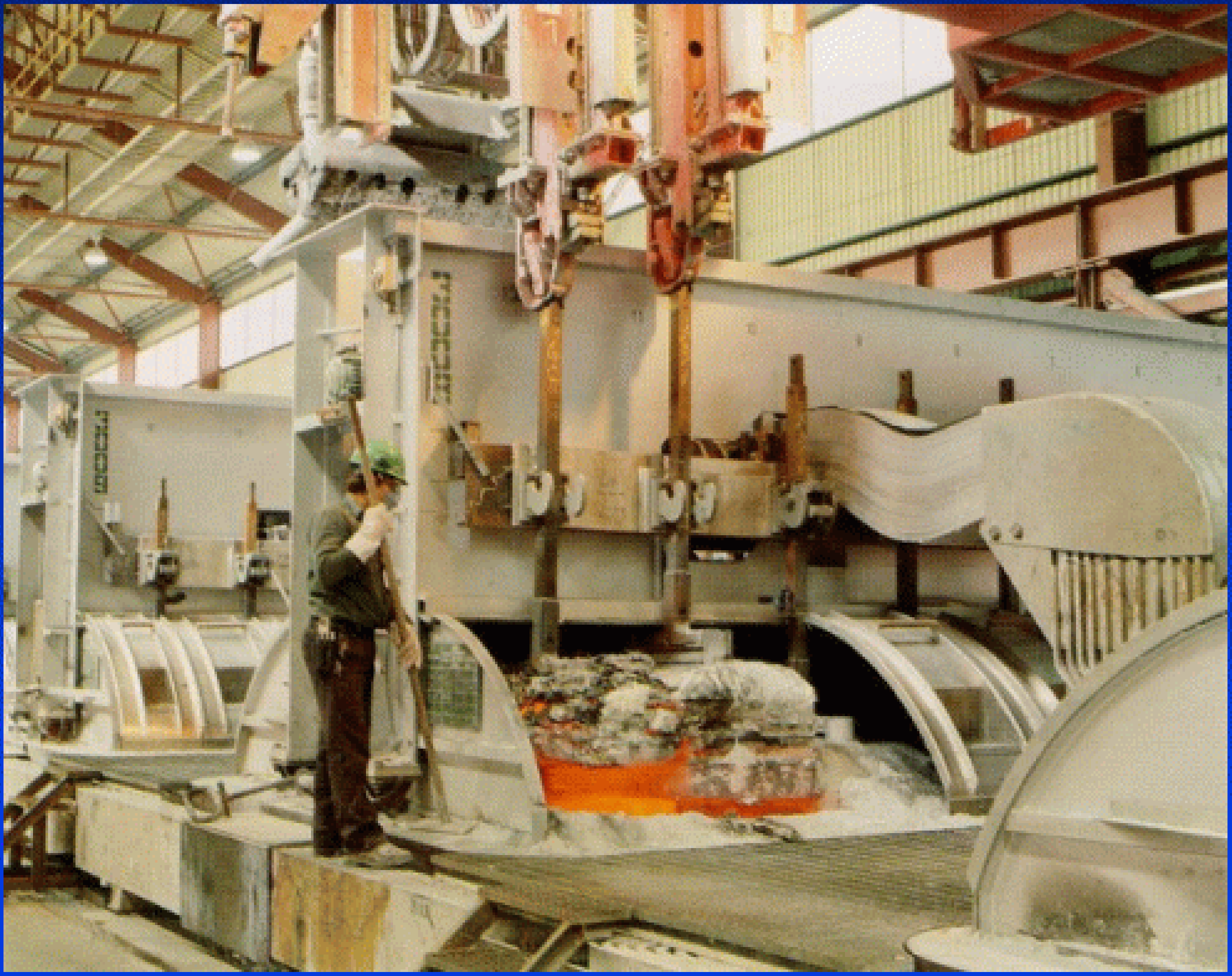
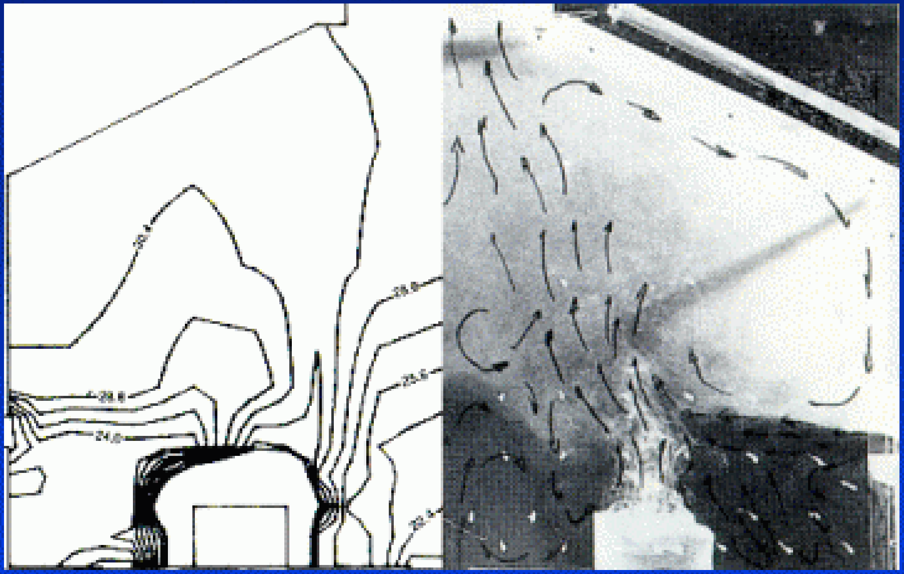
Introduction

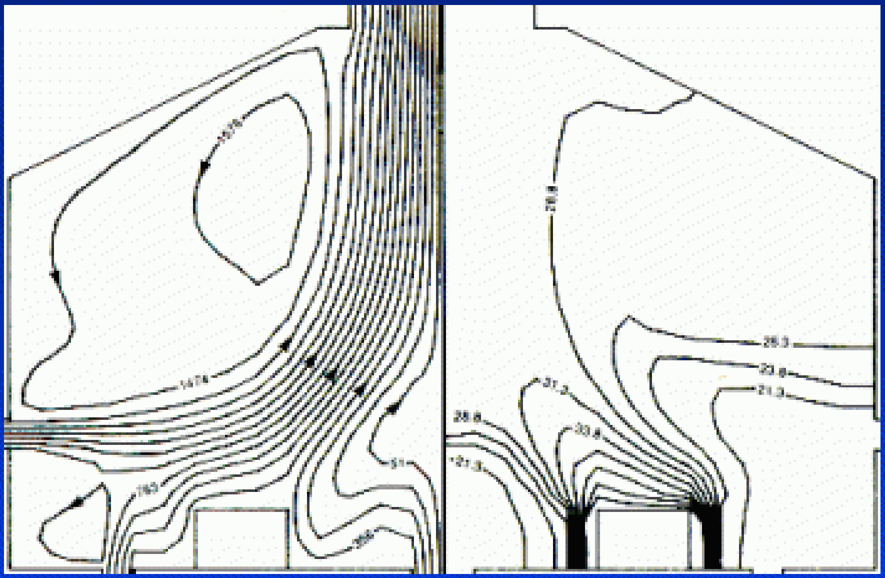


Aluminum reduction cells are very complex to model because it is a truly multi-physics modeling application involving, to be rigorous, a fusion of thermo-electro-mechanic and magneto-hydro-dynamic modeling capabilities in a complex 3D geometry.

1980, 2D potroom ventilation model



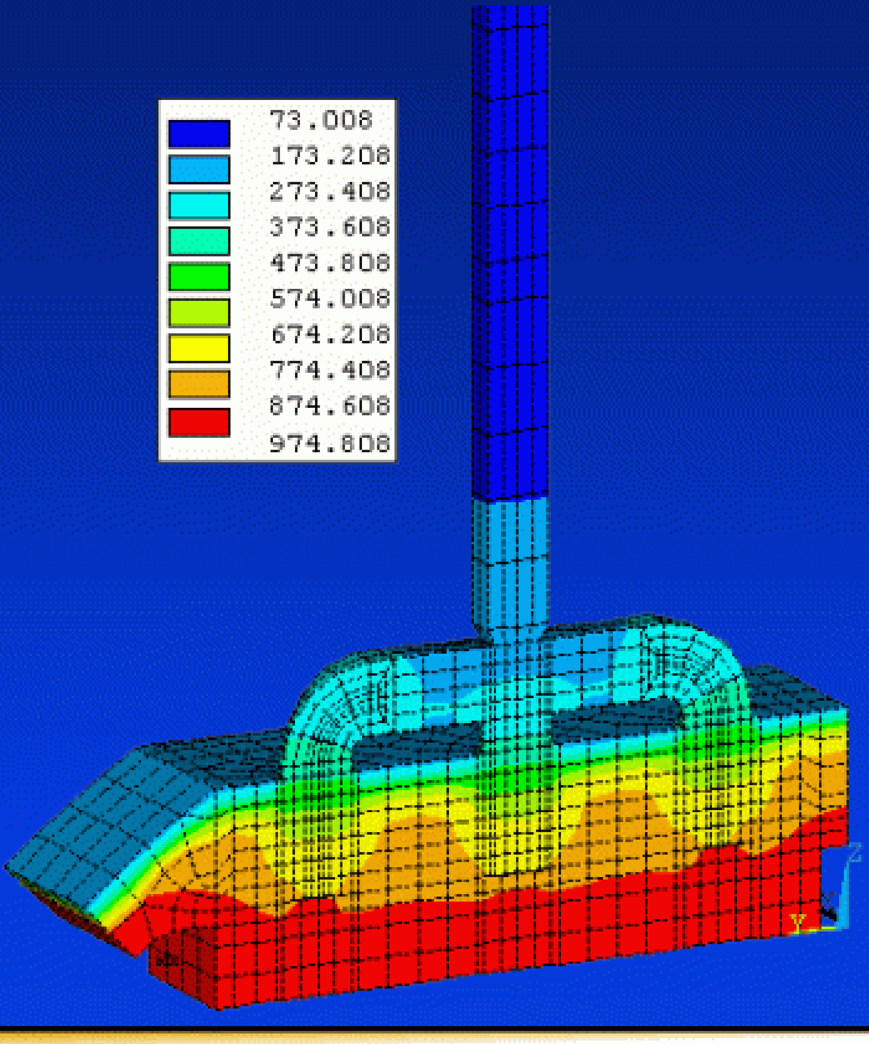
Experimental results



Best model results

The best results of my Ph.D. work: the 2D finite difference vorticity-stream function formulated model could not reproduces well the observed air flow regardless of the turbulence model used.

1984, 3D thermo-electric half anode model



A similar model was developed on ANSYS 4.1 installed on a shaded VAX 780 platform.

The very first 3D half anode model of around 4000 Solid 69 thermo-electric elements took 2 weeks elapse time to compute on the VAX.

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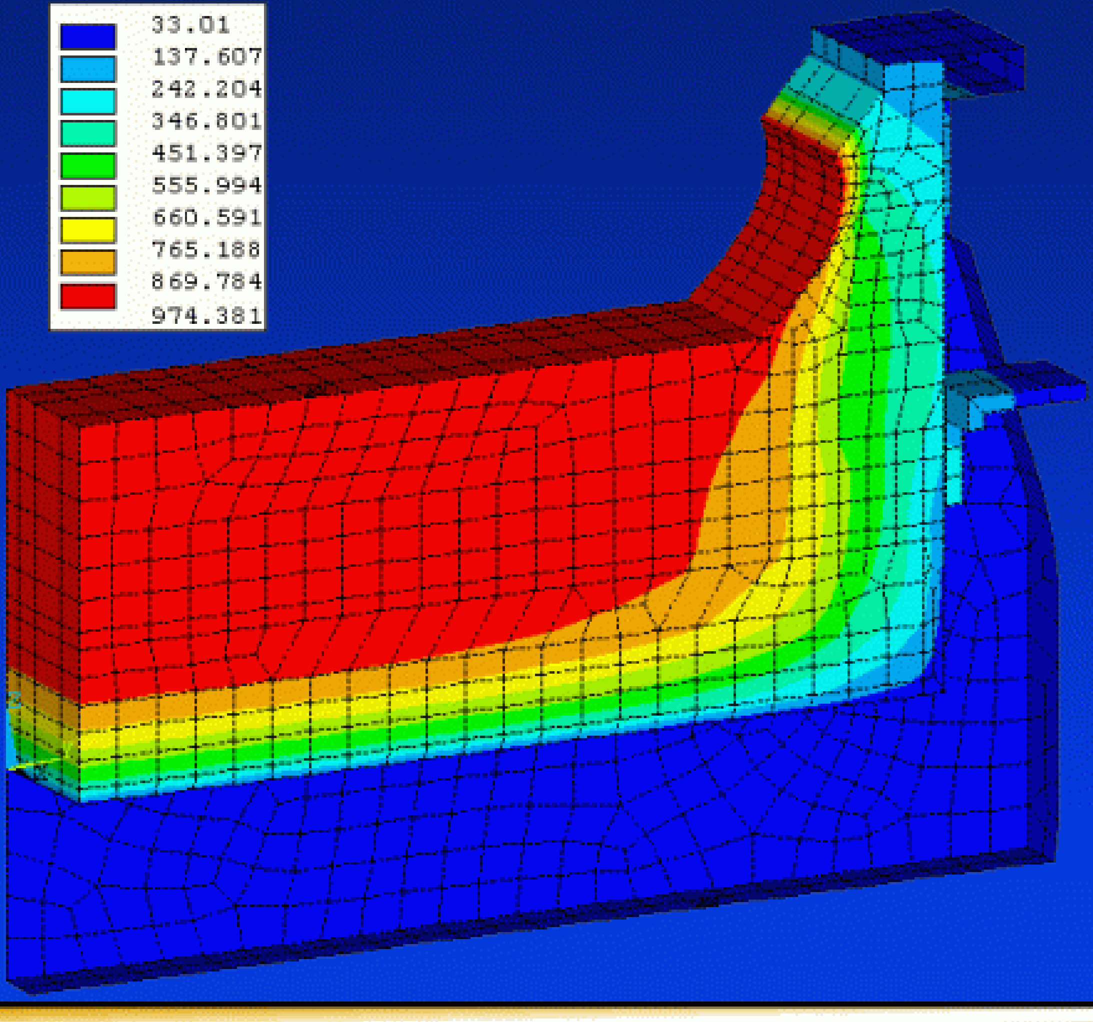
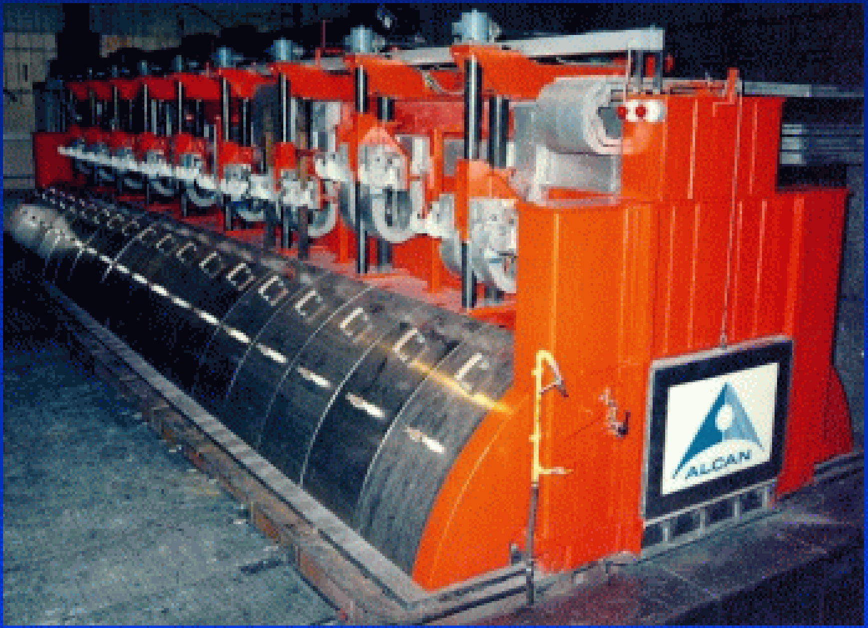
1986, 3D thermo-electric cathode side slice and cathode corner model



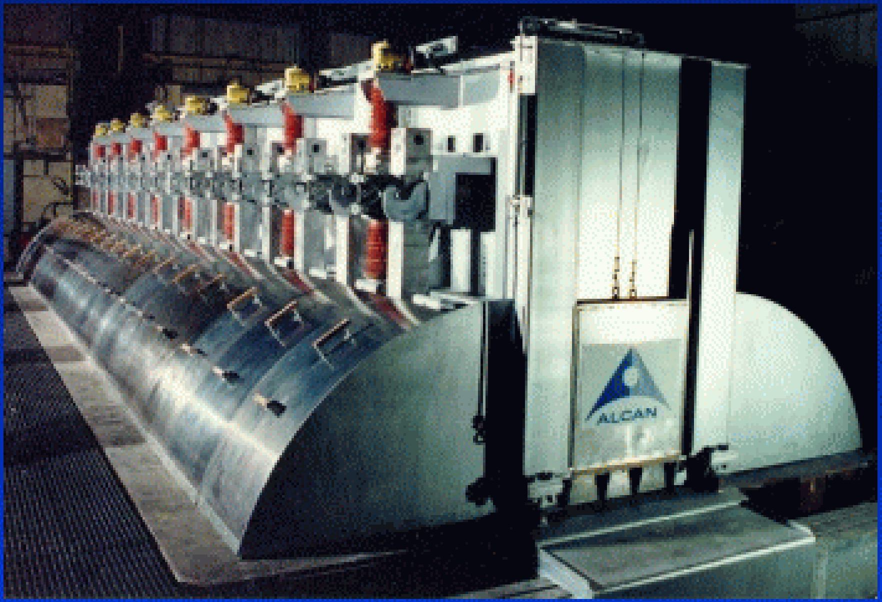
The next step was the development of a 3D cathode side slice thermo-electric model that included the calculation of the thickness of the solid electrolyte phase on the cell side wall .

Despite the very serious limitations on the size of the mesh, a full cathode corner was built next .

Design of 2 high amperage cell cathodes



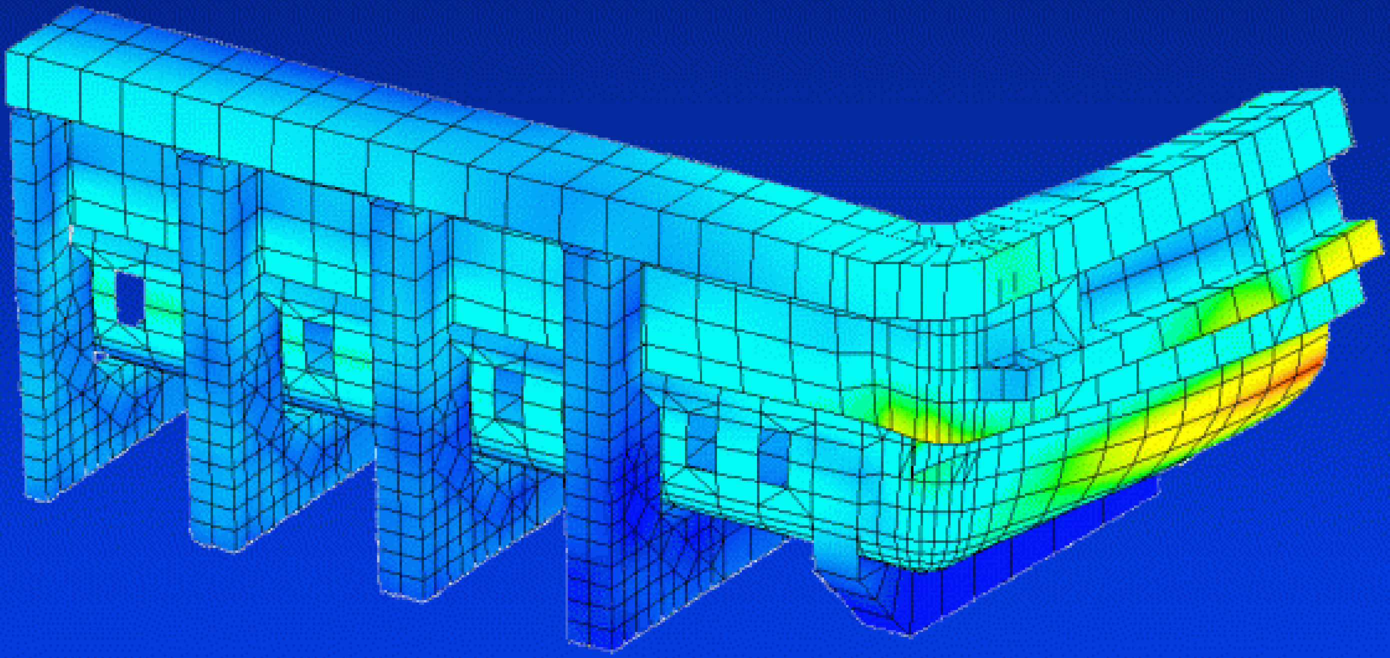
1987: Apex 4



1989: A310

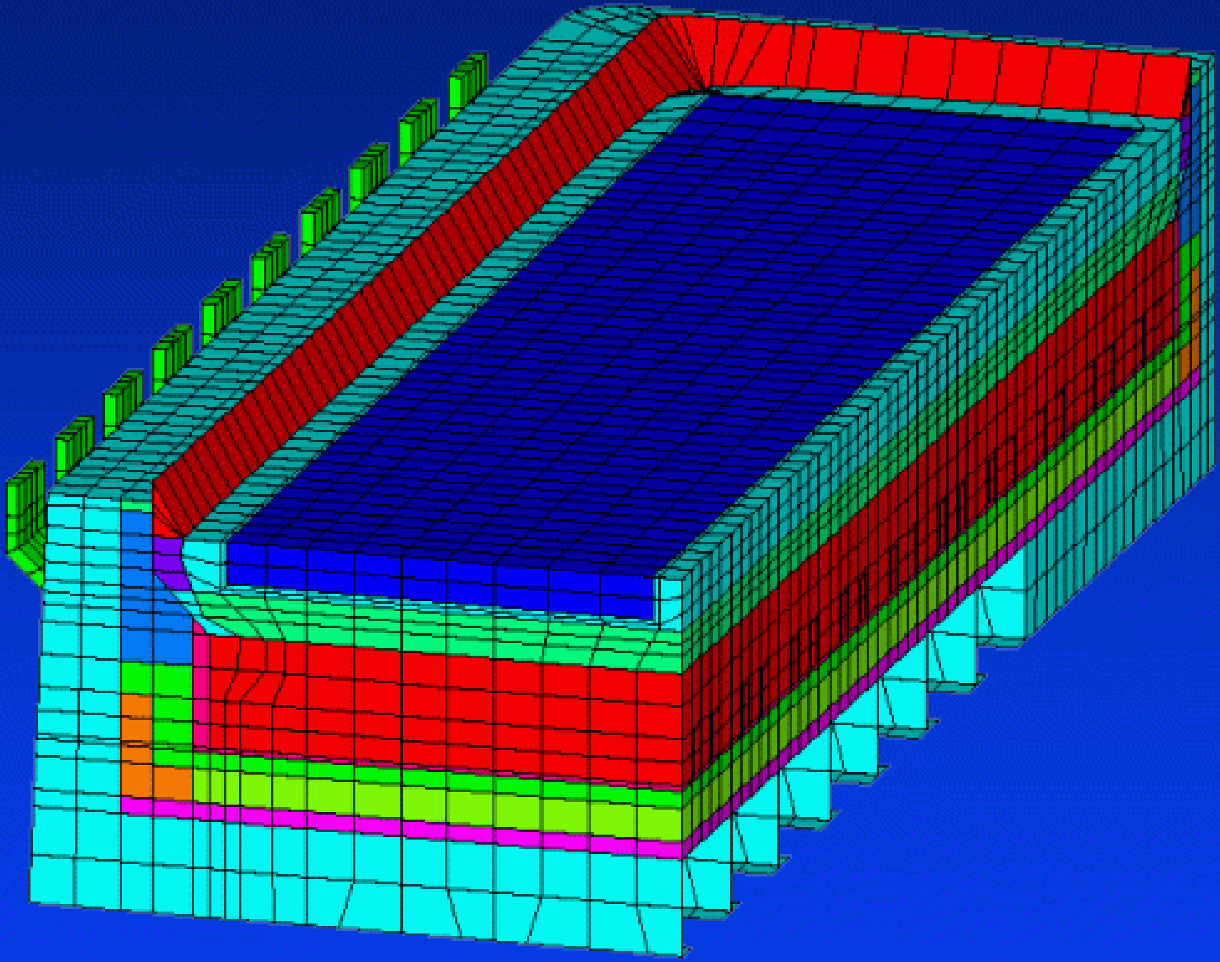
Comparison of the predicted versus measured behavior was within 5% in both cases, demonstrating the value of the numerical tools developed.

1988, 3D cathode potshell plastic deformation mechanical model



The new model type addresses a different aspect of the physic of an aluminum reduction cell, namely the mechanical deformation of the cathode steel potshell under its thermal load and more importantly its internal pressure load .

1992, 3D thermo-electric quarter cathode model



With the upgrade of the P-IRIS to 4D/35 processor, and the option to run on a CRAY XMP supercomputer, the severe limitations on the CPU usage were finally partially lifted.

This opened the door to the possibility to develop a full 3D thermo-electric quarter cathode model.

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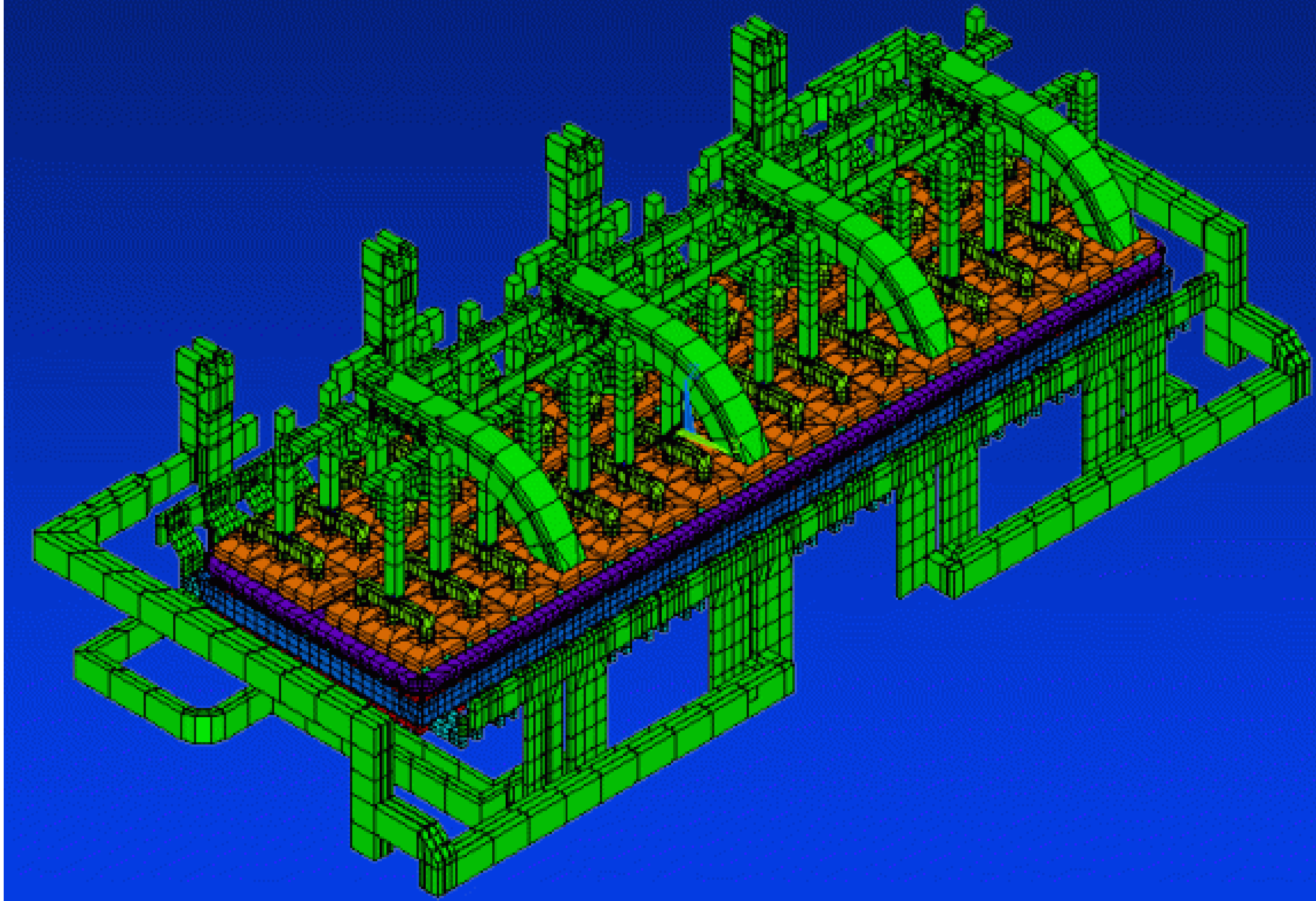
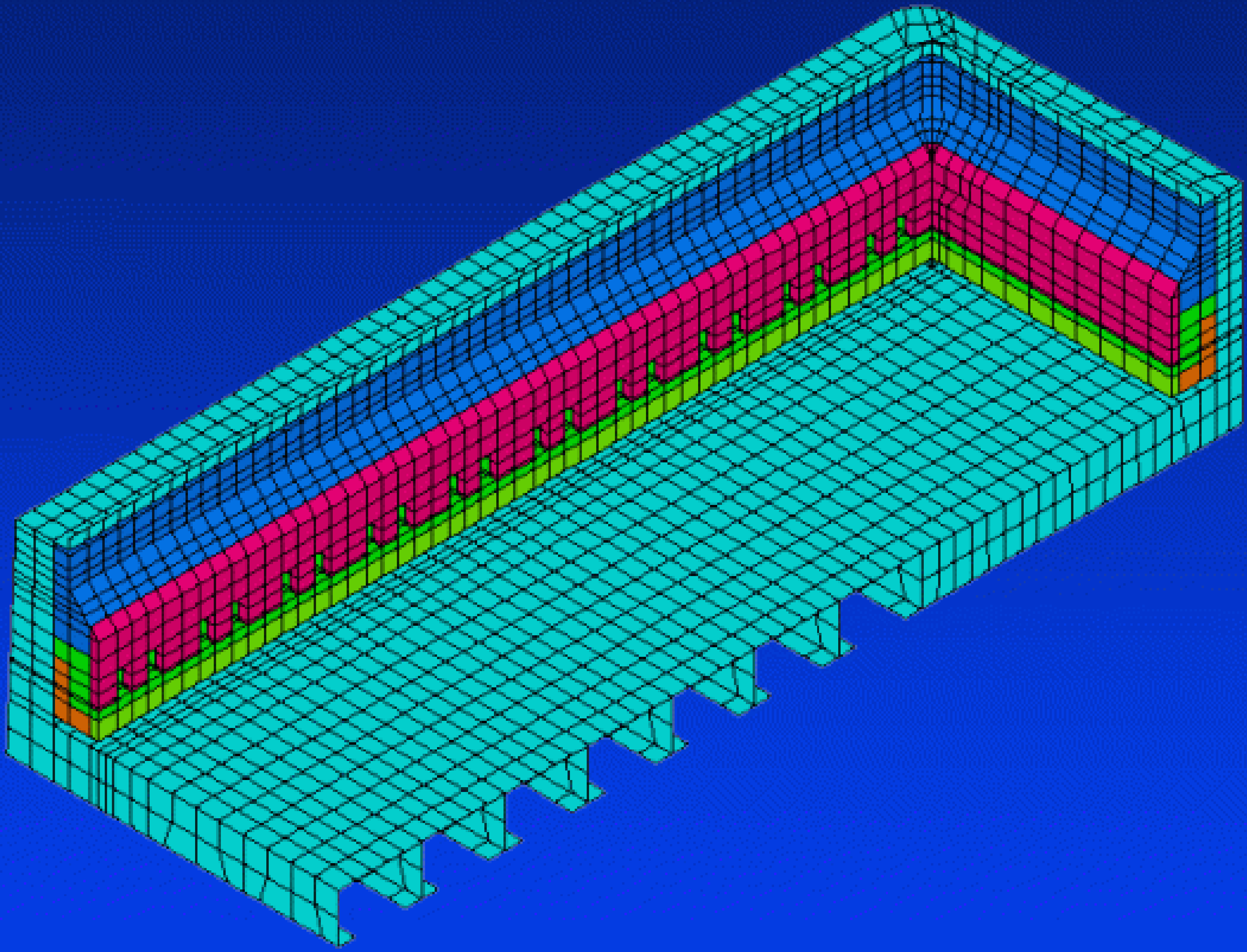
1992, 3D thermo-electric "pseudo" full cell and external busbars model



As a first step toward the development of a first thermo-electro-magnetic model, a 3D thermo-electric "pseudo" full cell and external busbars model was developed.

That model was really at the limit of what could be built and solved on the available hardware at the time both in terms of RAM memory and disk space storage.

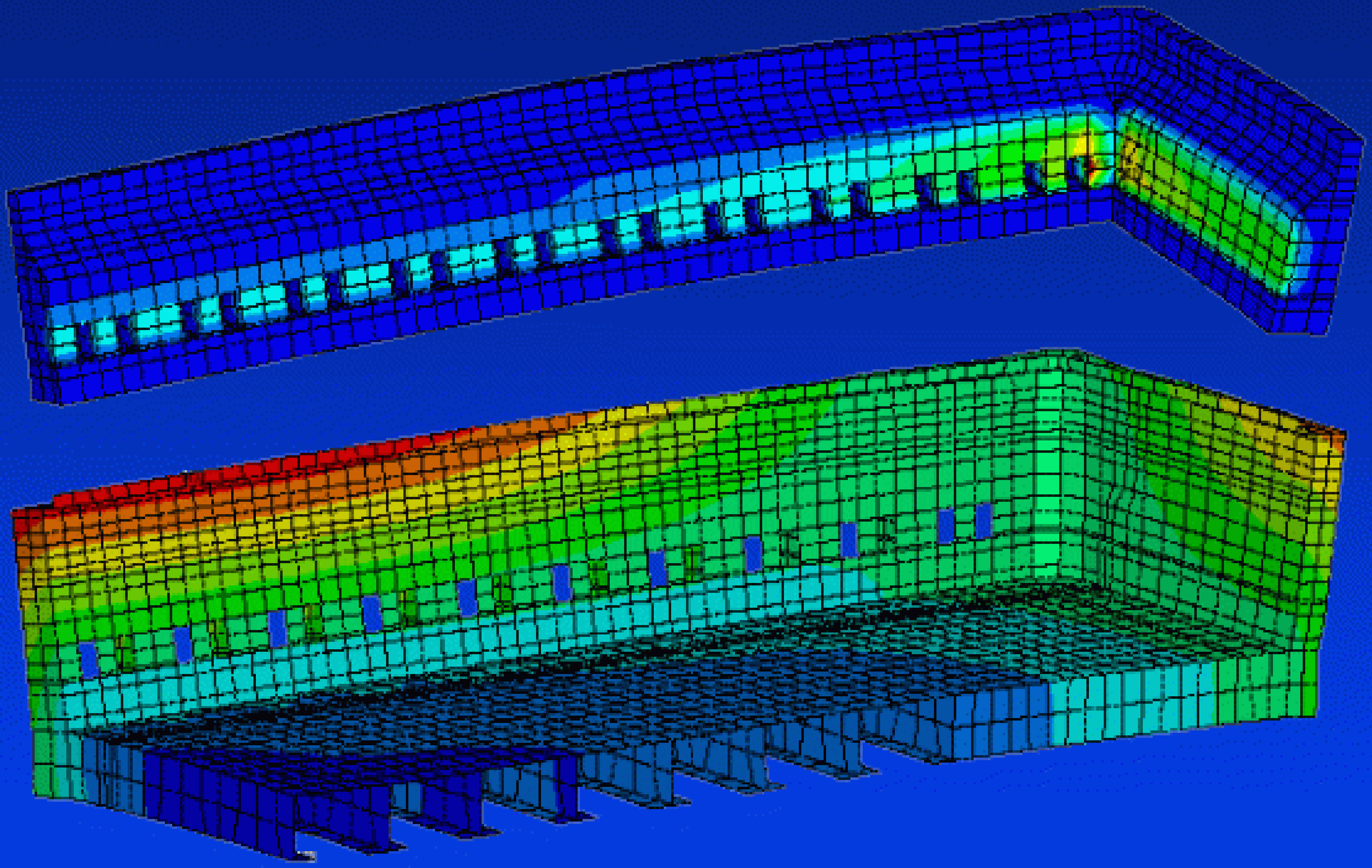
1992, 3D cathode potshell plastic deformation and lining swelling mechanical model



The empty quarter potshell mechanical model was extended to take into account the coupled mechanical response of the swelling lining and the restraining potshell structure.

As the carbon lining swelling due to sodium intercalation is somewhat similar to material creeping, different models that represented that behavior were developed.

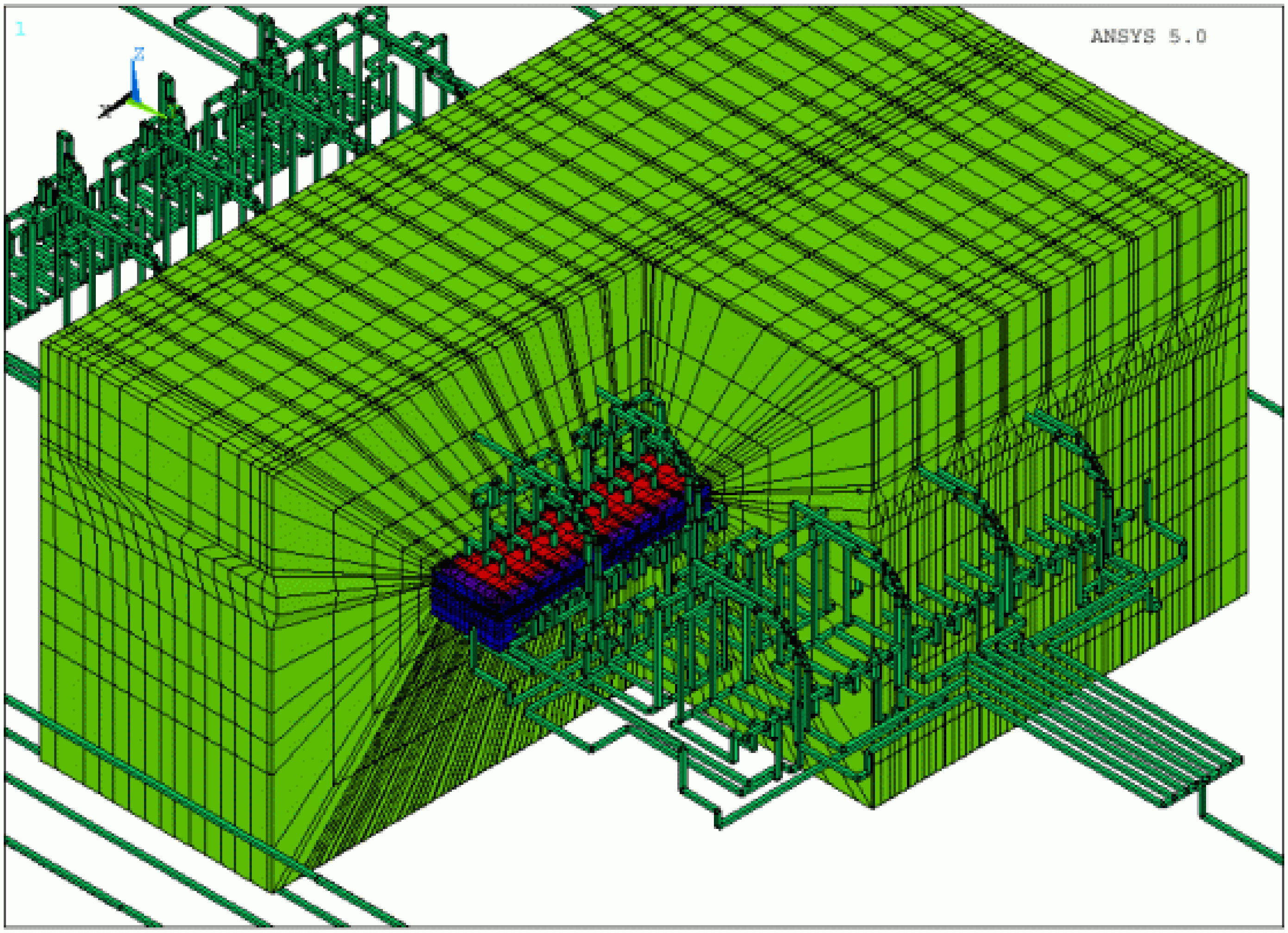
1992, 3D cathode potshell plastic deformation and lining swelling mechanical model



That coupling was important to consider as a stiffer, more restraining potshell will face more internal pressure from the swelling lining material.

Obviously, that additional load needed to be considered in order to truly design a potshell structure that will not suffer extensive plastic deformation.

1993, 3D electro-magnetic full cell model



The development of a finite element based aluminum reduction cell magnetic model clearly represented a third front of model development.

Because of the presence of the ferro-magnetic shielding structure, the solution of the magnetic problem cannot be reduced to a simple Biot-Savard integration scheme.

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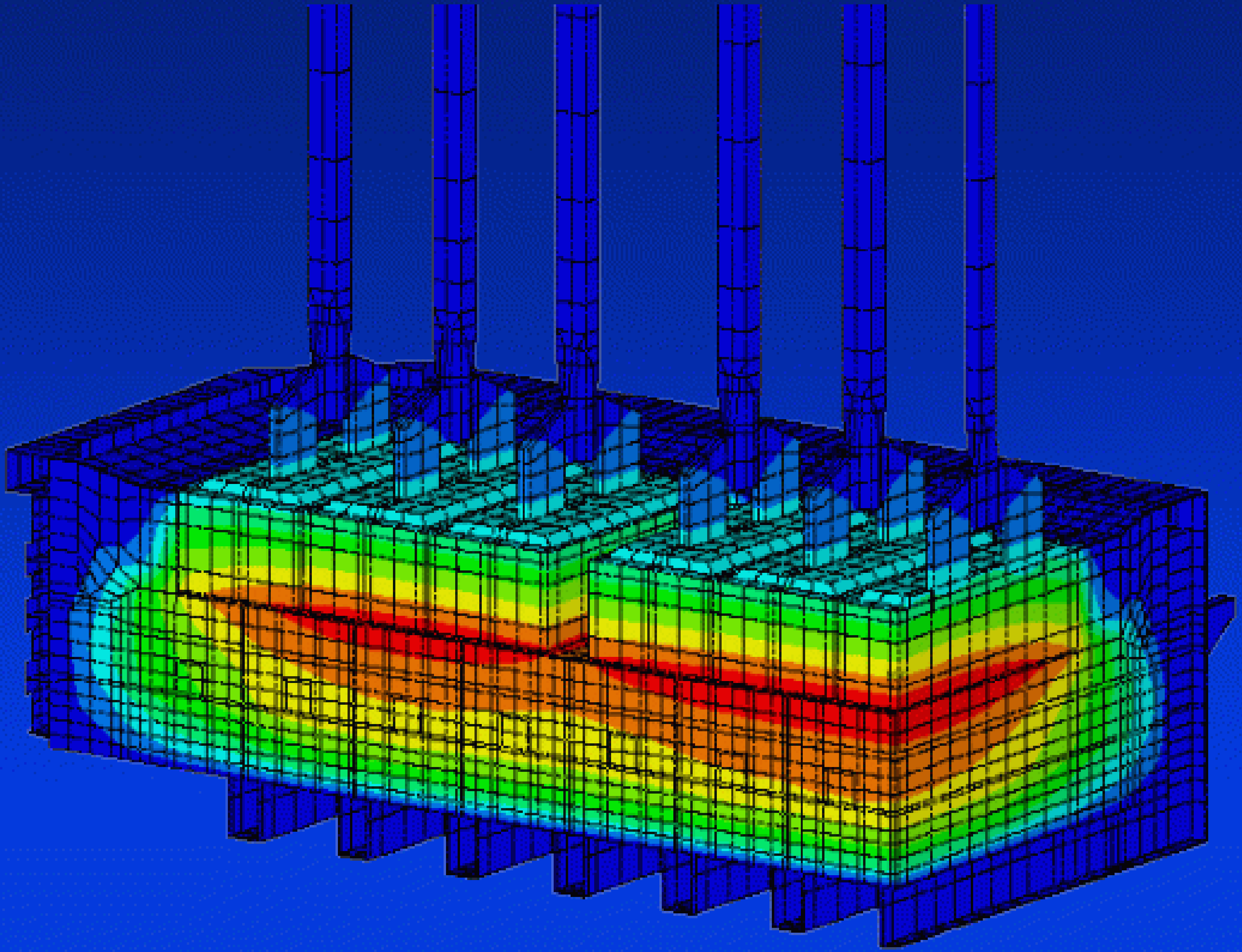
1993, 3D transient thermo-electric full quarter cell preheat model



The cathode quarter thermo-electric model was extended into a full quarter cell geometry in preheat configuration and ran in transient mode in order to analyze the cell preheat process .

The need was urgent, but due to its huge computing resources requirements, the model was not ready in time to be used to solve the plant problem at the time.

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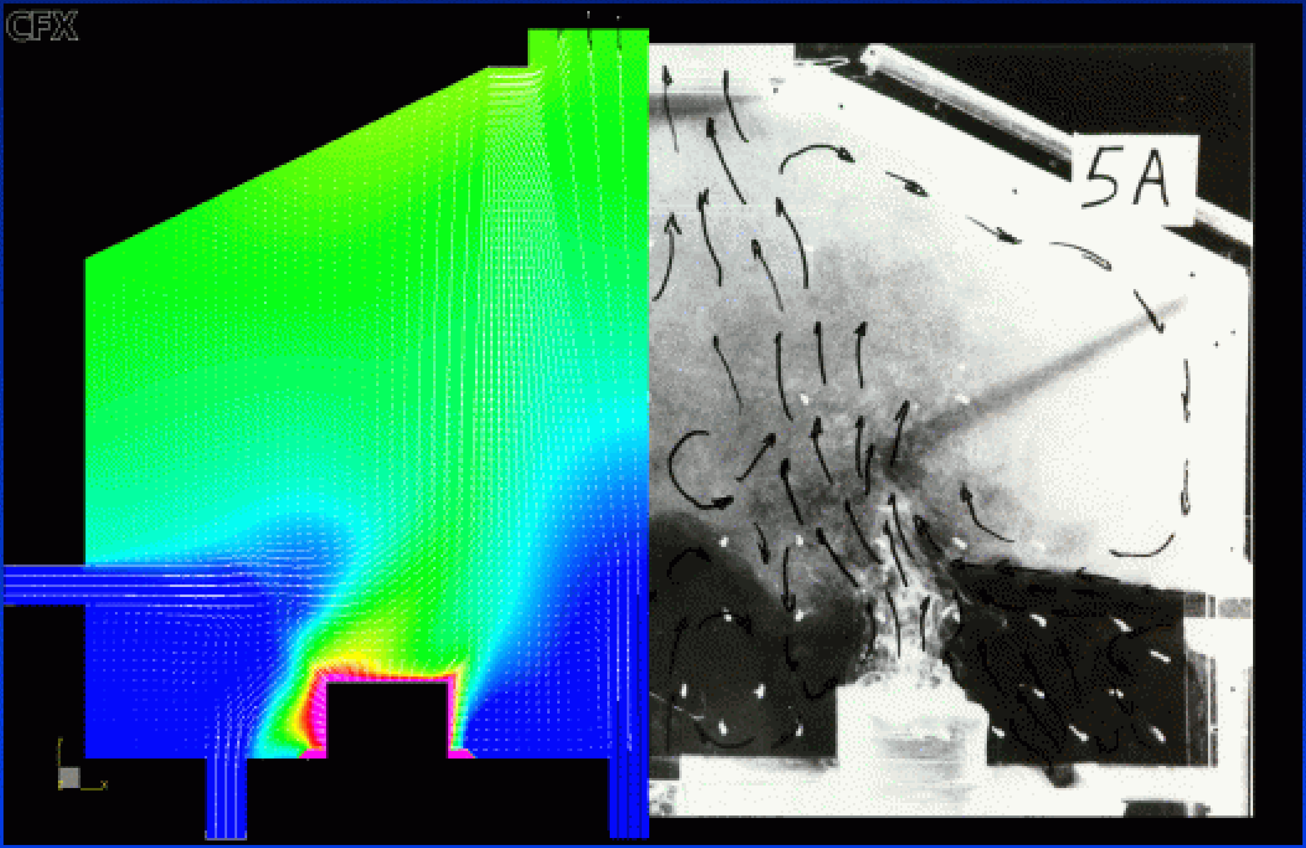
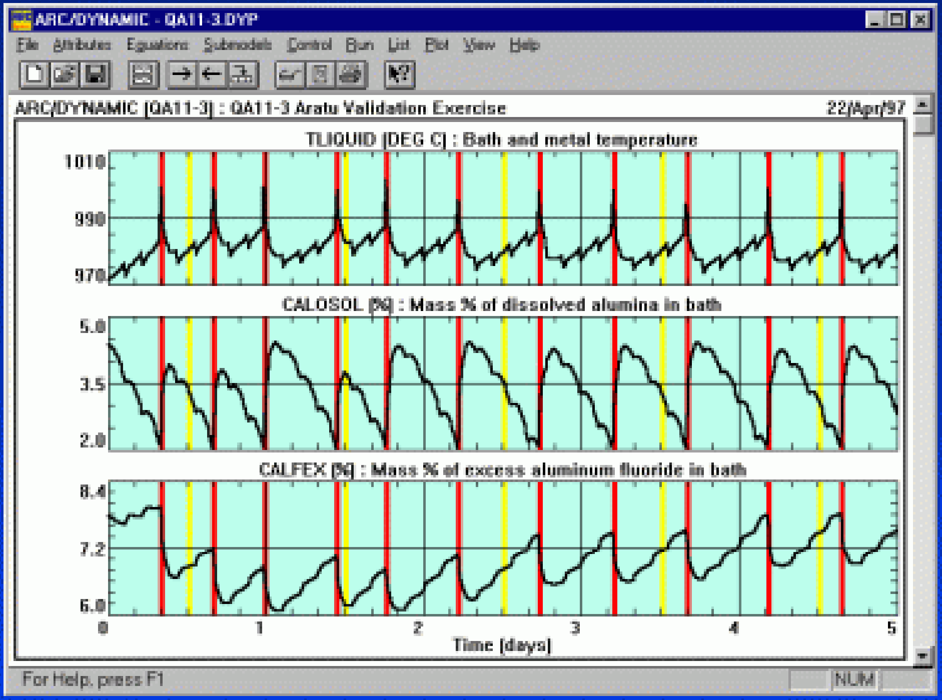
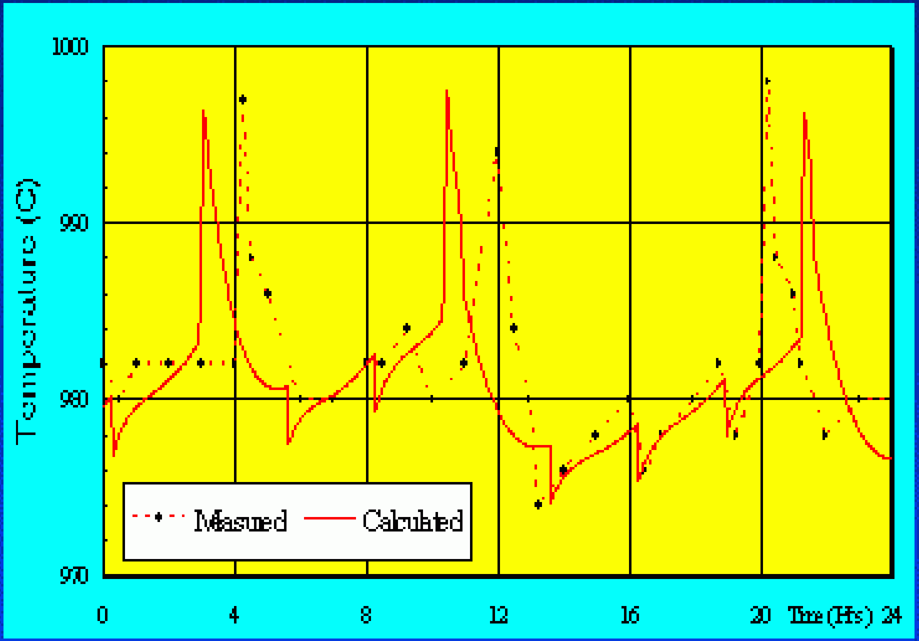
1993, 2D CFDS-Flow3D potroom ventilation model



2D “Reynolds flux” model results vs. physical model results

1994, lump parameters dynamic cell simulator





Originally commercialized under the name ARC/DYNAMIC, the upgraded simulator is now available under the name DYNA/MARC

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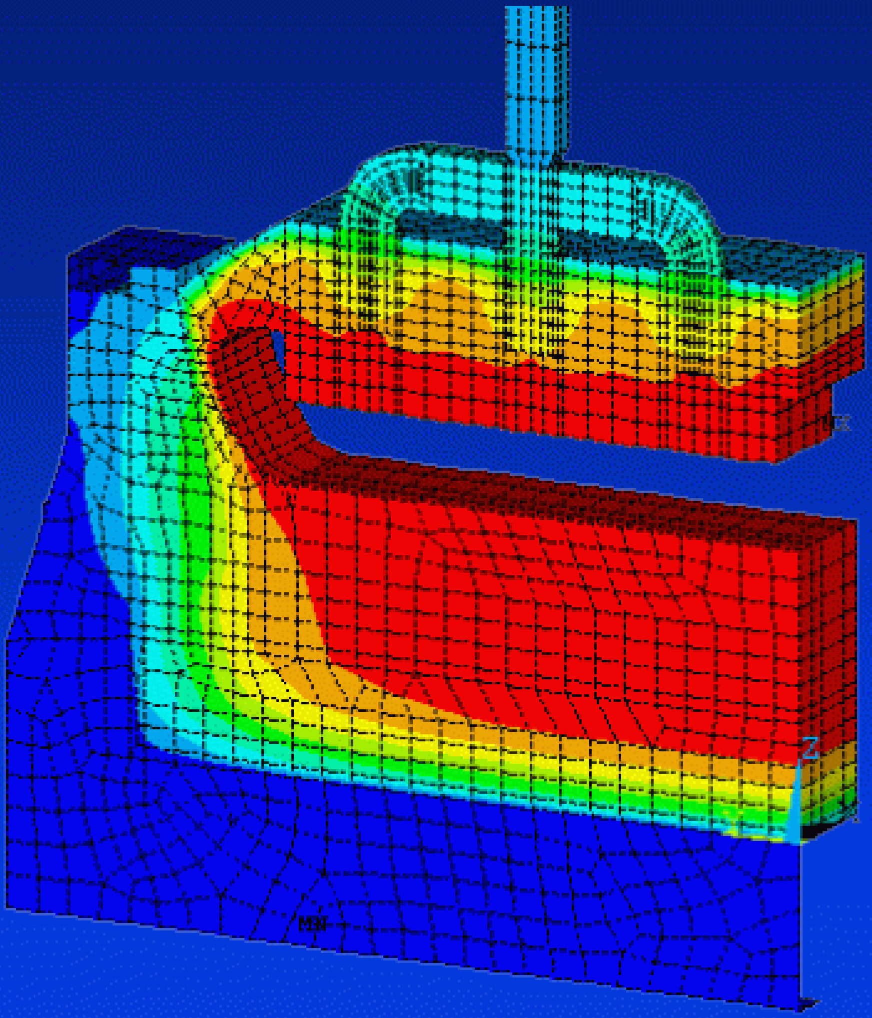
1998, 3D thermo-electric full cell slice model



As described previously, the 3D half anode model and the 3D cathode side slice model have been developed in sequence, and each separately required a fair amount of computer resources.

Merging them together was clearly not an option at the time, yet it would have been a natural thing to do. Many years later, the hardware limitation no longer existed so they were finally merged.

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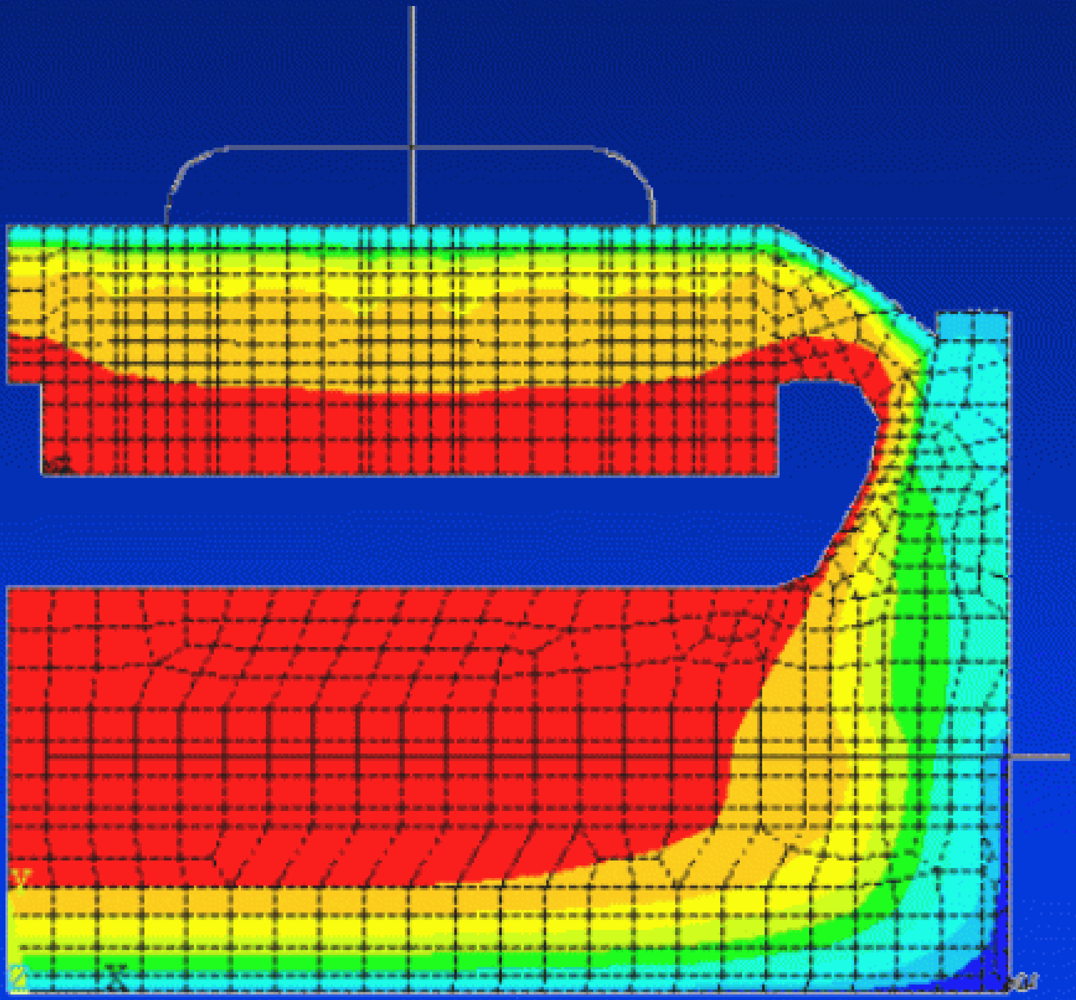
1998, 2D+ thermo-electric full cell slice model



2D+ version of the same full cell slice model was developed. Solving a truly three dimensional cell slice geometry using a 2D model may sound like a step in the wrong direction, but depending on the objective of the simulation, sometimes it is not so.

The 2D+ model uses beam elements to represent geometric features lying in the third dimension (the + in the 2D+ model).

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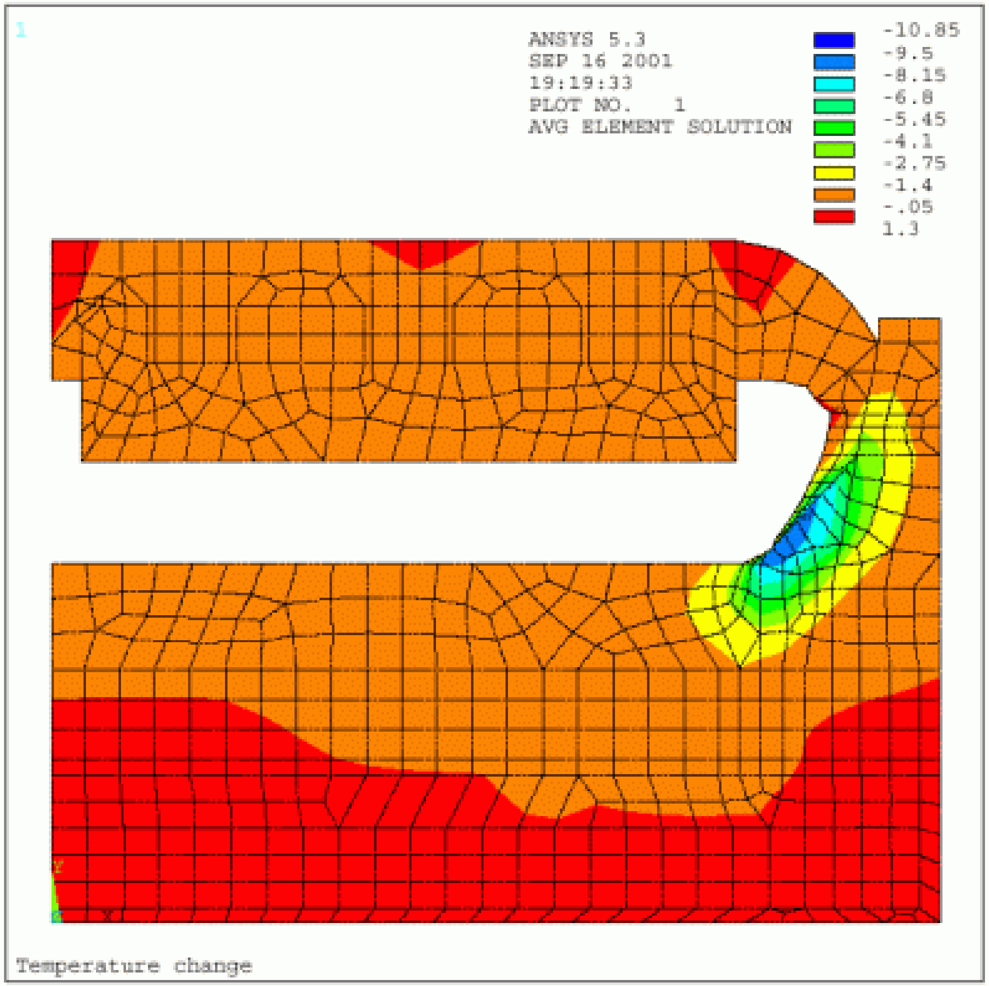
1999, 2D+ transient thermo-electric full cell slice model



An interesting feature of that model is the extensive APDL coding that computes other aspects of the process related to the different mass balances like the alumina dissolution, the metal production etc.

As that type of model has to compute the dynamic evolution of the ledge thickness, there is a lot more involved than simply activating the ANSYS transient mode option.

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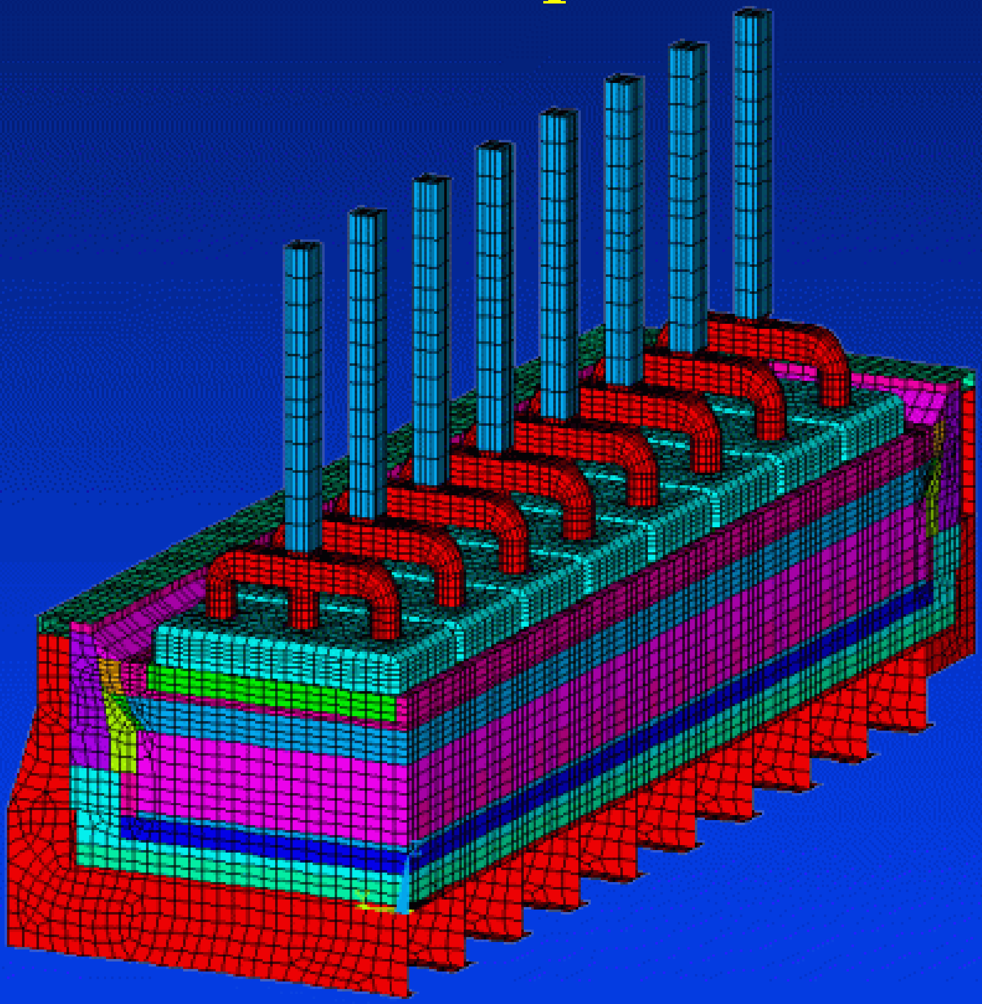
2000, 3D thermo-electric full quarter cell model



The continuous increase of the computer power now allows not only to merge the anode to the cathode in a cell slice model but also in a full quarter cell model .

The liquid zone can even be included if the computation of the current density in that zone is required for MHD analysis.

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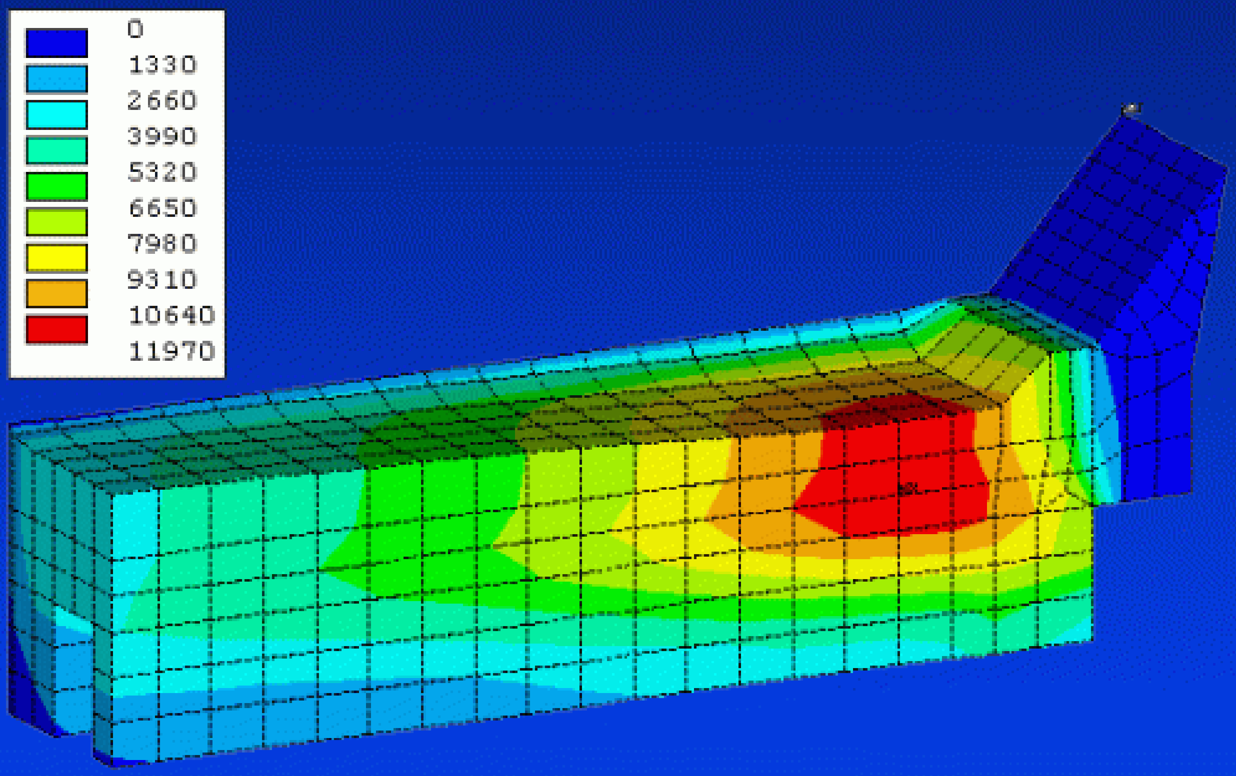
2000, 3D thermo-electric cathode slice erosion model



Cathode erosion rate is proportional to the cathode surface current density and that the initial surface current density is not uniform, the erosion profile will not be uniform.

Furthermore, that initial erosion profile will promote further local concentration of the surface current density that in turn will promote a further intensification of the non-uniformity of the erosion rate.

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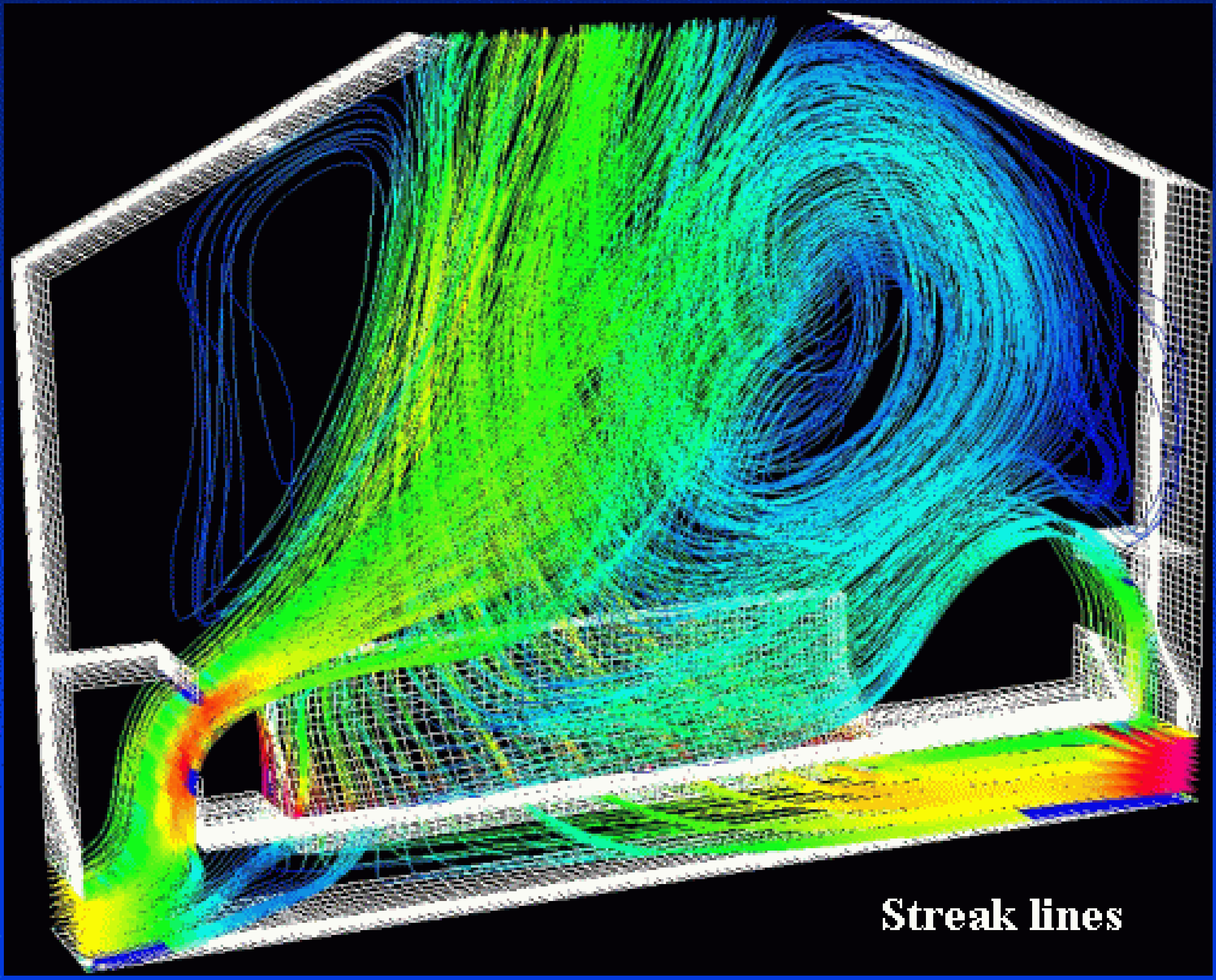
2001, 3D CFX-4 potroom ventilation model



Streak lines

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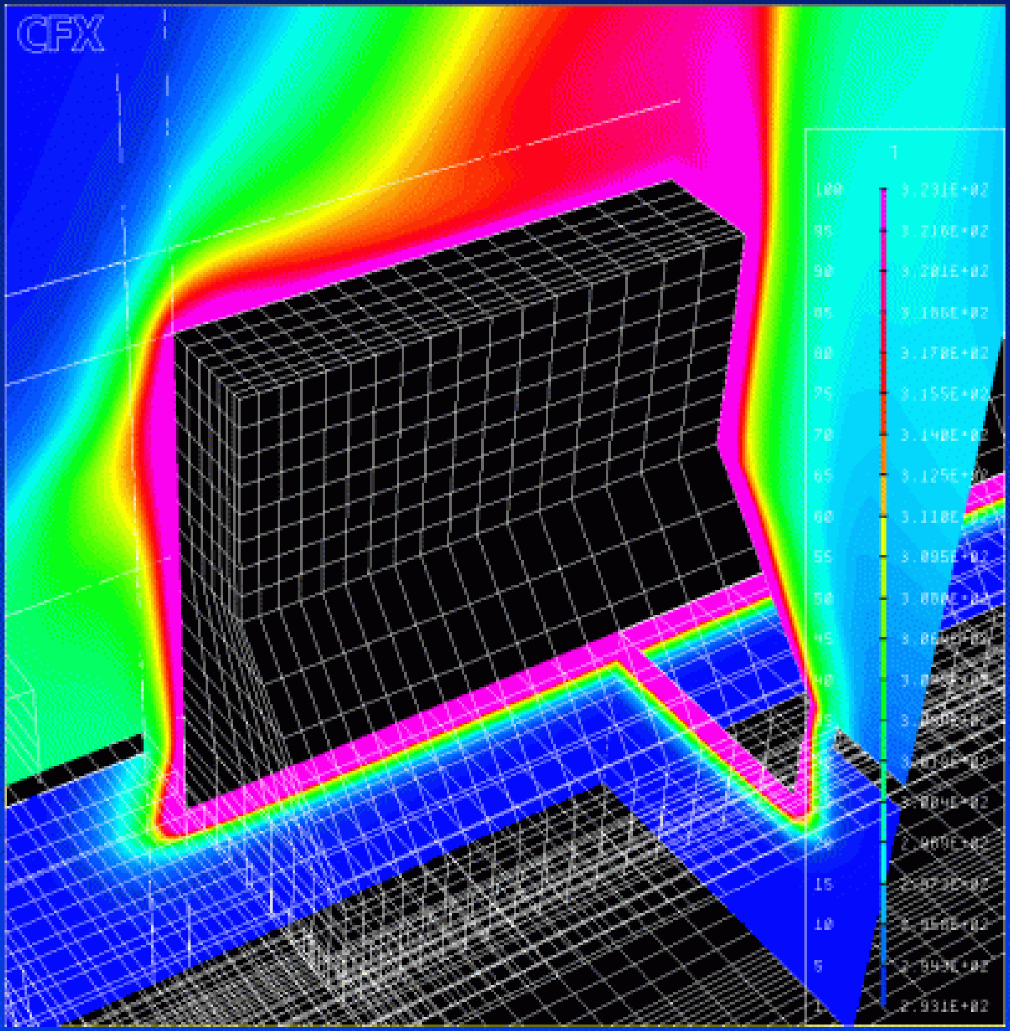
2001, 3D CFX-4 potroom ventilation model



Temperature fringe plot

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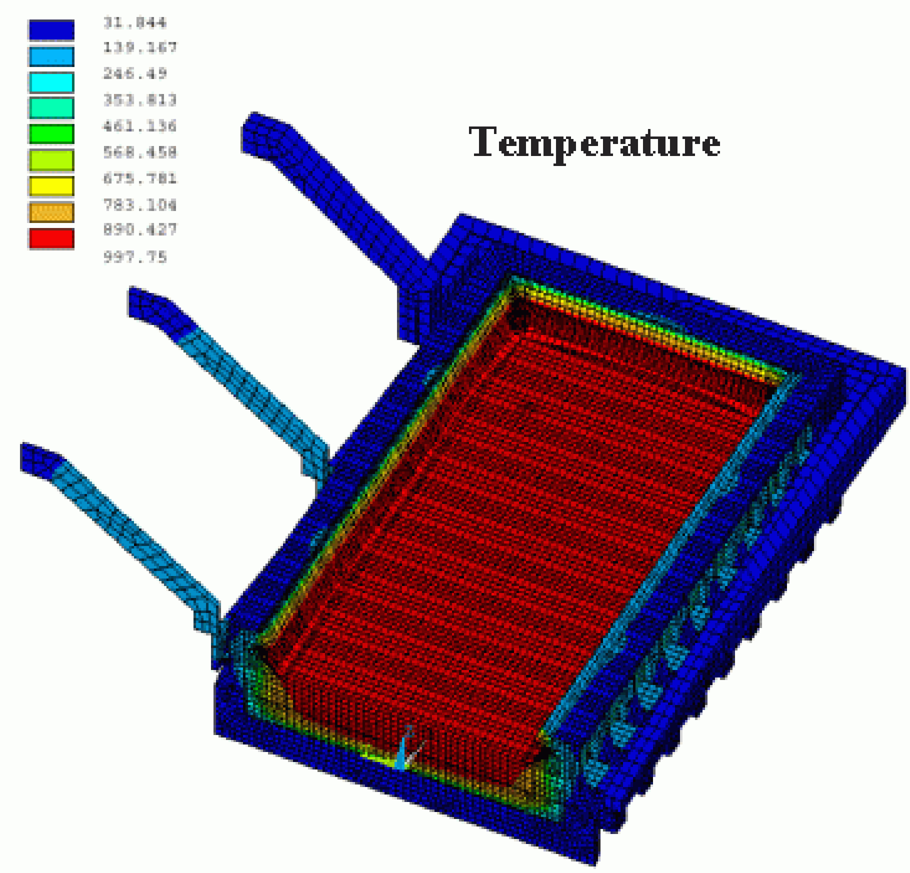
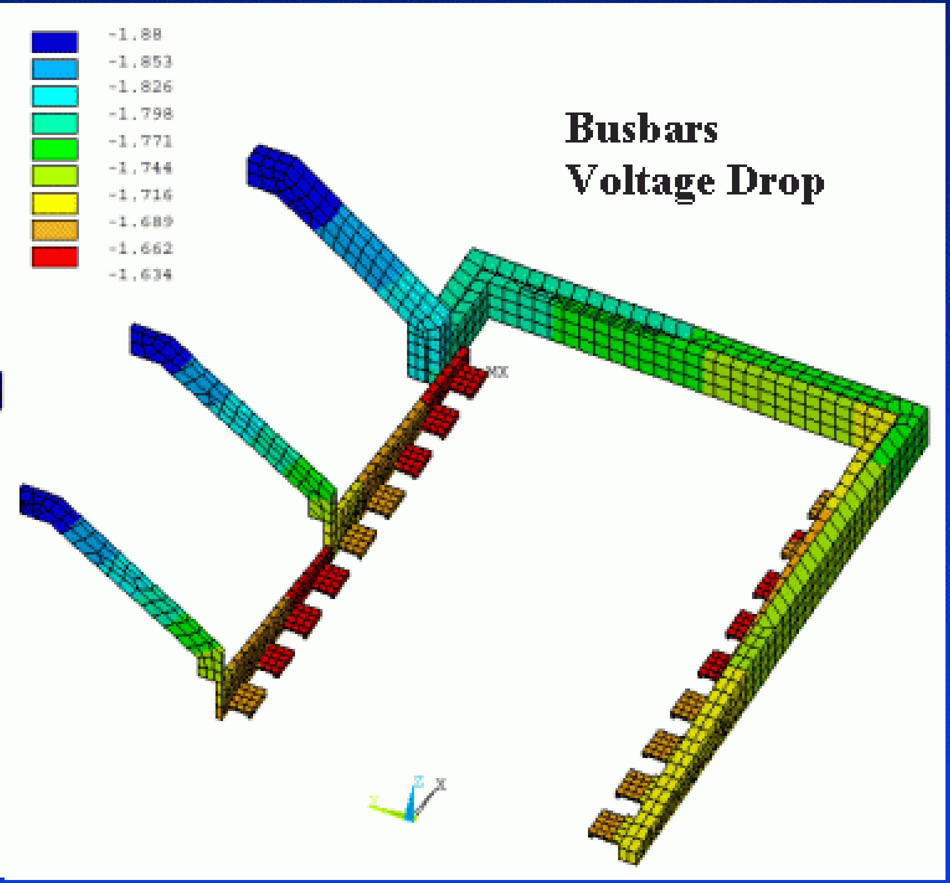
2002, 3D thermo-electric half cathode and external busbar model



Temperature



Busbars Voltage Drop

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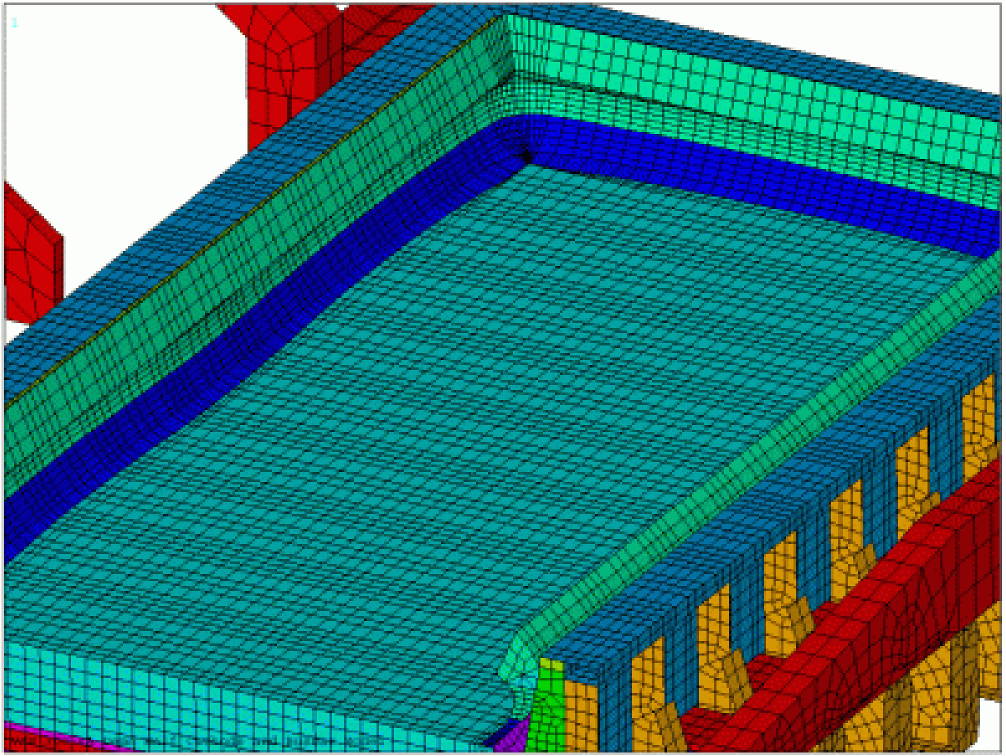
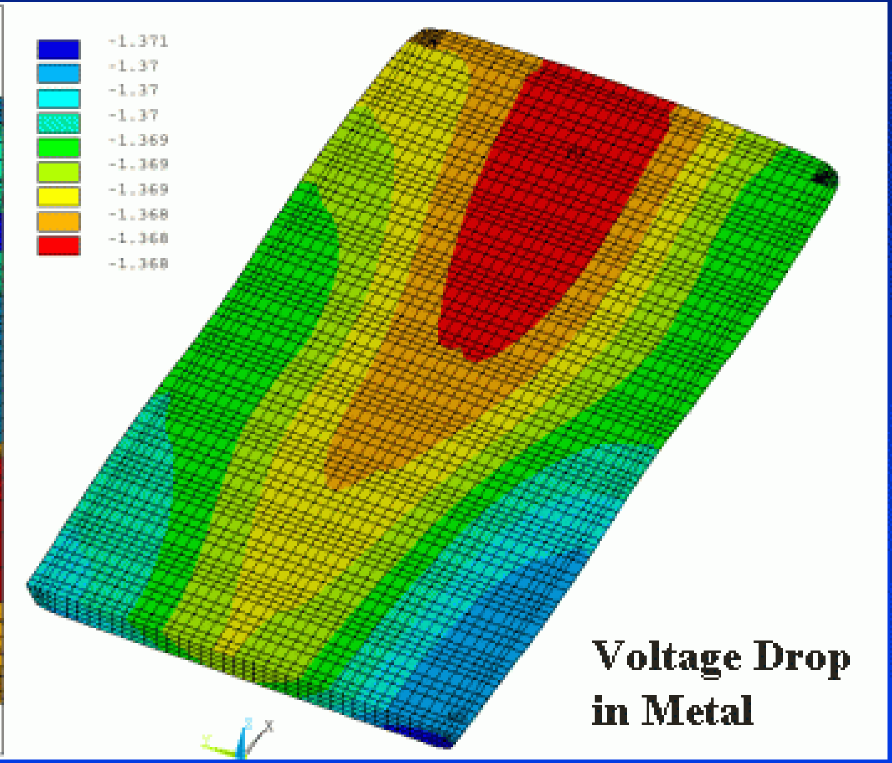
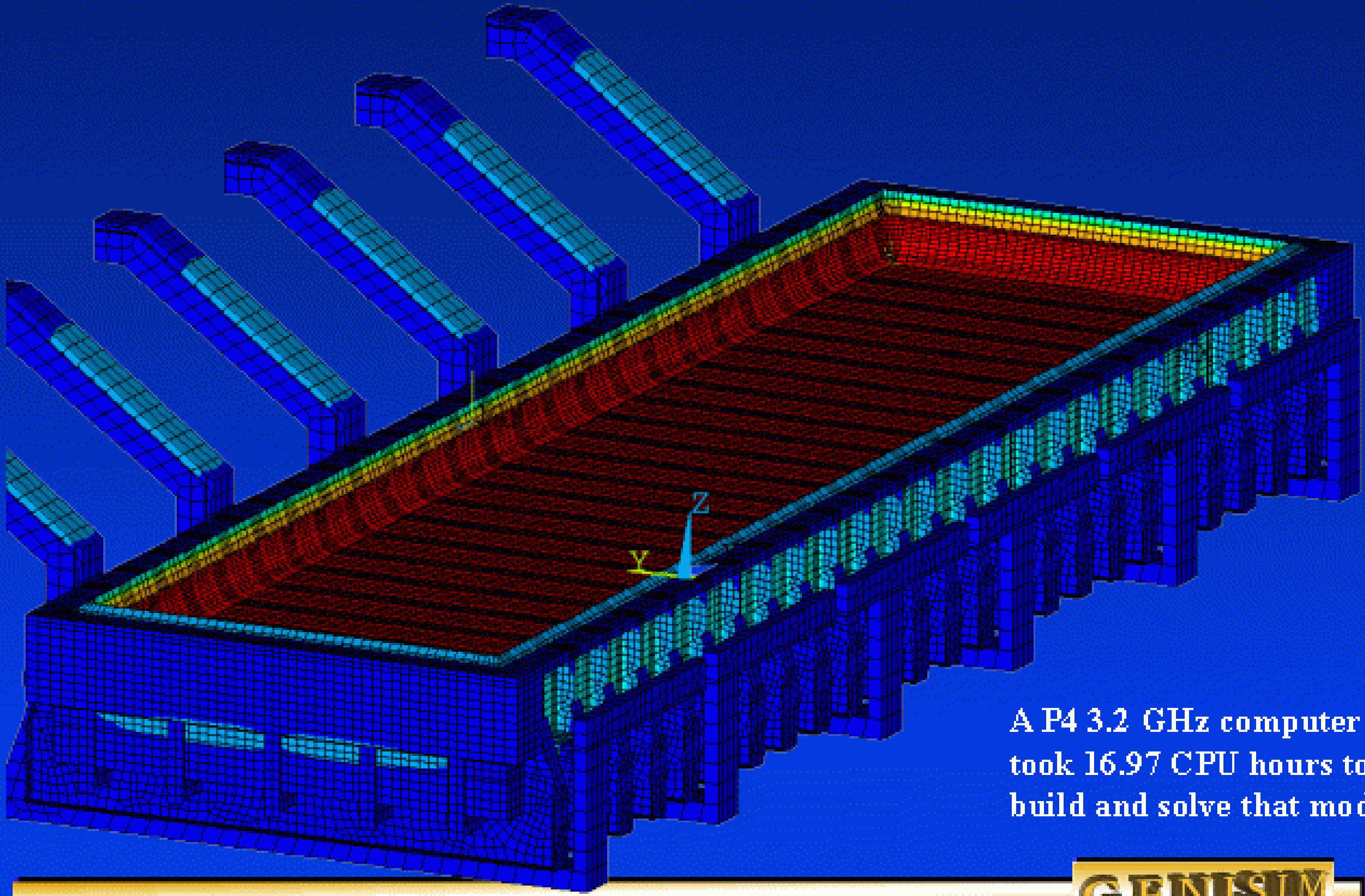
2002, 3D thermo-electric half cathode and external busbar model





Voltage Drop
in Metal

2003, 3D thermo-electric full cathode and external busbar model



A P4 3.2 GHz computer
took 16.97 CPU hours to
build and solve that model

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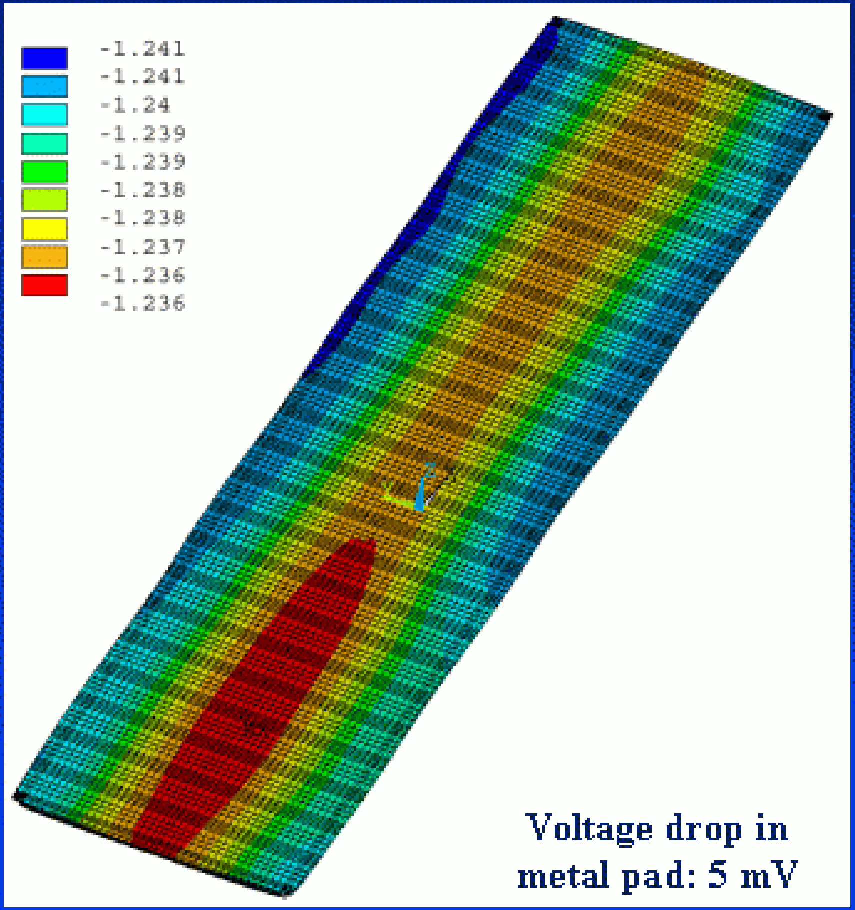
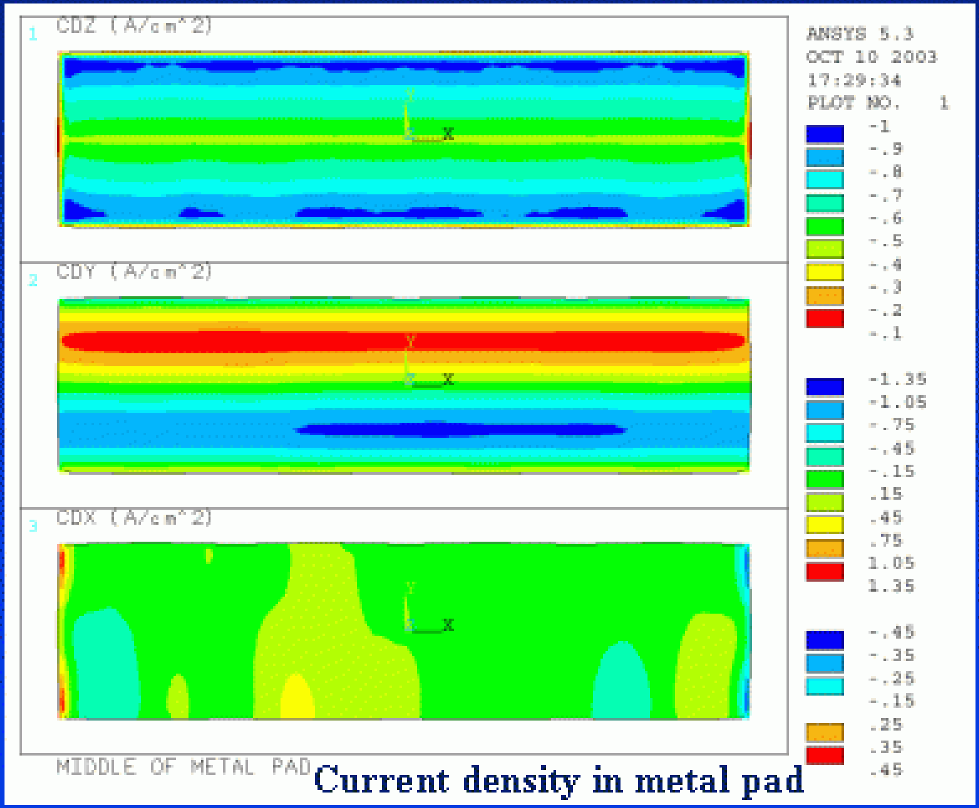
2003, 3D thermo-electric full cathode and external busbar model

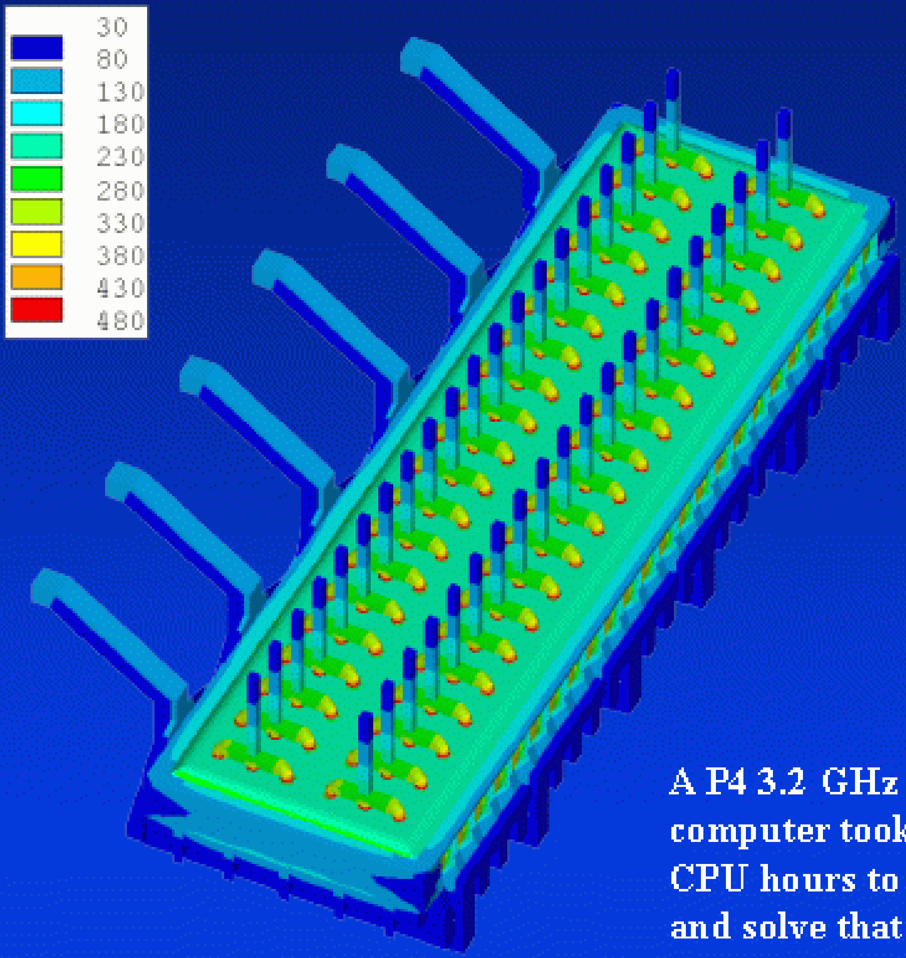


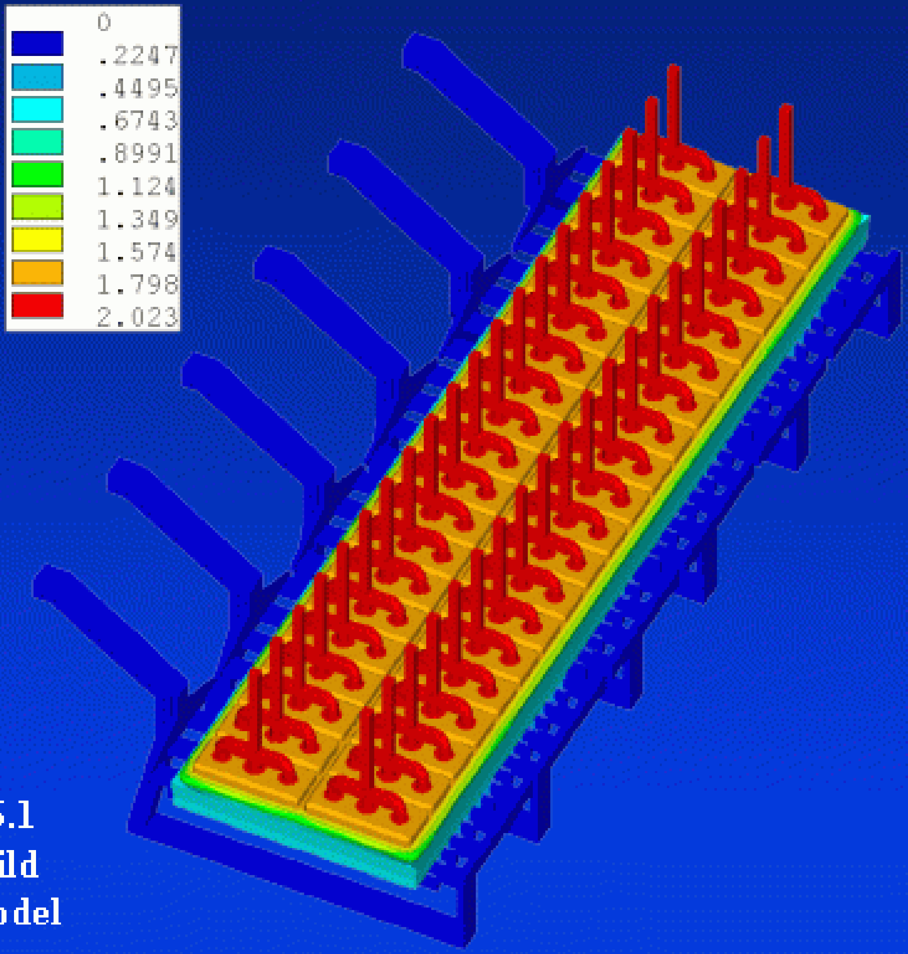
Voltage drop in metal pad: 5 mV



Current density in metal pad

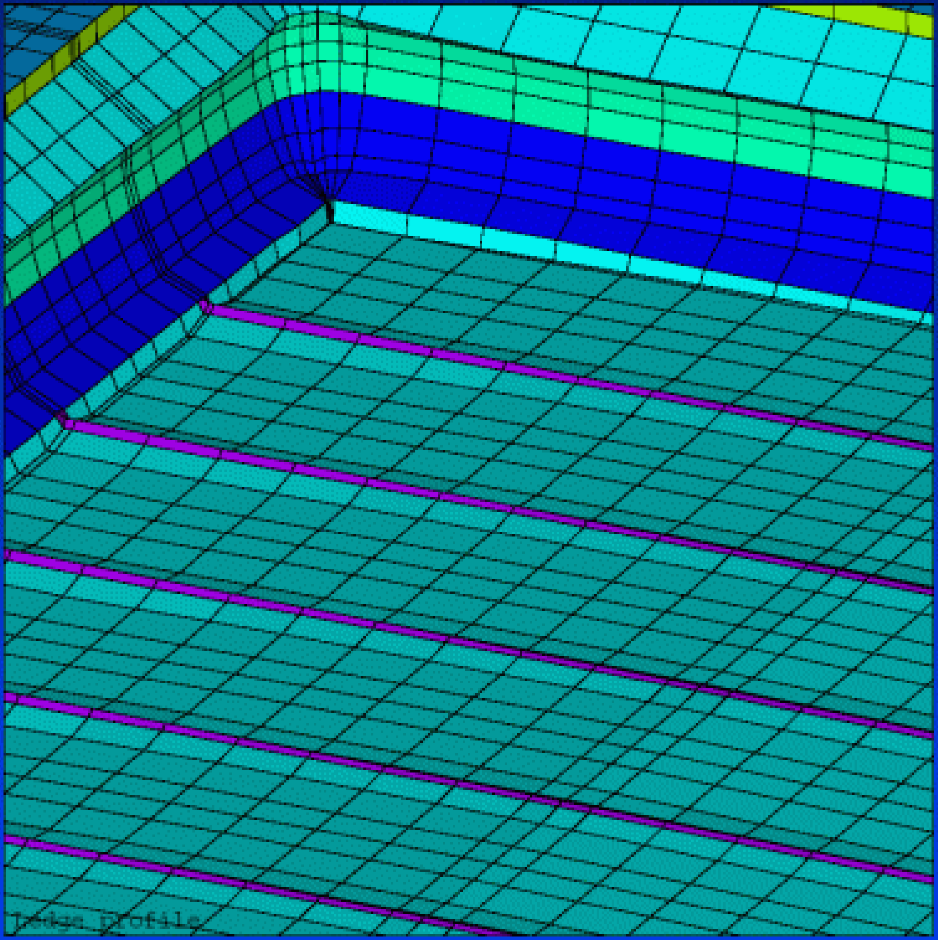
2004, 3D thermo-electric full cell and external busbar model





A P4 3.2 GHz
computer took 26.1
CPU hours to build
and solve that model

2004, 3D thermo-electric full cell and external busbar erosion model

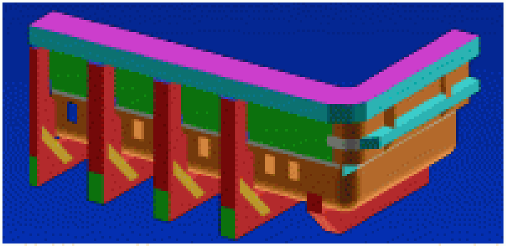


Once the geometry of the ledge is converged, a new iteration loop start, this time to simulate the erosion of the cathode block as function of the surface current density

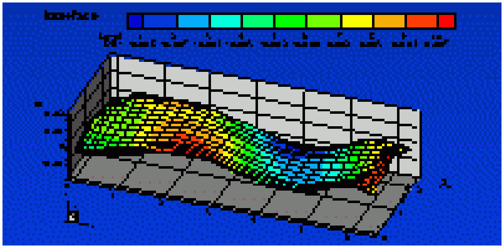
Future developments

Currently, we can fit Hall-Héroult mathematical models into three broad categories:

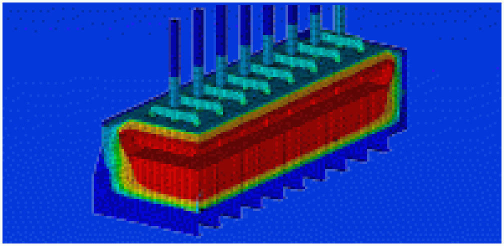
- Stress models which are generally associated with cell shell deformation and cathode heaving issues.



- 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.



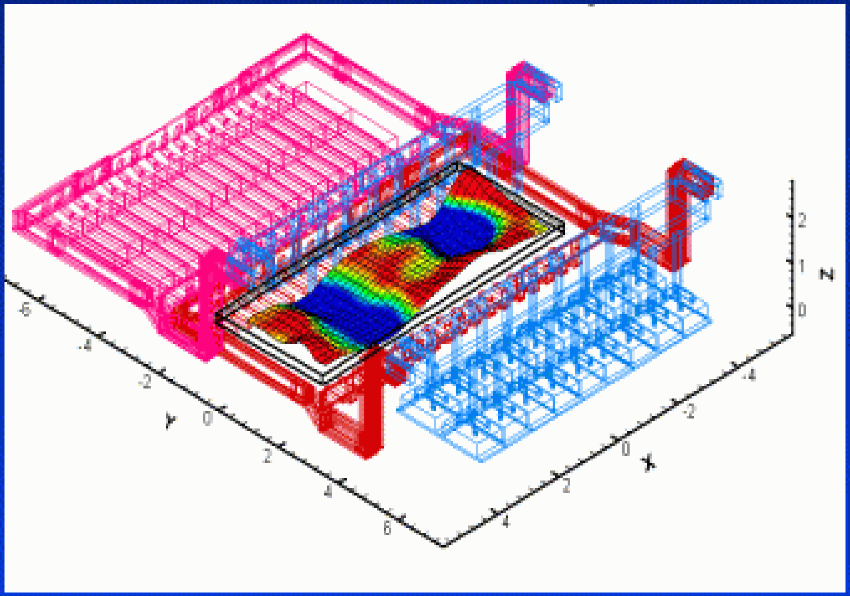
Cell Design

Future developments

Yet, to be rigorous, a fusion of those three types of model into a fully coupled multi-physics finite element model is required because:

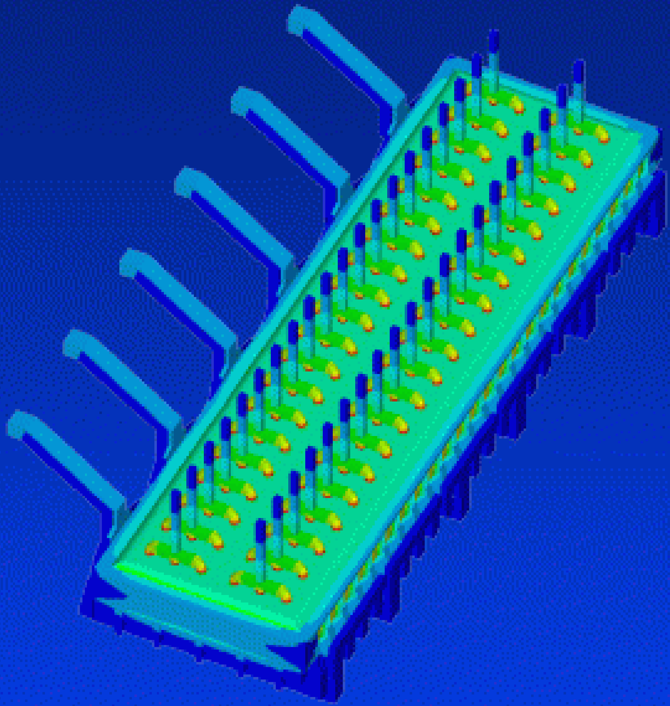
- MHD is affected by the ledge profile, mostly dictated by the cell heat balance design.
- local ledge profile is affected by the metal recirculation pattern mostly dictated by the busbars MHD design .
- shell deformation is strongly influenced by the shell thermal gradient controlled by the cell heat balance design.
- steel shell structural elements like cradles and stiffeners influence the MHD design through their magnetic shielding property.
- global shell deformation affects the local metal pad height, which in turn affects both the cell heat balance and cell stability

Weakly coupled 3D thermo-electric full cell and external busbar and MHD model



MHD model:

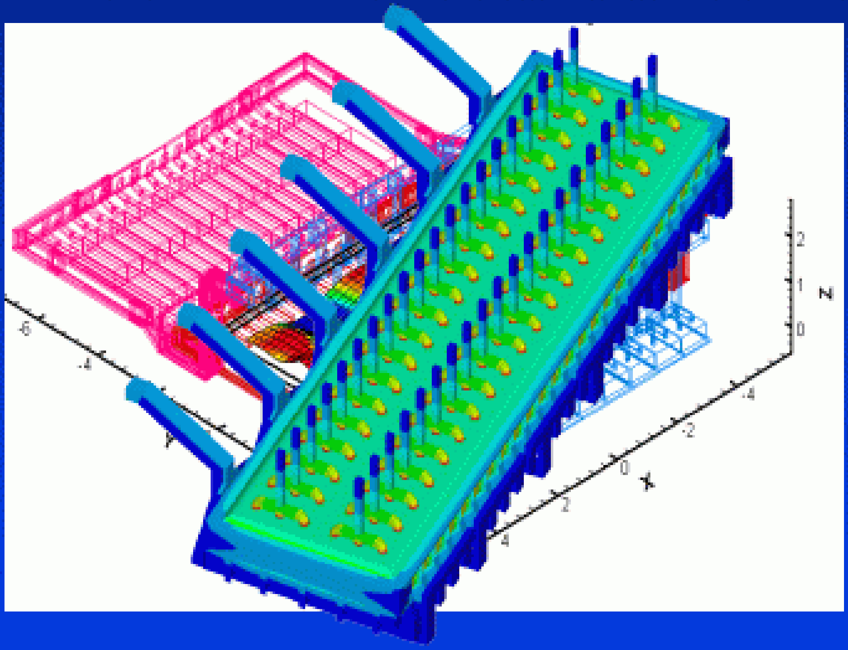
gives the liquids/ledge interface boundary conditions based on the average flow solution



Thermo-electric model:

gives the position of the ledge profile based on the heat balance solution

3D fully coupled thermo-electro-magneto-hydro-dynamic full cell and external busbar model



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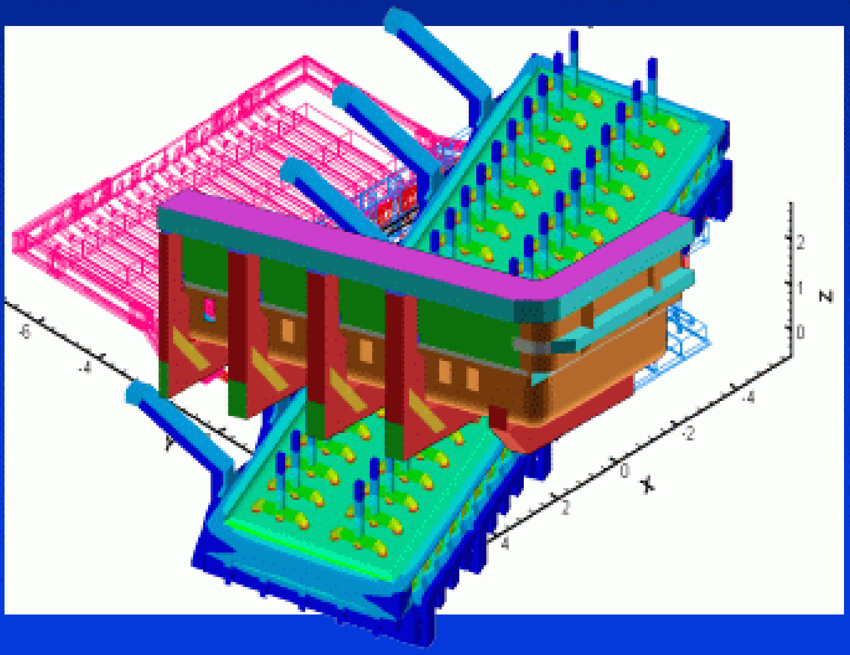
3D fully coupled thermo-electro-mechanico-magneto-hydro-dynamic full cell and external busbar model



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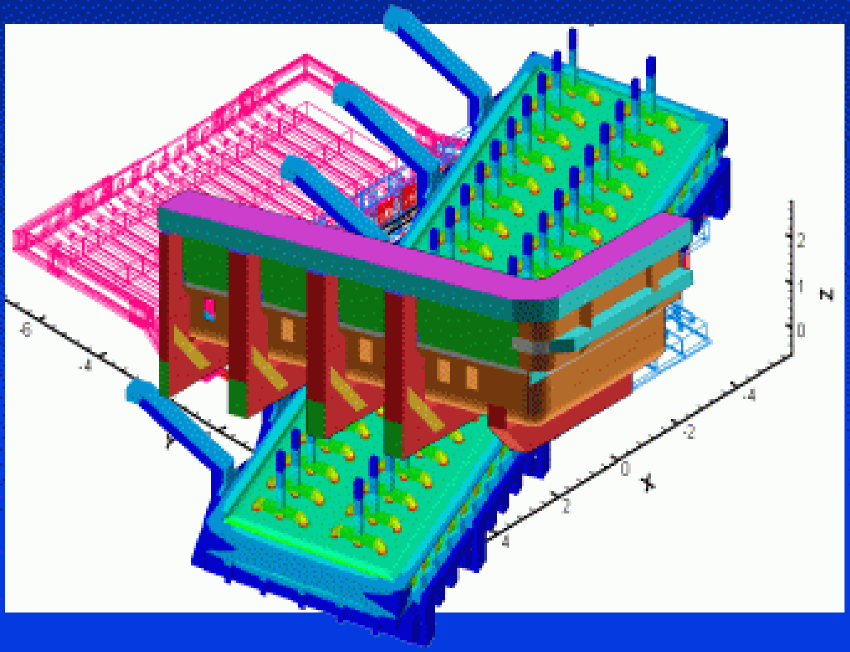
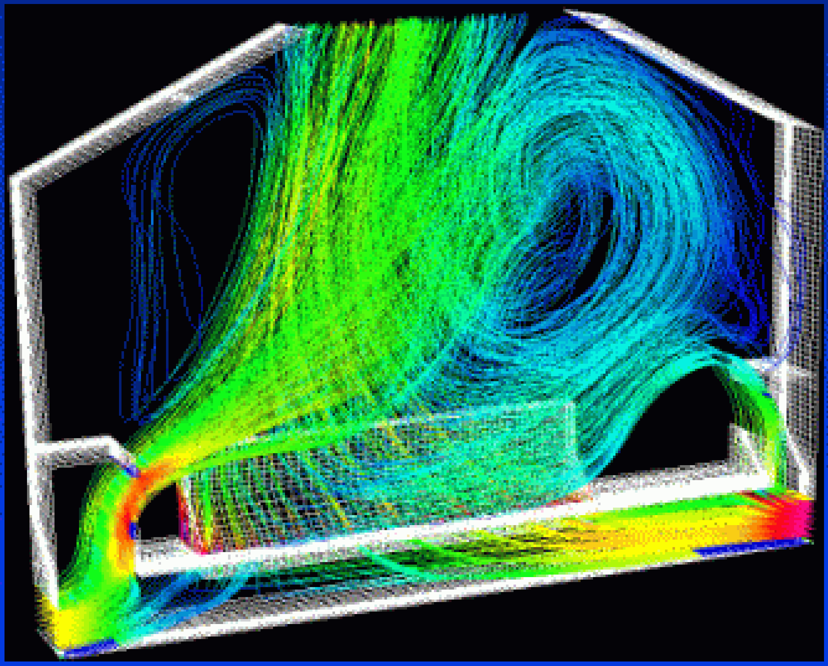
3D fully coupled thermo-electro-mechanico-magneto-hydro-dynamic full cell and external busbar model weakly coupled with a 3D potroom ventilation model





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Conclusions

- Only a truly multi-physics modeling application could be used as a design tool in order to fully take into accounts all of the complex interactions taking place in a H.H. cell.
- On the other hand, such a model even if it could be available today, could not be used as a practical design tool as it would require far too much computer resources to have a manageable turn around time and operating cost.
- As for past developments, the author believes that the rate of future model development will be mainly dictated by the Moore law.