Study of the Thermally-Induced Shell Deformation of High Amperage Hall-Héroult Cells

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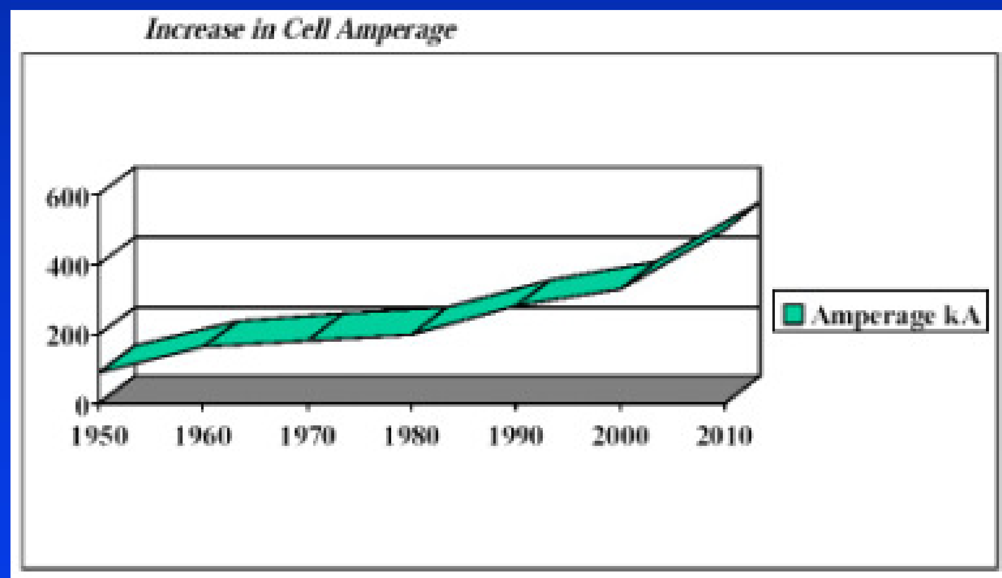
Plan of the Presentation

- Introduction
- Mechanical Aspect of the Cell Design
- Finite Element Modeling Approach
- Impact of Mesh Refinement
- 300 kA Cell Results
- 500 kA Cell Results
- Conclusions

Introduction

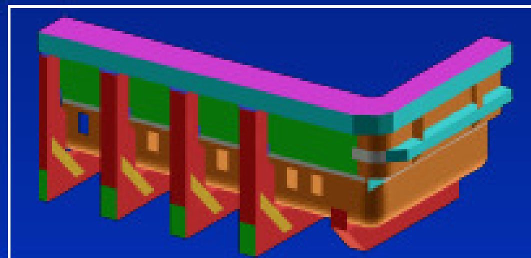
- It seems that the 20th century trend towards the regular introduction of new cell designs of higher and higher amperage has considerably slowed down in recent years.
- The AP30 cell design, the last major step in this evolution, is now more than 15 years old. The aluminum industry, in order to maintain the momentum of the last century, should already be using the AP50 or a similar technology for its current greenfield smelter projects.



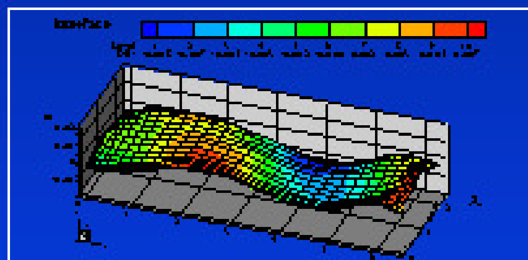
Introduction

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

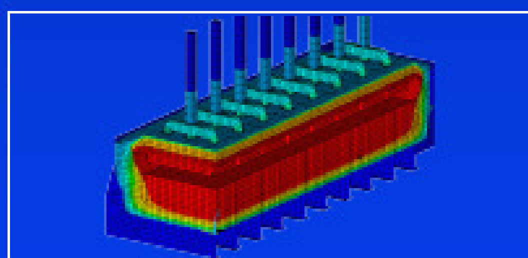
- Stress models which are generally associated with cell shell deformation and cathode heaving issues.



- 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

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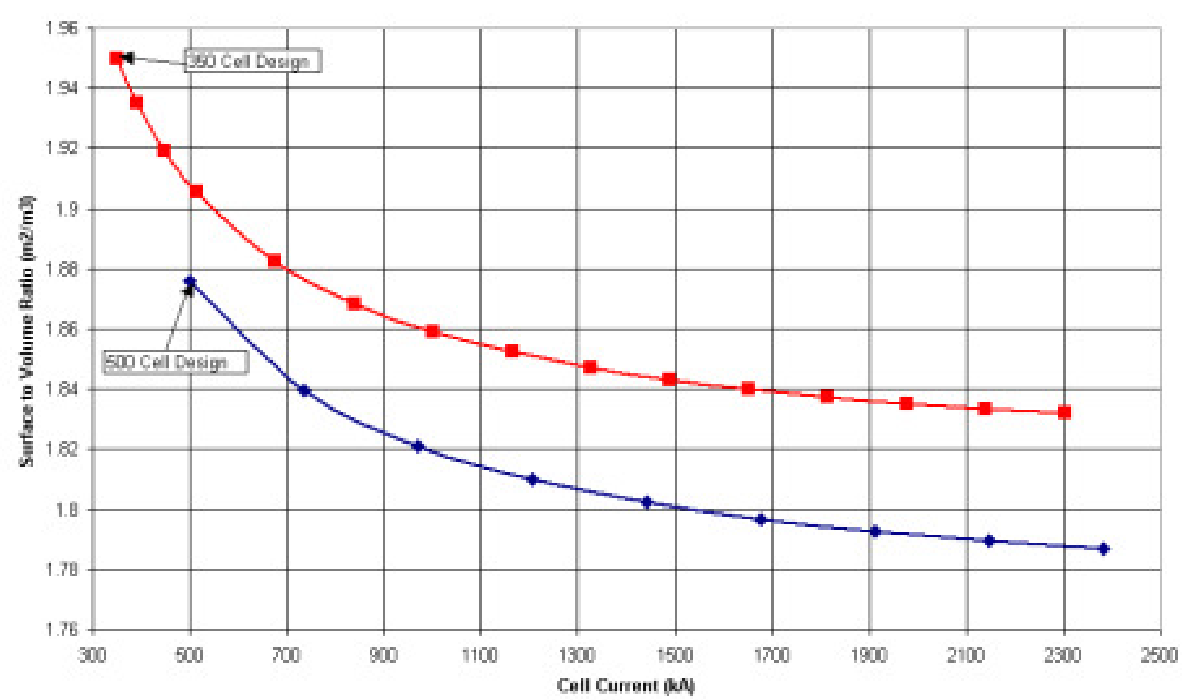
Introduction

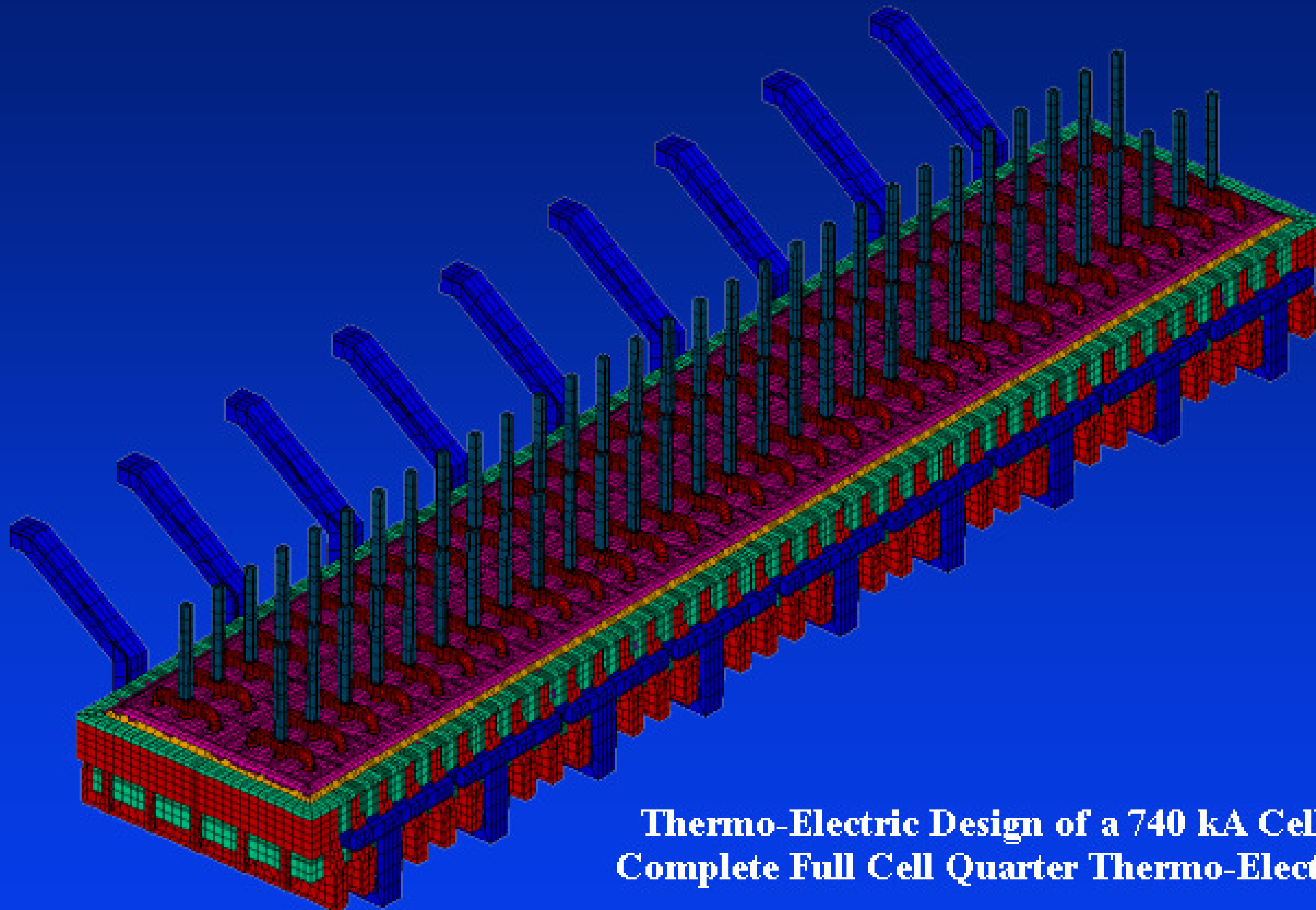
- One might argue that just as the Moore Law will eventually hit the quantum mechanics physical barrier in the computer industry, a similar barrier has already stopped the aluminum industry in its effort to continuously produce higher amperage cell designs.

- If it is the case, it has been clearly demonstrated that if there is a limit, that limit is not related to the cell heat balance aspect of the cell design.

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



Introduction



Thermo-Electric Design of a 740 kA Cell Using a
Complete Full Cell Quarter Thermo-Electric Model

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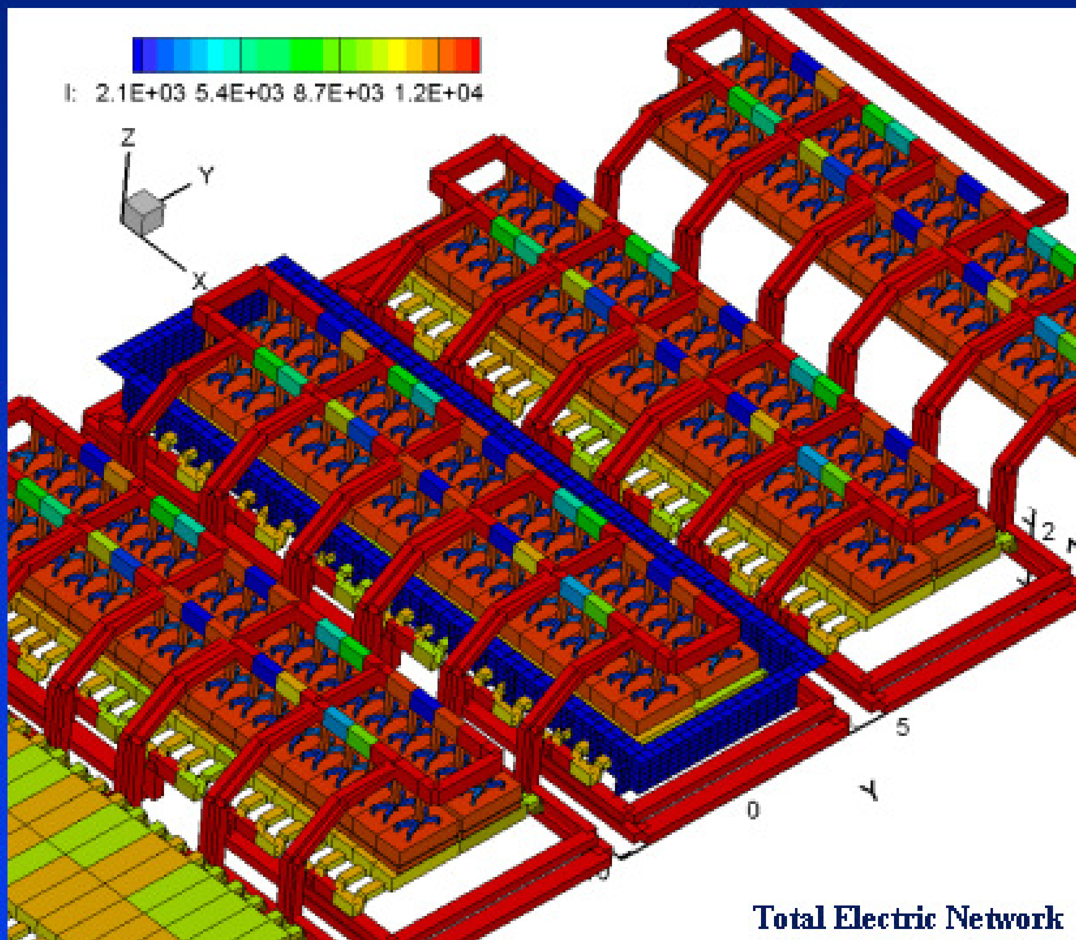
Introduction

- On the MHD cell stability aspect, as the cell gets longer and the return line influence increases, minimizing the longitudinal gradient of the Bz component of the magnetic field is certainly becoming more challenging. Yet the magnetic compensation techniques (asymmetric busbar, compensation loop, further extension of the return line location, etc) are not loosing their efficiency as the cell amperage increases. Some very well established MHD experts argue that there is a MHD barrier to the continuous increase of the cell amperage, other are not so sure.

- Even if the jury is still out on the possible existence of an MHD related cell amperage limit, there is no indication that we are currently near that limit as it was not that difficult to find a stable cell busbar configuration in order to produce a demonstration 500 kA cell design.

Introduction

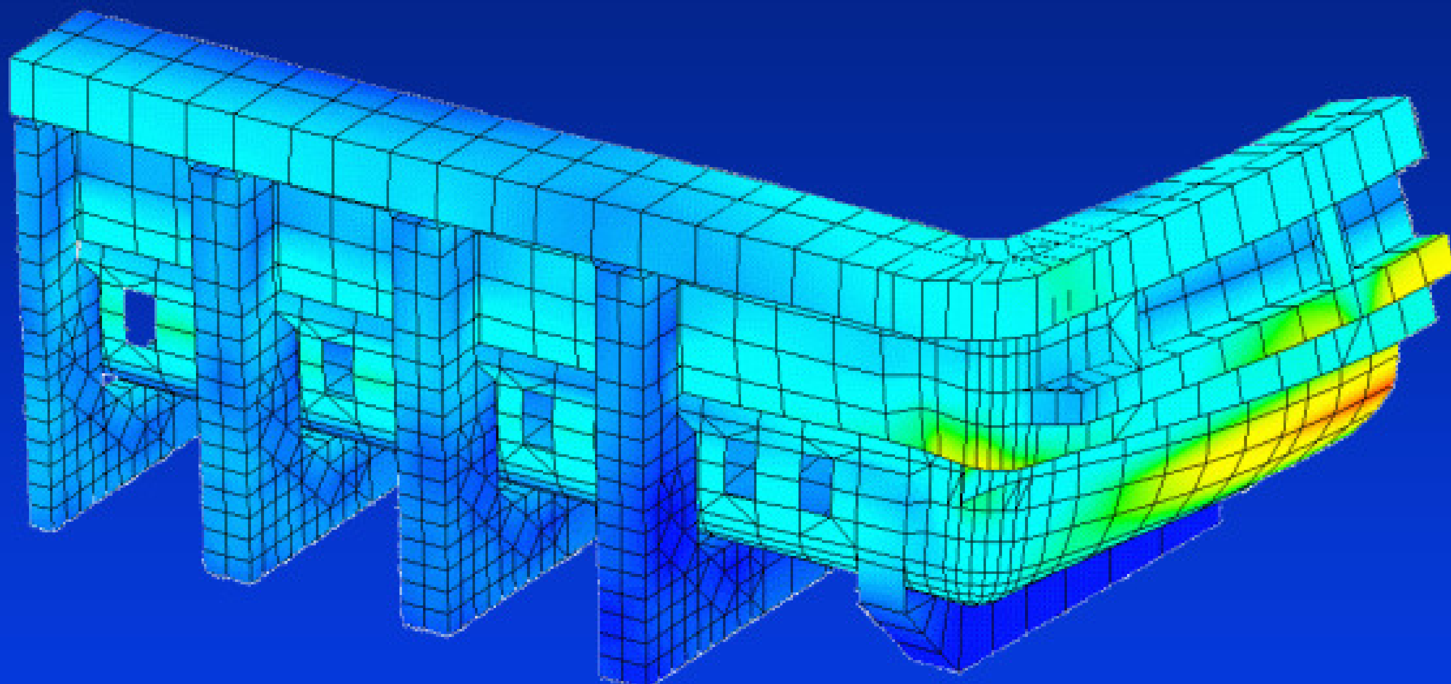


MHD Model of a 500 kA cell

Introduction

The mechanical aspect of designing a high amperage cell with a length to width aspect ratio of 4 or more is not well covered in the literature.

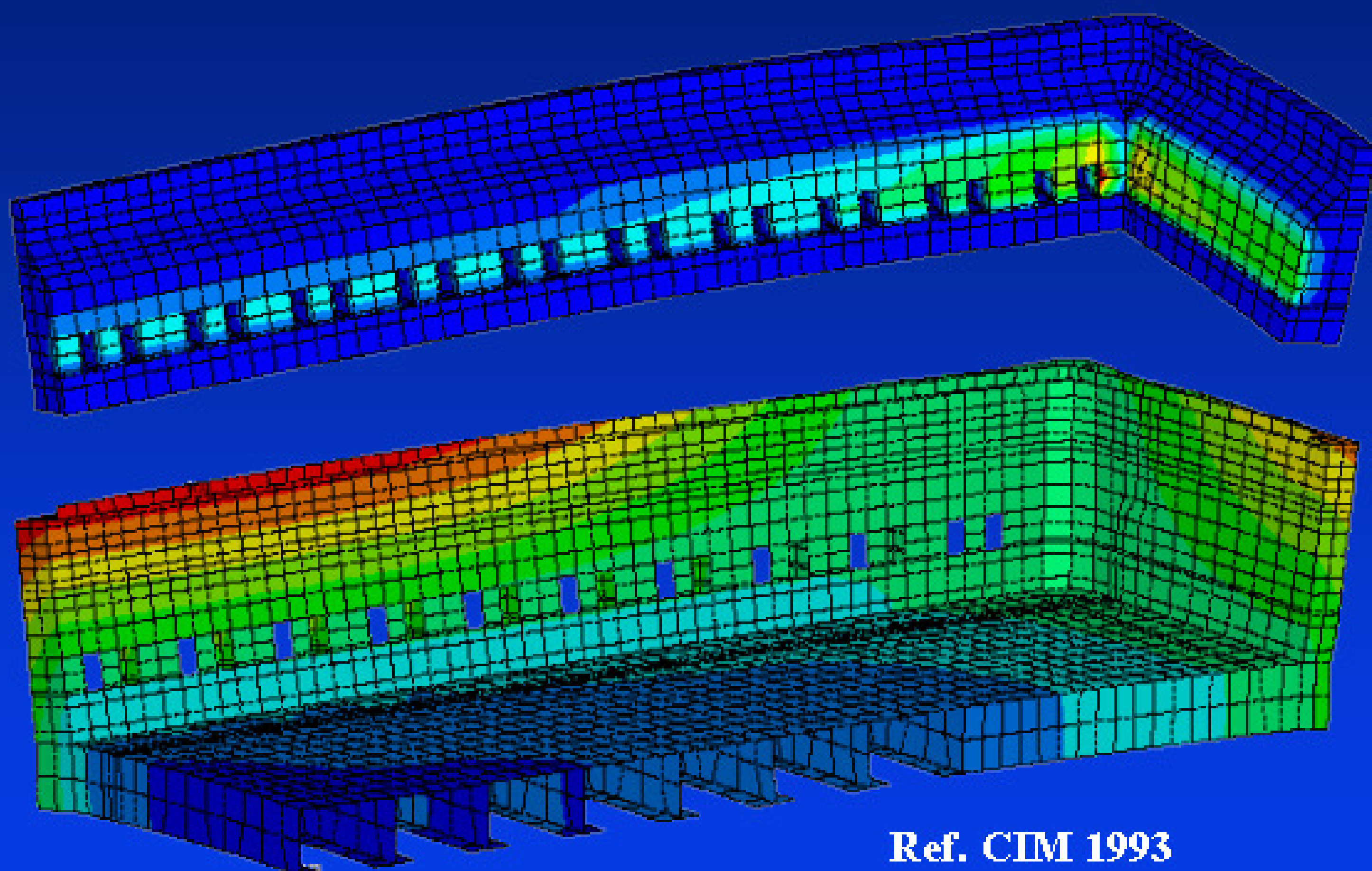
Mechanical Aspect of the Cell Design



Ref. TMS 1991

"Empty shell" mechanical model that addresses the problem of the plastic deformation of the cathode steel potshell under its thermal load and its internal pressure load.

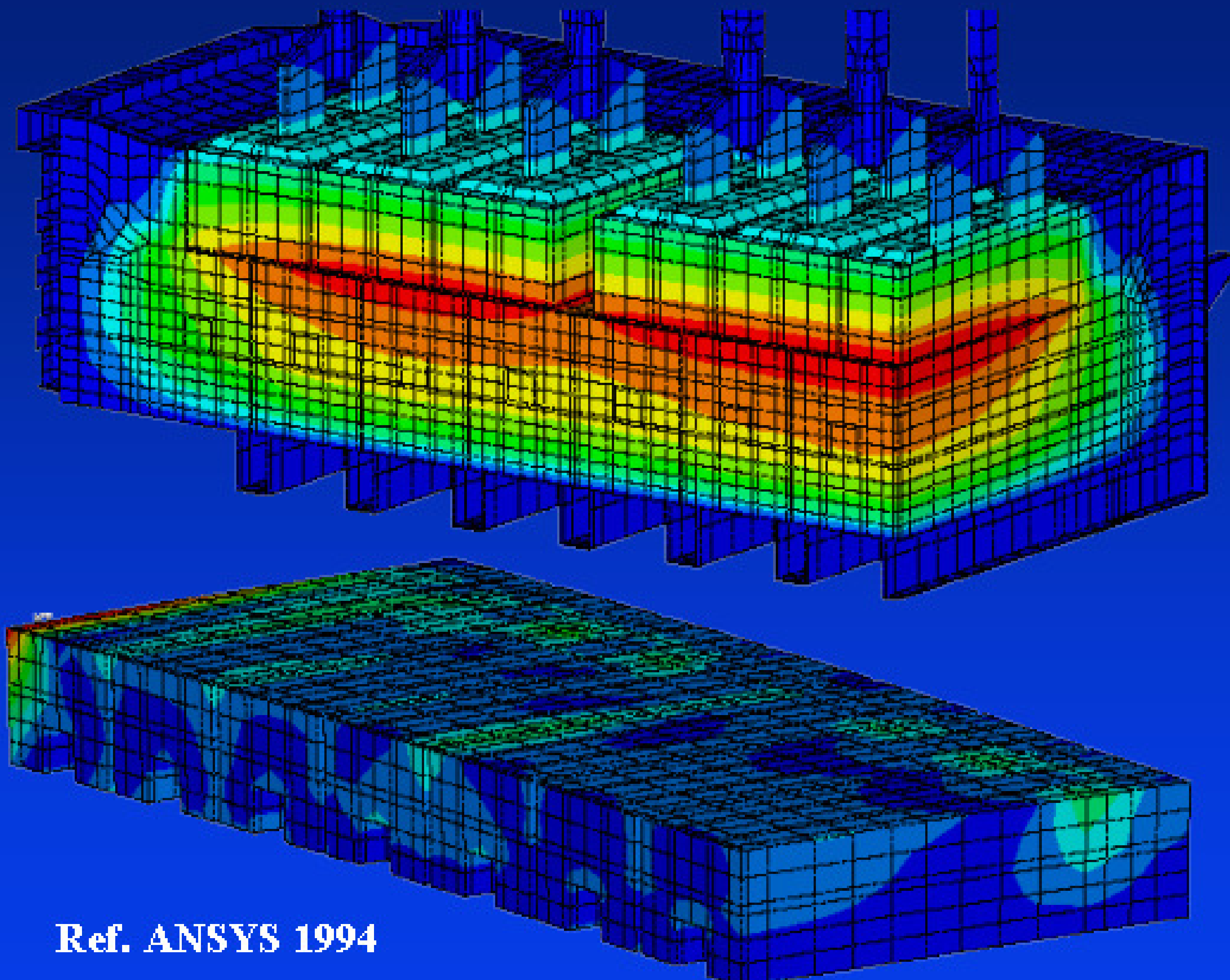
Mechanical Aspect of the Cell Design



"Almost empty shell" mechanical model that addresses the problem of the coupling between the restraining stiffness of the potshell and the internal pressure from the swelling lining material.

Ref. CIM 1993

Mechanical Aspect of the Cell Design



The full thermo-mechanical model represents the response of the cell from complex interactions between the refractory lining and the steel shell. The lining expands thermally, but some materials may also experience irreversible deformations like chemical swelling and contraction, plastic deformation, creep, etc. The shell also expands thermally, and it may also deform plastically.

Ref. ANSYS 1994

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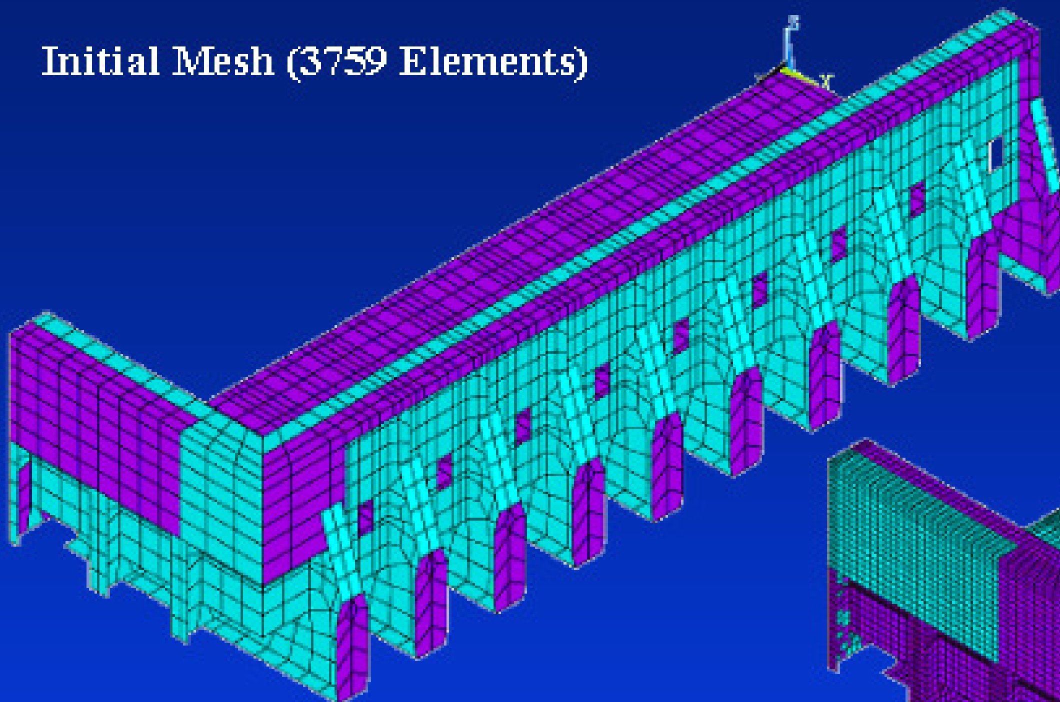
Finite Element Modeling Approach

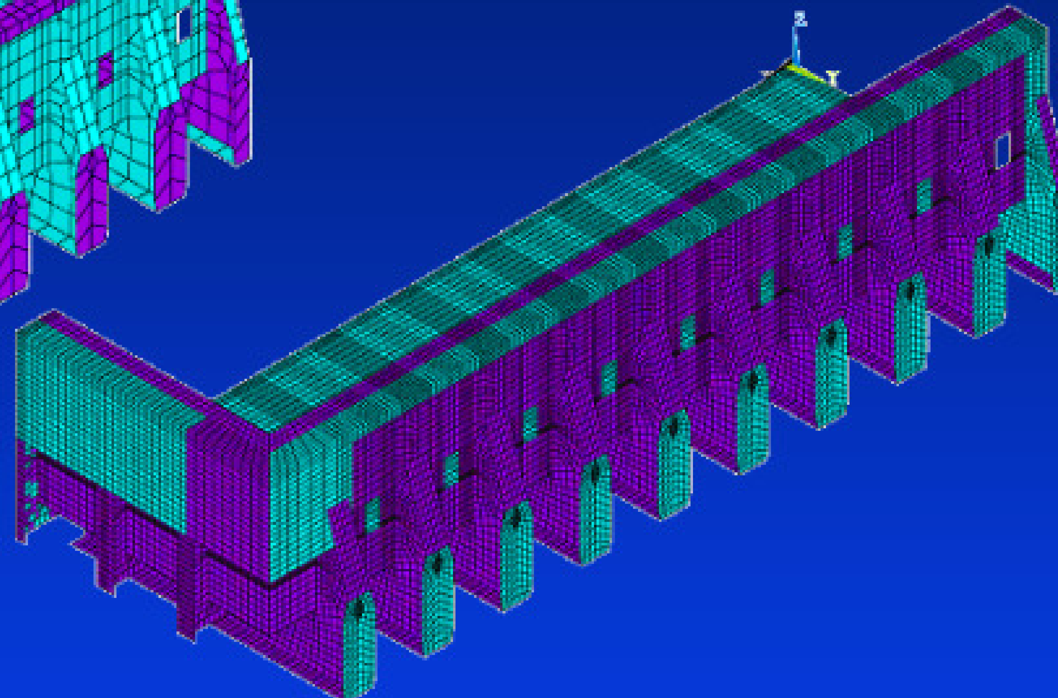
- The prediction of the mechanical response of an operating cell is a challenging task. As a first approximation and for comparison purposes, a simple “Empty-Shell” modeling approach was used.
- A quarter shell was modeled using four-nodes quadrilateral Finite Strain shell elements (*SHELL181*) in the commercial code ANSYS.
- The corresponding symmetry boundary conditions were imposed, while one point was supported in the vertical direction on the second closest cradle to the end wall.
- A constant downward pressure was applied on the shell floor to represent the combined weight of the lining and the liquids. A constant outward pressure was applied to the shell wall opposite to the cathode block to represent the effect of the lining expansion.
- The temperature distribution obtained from the full cell coupled thermo-electric model was applied as a body load to the shell and cradles.

Impact of Mesh Refinement

Initial Mesh (3759 Elements)



Refined Mesh (33831 Elements)



It is well known that the element size has a strong impact on the accuracy of a finite element solution. The adequate size is however physics-dependent. In a mechanical simulation using a non-linear constitutive law, for example plasticity, the response is strongly dependent on the strain level, which is obtained from the displacement gradient. Finer meshes are therefore required compared to a thermal simulation.

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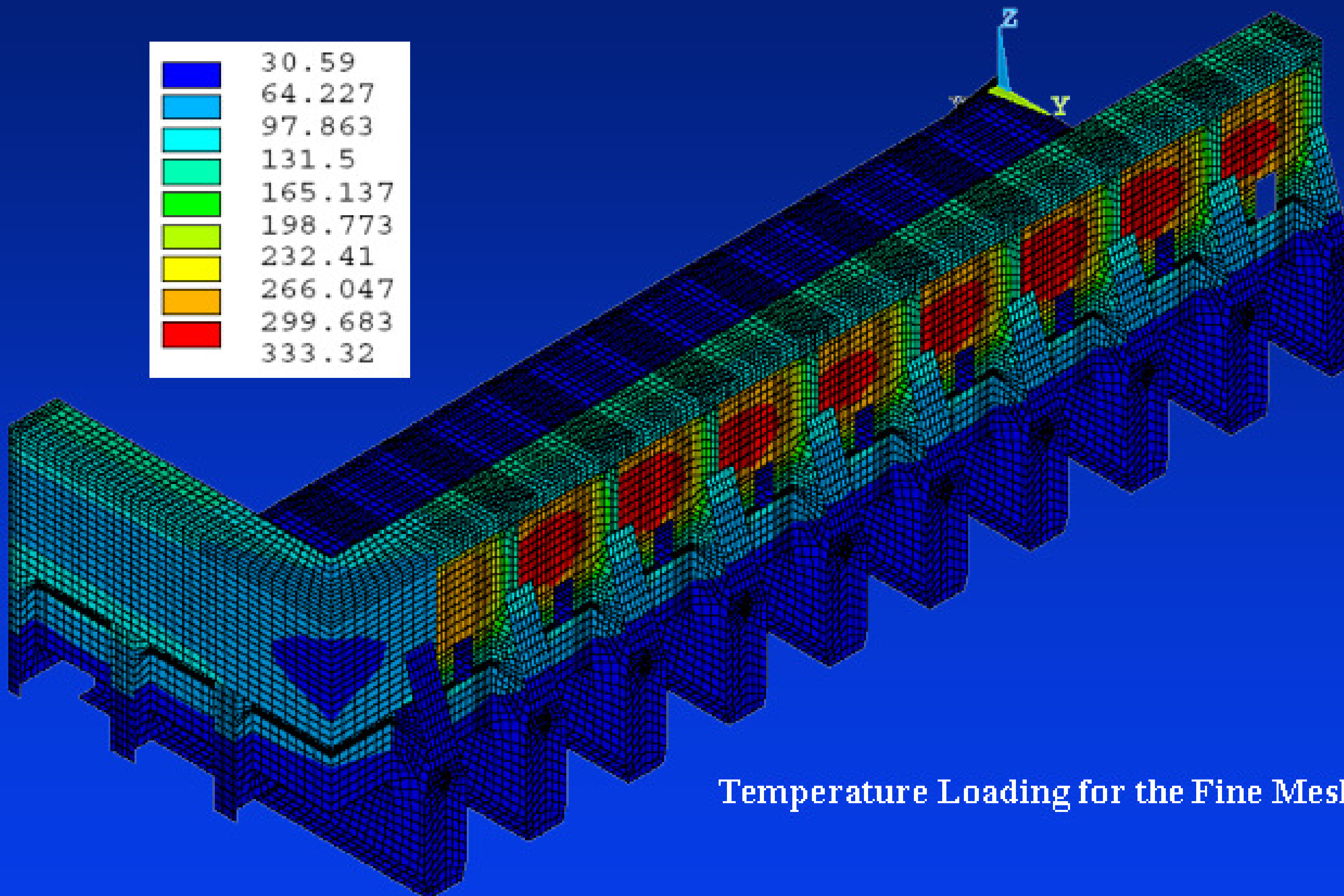
Impact of Mesh Refinement



Temperature Loading for the Fine Mesh Model

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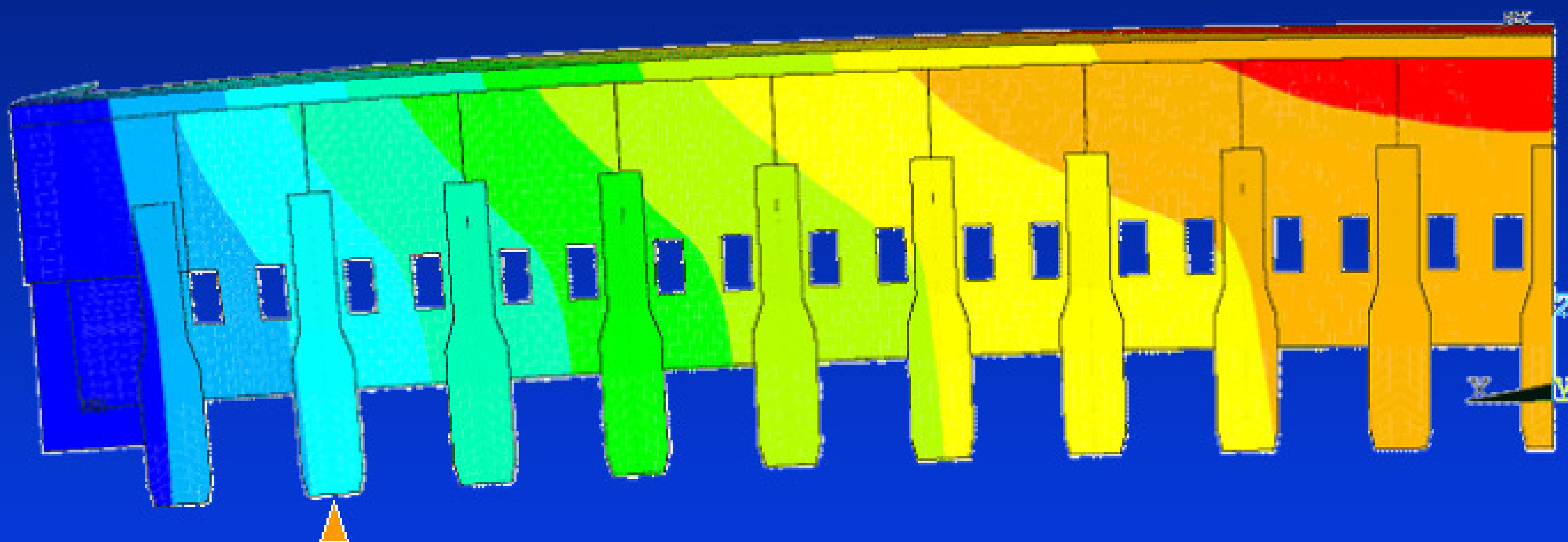
Impact of Mesh Refinement



Relative Vertical Displacement for the Fine Mesh Model

Impact of Mesh Refinement

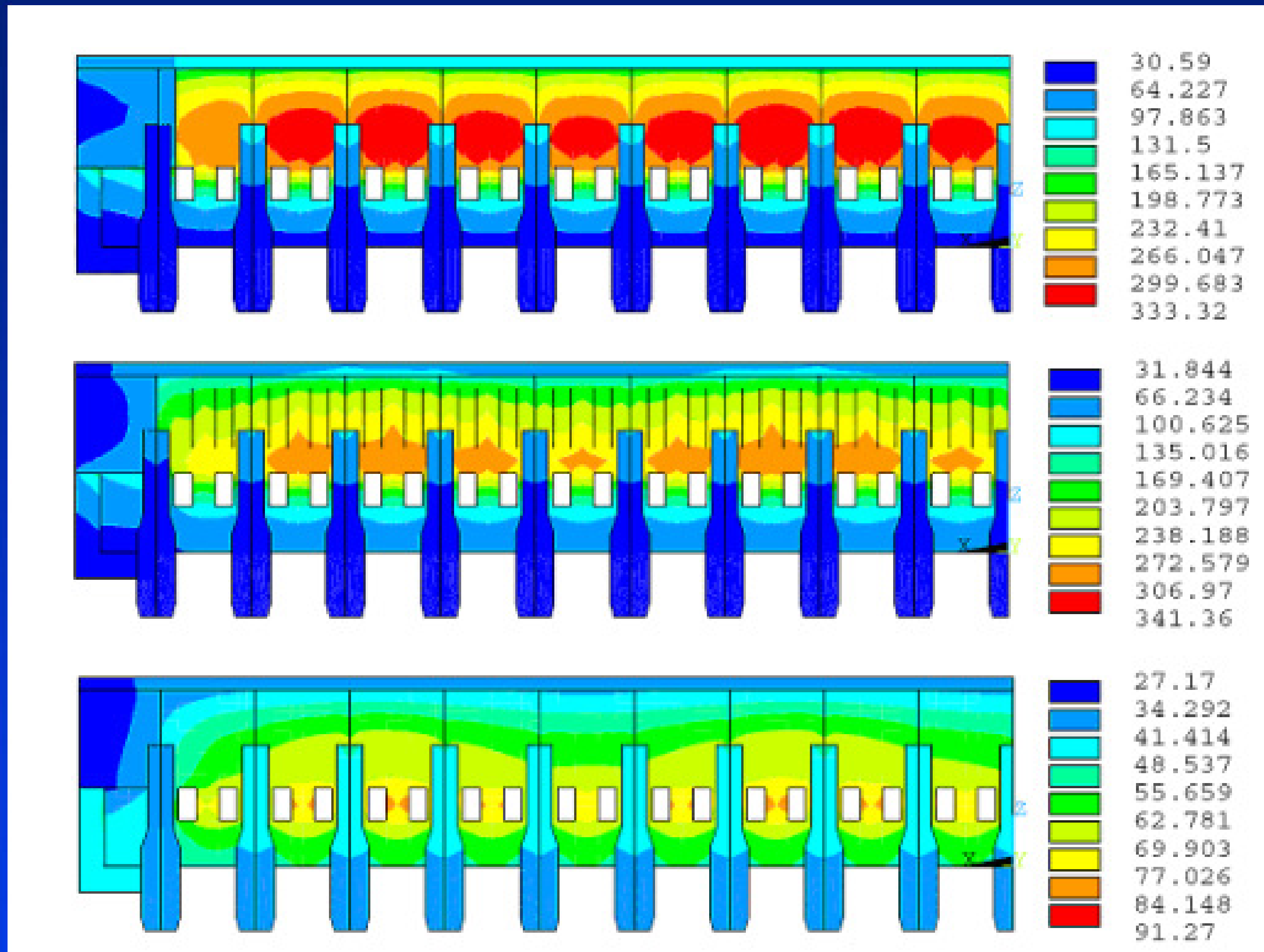
It is quite obvious that the initial mesh was inadequate for the mechanical analysis, as the maximum displacement is almost twice as large for the coarser mesh.

300 kA Cell Results

Base Case.

With Cooling Fins.

With Forced-Air Cooling.



Temperature distribution for the studied 300 kA cell configurations.

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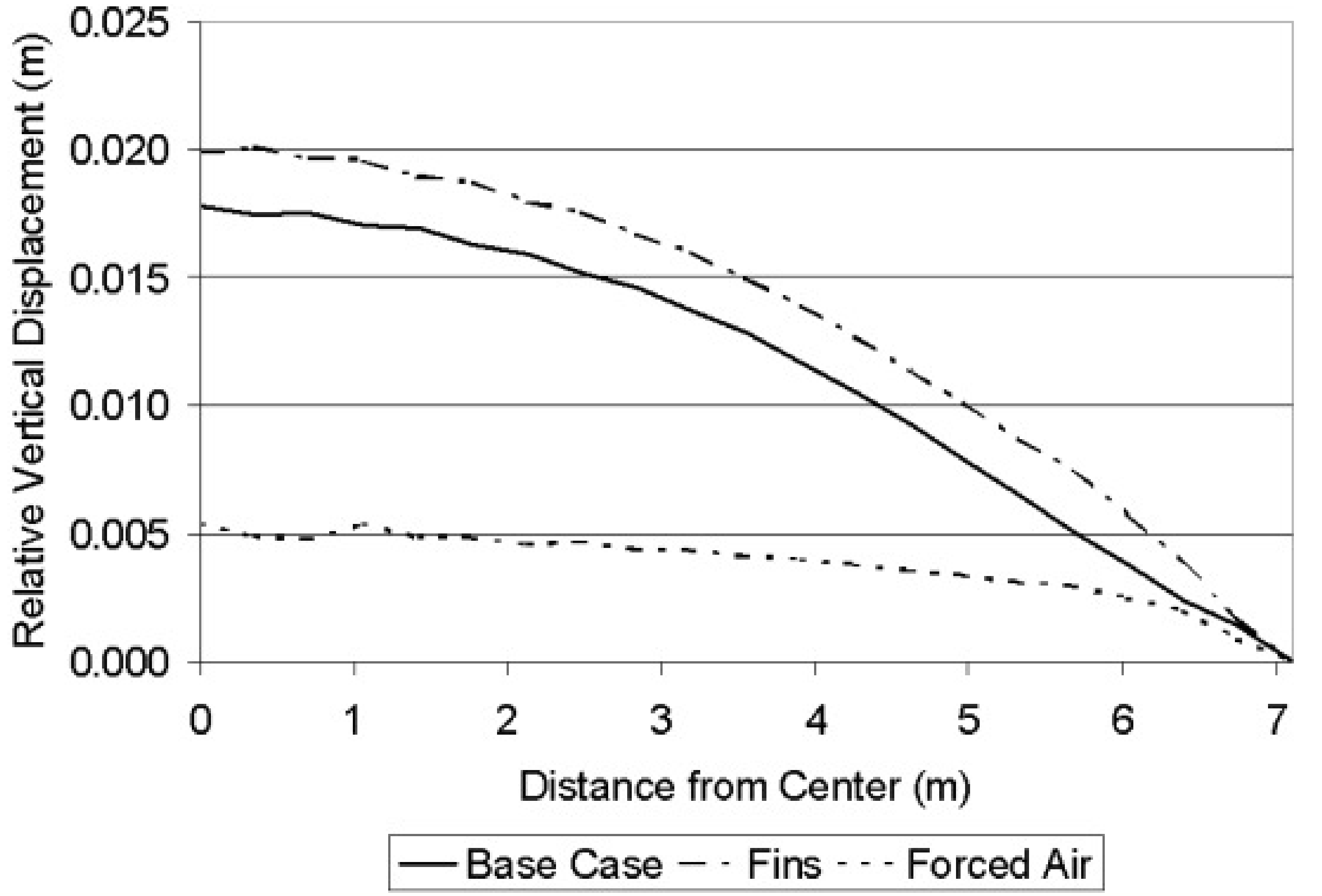
300 kA Cell Results



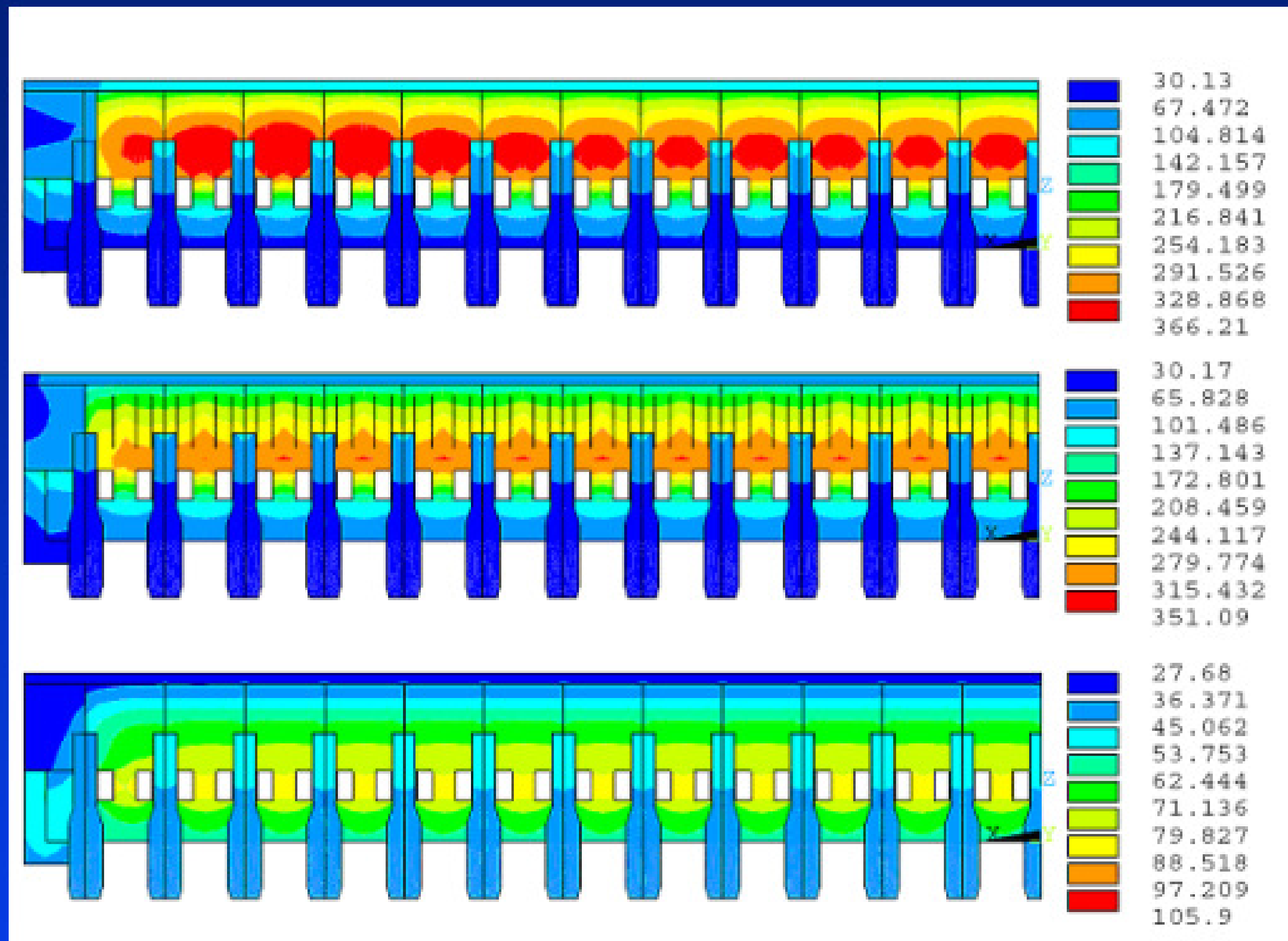
Comparison of the relative vertical displacement on the long axis of the 300 kA cell.

500 kA Cell Results

Base Case.

With Cooling Fins.

With Forced-Air Cooling.



Temperature distribution for the studied 500 kA cell configurations.

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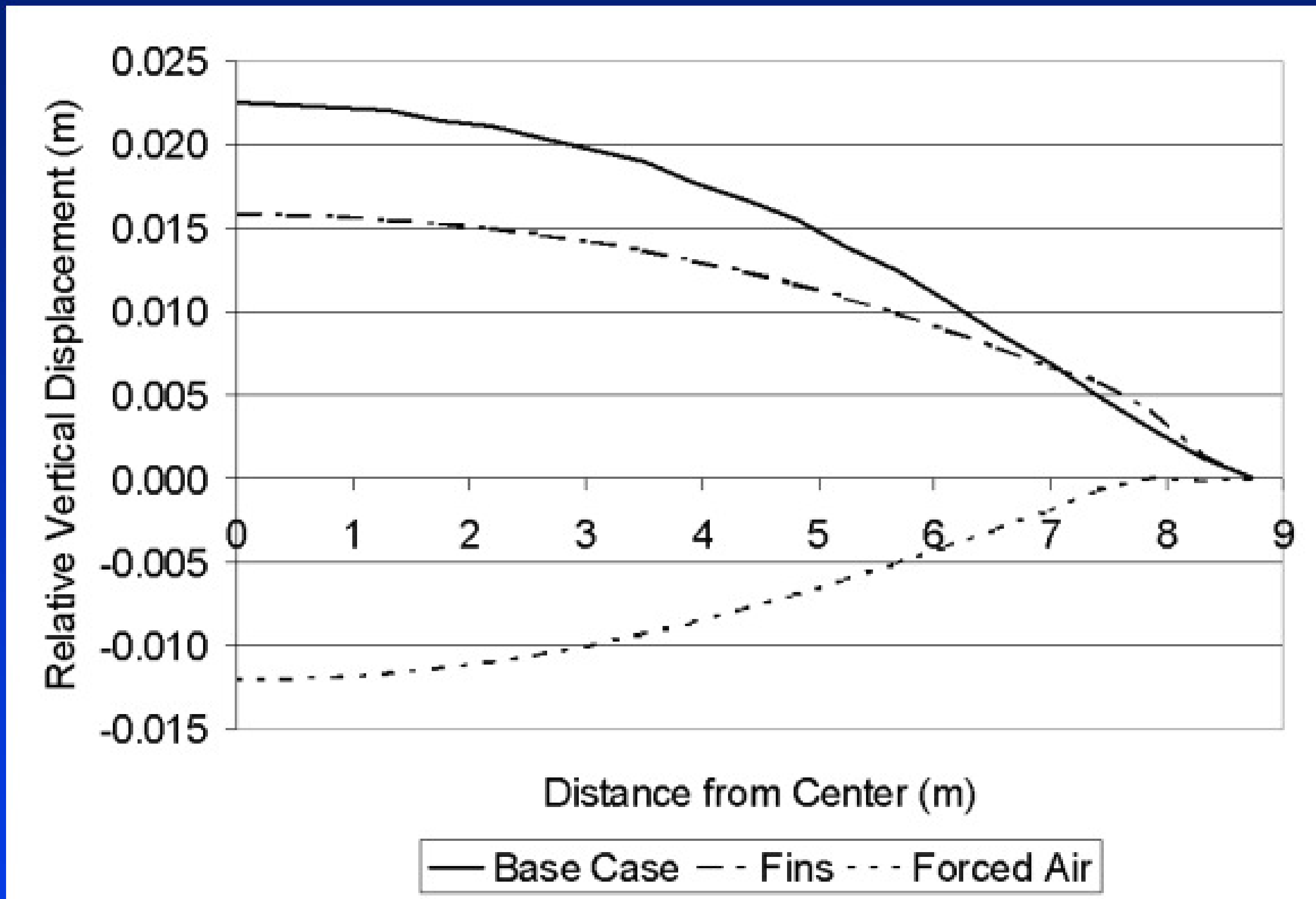
500 kA Cell Results



Comparison of the relative vertical displacement on the long axis of the 500 kA cell.

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Conclusions

- Simple "Empty-Shell" finite element models were used to assess the impact of two different shell sidewall cooling enhancement measures – fins and forced-air – on the relative upward displacement of the shell floor.
- It was shown that a good mesh for thermo-electrical simulations may not be adequate for a mechanical analysis, more so if non-linearities are present. The quality of the global solution depends on the ability to capture local phenomena such as in plane bending and plasticity.
- It was hinted that stiffer sidewalls lead to larger relative upward displacements. This is one of the reasons why cooling fins were not very successful in this aspect. Forced-air cooling reduced the relative displacement to almost nil for the 300 kA cell and even caused a downward relative displacement for the 500 kA cell.

Conclusions

- It is well known that the cradles of the AP30/AP35 are fully reinforced, so their sidewalls will be significantly stiffer than the studied design. It is likely that the magnitude of the relative upward displacement for these cells will be much larger than what has been computed for the 300 kA base case.
- Since it is likely that the magnitude of the relative upward displacement is larger in the AP50 than in the studied design, it is plausible that the forced-air cooling system is primarily used to solve this problem.