

Modeling Cathode Cooling Due to Power Interruption

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- **Thermal Cooling Modeling**
 - Effective Thermal Conductivity of the Liquid Metal
 - 2D+, 3D Slice, 3D Quarter
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Cell Cooling Historical Background

When the power input to cells is stopped, the internal cell heating due to the “Joule heating” effect stops.

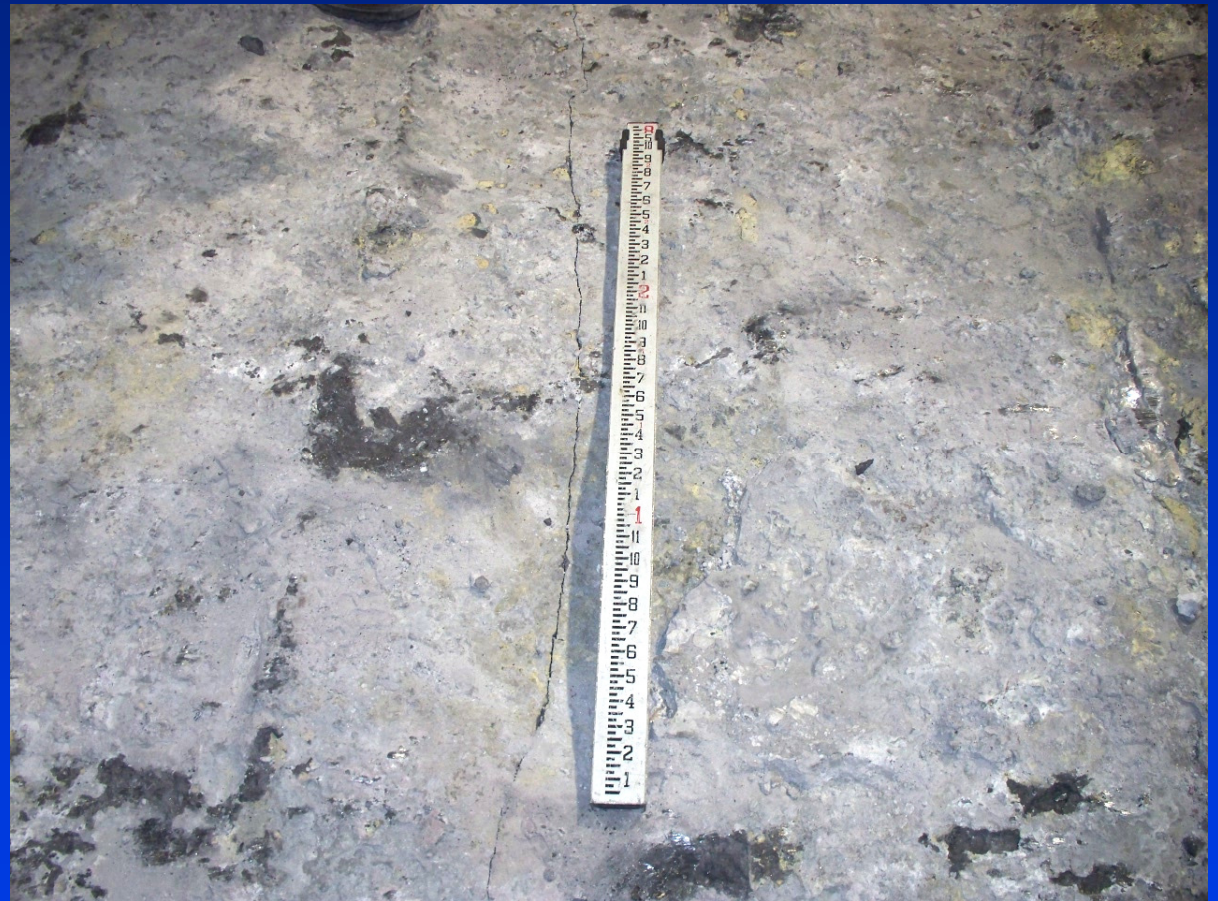
But, cells continue to dissipate heat at nearly the same rate as during normal operations with approximately 35% of the heat being transferred from the sidewalls 45% of the heat is transferred from top area of cells.

When power is off, the electrolyte temperature typically decreases at a rate of 15-20°C per hour. Cooling the electrolyte in cells below ~850 °C results in the solidification of bath and the shutdown of the operating cells in the potlines.

Cathode Cooling Cracks

The rapidly cooling of aluminum cells from 960°C to ambient 25°C due to potline shutdown results in the generation of cooling cracks on the cathode surface of nearly all cells in which the metal pads are removed and the surface is cleaned for inspection.

The cracks are formed in the cathode block during cooling and not during cell operation as indicated by the absence of bath or a yellow film of aluminum carbide on the surfaces of the crack.



The Fracture Behaviour of Carbon

The thermo-electro-mechanical behaviour of new cathode carbon has been described as elasto-plastic. Carbon cathode blocks initially behave elastically with reversible deformation as stress is applied, but when stress increases the carbon material starts to behave in a plastic manner with irreversible deformation until fracture occurs.

The cathode carbon is weakened as it undergoes ductile-brittle transformation during cell operation due to the cathode lining eventually becomes saturated (>3%) with sodium that intercalates and absorbs into the carbon lattice. This causes swelling and changes the properties of the carbon lining which makes the cathode material less ductile and more brittle.

Thermal Gradients in the Cathode Lining

Rapid cooling of cathodes due to power interruption generates an uneven temperature distribution in the cathode lining which results in a thermally induced mechanical stress sufficient to cause cracking.

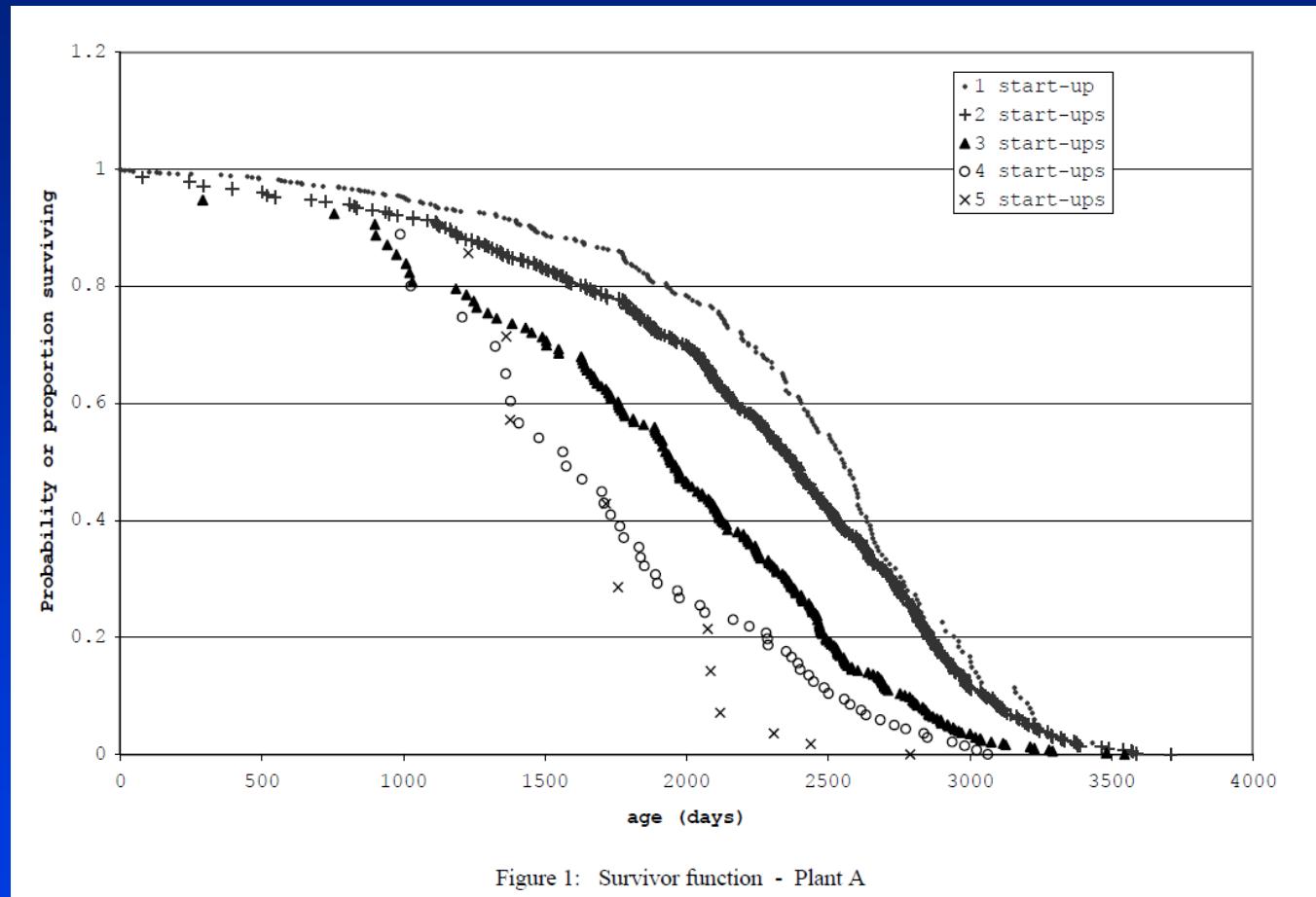
During cooling the top of the cathode blocks cool faster than the bottom of the cathode blocks resulting in large temperature gradients in the cathode lining.

Sørli and Øye, report that, “due to the very limited elasto-plastic deformation properties of carbon during rapid thermo-mechanical strain, the accumulated stress will be released in the form of surface energy as the bottom cooling cracks.”

Thermal Gradients in the Cathode Lining

Cooling cracks weaken the carbon lining as some may fill with aluminum upon restart; some cracks continue to expand and link up and become a basis for failure in the future.

The average loss in pot life due to shutdown and restart of individual potlines is about 200 days, but varies from 100 to 400 days at different aluminum smelters.

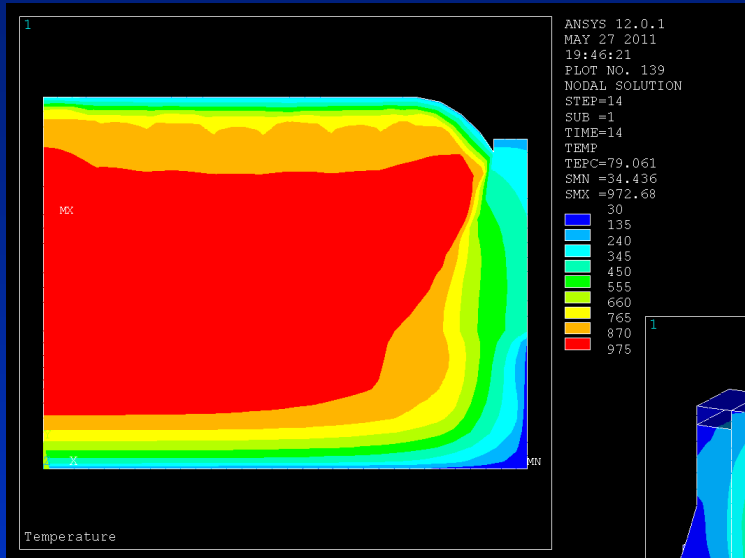


EFFECT OF MULTIPLE RESTARTS ON CELL LIFE

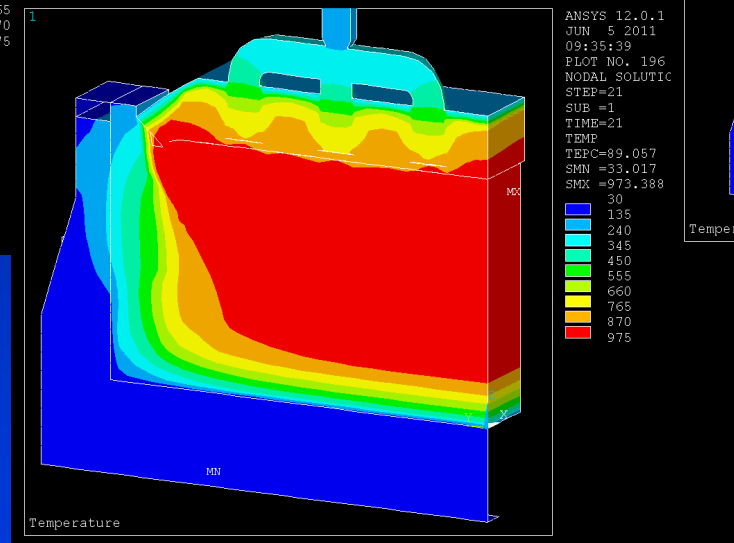
Paul Desclaux, TMS 2000

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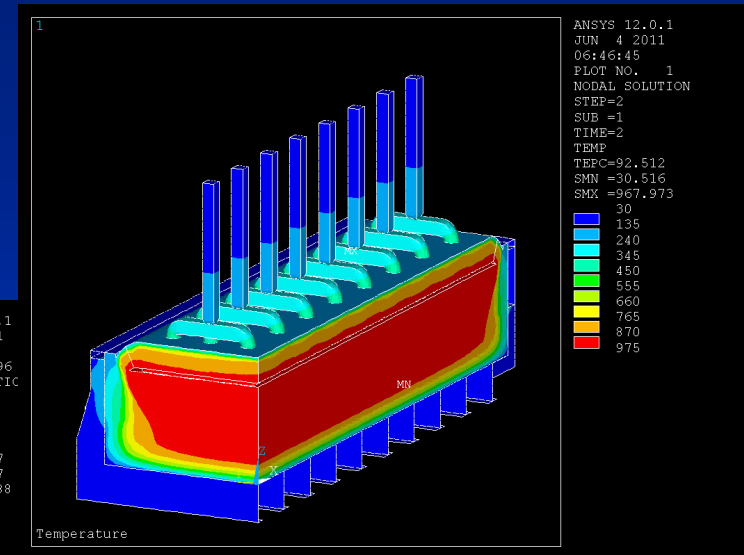
Thermal Cooling Modeling



2D+ full cell slice model



3D full cell slice model



3D full cell quarter model

New ANSYS® based thermal cooling models, (2D+ full cell slice model, 3D full side slice model and a 3D full cell quarter) were developed to determine the cathode cooling rates, the differences in the temperature gradients and the resultant stress from cooling cathodes for 24 to 48 hours.

Thermal Cooling Modeling

The initial conditions of the cooling models are those obtained by the steady-state thermo-electric models. The prebake cell is operating at 300 kA and 0.73 A/cm² of anode current density.

The cell is dissipating 610 kW while operating with a 6 °C liquidus superheat and 7 cm of ledge at the bath level and 4 cm ledge at metal level. The cell is operation at a 5 cm ACD with 20 cm of metal and 20 cm of bath.

Contrary to the approach used in steady-state models, the liquid zone as been added to the cooling models. Both the initially liquid bath and metal new materials have time dependent properties that cover the physic of the phase change:

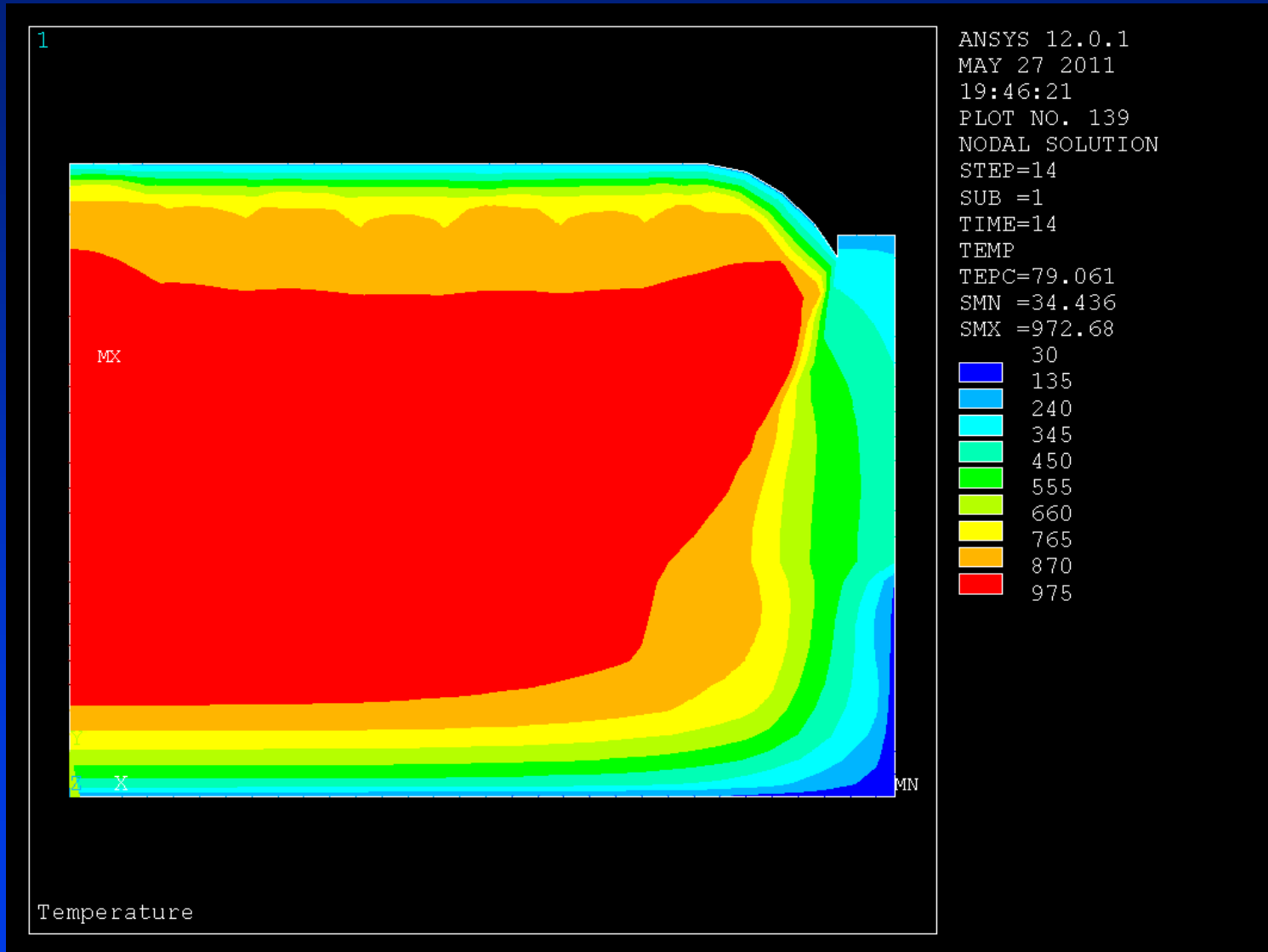
- 1) Different thermal conductivities before and after the phase change
- 2) Different specific heat before and after the phase change
- 3) Different specific heat between the liquidus and the solidus temperature to cover the latent heat of fusion

Effective Thermal Conductivity of the Liquid Metal

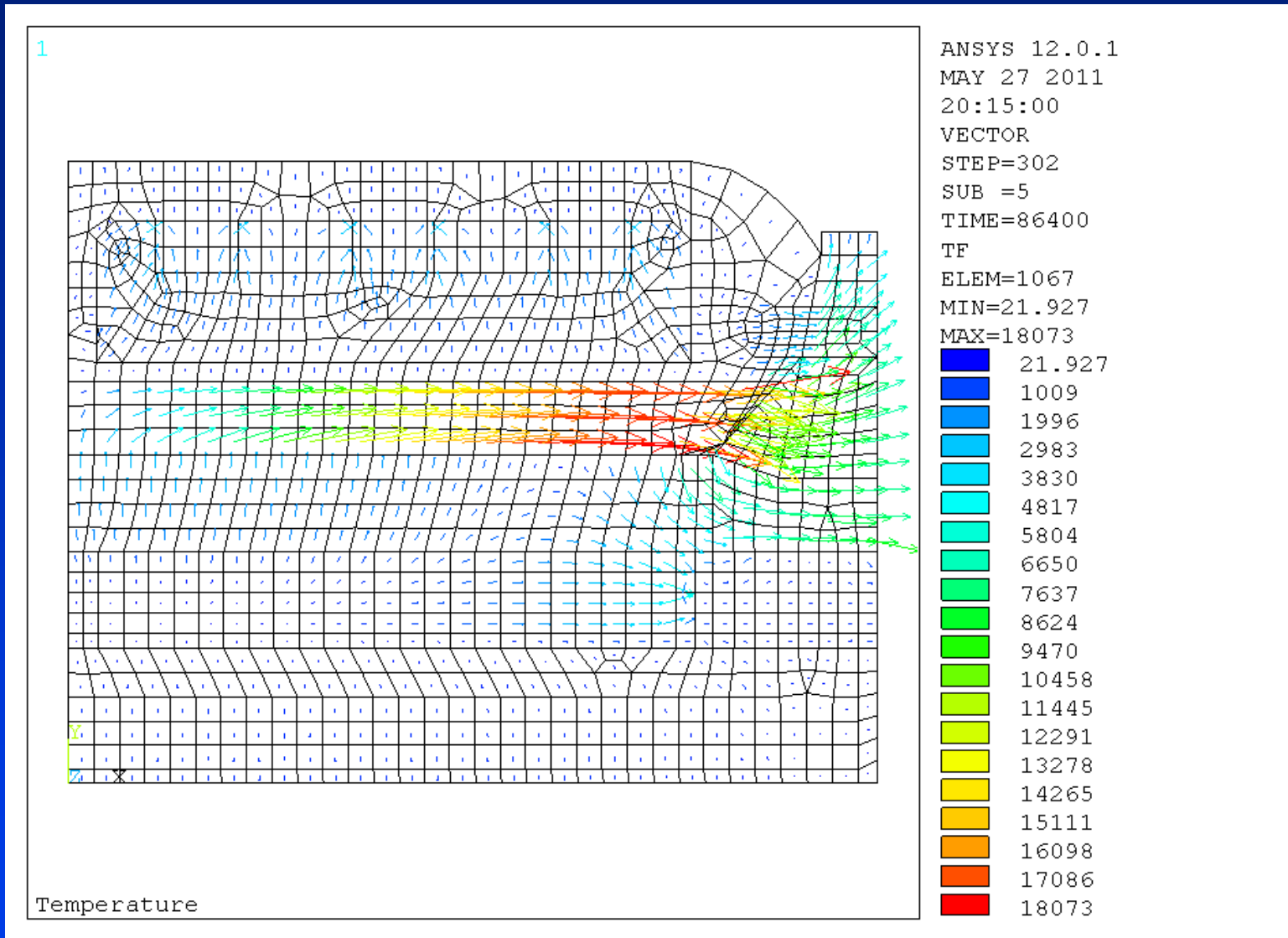
The concept of effective thermal conductivity is a convenient way to account of the effect of the heat transfer by natural convection in the metal pad without having the model the natural convection flow itself. Using the equation 11 proposed by T. Hadgu and al., the effective thermal conductivity of the liquid metal pad was estimated to be around 20 times its motionless thermal conductivity as the metal pad Rayleigh number was estimated to be around 4.9×10^8 :

$$k_{\text{eff}} = 0.057 * Ra^{0.296}$$

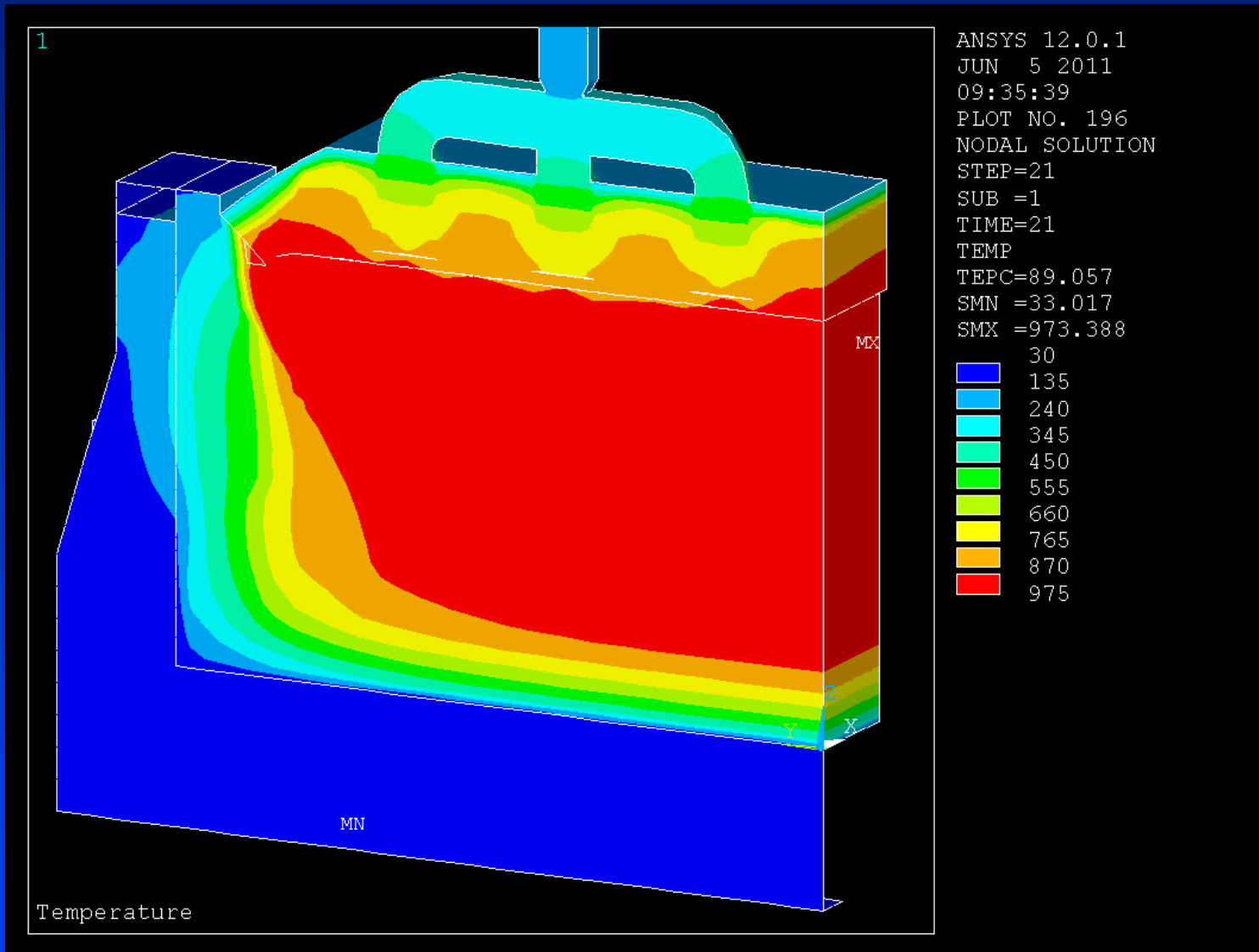
2D Side Slice Model: 20 cm Metal Pad



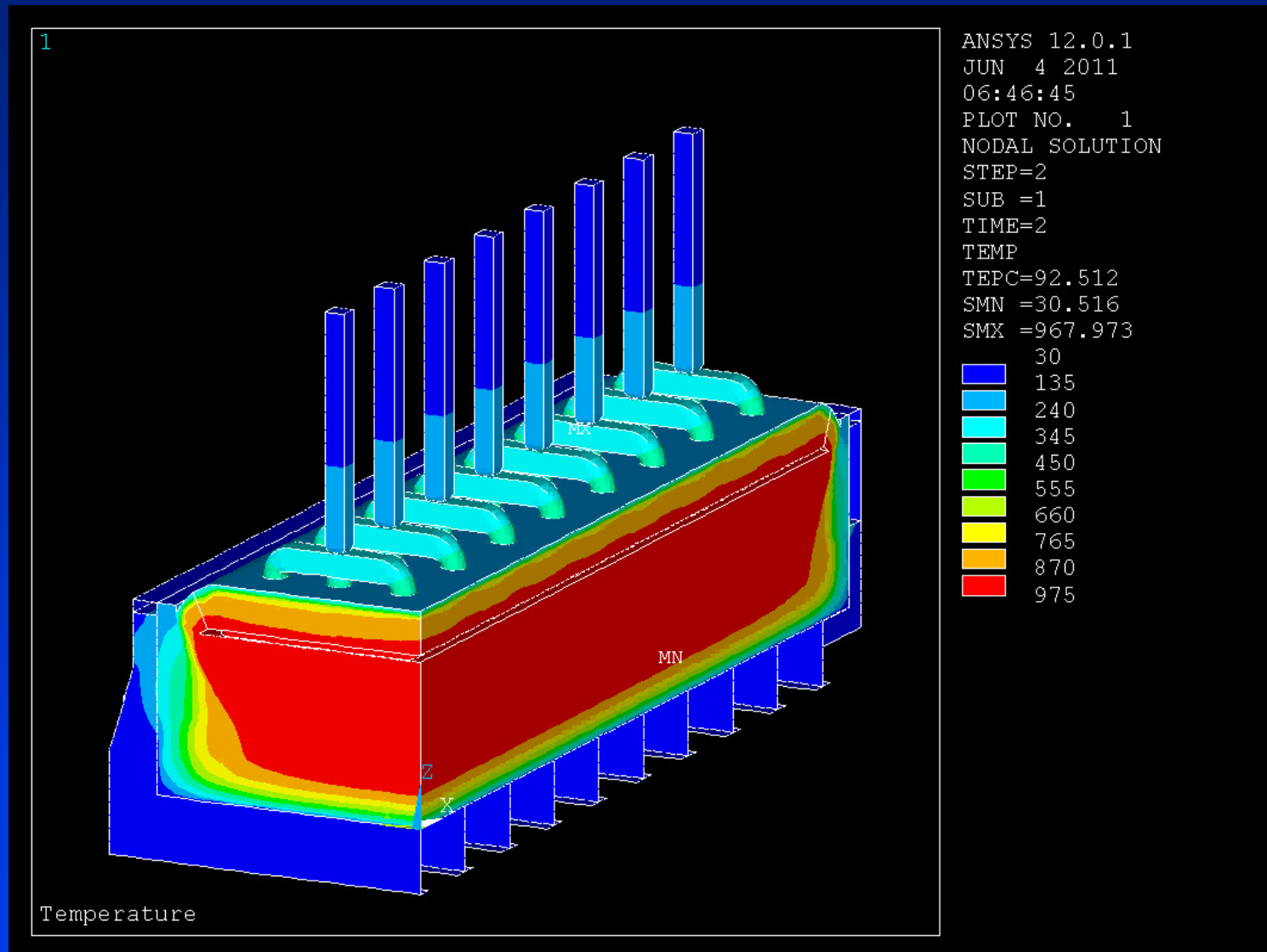
Effective Thermal Conductivity of the Liquid Metal



3D Side Slice Model: 20 cm Metal Pad



3D Quarter Model: 20 cm Metal Pad



Thermo-Mechanical Modeling

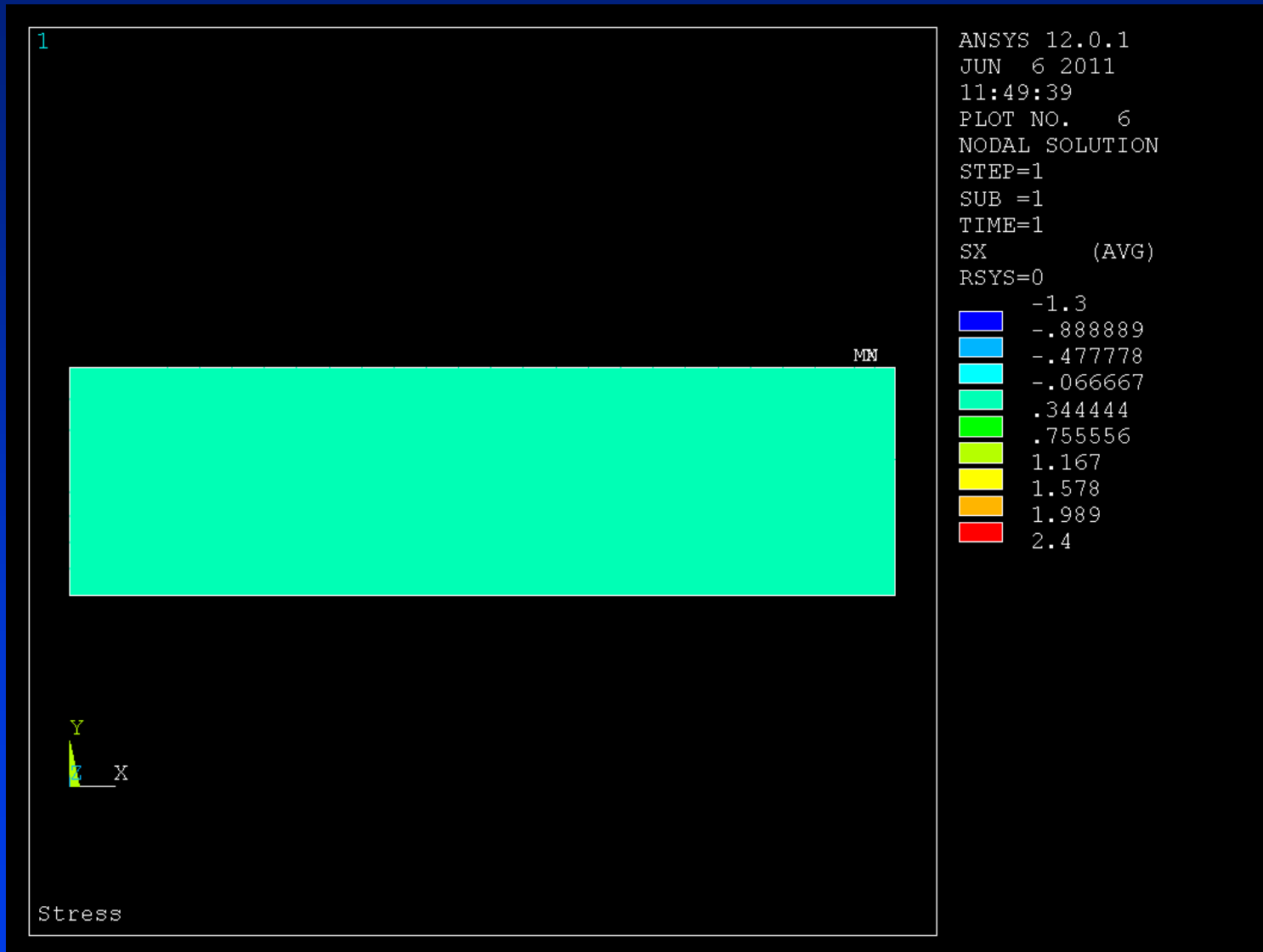
The next step is to use those thermal results to carry out the thermo-mechanical analysis. This step can be quite difficult as the mechanical behaviour of the cell lining is quite complex.

Contrary to the thermal problem, in initial state on the mechanical problem is totally unknown. Some thermo-electro-mechanical models of cell preheating have been reported in the literature, there are also cathode swelling mechanical models available, but no thermo-electric-chemical-mechanical models of the cell in steady state operation have been model to date.

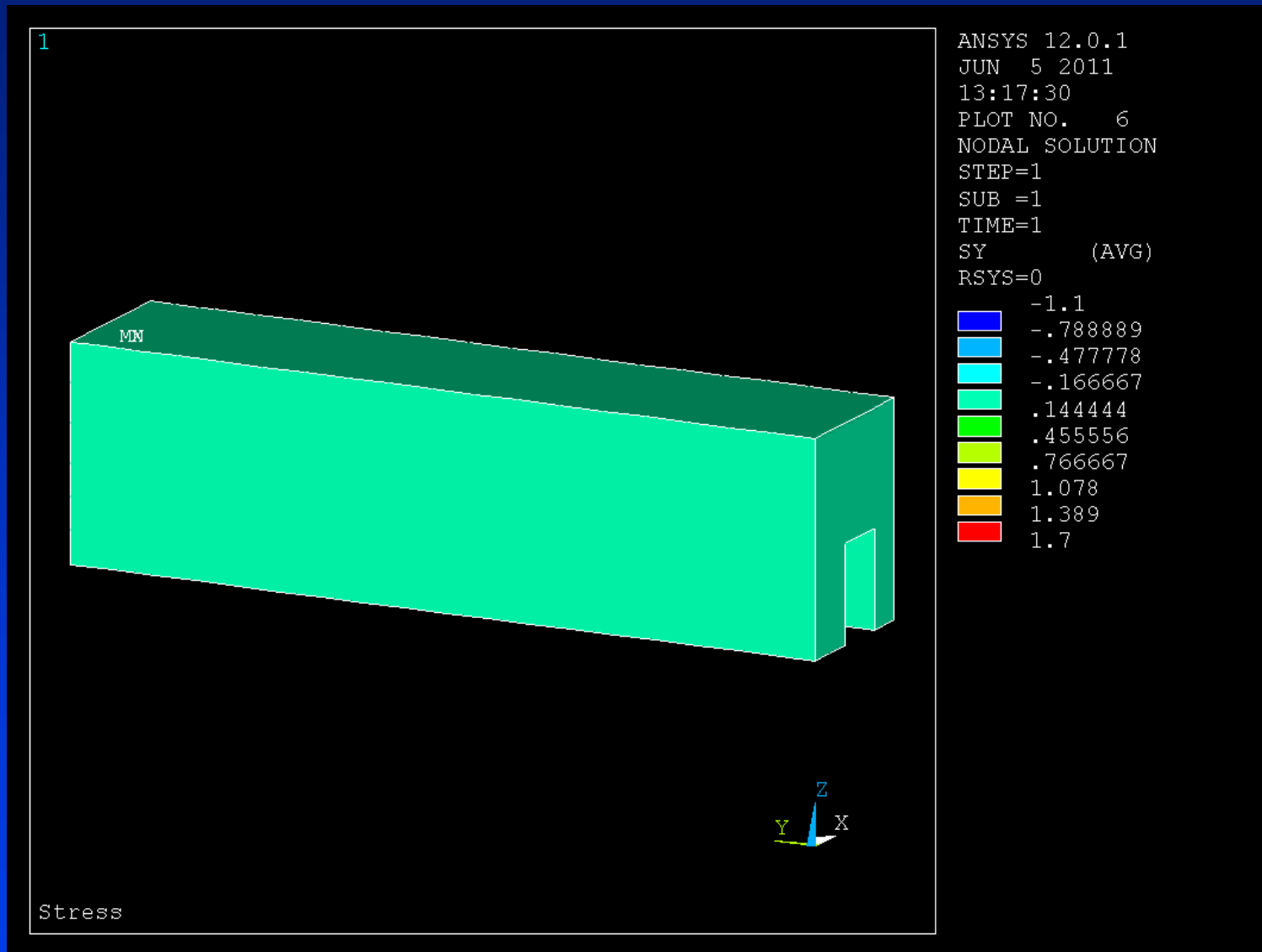
The thermo-mechanical models developed in this work are the simplest possible, they only model the cathode block using elastic mechanical properties to represent the cathode block mechanical behaviour which is a large simplification of the actual problem.

Furthermore, they assume that at time zero, in steady state operating condition, the cathode block is stress free under no mechanical constrains. As cooling proceed, the thermal load that will be use to carry the thermo-mechanical study is the differential temperature between the current thermal condition and the initial steady-state thermal conditions.

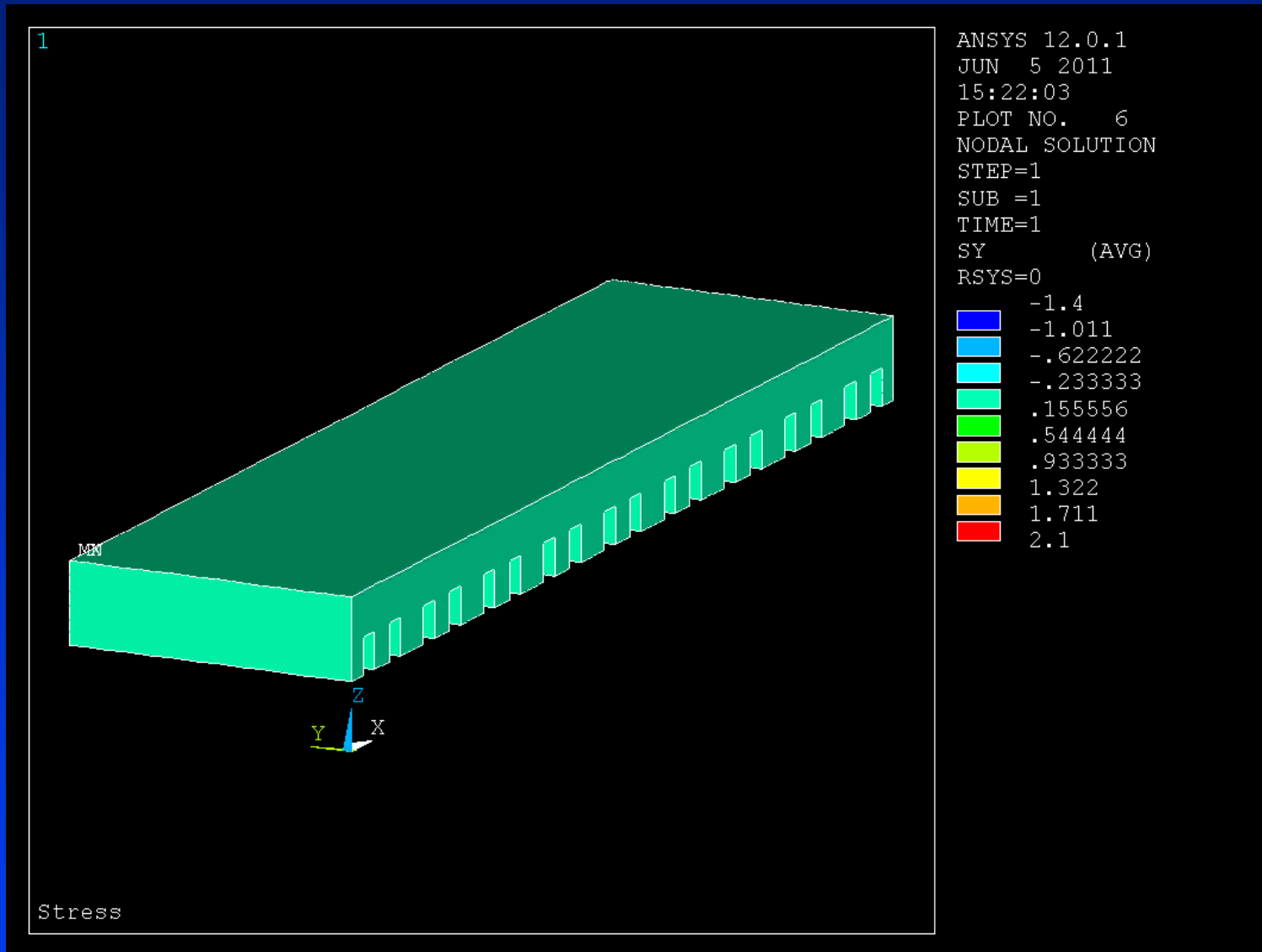
2D Side Slice Model: 20 cm Metal Pad



3D Side Slice Model: 20 cm Metal Pad



3D Quarter Model: 20 cm Metal Pad

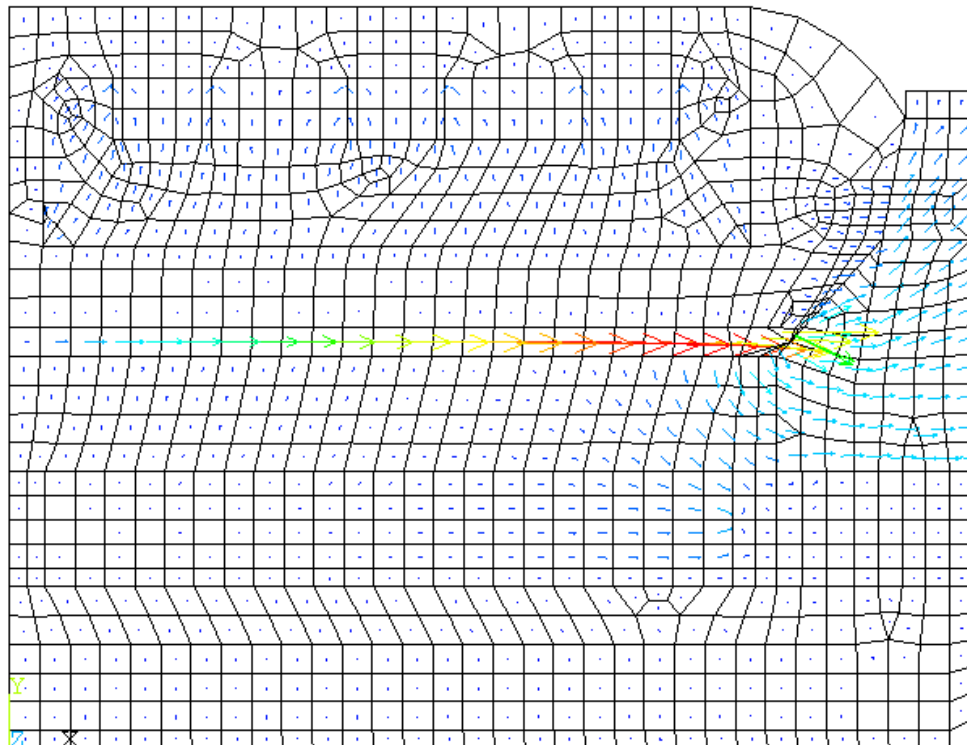


Models Applications

Even if the current thermo-mechanical cooling models are not perfect, they never-the-less constitute useful tools to investigate and identify potential solutions to the cathode block cracking problem due to cell cooling. Since it was clearly indentify that the reversed vertical gradient in the cathode block is generated by the excessive cooling efficiency of the metal pad, the models have been used to investigate the impact of removing 2/3 of the aluminum metal pad at the very beginning of the cell cooling.

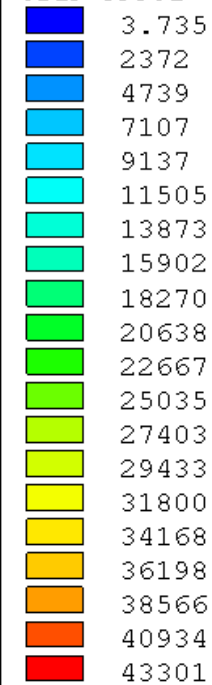
2D Side Slice Model: 7 cm Metal Pad

1



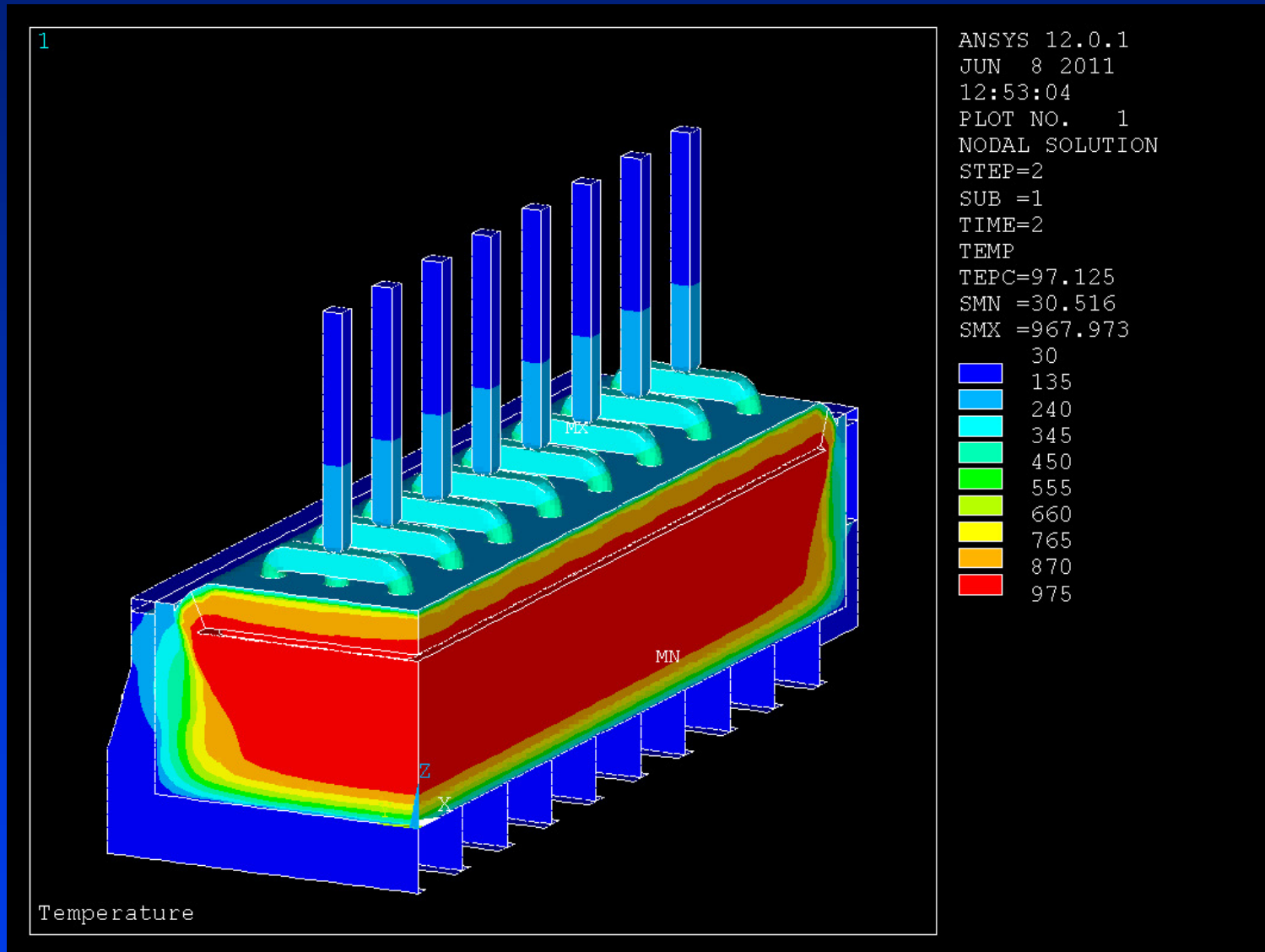
Temperature

ANSYS 12.0.1
MAY 29 2011
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TF
ELEM=1068
MIN=3.735
MAX=43301

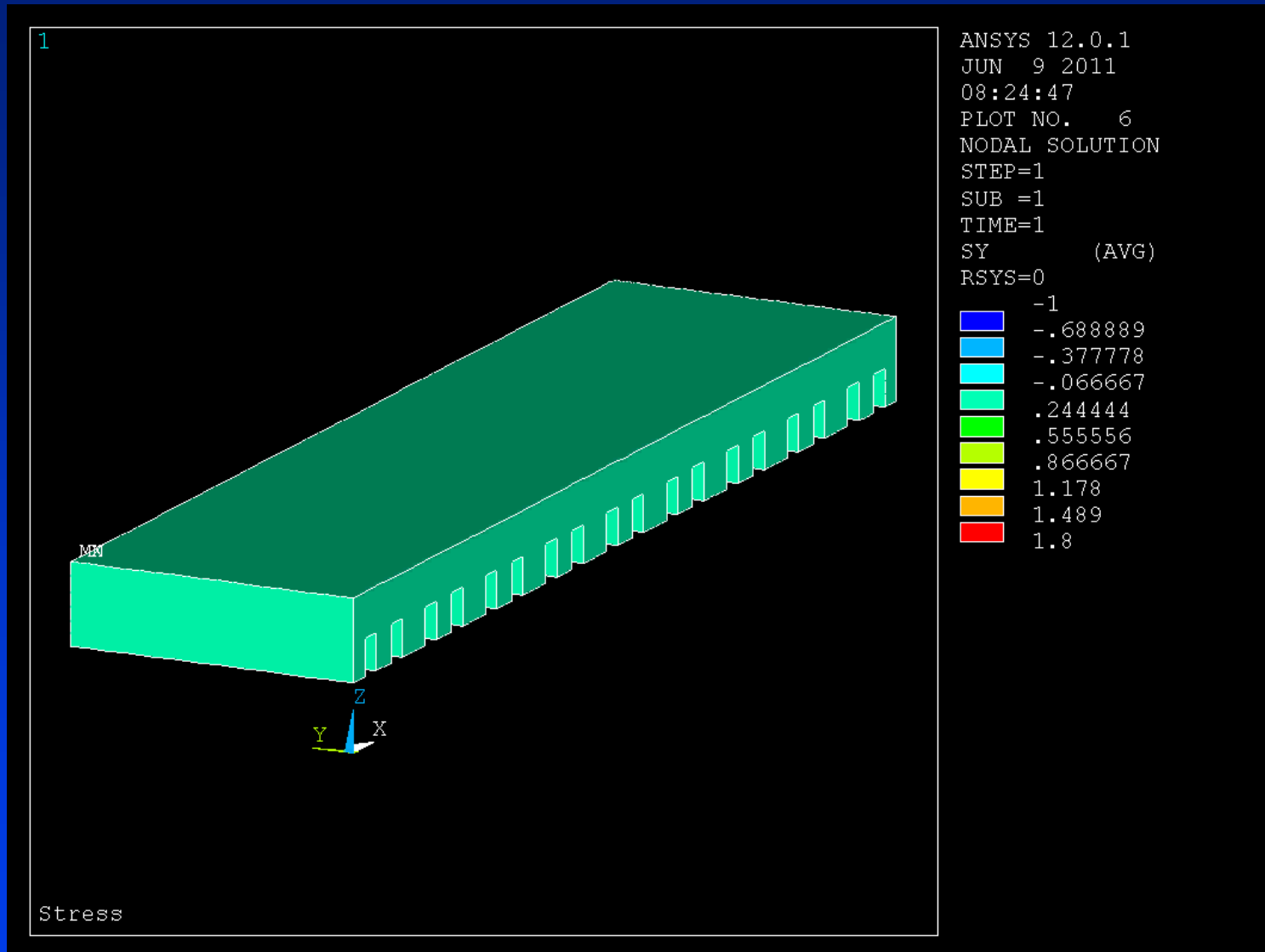


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3D Quarter Model: 7 cm Metal Pad



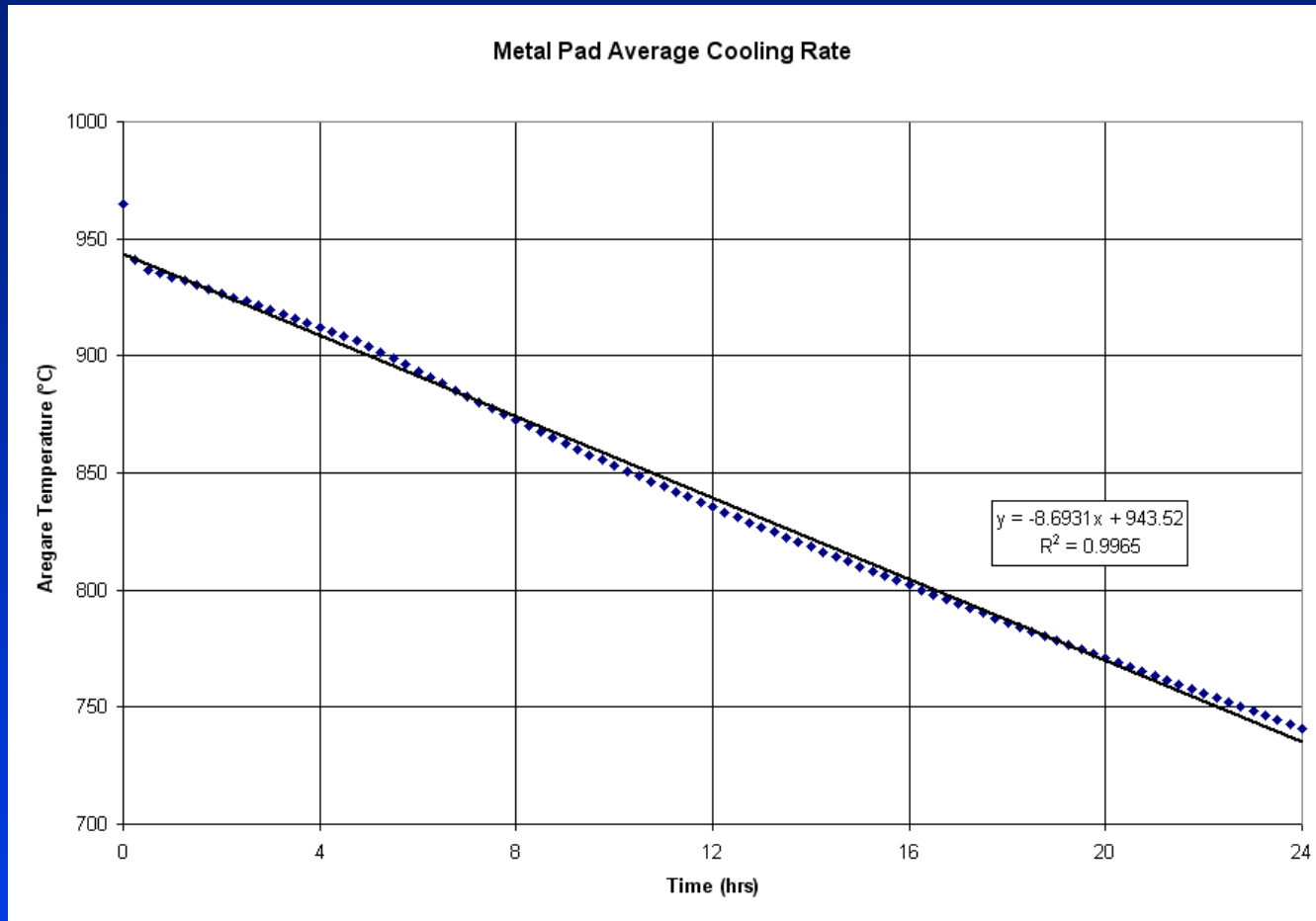
3D Quarter Model: 7 cm Metal Pad



Conclusions Part 1

- New ANSYS® based thermal cooling models, (2D+ full cell slice model, 3D full side slice model and a 3D full cell quarter) were developed to determine the cathode cooling rates, the differences in the temperature gradients and the resultant stress from cooling cathodes for 24 to 48 hours.
- Those thermal results have been used to carry out the thermo-mechanical analysis.
- The thermo-mechanical models developed in this work are the simplest possible, they only model the cathode block using elastic mechanical properties to represent the cathode block mechanical behaviour which is a large simplification of the actual problem.
- They also assume that at time zero, in steady state operating condition, the cathode block is stress free under no mechanical constrains. As cooling proceed, the thermal load that will be use to carry the thermo-mechanical study is the differential temperature between the current thermal condition and the initial steady-state thermal conditions.
- Since it was clearly indentify that the reversed vertical gradient in the cathode block is generated by the excessive cooling efficiency of the metal pad, the models have been used to investigate the impact of removing 2/3 of the aluminum metal pad at the very beginning of the cell cooling.

Average Metal Pad Cooling Rate



Average metal pad cooling rate obtained from a cell design using SiC side blocks operated at a higher current density and corresponding higher superheat prior to the shutdown.

Average Metal Pad Cooling Rate

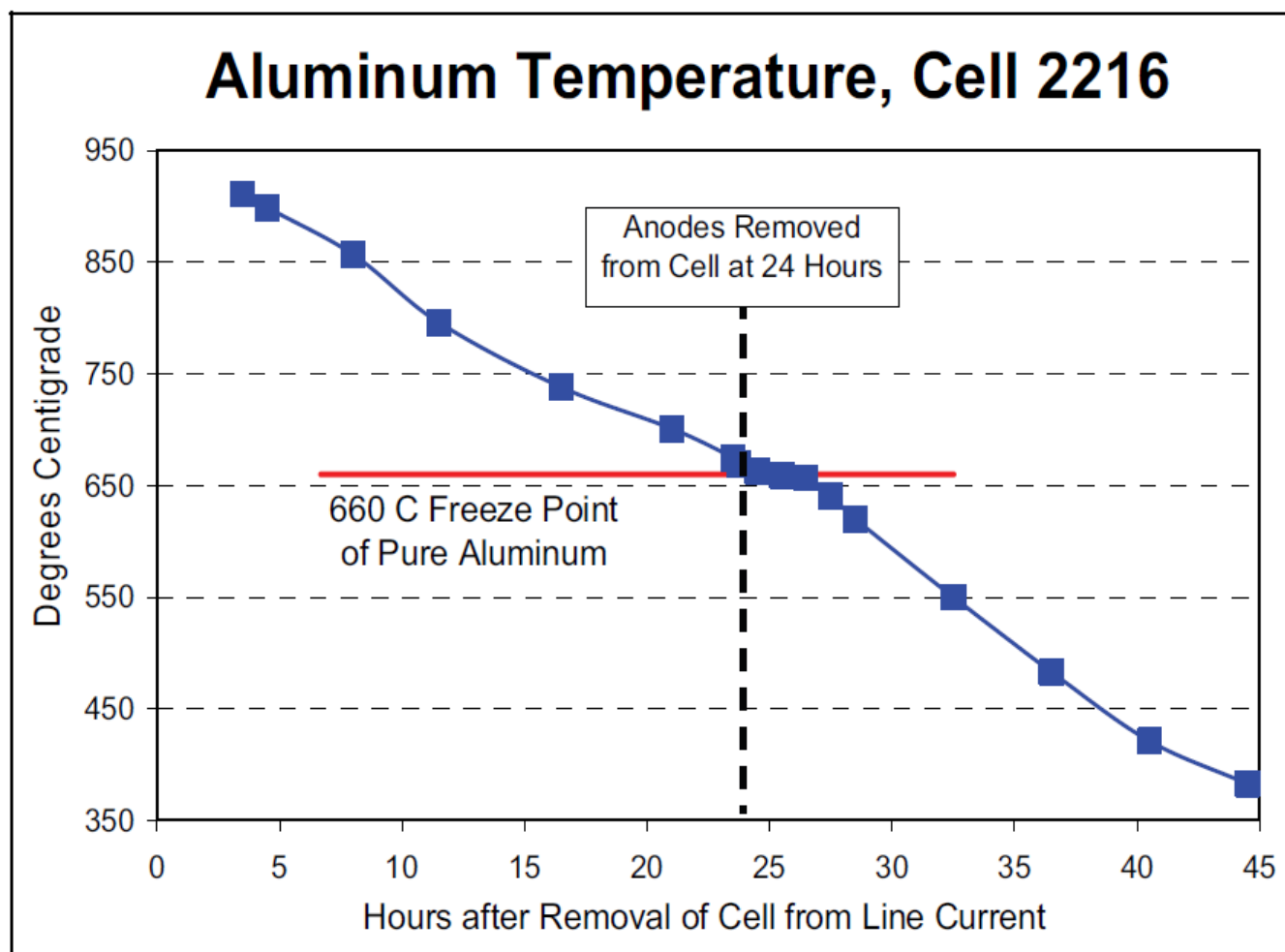
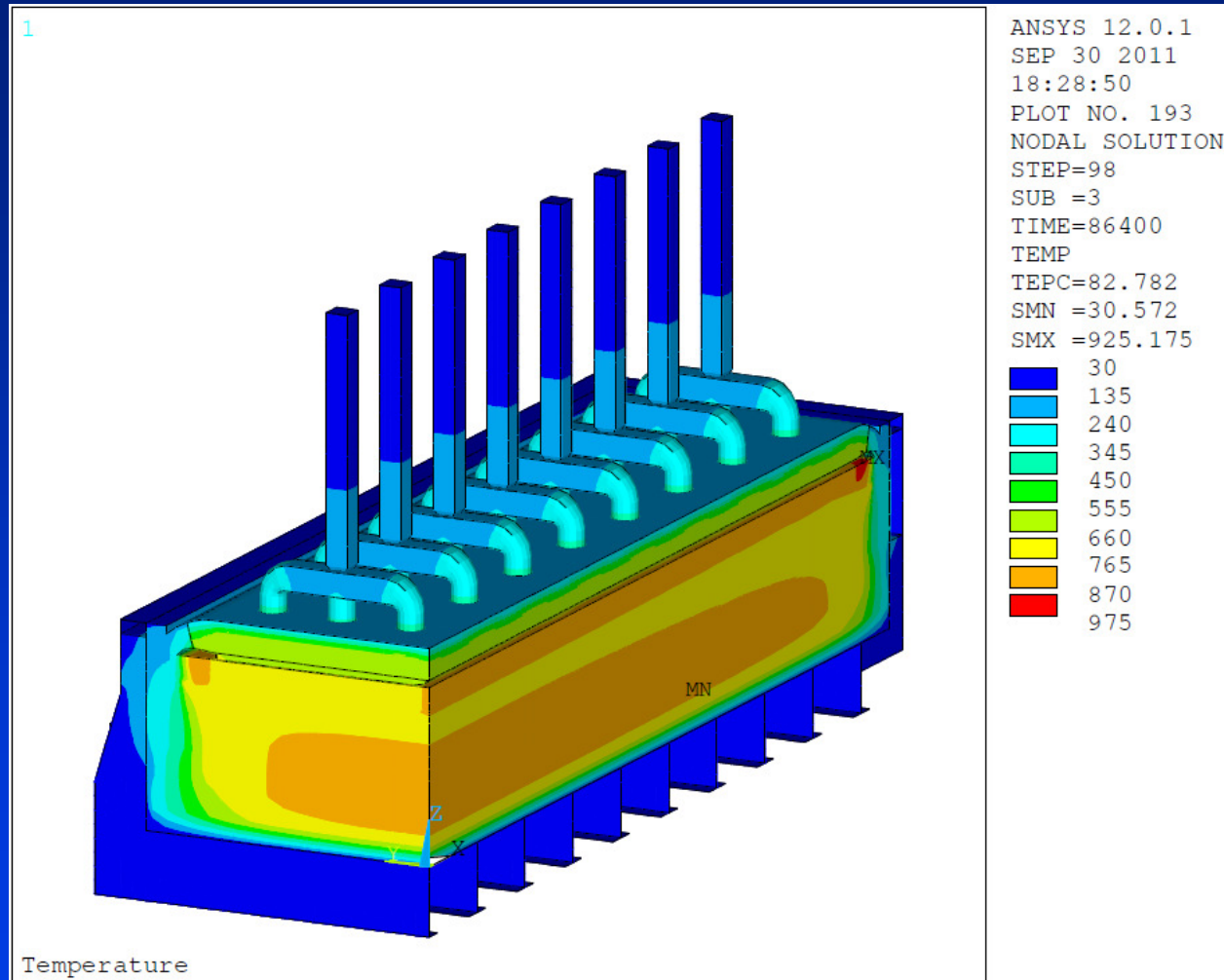


Figure 7. Aluminum temperatures for Cell 2216 after cell was removed from line current.

Measured cooling rate results extracted from Alcoa 2006 TMS paper:

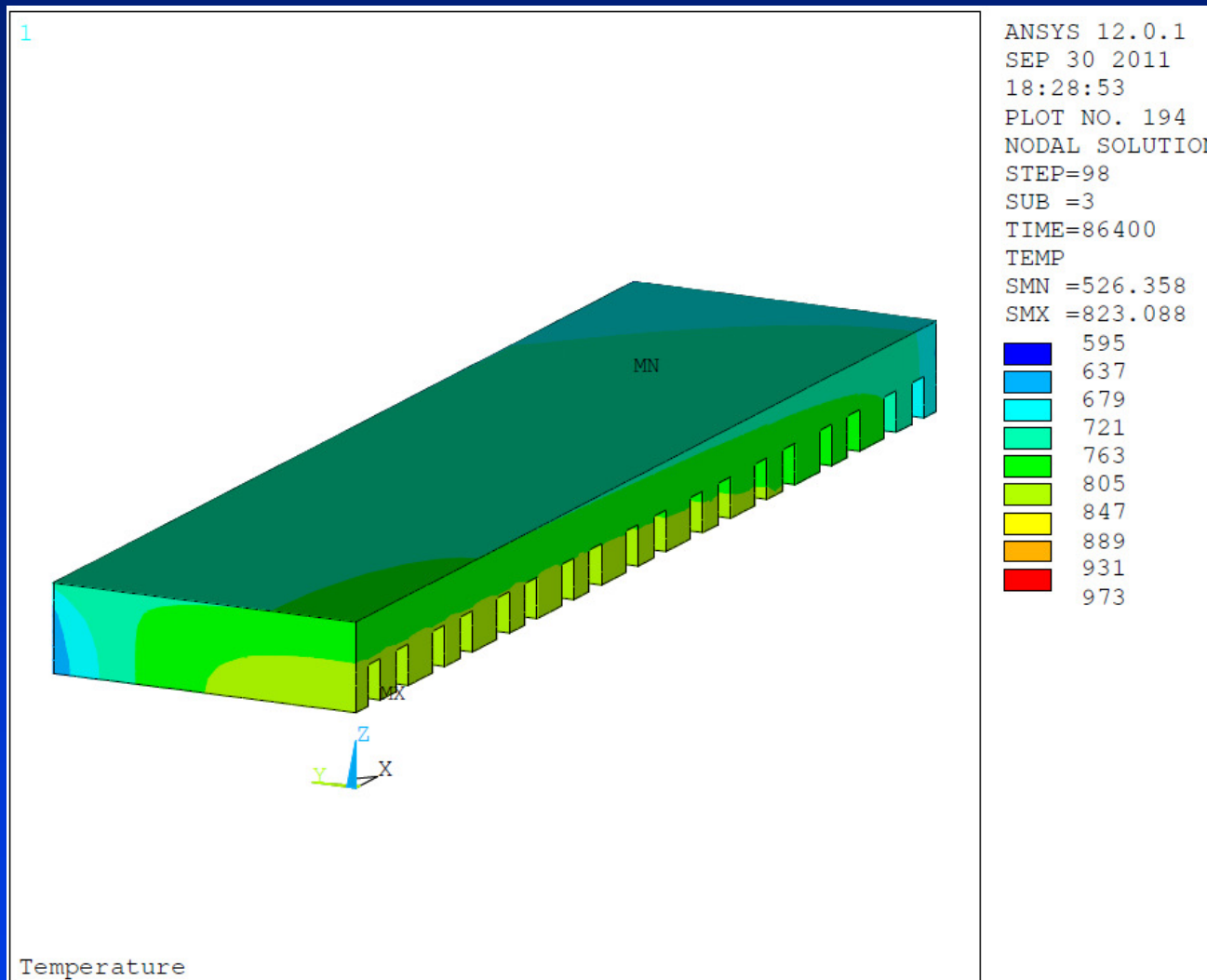
$$(950-650)/24=$$
$$12.5 \text{ } ^\circ \text{C/hour}$$

Thermal Modeling Results



Cell temperature obtained after 24 hours of cooling from the full quarter cell model

Thermal Modeling Results: Cathode Cooling



Cathode panel temperature, it can be noticed that the temperature on the cathode panel surface is lower than the one directly below at the collector bars level

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Thermo-Mechanical Modeling

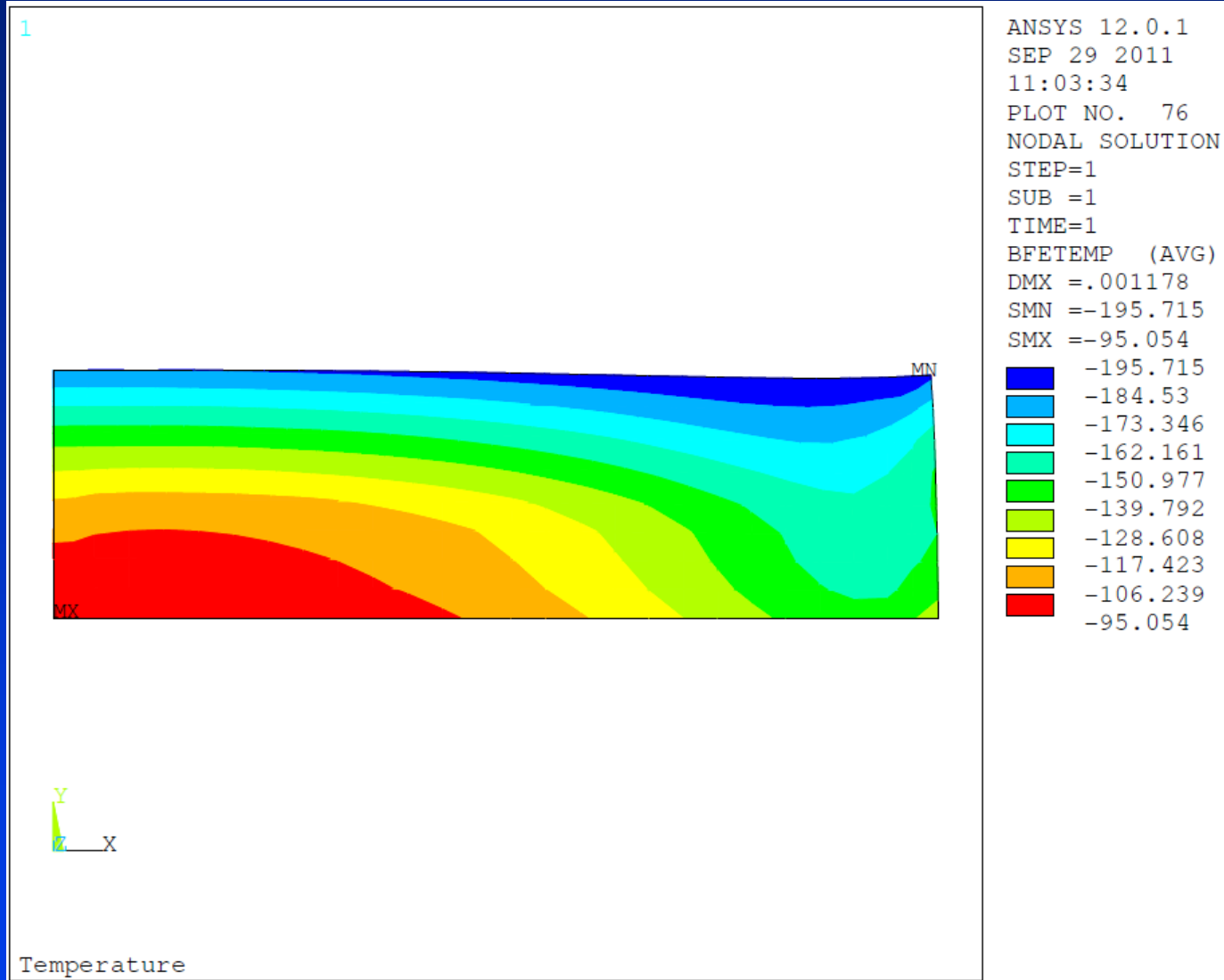
A level of tension stress of at least 8 MPa in the longitudinal direction of the cell is required to generate those cracks.

It was not possible to obtain that level of longitudinal tension stress in the previous study presented in our TMS 2012 paper.

In that previous study, the cathode panel was prevented to deflect down but was free to contract in both horizontal directions. By using this limited type of displacement constraints, the level of tension stress obtained was only around 2 MPa or about 4 times less than what is required to generate cooling cracks.

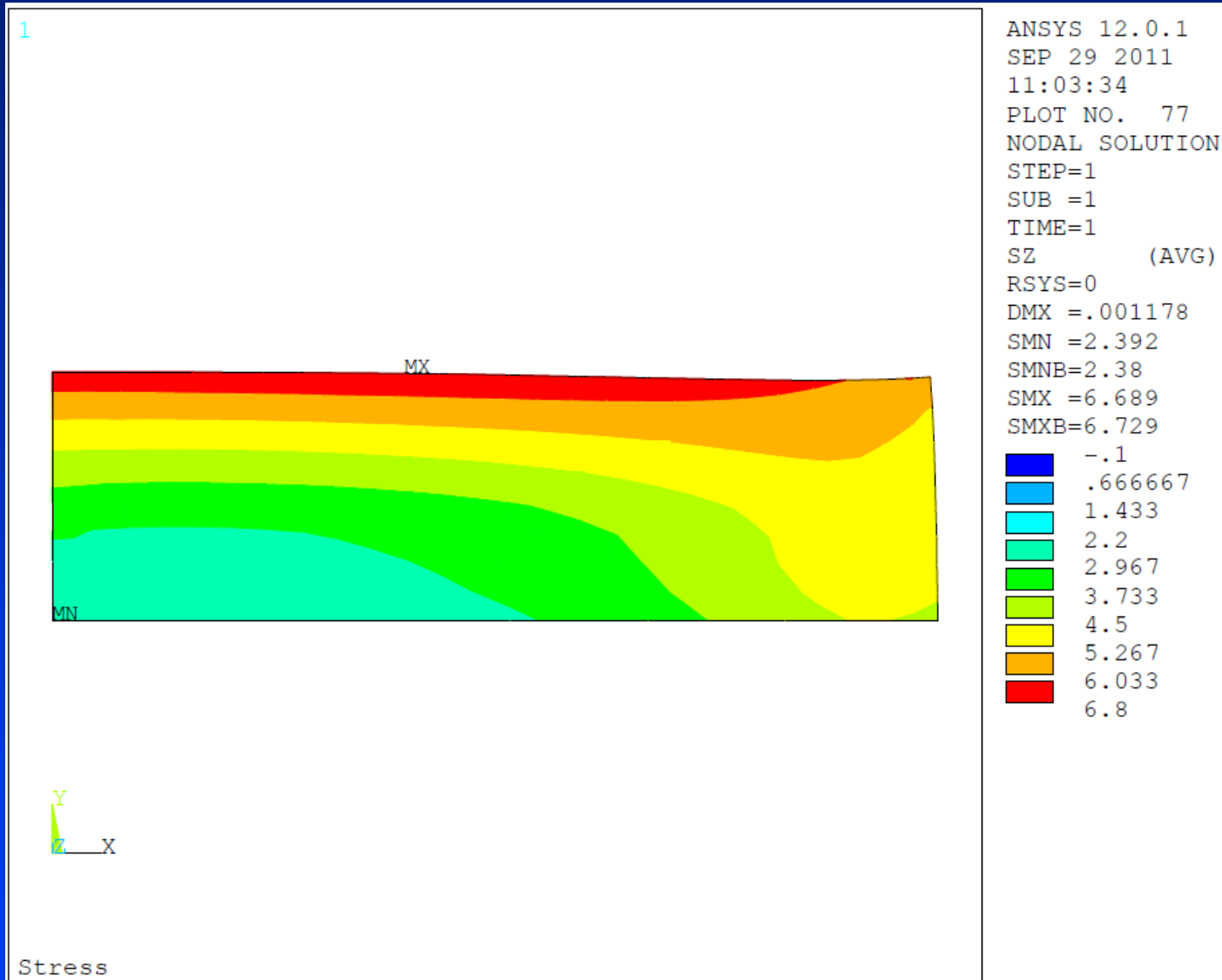
Yet, already in that previous study, the level of longitudinal tension stress obtained by solving the 2D thermal stress model in plain strain mode was sufficient to generate cooling cracks.

Thermo-Mechanical Modeling



Relative thermal gradient in the cathode block after 24 hours of cooling from the 2D model

Thermo-Mechanical Modeling



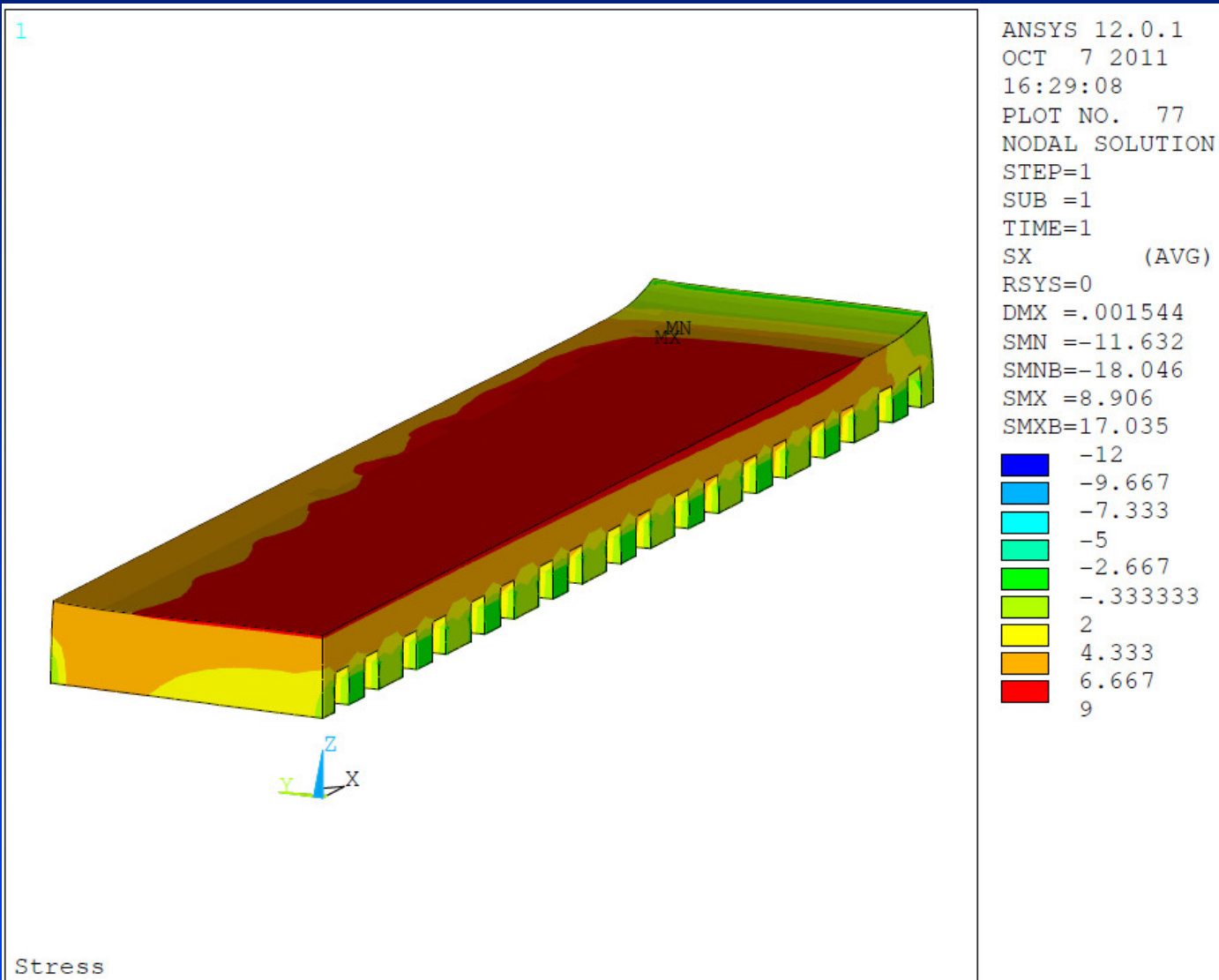
Longitudinal stress component in the cathode block after 24 of cooling from the 2D model in plain strain mode

Thermo-Mechanical Modeling

When assuming plain strain, the 2D model do predict longitudinal tension stress level high enough to expect cracking problems as it did in the initial study, but those results were then considered unrealistic as they are based on the assumption that the cathode is restrained from shrinking longitudinally.

After discussing the issue with Dr. Morten Sorlie the authors reconsidered the situation, according to Dr. Sorlie, the collector bars who are anchor by the pier are restraining the cathode panel to shrink freely in the longitudinal direction.

Thermo-Mechanical Modeling



Longitudinal stress component obtained using the 3D quarter cathode panel model assuming that the collector bars are preventing the vertical carbon faces in the slots to move longitudinally

Looking to a cure to the cathode cooling cracks problem

So with this type of motion restrains, there is enough longitudinal tension stress to generate transverse cracks so it is safe to assume that as Dr. Sorlie is proposing, collector bars do prevent the cathode panel to move freely in the longitudinal direction of the cell.

It was suggested that since it is the metal pad that is responsible for the generating of the reversed vertical gradient in the cathode blocks, tapping the metal pad as quickly as possible after the power shutdown should reduce the risk of cooling cracks formation.

Looking to a cure to the cathode cooling cracks problem

This conclusion was based on the assumption that the tension stress and the corresponding cooling cracks are generated to compensate for the fact that the cathode panel is not free to bend down. Under that assumption reducing the intensity of the reversed vertical thermal gradient did significantly reduced the intensity of the top surface tension stress. Yet that intensity was already 4 times less than required to produce cooling cracks!

Looking to a cure to the cathode cooling cracks problem

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The obvious cure the cooling cracks problem have already been indentify in the initial study presented at TMS 2012, the cell lining design needs to be modify in order to prevent the collector bars to be anchored in the pier region.

Conclusions Part 2

- It was demonstrated that it is possible to explain the cooling cracks formation by modeling.
- The cooling cracks formation can only be explained by the fact that the cathode panel as a whole want to shrink but the collector bars are preventing it to do so.
- The fact that the metal pad is cooling faster the top section of the cathode panel is compounding the problem but is not the main factor.
- Only a cell lining design change can be expected to provide a cure. The aim of the cell lining design change being to prevent the pier to rigidly anchoring the collector bars.