Modeling Cathode Cooling Due to Power Interruption

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Abstract

Extended electrical power interruptions often result in the shutdown and restart of aluminum cells in potlines. Cooling cells to ambient temperature causes irreversible and non-repairable damage to the carbon cathode lining, and ultimately causes the formation of numerous, often deep, cooling cracks on the surface of cathode blocks and in the seams between blocks and ultimately shorten potlife. It had been proposed that these cracks are caused because the strain setup by thermal gradients in the cooling cathode lining exceeds the strain capacity of the cathode, but heretofore there has been no supporting evidence to support this hypothesis.

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. The results indicate significant temperature gradients and corresponding stress develop during cooling to cause cracking of the cathode blocks. Reducing the aluminum metal level in cells during cooling was found to reduce the level of stress and thus reduce, if not eliminate the cathode surface cracks.

Introduction

During the past ten years, the shutdown and restart of aluminum potlines due to power interruptions have become all too frequent events in the aluminum industry. Ten major power interruptions at aluminum smelters were reported during the past ten years. [Reference 1] The majority of smelters that had long-duration, (>3 hours) power interruptions because of the transformer/rectifier failures were built 20 to 40 years ago. Harsh weather conditions such as ice storms, snow and high wind velocity are also a major factor in causing long-duration power interruptions. A somewhat surprising development is that some new modern high-amperage smelters have recently experienced long-duration power interruptions that resulted in the shutdown of potlines due to the temporary loss of power at their power generation stations and/or national grid system.

Cell Cooling

Cooling occurs in all cells in the potline when the amperage is significantly reduced or power is interrupted. 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. Astonishingly, some potlines have been reported to have survived power interruptions up to 8 hours.

Modern cells lose heat at a faster rate when power interruptions occur in potlines and thus are at a high risk compared with older cell technologies. Modern cells are deliberately designed to achieve a high heat loss by; enhanced cooling of the steel cathode shell using fins, fans and forced air cooling; increased duct evacuation velocity; larger anodes, larger cross-section collector bars and diameter steel stubs in anodes.

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 width of observed cooling cracks observed is from 1.6 to 3 mm; they often extend the length of the cathode blocks, ~300 cm. The distances between cooling cracks vary widely, but are typically found to occur about two cathode blocks apart.

The Fracture Behavior of Carbon

The thermo-electro-mechanical behavior of new cathode carbon has been described as elastoplastic. [Reference 2] 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. Microcracks can be generated during the calcinations and graphitization of cathode carbon materials. During loading the microcracks are gradually closed with volume contraction. Thereafter, when stresses become high, macrocracks are initiated in the material and begin to propagate until failure 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. Additionally cathode blocks are significantly weakened by micro-cracking caused by the diffusion of sodium into the carbon lattice.

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. Sørlie and Øye, [Reference 3] 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."

Once a cathode has developed cracks, gaps, etc. there is no known method to repair the damage. The rapid cooling of cells to 25°C due to power interruptions results in irreversible and non-repairable damage to cathodes. 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.

Thermal Cooling Modeling

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.

Modeling of the cell cooling after power interruption is not different from modeling cell preheating. [Reference 4] For example, the GeniSim's demo cell geometry used in cathode preheat models, was used to develop the thermal cooling models. The demo cell geometry was taken from a previous thermal modeling work. [References 5 and 6] It is a relatively modern cell design concept, but is obviously lacking the most recent innovations in cell design:

1) It uses 30% graphitic cathode block rather that 100% graphitized cathode block.
2) It uses 30% graphitic side blocks rather than graphite or silicon carbide sidewall blocks
3) It does not use cooling fins or compressed air cooling.

The initial conditions of the cooling models are those obtained by the steady-state thermo-electric models. [References 5 and 7] The prebake cell is operating at 300 kA and 0.73 A/cm^2 of anode current density. The cell is dissipating 610 kW while operating with a 6° 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

By adding the liquid zone, it is no longer possible to control the heat transfer between the liquid and the solid zones at the ledge profile surface. This is not desirable but in the case of a cooling model, unavoidable.

Effective Thermal Conductivity of the Liquid Metal

The key characteristic of the cooling of a cell is that the top section of the cathode block is cooling faster than the bottom section. This is explained by the fact that there is very little thermal resistance between the metal pad and the side ledge and that the liquid metal is a very good heat conductor even when it is motionless. Yet, during the cooling of the cell, the metal pad is not motionless, as it is put in motion by natural convection force that further enhances its effective thermal conductivity.

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., [Reference 8] 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 4.9E8:

$$k_{eff} = 0.057 * Ra^{0.296} \qquad (1)$$

2D+ Full Cell Slice Transient Thermal Model

Figure 1 presents the bath cooling cure obtained from the initial steady-state thermal solution of the 2D+ full cell slice model. This type of 2D model effectively represents the thermal effects of the anode rod, yoke and stubs and the cathode collector bars by representing them as extra 1D line elements hence the name 2D+. [Reference 5] From the initial condition, the 2D+ transient thermal (only) cooling model calculates the cooling down of the cell using exactly the same external boundary conditions as the steady-state thermal-electric model, so the initial heat losses are exactly the same as the cell steady-state heat losses. Those heat losses will gradually decrease as the cell temperature gradually decreases. The bath *solidus* was specified to be 930 °C in all the models, so the first bath cooling phase is when the bath is in the gradually freezing mushy zone. The final cooling rate of the bath is 5.5 °C per hour.

The thermal solution of the cathode lining after 24 hours of cooling is shown in Figure 2. It is very important to notice that after 24 hours of cooling, the model predicts that the bottom section of the cathode block will be hotter that the top section.

The reversed vertical thermal gradient in the cathode block are the major features of the results shown in Figure 3. The top surface of the cathode block is already at 822 °C in the middle of the block while the bottom surface directly below is still at 873 °C. This clearly indicates that the top section of the cathode surface is cooling much faster that the bottom section.

This can be easily explained by looking at the thermal flux in the cell after 24 hours of cooling as shown in figure 4. The aluminum metal pad is channeling the heat coming from the top of the cathode blocks and of the bottom of the bath out through the side walls as it is the less resistive path for the heat to escape out of the cell. Note that the cooling model is not predicting that the ledge at the metal level will get thicker.

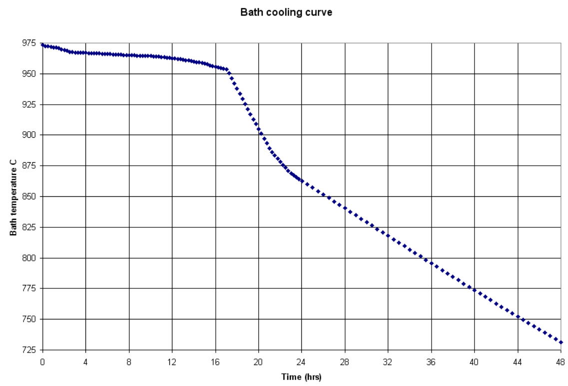

Figure 1: Bath cooling curve

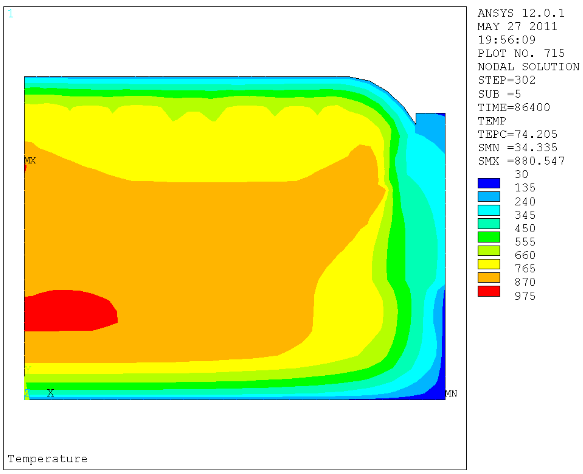

Figure 2. 2D full slice temperature profile after 24 hours of cooling.

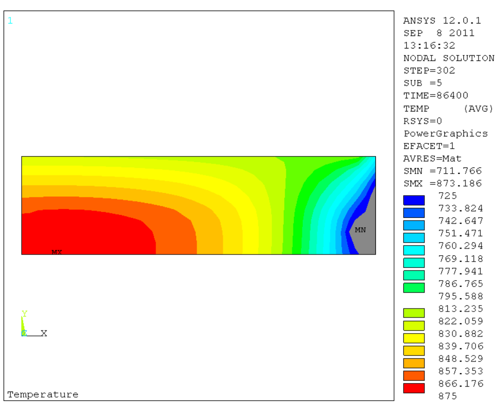

Figure 3. 2D temperature of the cathode block after 24 hours of cooling.

Because it is only a 2D+ model, the calculations ran relatively fast, a 64 bits dual core Intel Centrino T9300 Dell Precision M6300 portable computer running ANSYS® 12.0 version took only 20 minutes elapse time to solve for 48 hours of cooling using a 1 minute time step.

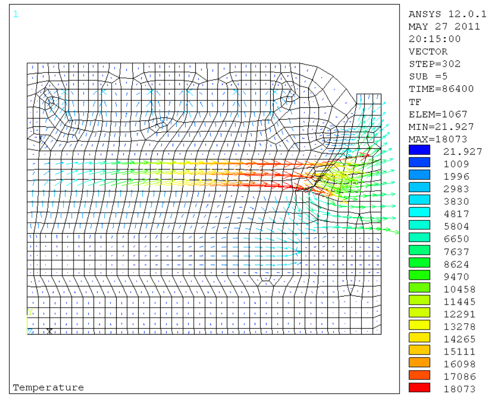

Figure 4. Thermal flux in the cell after 24 hours of cooling.

3D Full Cell Slice Transient Thermal Model

2D+ models are excellent tools to quickly test new modeling approach or new design proposal, but they also have serious geometric limitations. For example, is it obvious that it is only possible to use the obtained thermal results to run a 2D thermal stress analysis which are presented later in this article.

The next level of complexity after the 2D+ full-slice of a cell is the 3D full-slice of a cell. The thermal solution for the 3D full-slice of a cell is shown in Figure 5 after 24 hours of cooling. The cooling characteristic for the anode rod, anode yoke and stubs and the cathode collector bar are better represented in such a model compared with 2D+ thermal models. In addition the cooling effect of the welded cradle is accounted for in the 3D thermal model. As a result the cell is predicted to cool a little faster with this type of model.

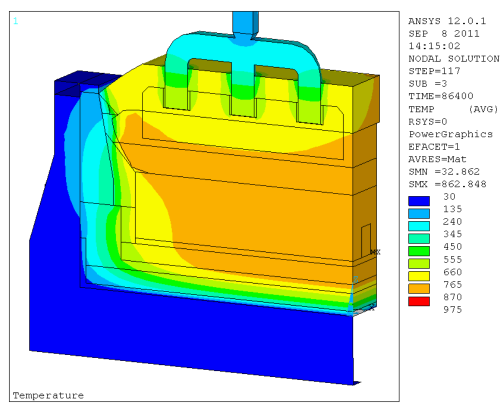

Figure 5. 3D full-slice of a cell temperature profile after 24 hours of cooling.

The drawback for the extra accuracy obtained in 3D thermal models is that the turn-around time increases due to the time required for each step size in the model calculations. Because the cell cooling rate is relatively slow a 5 minutes time step size was used to solve the transient 3D slice model and as a result it took only 23.3 minutes wall clock time to model 48 hours of cooling.

The reversed vertical thermal gradient in the cathode block are highlighted again in figure 6. The top surface of the cathode block has decreased to 814 °C, in the middle of the block, while the bottom surface directly below is at 862 °C.

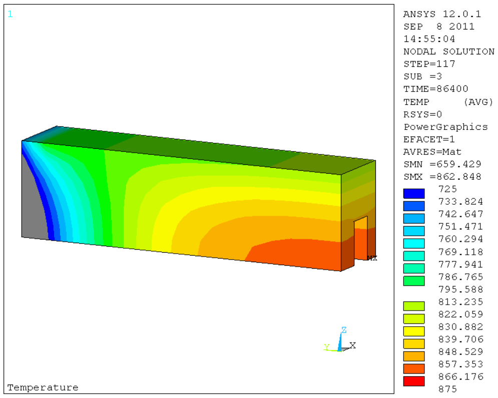

Figure 6: 3D temperature profile of the cathode block after 24 hours of cooling.

<u>3D Full Cell Quarter Transient Thermal Model</u>

It would appear that a 3D full cell slice thermal model provides a lot more information for very little extra turn-around time. Obviously, the 2D+ full cell slice thermal model would run 5 time faster with the same 5 minutes time step that was used with the 3D full cell slice model. But more importantly, a 3D thermal slice model is not that much more useful that a 2D+ thermal model in order to run a thermal stress analysis because there is no set of obvious of mechanical boundary condition that can be apply on the second Y-Z plane. For that reason, there is no substitute for running a full cell quarter thermal model. The thermal solution for a full cell quarter thermal model is shown in Figure 7 after 24 hours of cooling of the cathode lining. It is oblivious that the corner section of the cell cools faster than the center section so globally the 3D full-quarter cell is predicting that the cell is cooling a bit faster than the 3D full cell slice model.

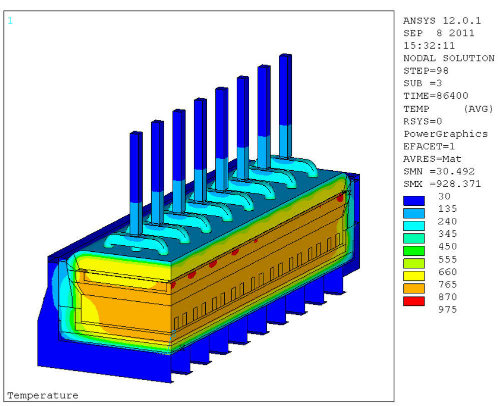

Figure 7. 3D Full-quarter cell temperature profile after 24 hours of cooling.

The thermal solution of only the cathode *panel* is shown in Figure 8. The top surface of the cathode block has decreased to 804 °C, in the middle of the panel, while the bottom surface directly below is at 851 °C. The 3D full-quarter cell model took 7.8 hours wall clock time to model 24 hours of cooling.

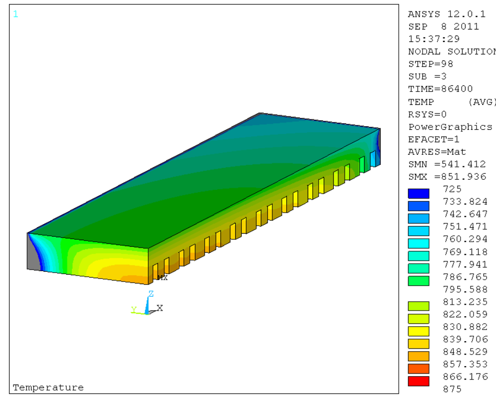

Figure 8: 3D temperature profile of the cathode block panel after 24 hours of cooling.

Thermo-Mechanical Modeling

<u>2D Cathode Block Elastic Thermo-Mechanical Model</u>

Once thermal results have been generated using transient thermal models 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 behavior of the cell lining is quite complex. First, 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. [Reference 9] There are also cathode swelling mechanical models available. [Reference 10] But no thermo-electric-chemical-mechanical models of the cell in steady state operation have been model to date.

The first type of thermo-mechanical model developed in this work is the simplest possible, it is a 2D plain strain elastic thermo-mechanical model. It only models the cathode block in 2D using elastic mechanical properties to represent the cathode block mechanical behavior which is a large simplification of the actual problem.

Furthermore, is assume that 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. The thermal stresses that will be generated will be produced by the non-uniform shrinkage of the cathode block caused by the thermal gradient of that differential temperature in the block.

That thermo-mechanical analysis can be carried out independently using any set of thermal results obtained during the transient thermal analysis. It is possible to proceed this way because, for this simple type of thermo-mechanical analysis, the results are not path dependent. Because the reversed vertical gradients are at the maximum after 24 hours of cooling, the stress results will be presented for that point in time in the cooling process. Figure 10 shows that after 24 hours of cooling, the temperature at the top edge of the cathode block had dropped by 159 °C while it has only dropped by 76 °C at the middle of the bottom section.

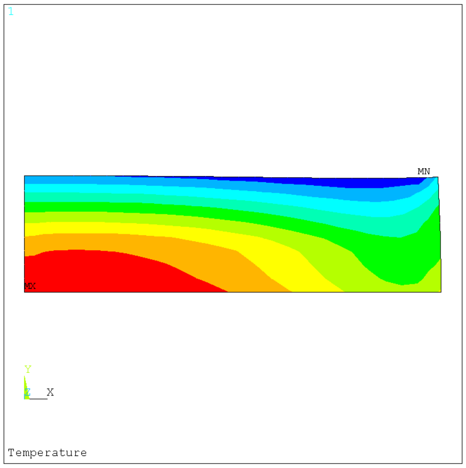

Figure 9. Differential temperature profile of the cathode block after 24 hours of cooling.

Stress in the long direction on the cathode block (which is the X direction for the 2D model) will be presented. Positive number indicate tension while negative values indicate compression. Cathode block will crack under tension and as we can see in figure 10, the top block section is indeed predicted to be under 2.3 MPa of tension stress.

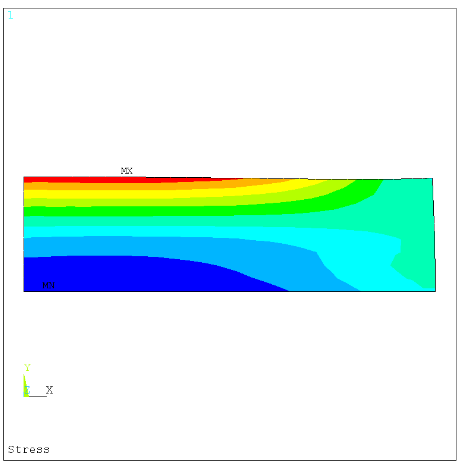

Figure 10. Thermal stress in the cathode block after 24 hours of cooling.

3D Cathode Block Elastic Thermo-Mechanical Model

The 3D cathode block thermo-mechanical model uses the geometry and the thermal results of the 3D full cell side-slice thermal model. This type of mechanical model presents a problem on mechanical boundary condition on the second Y-Z plane (notice that the Y direction is the long direction of the cathode block in the case of the 3D models, the Z direction is the vertical direction). A repetitive symmetric boundary condition was used which assumes that the cell is infinitively long.

So again for the type of mechanical model looking at the predicted stress in the long direction of the cell (width of the cathode block) is not realistic due to the inaccurate boundary condition. Stress in the long direction of the cathode block after 24 hours of cooling are presented in figure 11, they are quite similar to the one obtained with the 2D model with the prediction of 2.1 MPa of tension stress at the middle top section of the cathode block.

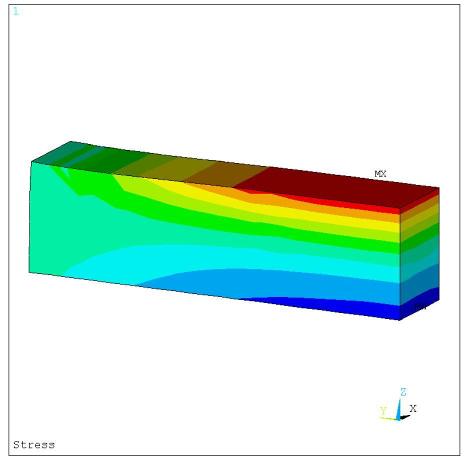

Figure 11. Thermal stress in the cathode block after 24 hours of cooling.

3D Quarter Cathode Panel Elastic Thermo-Mechanical Model

The 3D quarter cathode panel thermo-mechanical model is the only type of mechanical model that can produce reliable stress prediction in the long direction of the cell (X direction in the 3D models) which is the direction that is responsible to creating cracks that will run along the long direction of the cathode block.

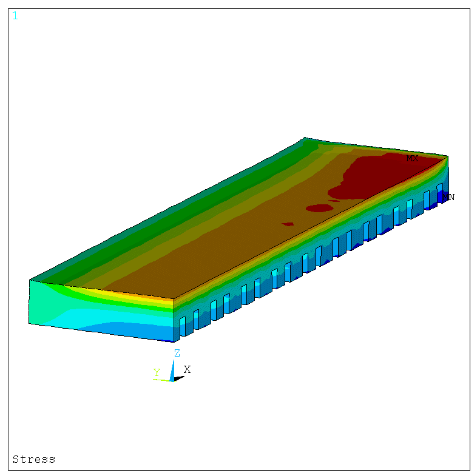

Figure 12: Thermal Y stress in the cathode panel after 24 hours of cooling.

The mechanical stress in the Y direction is shown in Figure 12 for comparison purposes with the 2 previous type of models and in the X direction in the figure 13. The tension stress in the Y direction increases up to 2.2 MPa in the middle top section of the cathode panel, close to the end wall. The increase in the tension stress in the X direction is only up to 1.5 MPa in the middle of the first cathode block close to the end wall. Thereafter there is a local maximum at the middle of each cathode block in the cathode lining.

Thus the current model cannot explain why the most common cracks are running along the long direction of the cathode block rather than along the long direction of the cell as it is predicts the reversed. There are many possible explanations for these results. One of them is that the current model does not considering the small joint between block to have the exact same thermal and mechanical properties as the cathode blocks; this is potentially an over simplification.

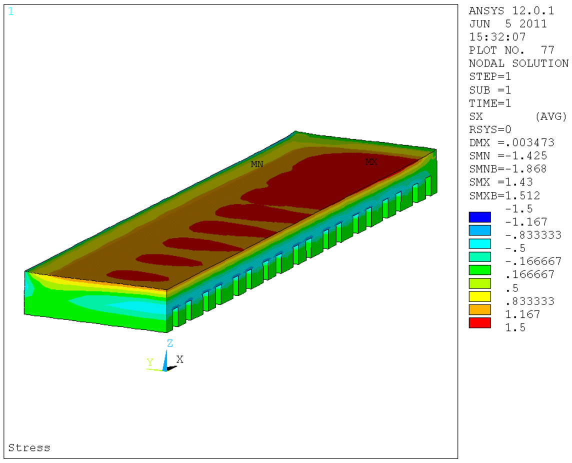

Figure 13: Thermal X stress in the cathode panel after 24 hours of cooling.

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.

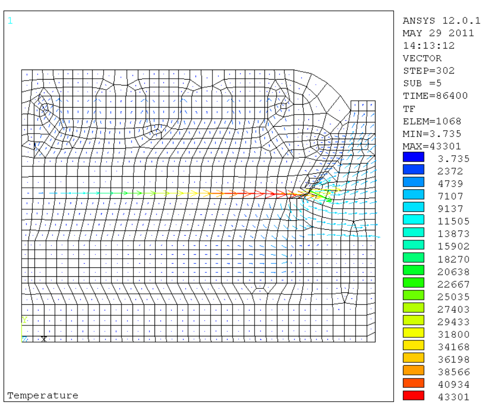

Figure 14: Thermal flux in the cell after 24 hours of cooling with 3/3 metal removed.

The thermal flux is shown Figure 14 when 2/3 of the metal pad is removed at the very beginning of the cell cooling. The resulting tension stress is shown in Figure 15 in the X direction after 24 hours of cooling. The intensity of the tension stress is reduced by 1/3 to about 1.1 MPa. Reducing thickness of the metal pad thickness even more would continue to help reducing the risk of getting cooling cracks on the cathode surface, but there is obviously a practical limit a how much metal can be tapped out of cells.

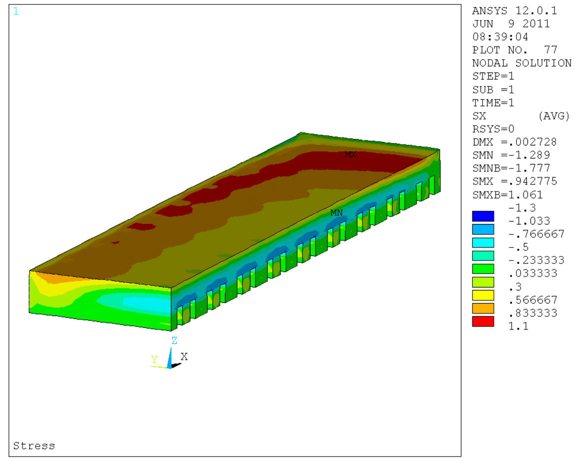

Figure 15: Thermal X stress in the cathode panel after 24 hours of cooling with 2/3 metal removed.

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