EVALUATION OF THERMAL STRESSES DUE TO COKE PREHEAT OF A HALL-HÉROULT CELL

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ABSTRACT

A transient heat transfer model of a Hall-Héroult cell is developed to predict the temperature profile due to coke preheat and evaluate the resulting thermal stresses in the cathode. The impact of changing the coke bed profile, modifying the anode shadow, changing the cathode block geometry and changing the mechanical properties of the mix around the cathode panel is evaluated.

The ANSYS Parametric Design Language is used extensively to develop a parametric model geometry and write custom macros for creating material property libraries, defining boundary conditions, optimizing the time step in the transient solution and generating output reports. Nonlinear material properties and convection/radiation boundary conditions are considered. Also, gap elements are used to define the interaction between the cathode panel and the surrounding materials.

INTRODUCTION

Aluminum is produced from alumina ($A1_2O_3$) by reduction, a chemical term meaning the removal of oxygen. The process takes place in electrolytic cells known as pots. The cathode of a typical Hall-Héroult cell consists of several prebaked carbon blocks surrounded by a ramming mix and various insulation materials. The whole assembly sits in a steel shell supported on cradles and serves as a containment vessel for the liquid metal and electrolyte. The anode part consists of prebaked rectangular carbon anodes immersed in the electrolyte and suspended from an anode busbar. Electrical current passing from the anode through the electrolyte to the metal pad reduces the alumina molecules into aluminum and oxygen. The oxygen reacts with the anode carbon to form carbon dioxide. The aluminum, being heavier than the electrolyte settles to the bottom of the pot.

Several methods are used to preheat a cell to the operating temperature. They include direct resistance preheating using a coke bed with full or shunted line current, liquid bath, liquid metal or indirect heating using flame burners or removable electric panels. Regardless of the procedure used, it is important to bring the cell to the operating temperature as soon as possible without introducing detrimental thermal gradients in the structure. The procedure is a delicate balance between the economic cost of the preheat and loss of metal production versus future savings resulting from extended potlife [1].

Early cathode failures can occur during preheat due to large thermal gradients. Failure may also occur shortly after the addition of bath and metal in part due to the high stresses introduced during the preheat. The cost of relining a cell and the cost of loss of production can be considerable so that a good understanding of the stresses in the lining during preheat is desirable.

This paper describes the use of the ANSYS finite element program to study the thermal gradients in the lining during a coke preheat and evaluate the corresponding stress distribution. A transient heat transfer model is created to calculate the temperature distribution during a 36 hours preheat. Several geometry changes to the cathode and anodes as well as the coke bed and operating parameters are evaluated. The model is validated by comparing the model results to measurements taken during preheat of several operating cells. The stresses in the carbon blocks due to the temperature profile predicted in the transient analysis are calculated using several models. The following sections describe in detail the various models used.

HEAT TRANSFER MODEL

The heat source during direct resistance preheating using a coke bed is the joule heat from the electric resistance of the cell. The preheat process consists of placing a layer of coke on the surface of the cathode and lowering the anode to sit on it under its own weight (see Figure 1). The cell amperage is increased at discrete time intervals using shunts. This is accompanied by a reduction in the cell voltage drop as a result of the burning of the coke.

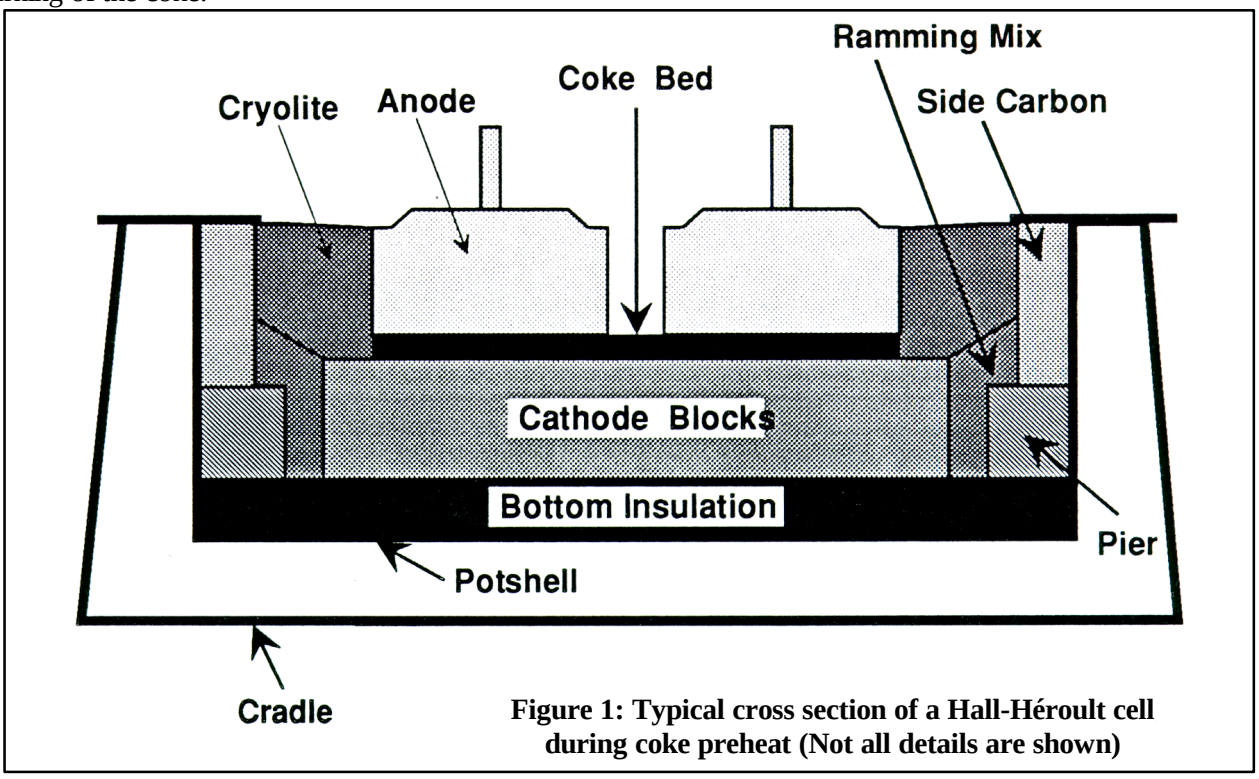

Figure 1: Typical cross section of a Hall-Héroult cell during coke preheat (Not all details are shown)

Model Characteristics

The maximum temperature of the cathode at the end of the preheat is around 900 °C. It varies with the duration of the preheat, the shape and size of the coke bed, the cell amperage and shunting schedule, the overall thermal and electrical resistance of the cell, and the heat loss by convection and radiation to the surrounding environment.

The development of a transient heat transfer finite element model to accurately predict the temperature of the cathode required that the factors mentioned previously be considered. The following features were built into the model to achieve an adequate level of accuracy:

- ***The geometry and layout of the various materials was accurately represented.*** The bottom insulation (see Figure 1) and the pier consist of several layers of different types of refractory brick. The cathode blocks include the carbon, steel collector bars and the rodding around them. Similarly, the anodes include the carbon, steel studs and spreader beam, rodding around the studs and the aluminum anode bars. All these components were included in the model.

- ***Temperature dependent material properties were used.*** The material properties vary considerably over the temperature range of the preheat (room temperature to ~900 °C). More than 30 materials were used in the model. Properties for each material were defined using a macro library. Temperature dependent values were specified for each property (KXX, RSVX, C and DENS). In some cases orthotropic values were specified to define different values in different directions. Furthermore, properties of the rodding around the collector bars and anode studs were modified to include the contact resistance between the various materials.
- ***The thermal boundary conditions were accurately defined.*** The joule heat input was calculated automatically by ANSYS using the coupled field capabilities and 3D thermo-electric solid elements (STIF69). Temperature dependent equivalent surface film coefficients representing both convection and radiation effects, were defined on each surface. The surface orientation, characteristic length, view factor and emissivity were taken into account in the calculation. The coefficients were calculated in ANSYS using a special macro developed for that purpose.
- ***The electrical boundary conditions were closely followed.*** Time history plots of the cell voltage and line current are shown in Figure 2 resulting in a linear power curve. The resistivity of the coke layer was continuously adjusted (see below) to maintain the cell voltage shown in Figure 2. This history was modeled parametrically to allow for changing the time as well as the amperage and/or voltage drop.

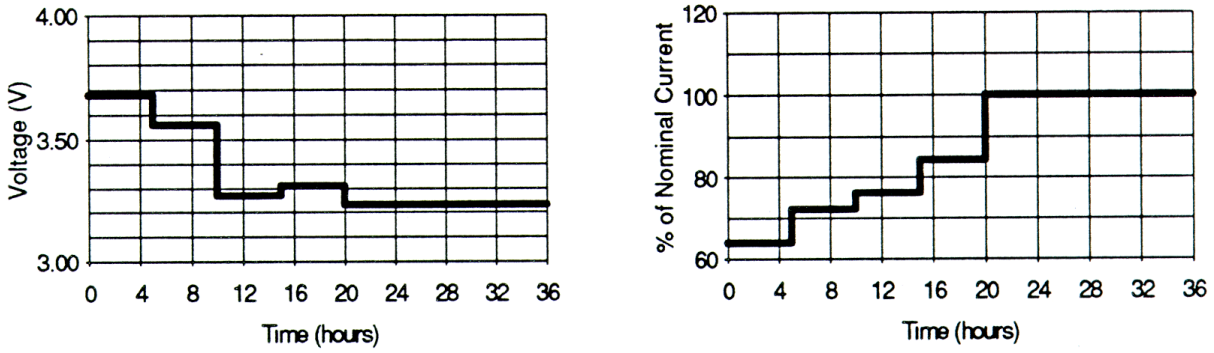

Figure 2: Time history of cell voltage and line current

Two other issues that needed consideration in the model were maintaining the cell voltage drop shown in Figure 2 and defining an integration time step for the transient solution. As mentioned previously, the coke layer burns during the preheat resulting in a drop in the cell resistance and a corresponding drop in the cell voltage. One method of representing this phenomenon would be to use birth and death cements. Unfortunately, these elements were not available in Revision 4.4A of ANSYS which was used to develop and run the model. Instead, the electrical resistivity (RSVX) of the coke material was continuously adjusted to ensure that the cell voltage drop calculated in the model was equal to the actual drop recorded during cell operation. The calculation was performed in a special ANSYS macro. A new value of RSVX was calculated and used for each load step in the transient.

The integration time step was manually calculated for each load step using a macro. The automatic time step calculation available in ANSYS could not be used for two reasons. The first had to do with the adjustment of the coke resistivity. This process forced the use of one iteration per load step in order to be able to follow the voltage curve. Furthermore, the change of material properties required a solution restart for each load step. The second reason had to do with the thermo-electric coupling. Revision 4.4A did not have the capability to monitor the electric field solution and use the change in the voltage for predicting a new time step size. As a result, a macro was developed to calculate the integration time step. Four criteria were defined in the macro for controlling the step size:

- The temperature increase between successive load steps could not be more than a prescribed value.
- The increase in the voltage drop in the cathode and in the anode was limited to a prescribed value.
- Two small steps were used every time a shunt was dropped. These were needed to account for the change in the resistivity of coke and to account for the time lag in calculating the joule heat.
- Minimum and maximum values were defined for the time step.

A single iteration was used in each load step so that the duration of the load step was equal to the integration time step. The macro ensured that a load step always coincided with a shunt drop.

Model Options

The model was designed to evaluate several design alternatives. The finite element mesh of a quarter model of the standard design is shown in Figure 3. Three basic geometry changes were built into the model, namely: changing the geometry of the block closest to the end wall, changing the coke bed layout and changing the location of the two anodes closest to the end wall. A partial plot of the corner showing the cut block geometry and ring coke bed are shown in Figures 4 and 5 respectively. Any combination of the above configurations could be created by simply changing three parameters. A total of 18 different designs could be run. Additional flexibility was provided by using parameters to define all the dimensions used in the model.

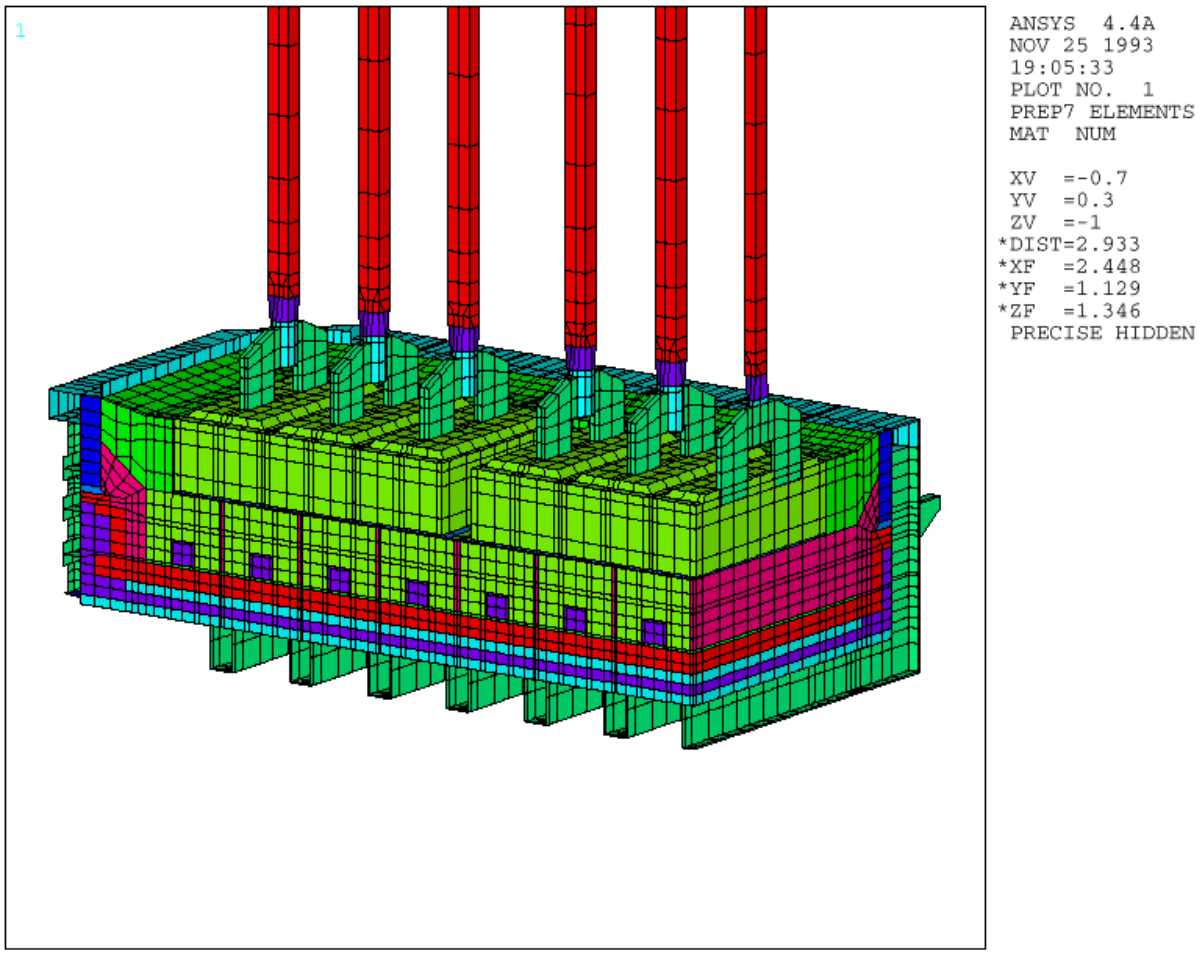

Figure 3: Quarter model - standard design

The quarter model shown in Figure 3 had over 33000 elements. A typical run required 45 load steps to model a 36 hours preheat. The total elapsed time for running the model on an HP715 workstation was close to 48 hours. This constituted a long elapse time especially in the initial stages of the project when the model was being debugged. In order to reduce the elapsed time two smaller models were developed. The first was a center segment that included 2½ anodes and 3 cathode blocks. This model was accurate at predicting the behavior at the center of the cell. The second variation was a corner model which included the 3 anodes and 4 cathode blocks closest to the end wall. This option provided accurate results near the corner. Both models were used extensively to calibrate the model with measured data. Once acceptable results were achieved, a full quarter model was processed for final validation. From there on quarter models were used to evaluate the various design alternatives.

The development of these smaller models was very easy to implement since the structure had considerable symmetry in it. For example, the anodes were created by generating a quarter model of an anode and mirroring it twice. Additional anodes were generated using the NGEN and EGEN commands with appropriate increments. The same procedure was used to model the cathode blocks and the end wall. All the base segments were created using solid modeling. Other segments such as the coke bed and the cryolite were created by direct generation of nodes and elements. The NUMOFF command was used to offset the entity numbers, thus simplifying the creation of each segment.

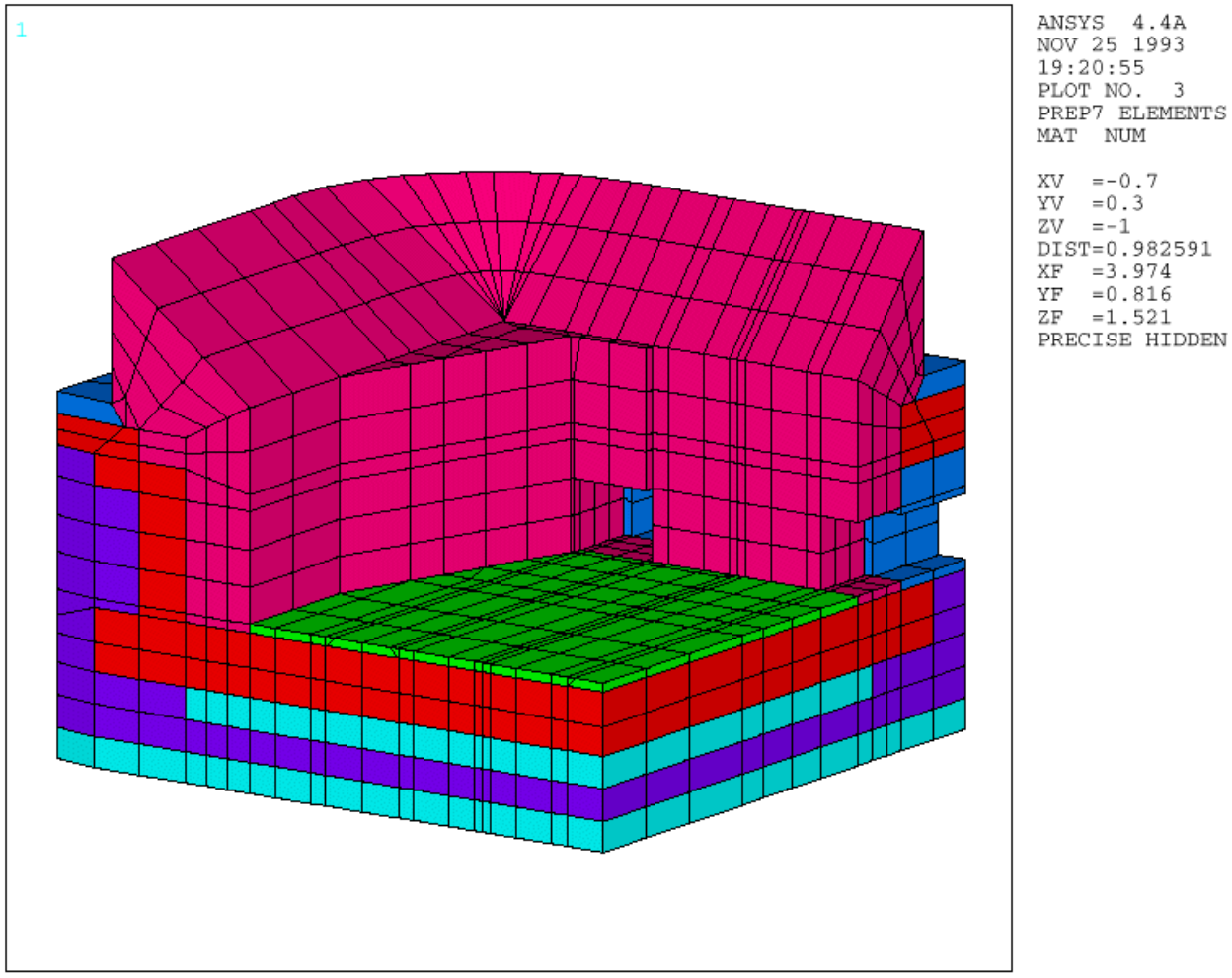

Figure 4: Cut block detail

Another concern with the model was the amount of disk space required to store the results. The FILE12 for each load step was close to 43 Mbytes while FILE11 and FILE03 were 220 and 75 Mbytes respectively. Since the main interest was in the temperature solution, it was decided to store a complete FILE12 only at selected times in the transient. By using AUX1 it was possible to copy the temperature and voltage solution from each load step to a single file and store a complete FILE12 at a user specified interval in the transient.

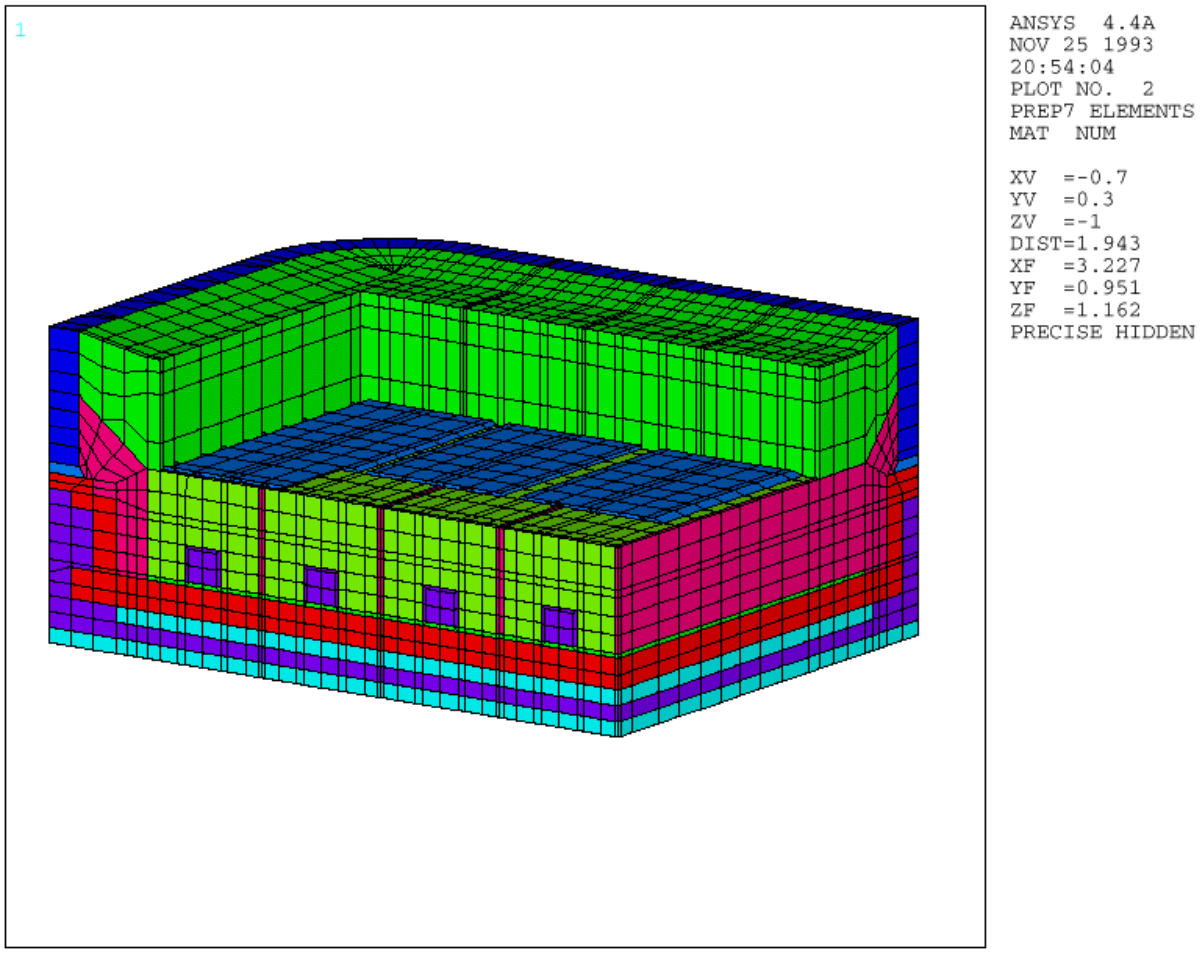

Figure 5: Corner model – last two anodes moved

Model Results and Validation

Several macros were developed to extract results from the model and store them in table format using the *MSG command. These included voltage statistics for each load step, heat balance tables, calculation of the total power curve during the preheat and several other items. Input files were created to plot the time history of selected points to be compared with measured data. In general, these points did not coincide with nodes in the model. Linear interpolation within the appropriate elements of the model was used in POST26.

Figure 6 shows a contour plot of the temperature at the end of a 36 hours preheat for the standard design. The model was validated by comparing the ANSYS results to measured data [2]. Several pots were instrumented in the plant with thermo-couples and transducers to measure the cathode temperature and deflection. Figure 7 shows a typical graph where multiple points within a cell as well as values from four cells were compared to ANSYS results. Several runs were executed to calibrate the model and evaluate the impact of various design changes and preheat practices.

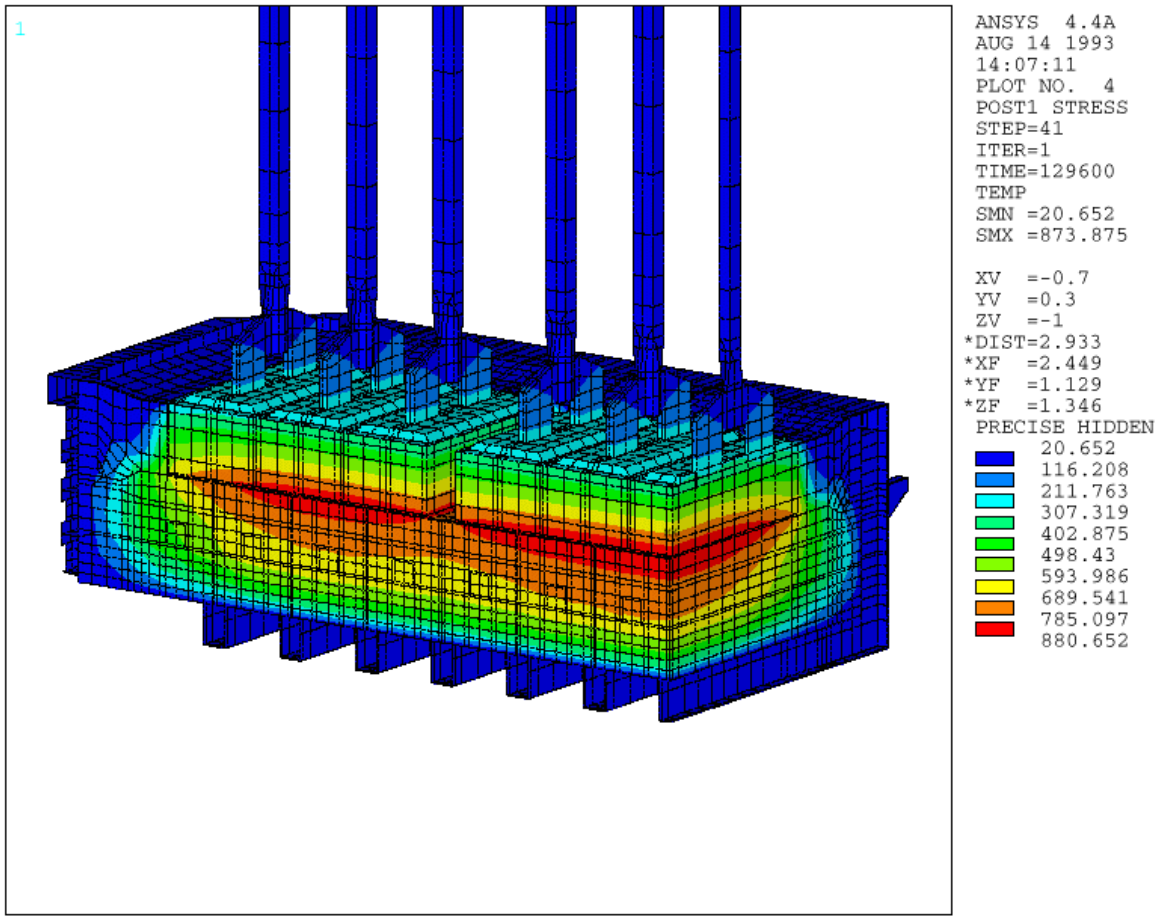

Figure 6: Temperature profile at 36 hours – standard design

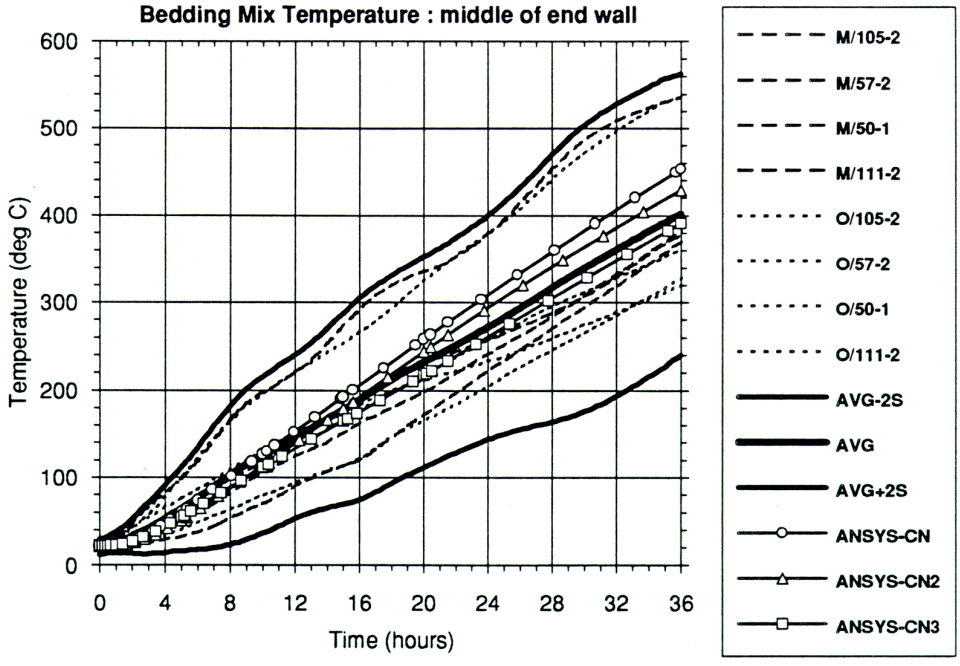

Figure 7: Comparison of model results with measured data

STRESS MODELS

The main objective of the study was to calculate the stress in the cathode blocks and evaluate design alternatives to find ways to reduce the stress level and the potential for early failure. The stress analysis model was created from the heat transfer model by simply changing the element types in the model and specifying the material properties and displacement boundary conditions. The temperature distribution was automatically stored on FILE04 in the heat transfer run. The ANSYS TREAD command was used to input the temperatures into the stress model.

Two additional factors were considered in developing the stress model. The first related to the material properties of the mix between and around the cathode blocks. The Young's modulus and the coefficient of thermal expansion are both a function of temperature and they vary considerably during the preheat period. The mix is a "soft" paste at room temperature and solidifies between 450 and 650 ^{o}C above which it has properties similar to carbon. Calculation of the stress at the end of the preheat required an incremental solution that accounted for the baking of the mix. Such a solution capability is not available in ANSYS.

The second factor that was considered in the stress analysis was the interaction between the various components within the cell. The difference between the coefficient of thermal expansion of the mix and carbon, and the thermal gradients in the structure tend to crack the mix adjacent to the block. As a result no shear forces are transferred at the mix/carbon interfaces. Similarly, no shear forces are transferred at the mix/pier interface (see Figure 1), the pier/bottom insulation interface and the cathode blocks/bottom insulation interface. Also, the potshell and the lining can slide and separate relative to each other and the cradles are welded to the potshell only at the middle of the side wall.

Three types of models were used to calculate the stress:

- A model of a single unsupported cathode block without the surrounding mix. This represented the situation of a mix temperature below the baking temperature. It provided the level of stress due to only the thermal gradient within the block.
- A model of the cathode blocks and the mix and around them. Variations of the boundary conditions on the mix, the mix properties and the behavior at the mix/carbon interface were investigated. This model represented the interaction between blocks due to the overall thermal gradients in the panel and provided an upper bound on the stress.
- A full quarter model of the cell with gap elements at all the interfaces where no shear forces are transferred.

The three models represented increasing levels of complexity and resource requirements. The first two ignored the baking phenomenon and provided upper bounds on the stress. They were used to compare various alternatives and provide insight into the behavior of the cell. The third model had not been run at the time of writing the paper pending the completion of work on modeling the baking behavior.

Figure 8 shows a contour plot of the stresses in the cathode blocks at the end of a 36 hours preheat using a standard cell design and a full coke bed. The stress levels were significantly higher than the failure stress of the carbon used in the blocks. The location of the high stress coincided with cracks observed in failed pots. This confirmed that the model represented the true cell behavior. To further validate the model, a bias coke bed solution was performed. It predicted high stresses that could crack the block at exactly the same locations observed in failed pots.

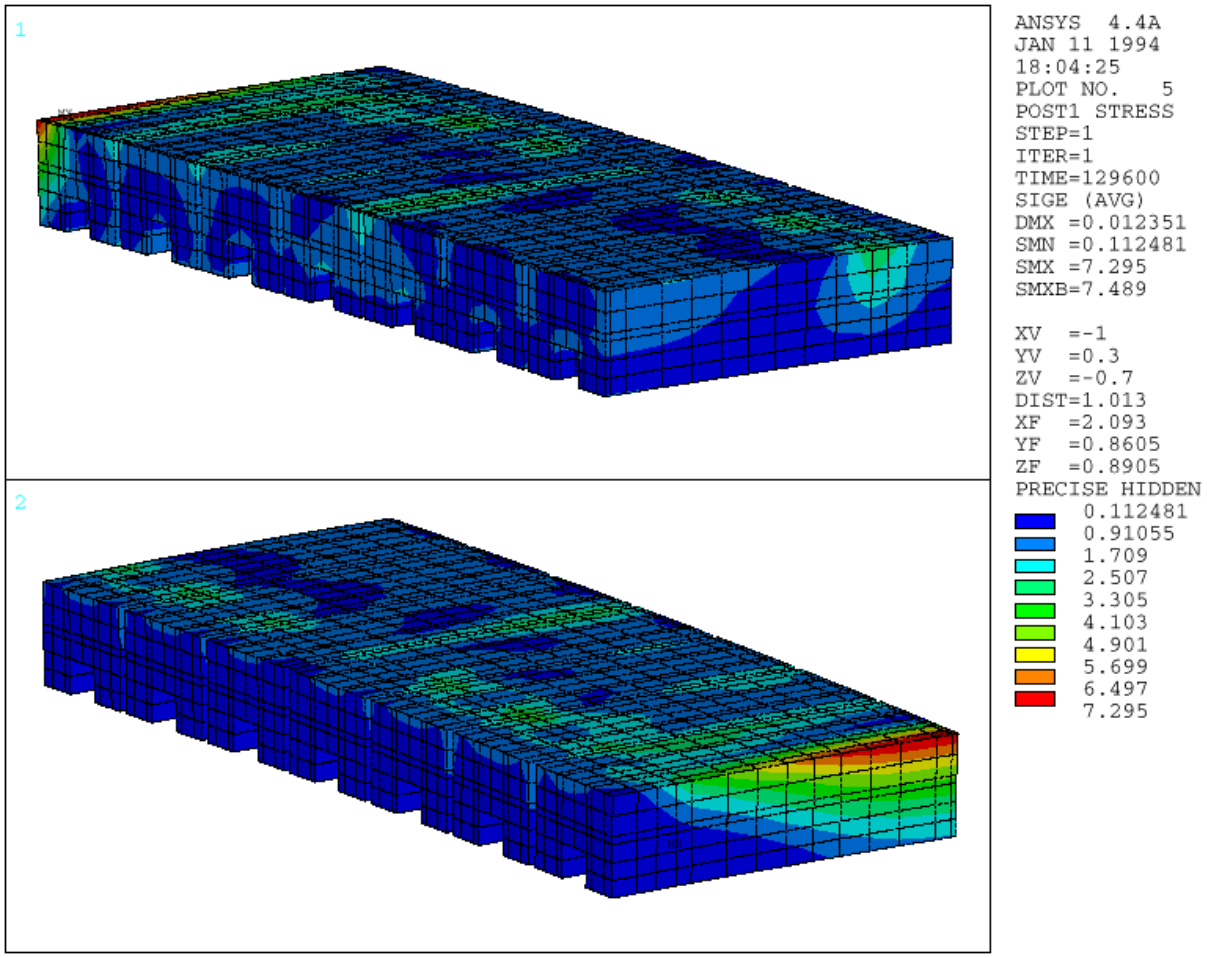

Figure 8: Equivalent stress in the cathode blocks at 36 hours - standard design

CONCLUSION

A comprehensive finite element model of a Hall-Héroult cell was developed to study the stresses due to thermal gradients present during the cell preheat. The model was validated by comparing analysis results to field measurements. Failures predicted using the models coincided with actual failures observed in the plant. Design changes that would reduce the likelihood of early failure have been identified and verified using the above models.

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