Modeling Cathode Cooling after Power Shutdown

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Introduction

Experience has shown that shutting down and restarting aluminum electrolysis cells due to extended electrical power interruptions at aluminum smelters causes irreversible and non-repairable damage to the cathodes, and consequently shortens pot-life. The average loss in pot life due to shutdown and restart of individual potlines is estimated to be about 200 days, but varies from 100 to 400 days at different aluminum smelters. Cooling cells to ambient temperature causes the formation of numerous, and often deep cooling cracks on the top surface of the carbon cathode lining, (in the cathode blocks as well as the seams between blocks). The mechanism for the formation the cooling cracks has not previously been determined.

Although there have been numerous publications regarding the preheating of cathode lining of aluminum electrolysis cells, this work represents the first to effectively model the cooling of cathode linings due to a power outage, and report the extent and consequence of thermal gradients formed in the cathode lining during cooling causing crack formation in the cathode lining in aluminum cells

Power Interruptions at Aluminum Smelters: During the past ten years there has been an increase in the shutdown and restart of aluminum potlines due to long duration power interruptions, (> 3 hours) at aluminum smelters. [Reference 1] Aluminum companies have been very successful in using *amperage creep* to increase productivity and profitability at most existing aluminum smelters, but it has come at a price, as it tends to shorten the lifetime of transformer/rectifiers systems. For instance, the majority of smelters that experienced shutdown of potlines due to long power interruptions were due to failure of the transformer/rectifier systems, especially at older aluminum smelters built 20 to 40 years ago. Harsh weather conditions such as ice storms, snow and high wind velocity are also major factors in causing shutdown due to long duration power interruptions, and are frequent in China during winter. A somewhat surprising development is that several new modern high-amperage smelters, (e.g., Fjardaal, Qatar and Dubal) have experienced recent shutdown of potlines due to the temporary loss of power at their power generation stations and/or national grid system.

Cooling the electrolyte below 850 °C results in the solidification of bath and eventually the shutdown of the operating cells in the potlines. It requires a great deal of effort, pre-planning and experience to survive power interruptions that last longer than 3 hours. However it is astonishing that are a few instances in which potlines have been reported to survive power interruptions up to 8 hours.

Cathode Cooling Cracks: The rapidly cooling of aluminum cells from an operating electrolyte temperature ~960 °C to ambient 25°C due to potline shutdown results in the generation of cooling cracks on the cathode surface; this phenomena is observed in most all cells in which the metal pads are removed and the surface 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 as seen in figure 1. The width of observed cooling cracks observed are generally from 1.6 to 3 mm and may 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; however when the stress continues to increase the carbon material starts to behave in a more plastic manner with irreversible deformation until fracture occurs. Micro-cracks can be generated during the calcinations and graphitization of cathode carbon materials; during loading the micro-cracks are gradually closed with volume contraction. Thereafter, when stresses become high, macro-cracks 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. In addition, the cathode blocks are significantly weakened by micro-cracking caused by the diffusion of sodium into the carbon lattice.

Thermal Gradients in the Cathode Lining: *It is proposed that 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 report that, "due to the very limited elastoplastic 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." [Reference 3] 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.

Thermal Modeling Results

Cathode cooling rate: When a cell loss power, it initially continues to dissipate the same amount of heat, but there is no more Joule produced, so the cell start to cool down. The average cooling rate depends on the intensity of the heat loss which itself depends on the operating conditions prior to the power shutdown and the cell thermal mass. Modern high amperage cells are typically designed and operated to maximize production so they are operated at very high current density and corresponding high cell superheat, thin side ledge thickness and high side wall heat flux.

As demonstrated in [Reference 4] it is possible to model cathode cooling. The cell design and cell operating conditions used in that previous study were typical of early 1990 high amperage conditions so the resulting cooling rate was correspondingly less that the one recently measured [Reference 5]. Figure 2 presents the average metal pad cooling rate obtained using a retrofitted cell design using SiC side blocks operated at a higher current density and corresponding higher superheat prior to the shutdown. That average cooling rate is very similar to those presented in figure 10 of [reference 5]. Figure 3 presents the cell temperature obtained after 24 hours of cooling from the full quarter cell model while figure 4 presents only the cathode panel temperature section. It can be noticed that the temperature on the cathode panel surface is lower than the one directly below at the collector bars level.

Cathode cooling cracks: That cell cooling is sufficient to produce cooling cracks on the cathode surface mostly in the transverse direction of the cell as the one presented in figure 1. A level of tension stress of at least 8 MPa in the longitudinal direction of the cell is required to generate those cracks according to the cathode block properties presented in [Reference 6].

It was not possible to obtained that level of longitudinal tension stress in the previous study [Reference 4]. 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 constrains, the level of tension stress obtained was only around 2 MPa or about 4 times less that was 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 generated cooling cracks. Figure 6 presents that longitudinal stress component obtained using the 2D thermal stress model in plain strain mode with the thermal gradient after 24 hours presented in figure 5 itself the results the new transient analysis model producing the new faster cooling rate. Like in the previous study [reference 4], the thermal gradient used to carry-up the thermal stress analysis is obtained by subtracting the initial steady state temperature to the temperature obtained after 24 hours of cooling.

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 reconsided 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. Figure 7 is presenting the 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. As it can be seen in figure 7, with this type of motion restrains, there is enough longitudinal tension stress to generate transverlase 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.

Looking to a cure to the cathode cooling cracks problem: In the previous study [Reference 4], 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. 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!

The new assumption is that the cathode panel as a whole, but more so the top section want to shrink but the collector bars are anchoring the bottom section of the cathode panel preventing it to move. Under those conditions the only option left to the cathode panel is to generate cooling cracks. This was confirmed by model results.

In a way, the obvious cure the cooling cracks problem have already been indentify in the previous study [reference 4], the cell lining design needs to be modify in order to prevent the collector bars to be anchored in the pier region. A third study could demonstrate that, assuming that there is a practical solution to this new lining design requirement which is far from being obvious.

Conclusions

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.

In that context, 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.

References

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Authors

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Dr. Alton Tabereaux is a technical consultant in resolving issues and improving productivity at aluminum smelters since 2007. He graduated with a PhD in Chemistry from the University of Alabama in 1971 and then worked for 33 years as a manager of research and process technology for both Reynolds and Alcoa Primary Metals. He was Recipient of JOM Best Technical Paper Award in 1994 and 2000, editor of Light Metals in 2004 and received TMS Light Metals Distinguished Service Award in 2007. He is a lecturer at the annual International Course on Process Metallurgy of Aluminium held in Trondheim, Norway and an instructor at annual TMS Industrial Aluminum Electrolysis Courses. He has published over 65 technical papers and obtained 17 US patents in advances in the aluminum electrolysis process.

Figure 1: Transverse cathode cooling crack

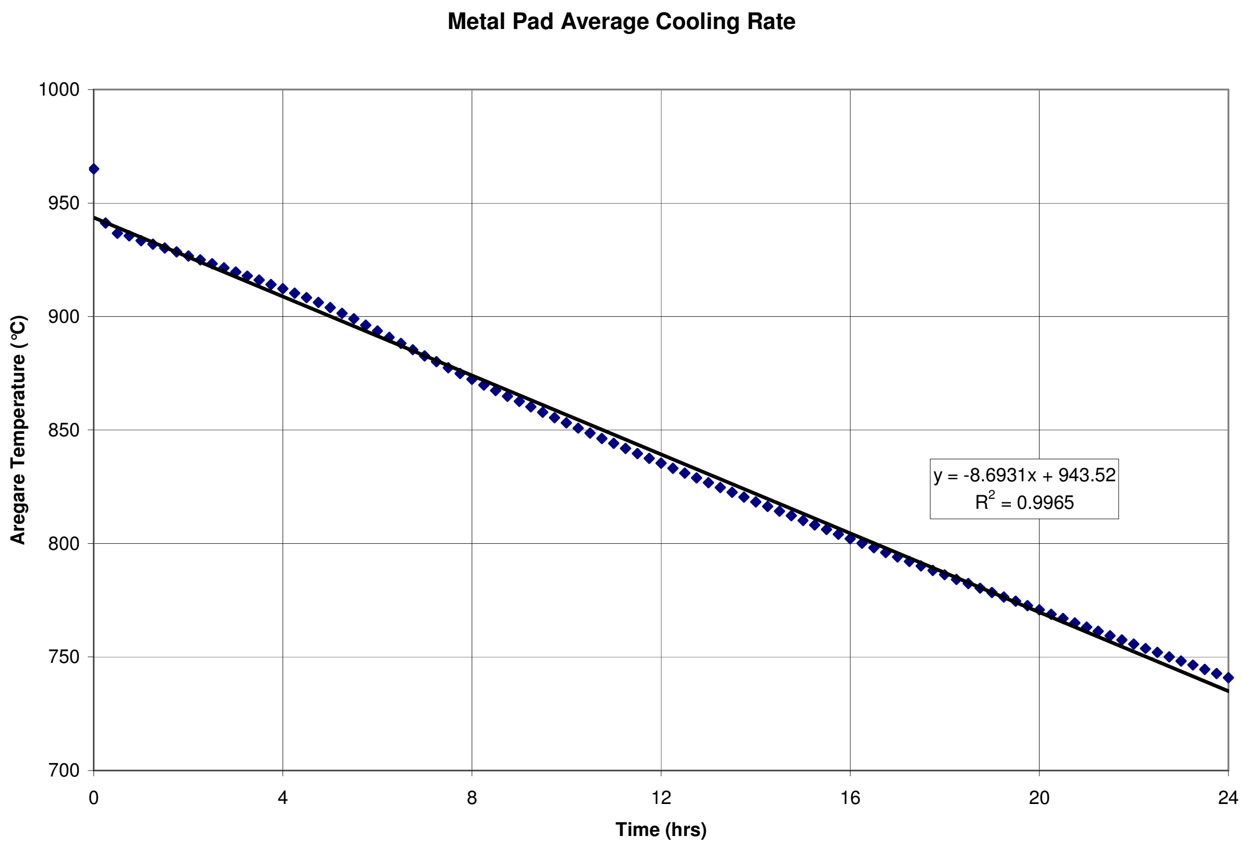

Figure 2: Average metal pad cooling rate from the quarter cell model

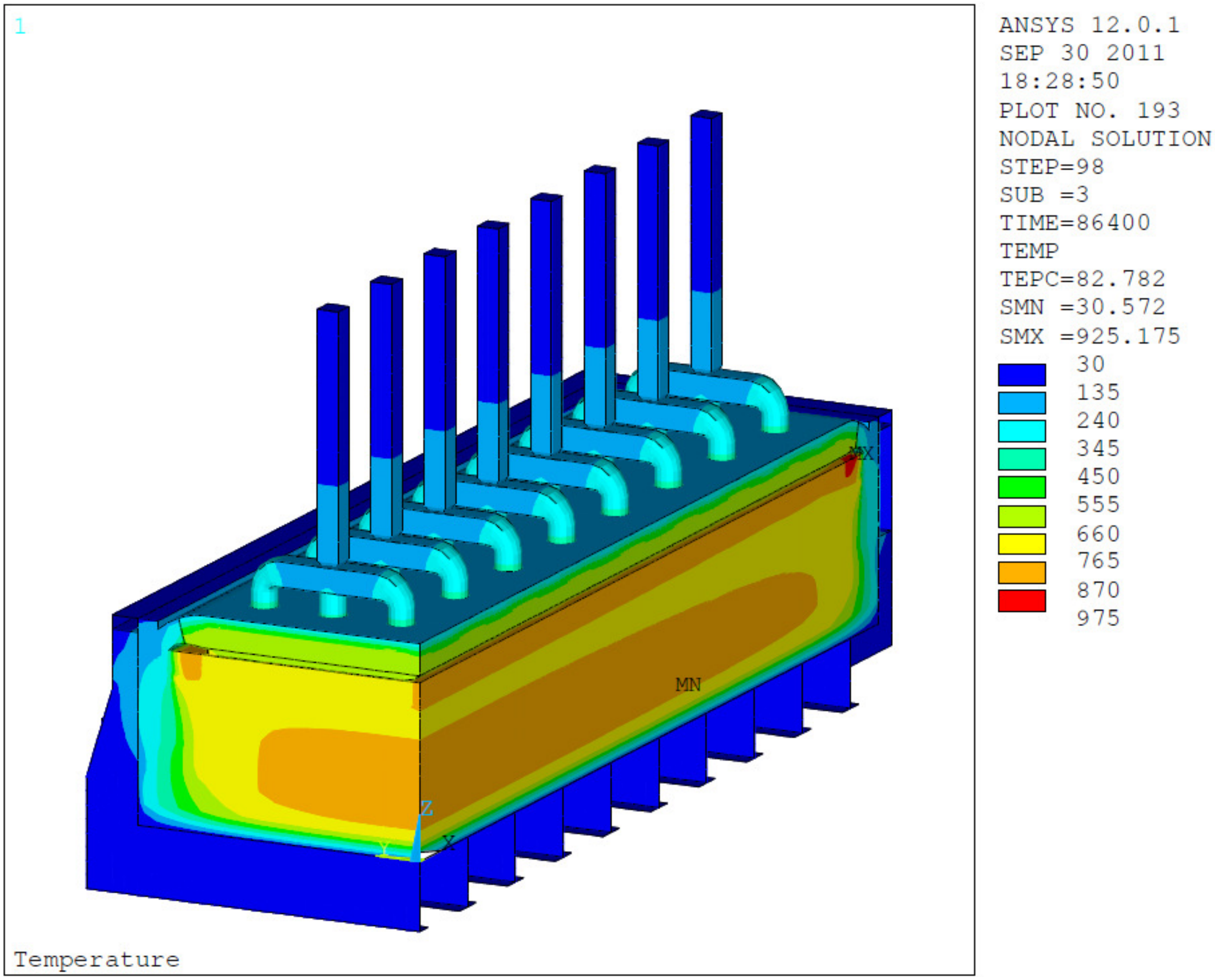

Figure 3: Temperature after 24 hours of cooling from the 3D quarter cell model

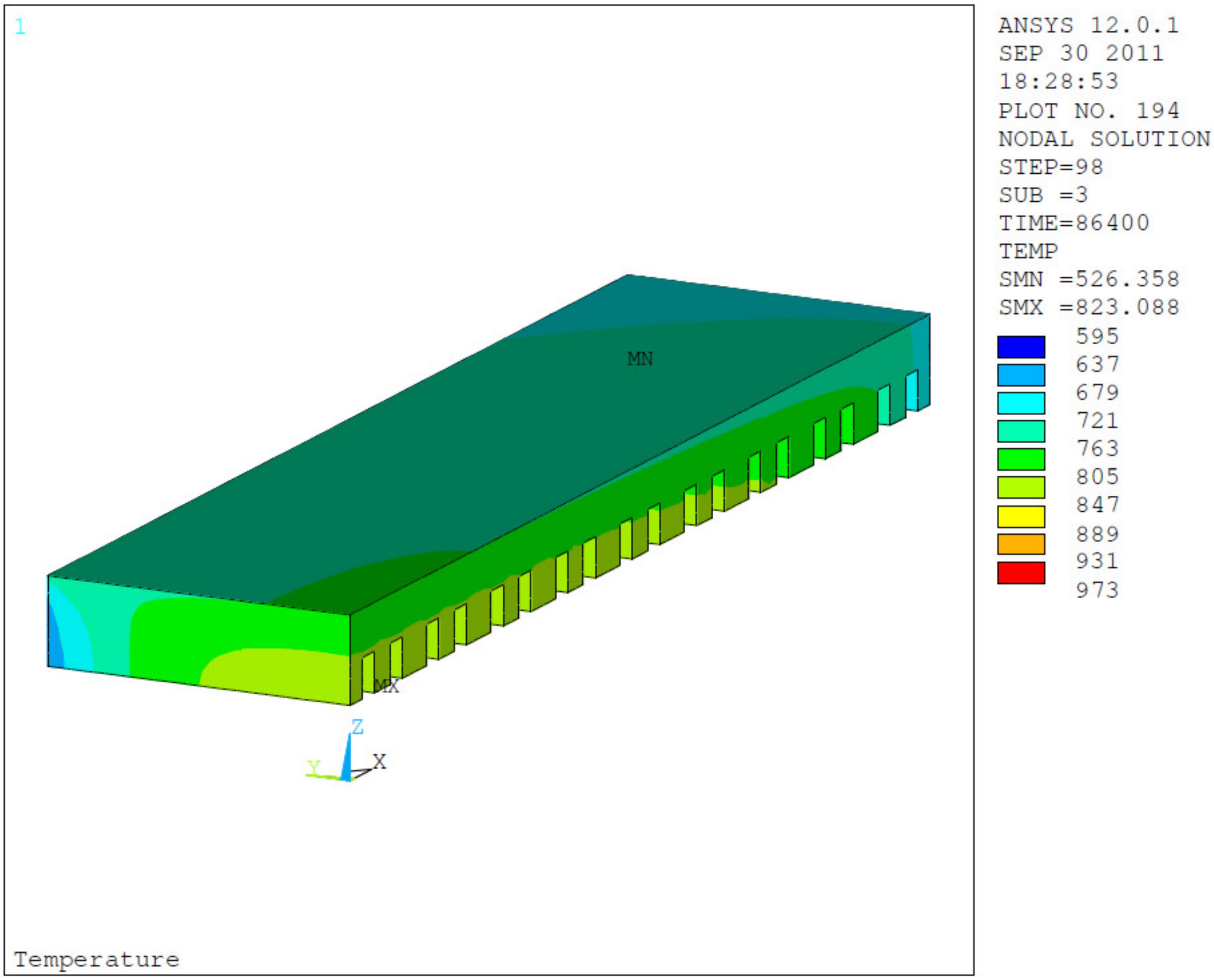

Figure 4: Temperature of the cathode panel after 24 hours of cooling from the 3D quarter cell model

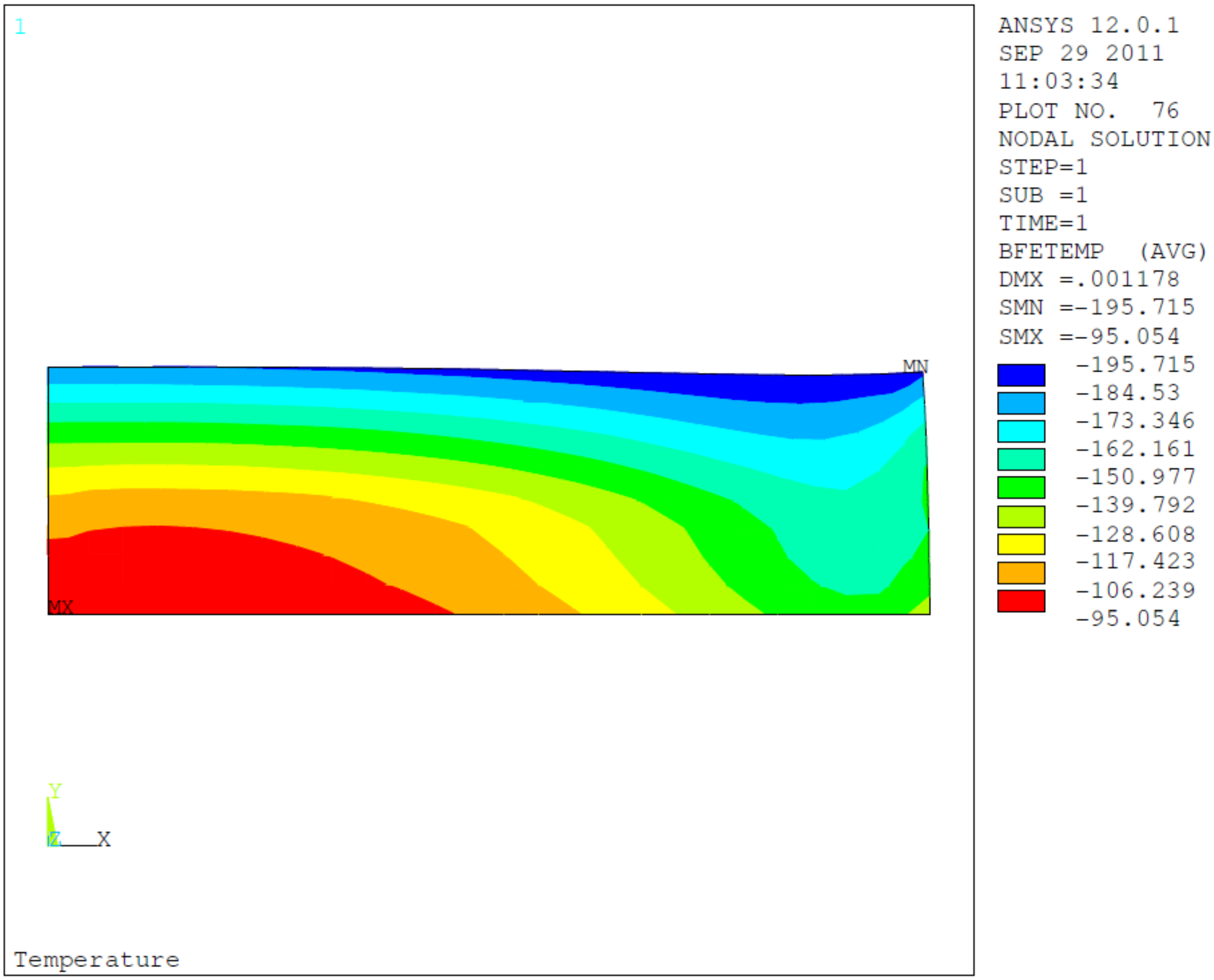

Figure 5: Relative thermal gradient in the cathode block after 24 hours of cooling from the 2D model

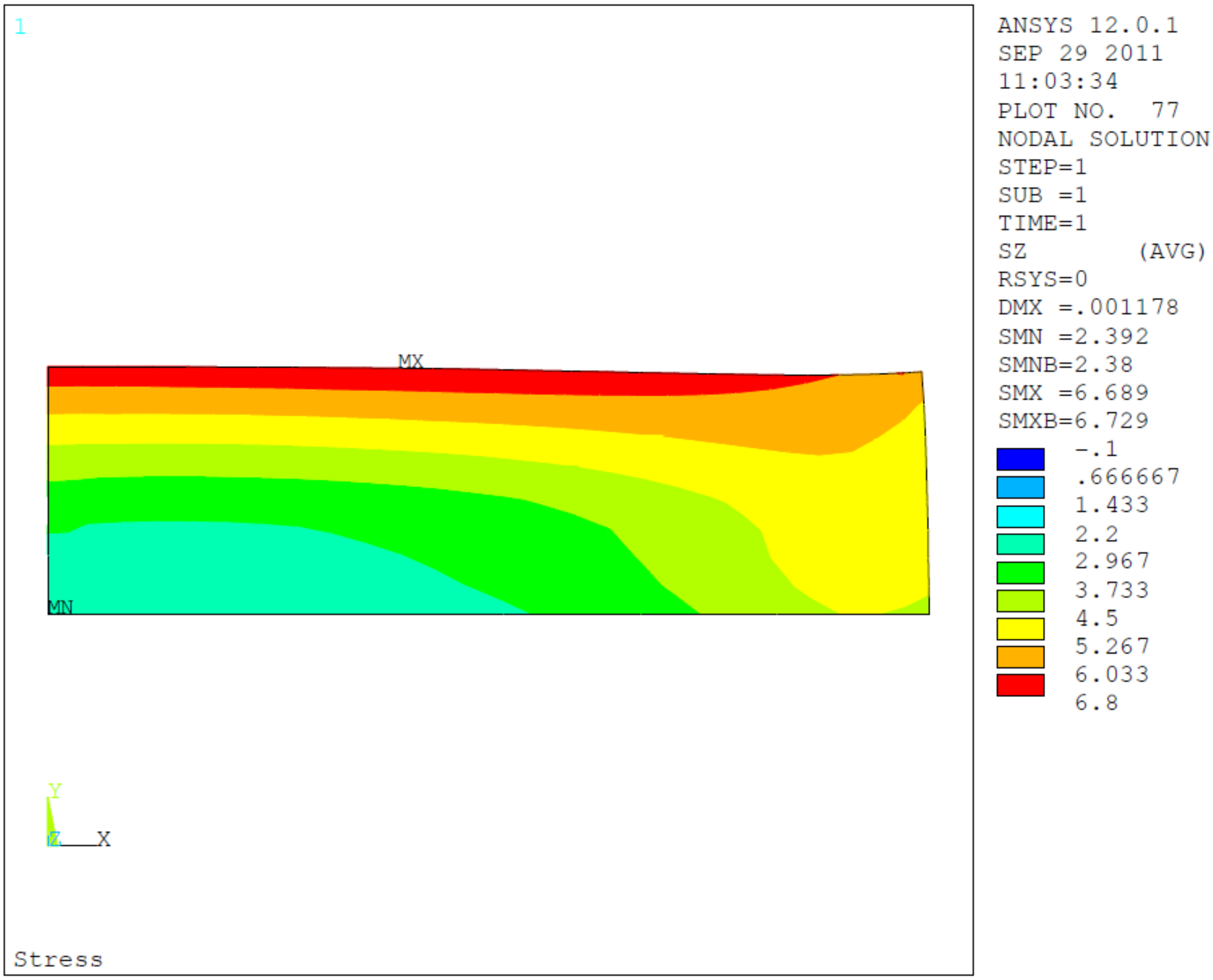

Figure 6: Longitudinal stress componant in the cathode block after 24 of cooling from the 2D model

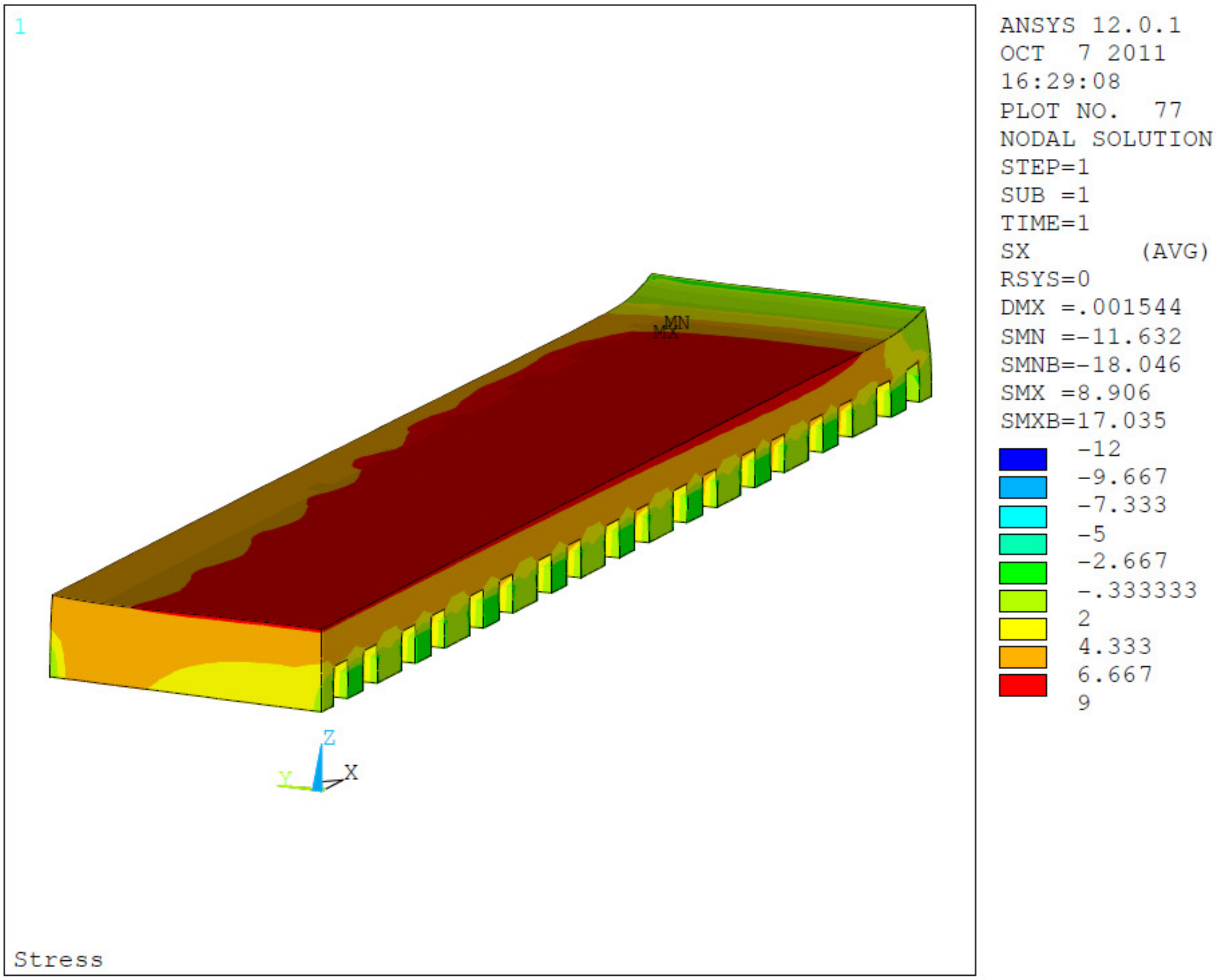

Figure 7: Longitudinal stress componant in the cathode panel after 24 of cooling from the 3D quarter cathode cell model