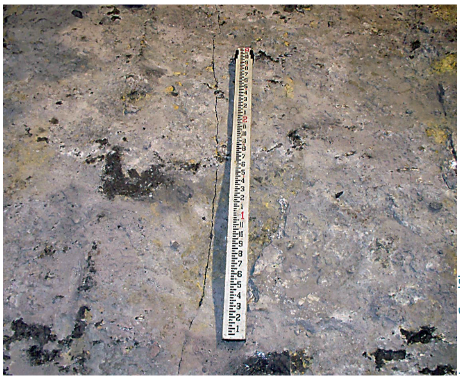
Modelling cathode cooling after power shutdown

M. Dupuis, Jonquière and A. Tabereaux, Muscle Shoals

When a long power outage imposes a shut-down and restart of electrolysis cells at aluminium smelters, this causes irreversible and non-repairable damage to the cathodes. Experience has shown that this damage shortens pot life on average by about 200 days, but the loss in pot life varies from 100 to 400 days at different aluminium 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, both in individual cathode blocks and in 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 pre-



Images: GeniSim

Fig. 1: 1 metre length of transverse cathode cooling crack

heating of cathode lining of aluminium electrolysis cells, this work represents the first to effectively model the cooling of cathode linings due to a power outage. It is also the first to report the extent and consequence of thermal gradients formed in the cathode lining during cooling, and to relate these to stresses and crack formation.

Power interruptions at aluminium smelters: During the past ten years there has been an increase in the shutdown and restart of aluminum potlines due to long power interruptions (of more than three hours) at aluminum smelters [1]. Aluminium companies have been very successful in using amperage creep to increase productivity and profitability at most existing aluminium smelters. But this increase has come at a price, as it tends to shorten the lifetime of transformer/rectifier systems. For instance, the majority of long power interruptions were due to failure of the transformer/rectifier systems, especially those 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 long power interruptions, and are frequent in China during the Winter. A somewhat surprising development is that several modern high-amperage smelters (e.g. Fjardaal, Qatar and Dubal) have experienced recent shutdown of potlines due to failures at their power generation stations and/or in national grid system.

Cooling the electrolyte to below 850 °C causes the bath to solidify and risks the shutdown of the operating cells. It requires a great deal of effort, prior planning and experience to survive power interruptions that last longer than three hours. However, it is astonishing that there are a few reported instances in which potlines have survived power interruptions of up to eight hours.

Cathode cooling cracks: The rapid cooling of aluminium cells from an operating electrolyte temperature ~960 °C to ambient 25 °C due to potline shutdown generates cooling cracks on the cathode surface; this phenomenon is observed in almost all cells in which the solidified metal pads are removed and the surface cleaned for inspection. The cracks are certainly formed in the cathode block during cooling, and not during cell operation, because there is no bath or a yellow film of aluminium carbide on the surfaces of the cracks as shown in Fig. 1. The width of observed cooling cracks is 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.

Fracture behaviour of carbon: The thermo-electro-mechanical behaviour of new cathode carbon has been described as elastoplastic [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, and undergoes irreversible deformation until fracture occurs. Micro-cracks can be generated during calcining and graphitisation of cathode carbon materials; but under compressive loading the micro-cracks tend to gradually close with volume contraction. Thereafter, when stresses become high, macro-cracks are again initiated in the material and they begin to propagate until failure occurs. The cathode carbon is weakened as it undergoes ductile-brittle transformation during cell operation. The cathode lining eventually becomes saturated, (more than 3%) with interstitial sodium absorbed into the carbon lattice. This sodium causes swelling and changes the properties of the carbon lining, making 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: This paper explains how rapid cooling of cathodes due to power interruption generates an uneven temperature distribution in the cathode lining. The temperature gradient results in a thermally induced mechanical stress which is sufficient to cause cracking. During cooling, the top of the cathode blocks cools faster than the bottom, resulting in large temperature gradients. 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 as surface energy in the form of bottom cooling cracks" [3]. Cooling cracks weaken the carbon lining, as some of them may fill with aluminium upon restart; some cracks continue to expand and link up, and so become a basis for later pot failure.

Thermal modelling results

Cathode cooling rate: When a cell loses pow-

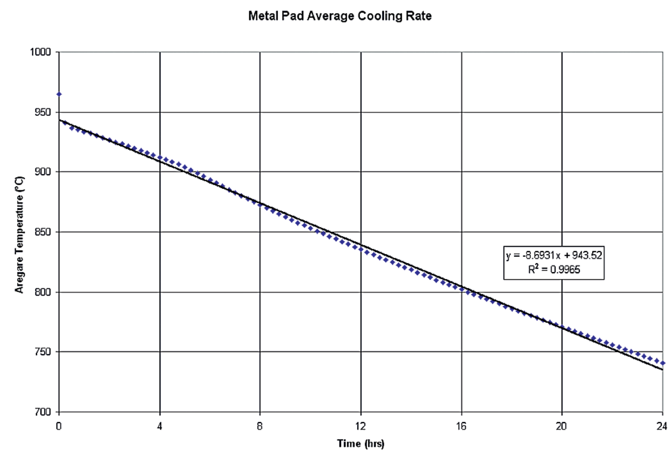


Fig. 2: Average metal pad cooling rate, from the quarter cell model

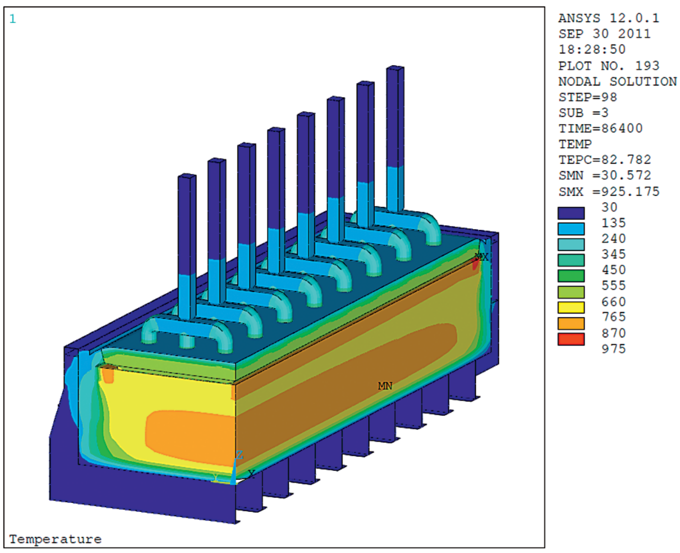


Fig. 3: Temperature after 24 hours of cooling, from the 3D quarter cell model

er, it initially continues to dissipate the same amount of heat. But there is no more heat input, so the cell starts 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 on the cell's thermal mass. Modern high amperage cells are typically designed and operated to maximise production, so they work at very high current density and correspondingly high cell superheat, with thin side ledge thickness and high side wall heat flux.

As the authors demonstrated in [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 than the rate recently measured [5]. Fig. 2 shows the average metal pad cooling rate measured on a retrofitted cell design with SiC side blocks. This cell operated at a higher current density and correspondingly higher superheat prior to the shutdown. Its average cooling rate is very similar to that shown in Fig. 10 of [5]. Fig. 3 presents the cell temperature distribution after 24 hours of cooling, calculated from the full quarter cell model, while Fig. 4 presents only the cathode panel temperature section. It can be seen that the temperature on the cathode panel surface is lower than that directly below at the collector bar level.

Cathode cooling cracks: This cell cooling is sufficient to cause cooling cracks on the cathode surface. The cracks run mostly in the transverse direction of the cell, like the one shown in figure 1. A longitudinal tension stress of at least 8 MPa is needed to generate those cracks, according to the cathode block properties presented in [6].

It was not possible to predict that level of longitudinal tension stress in the previous study [4]. In that model, the cathode panel was prevented from deflecting down, but it was free to contract in both horizontal directions. By using this limited type of displacement constraint, the level of tension stress predicted was only around 2 MPa, which is about four times less than that required to generate cooling cracks.

Yet, already in that previous study, the longitudinal tension stress was sufficient to generate cooling cracks when the 2D thermal stress model was solved in plain strain mode. Fig. 6 shows the longitudinal stress component obtained using the 2D thermal stress model in plain strain mode, using the thermal gradient after 24 hours, as shown in Fig. 5. Figure 5 is itself the result of the new transient analysis model which produces the faster cooling rate. As in the previous study [4], the thermal gradient used for the thermal stress analysis is the difference between the initial steady state temperature and the temperature calculated after 24 hours of cooling.

When assuming plain strain, the 2D model does predict longitudinal tension stresses high enough to cause cracking, 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 Morten Sørlie, the authors reconsidered the situation; according to Sørlie, the collector bars which are anchored by the pier substantially prevent the cathode panel from shrinking freely in the longitudinal direction. Fig. 7 shows the longitudinal stress component obtained using the 3D quarter cathode panel model. This assumes that the collector bars prevent the vertical carbon faces in the slots from moving longitudinally. As can be seen in Fig. 7, this type of restraint generates enough longitudinal tension stress to cause transversal cracks. So it is safe to assume that as Sørlie pro-

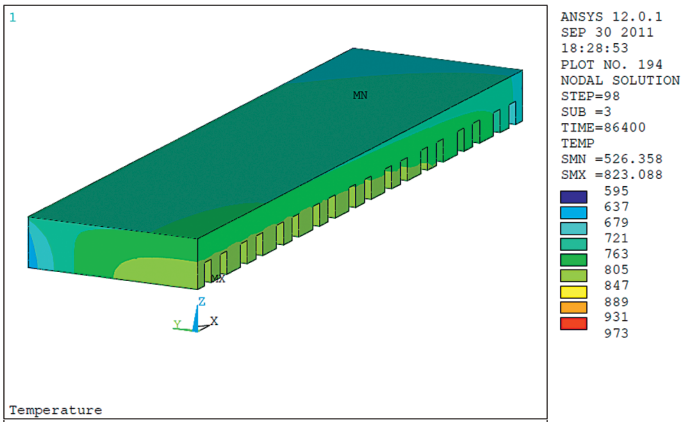


Fig. 4: Temperature of the cathode panel after 24 hours of cooling, from the 3D quarter cell model

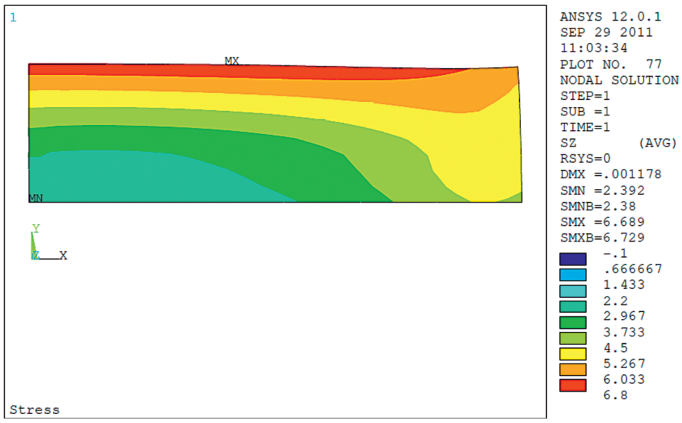


Fig. 6: Longitudinal stress component in the cathode block after 24 hours of cooling, from the 2D model

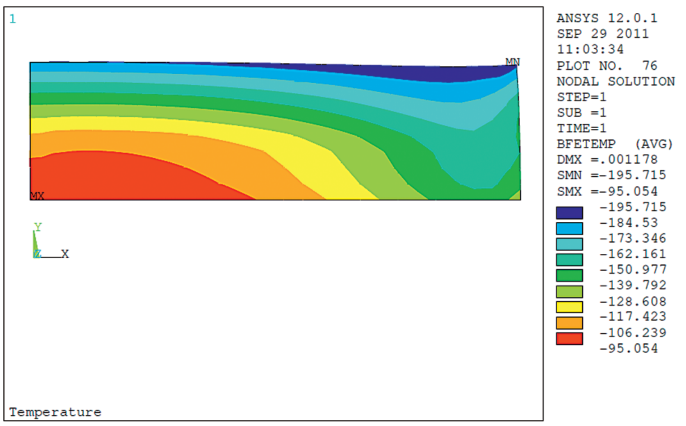


Fig. 5: Relative thermal gradient in the cathode block after 24 hours of cooling, from the 2D model

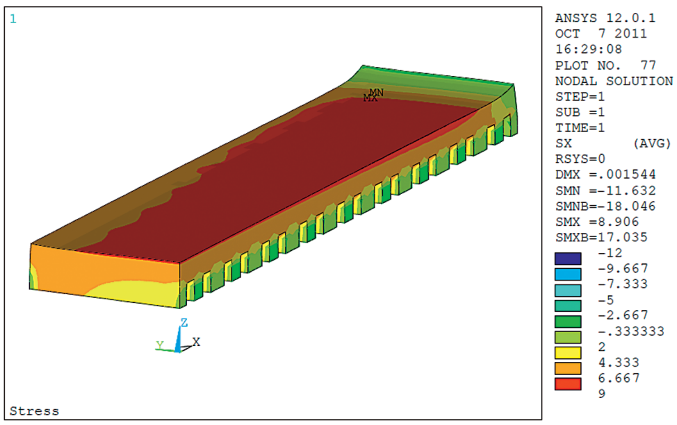


Fig. 7: Longitudinal stress component in the cathode panel after 24 hours of cooling, from the 3D quarter cathode cell model

poses, collector bars do substantially present the cathode panel from shrinking freely in the longitudinal direction of the cell.

Looking to a cure to the cathode cooling cracks problem: In the previous study [4], it was suggested that since it is the metal pad that generates the reversed vertical thermal gradient in the cathode blocks, then tapping the metal pad as quickly as possible after the power shutdown should reduce the risk of cooling crack formation. This conclusion assumes that the tension stress and the corresponding cooling cracks arise because the cathode panel is not free to bend down. Under that assumption, reducing the intensity of the reversed vertical thermal gradient did significantly reduce the top surface tension stress. Yet, that stress intensity was already four times less than is required to produce cooling cracks!

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

In a way, the cooling cracks problem was already identified in the previous study [4]: the cell lining design needs to be modified so as to avoid anchoring the collector bars in the pier region. A third study could demonstrate this stress reduction, assuming that there is a structural solution to this new collector bar design requirement. So far, such a solution is far from obvious.

Conclusions

This paper demonstrates that mathematical modelling can explain the cooling crack formation because the cathode panel as a whole tries to shrink, but the collector bars prevent this. The metal pad cools the top section of the cathode panel faster, which compounds the problem, but this is not the main factor.

It therefore appears that only a cell lining design change can be expected to provide a cure. The aim of such a cell lining design would be to prevent the pier from rigidly anchoring the collector bars.

References

[1] A.T. Tabereaux, 'Electrical Power Interruptions: An Escalating Challenge for Aluminum Smelters', Light Metal Age 69 (2011)1, 26-32.

[2] G. D'Amours, M. Fafard, A. Gakwaya, and A.A. Mirchi, 'Mechanical Behavior of Carbon Cathode: Understanding, Modeling and Identification', Light Metals 2003, ed. P. N. Crepeau (TMS, Warrendale, Pa.), 633-640.

[3] M. Sørlie and H.A. Øye, 'Cathodes in Aluminium Electrolysis,' Aluminium-Verlag Marketing & Kommunikation GmbH, Düsseldorf, Germany, 3rd Edition 2010, 662 pp.

[4] M. Dupuis and A. Tabereaux, 'Modeling Cathode Cooling due to Power Interruption', Light Metals 2012, (TMS, Warrendale, Pa) to be published.

[5] K. F. Lalonde, W. Cotton and R. M. Beeler, 'Rate of Metal Cooling in Aluminum Reduction Cell removed from Line Current – Method and Model', Light Metals 2006, ed. T. J. Galloway (TMS, Warrendale, Pa.), 291-295.

[6] J. Hop, A. Store, T. Foosnaes and H.A. Øye, 'Chemical and Physical Changes of Cathode Carbon by Aluminium Electrolysis', VII International Conference on Molten Slags Fluxes and Salts, The South African Institute of Mining and Metallurgy, (2004), 775-781.

Authors

Dr. Marc Dupuis is a consultant specialised in the applications of mathematical modelling for the aluminium industry since 1994, the year when he founded his own consulting company GeniSim Inc. (www.genisim.com). Before that, he graduated with a Ph.D. in chemical engineering from Laval University in Quebec City in 1984, and then worked ten years as a research engineer for Alcan International. His main research interests are the development of mathematical models of the Hall-Héroult cell, dealing with the thermo-electric, thermo-mechanic, electro-magnetic and hydrodynamic aspects of the problem. He was also involved in the design of experimental high amperage cells and in the retrofit of many existing cell technologies.

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 is 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 aluminium electrolysis process.