Essential Readings in Light Metals: Aluminum Reduction Technology.
Edited by Geoff Bearne, Marc Dupuis and Gary Tarcy.
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4. OPERATIONS

More than 200 papers have been published in the *Light Metals* proceedings on aspects of reduction process operations (mainly describing operational practices). The selected papers in this section illustrate the remarkable technical development and increase in understanding that has taken place in this field over the last half century. In addition to providing a historical perspective, the papers should also help process engineers to address some of the technical challenges that they will encounter in their work.

The papers cover topics of longstanding interest, such as the effects of anode setting, alumina and other material handling and property impacts, anode cover and crust considerations, operational improvement, cell preheat, and cell start-up.

Smelters in most aluminum producing countries have been under pressure from increasing power prices in recent years. In response there has been increasing interest in power modulation schemes and procedures for stopping and restarting of potlines, despite the fact that steady operation at continuous current is highly preferred. As a result of this focus around a quarter of the papers in this section are dedicated to these topics.

The papers included in the list of recommended readings at the end of the section are also highly relevant.

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CURRENT PICKUP AND TEMPERATURE DISTRIBUTION IN NEWLY SET PREBAKED HALL-HÉROULT ANODES

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Abstract

The layer of frozen bath formed on newly set anode blocks in prebake Hall-Héroult cells was observed visually. At maximum, the layer on the horizontal part of the anode had a thickness corresponding to the interpolar distance. No frozen bath could be observed on the vertical sides of the cold anode block, however. The current pickup and temperatures recorded in newly set anodes showed good correlation to the visual observations.

Temperature measurements within hot anode blocks during periods when the neighbouring anode butt was replaced showed that the newly set anode block induces a substantial cooling of the warm block. This temperature reduction is interpreted as partly being caused by heat radiation from the hot block to the cold one.

Introduction

As the price for electricity in most countries is steadily increasing, it is essential to operate a given cell type at the lowest feasible power consumption (low ACD, but with a tolerable level of operational problems). In order to achieve this, a thorough understanding of the key processes in the Hall-Héroult cells is necessary.

In modern Hall-Héroult cells with point feeding and sophisticated data acquisition and regulation systems, the replacement of used anode blocks is a main cause for creating perturbations from steady state operation. Since the newly set anode block is at room temperature, a thick insulating frozen bath layer will be formed, which may substantially affect the magnetic fields and the heat balance of the cell. It is important to obtain more information on how the anode setting affects the cell performance. In this work, the current pickup, the temperature distribution, and the freeze profiles for newly set blocks were studied. The results are compared to the simulations presented by Grjotheim, Welch and Taylor [1].

Experimental

As a part of a parameter study, the current of all the anodes in a modern high amperage point feeded prebake cell at a Hydro Aluminium plant was measured every 30 seconds during a period of several months. During the same period, the temperature distribution within single anodes of the same cell was measured as well. Some of the results obtained in that study are reported earlier [2,3].

The current distribution in the cell was determined by measuring the potential drop across equal sections of all the anode stems at periodic intervals by means of a logging unit (AAC2, INTAB, Stockholm, Sweden). The recordings were stored in the memory of the logging unit for periods of up to one week before being transferred to a portable PC.

The temperature distribution in single anode blocks was determined by measuring the temperature at the bottom of totally 16 holes (12 mm dia.) by type K thermocouples. The thermocouples were standardized vs. the melting point of Ag (961.9 °C). The holes (of different depth) were drilled into the anode from the top. The thermocouples were protected by 10x6 mm dia. mullite tubes ("Pythagoras", supplied by Haldenwanger, München, Germany). The thermocouple positions are given in Figure 1. The thermocouple signals were recorded and stored by the same type of logging unit as mentioned above.

The freeze profiles on newly set anode blocks were determined by taking the block out of the cell after different times of exposure to the bath. Samples were taken of the frozen bath layer, before the block was installed in the cell again. Each anode block was removed only once.

Results and Discussion

Freeze Profile and Freeze Composition

Figure 2 and Figure 3 show the freeze profiles on two anode blocks which were removed from the cell 90 and 259 minutes after the first setting, respectively. The anodes were removed from the same position in two different cells which had roughly the same difference between operational temperature and liquidus temperature ("overtemperature").

As shown in Figure 2, the bath freezes onto the horizontal part of the anode, forming a layer with thickness corresponding to the interpolar distance. This is in agreement with the simulations reported by Grjotheim et al. [1]. However, contrary to what is shown in their work, it was not possible to detect any frozen bath on the vertical sides of the anode 90 minutes after setting. It is not known, however, whether the vertical sides were fully or partly covered with freeze at an earlier stage.

One possible explanation for this lack of freeze could be the formation of dendrites during the rapid freezing taking place shortly after immersion. The dendrites might then be removed from the vertical surfaces due to the intense gas induced convection in the inter-anode gap. It should also be noted that the first layer of bath which freezes onto the anode surface has the same composition as the bulk of the electrolyte (see below). Melting of such quenched bath starts at the solidus temperature, which is considerably lower than the liquidus temperature. The reason for the observed lack of freeze on the vertical surfaces after 90 minutes is not clear, however, and this calls for a further investigation. Valuable information would probably be obtained by taking out the anode blocks at shorter intervals after setting.

Figure 3 shows a representation of the frozen layer 259 minutes after anode setting. The frozen bath layer had then started to melt along the edges of the anode. Less of the layer was melted near the edge facing the side channel than on the centre channel side, however. This probably reflects a higher heat transfer coefficient at the centre channel. The "spikes" visible close to the centre of the anode are lumps of frozen crust that were captured during the rapid freezing taking place upon immersion.

Analyses of the bath layer revealed a gradient in composition throughout the layer. Close to the anode surface, the freeze composition was found to be the same as in the bulk of the liquid electrolyte (10.9 wt% access AlF_3 and 5.1 wt% CaF_2). Close to the outer surface of the frozen layer (formed ≈ 90 minutes after setting), the amounts of excess AlF_3 and CaF_2 were reduced to 5.2 wt% and 3.0 wt%, respectively.

The change in the analyzed bath compositions can be rationalized by considering the variation in the freezing rate. Upon anode setting, a layer of bulk bath will be quenched onto the anode surface. As the anode heats up and the frozen layer becomes thicker, the heat flux and hence the rate of freezing decreases. Lower freezing rates allow the removal of bath components by diffusion, until pure cryolite is obtained at equilibrium conditions (zero freezing rate).

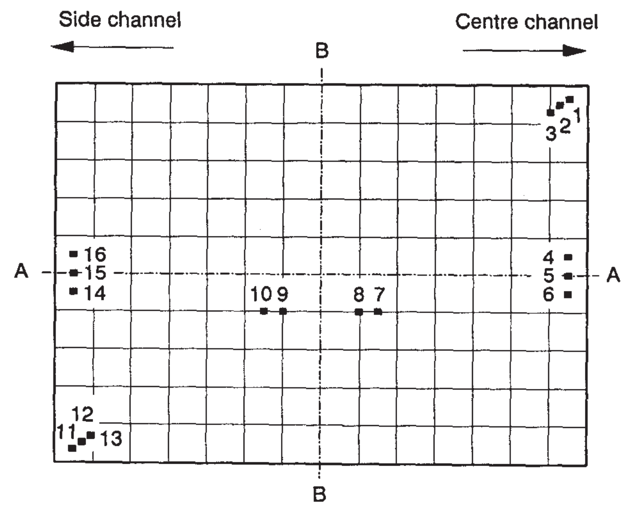

Figure 1: Planar view of the thermocouples positions when measuring the temperature distribution in anodes of a high amperage point fed prebake cell in a Hydro Aluminium plant. The distance between the thermocouples and the horizontal anode surface is given in the "result" section. Thermocouples 1 through 6 were facing the centre channel in the cell.

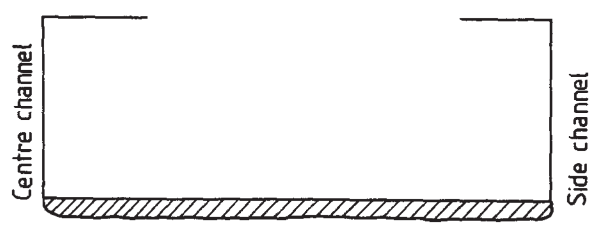

Figure 2: Observed layer of frozen bath on an anode block which was removed from the cell 90 minutes after setting. Section through the plane A-A in Figure 1.

Current Pickup

Figure 4 shows typical current versus time recordings for newly set anode blocks in a high amperage cell. The different curves are for anode settings higher than, according to, and lower than the standard practice in the actual Hydro Aluminium plant.

The middle curve in Figure 4 (anode setting according to plant practice) is similar to a simulated curve presented by Grjotheim et al. [1]. There are, however, two distinct differences between their simulations and our measured data: 1) In the present investigation there was a small, but detectable, current immediately after the anode setting. The simulations of Grjotheim et al., however, indicated a 200 minutes period from anode replacement to any detectable current. It is likely that

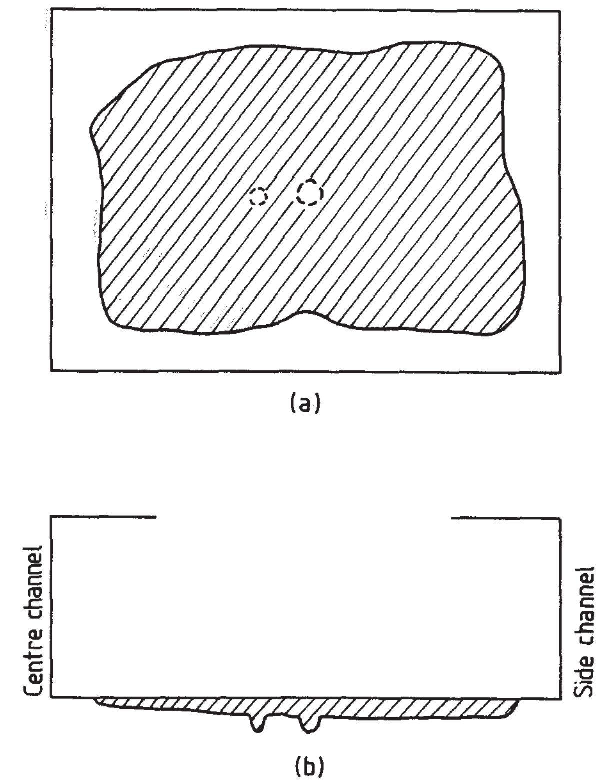

Figure 3: Observed layer of frozen bath on an anode block which was removed from the cell 259 minutes after setting. a) - Planar view of the freeze, b) - Section through the plane A-A in Figure 1.

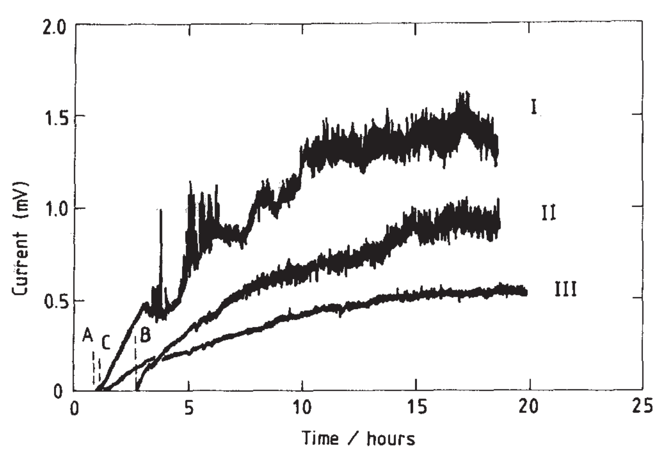

Figure 4: Typical current versus time curves recorded for replaced anode blocks in a high amperage Hydro Aluminium prebake cell. I - Anode set 2 cm lower than standard plant practice, II - Anode set according to standard plant practice, III - Anode set 2 cm higher than standard plant practice. The anode blocks were set at events "A", "B", and "C", respectively.

the reason for this discrepancy is the observed absence of frozen bath on the vertical sides of the anode block in the present work (Figures 2 and 3), whereas a rather long lived frozen layer was found also on the anode sides in the model of Grjotheim et al. [1]. 2) The current rise is much faster in the present investigation than simulated by Grjotheim et al. This discrepancy could be due to different overtemperatures and heat transfer coefficients, or to the above mentioned difference regarding frozen bath on the sides of the anode. Different setting strategies may also be important (same height as the butt, or higher setting? Random setting pattern, or subsequent setting of neighbouring blocks?).

In the present work, there was a good correlation between the visually observed freeze profiles (Figures 2 and 3) and the current pickup. From the current vs. time curves and the temperature measurements (see below), most of the frozen bath appears to be melted away about 15 hours after the anode setting. This period is, however, dependent on factors such as overtemperature, heat transfer coefficient and setting height. Setting the anode lower than standard practice leads to a more rapid increase in the current (Figure 4). However, a too low setting often gives operational problems later in the anode life [4,5]. On the other hand, anode setting higher than normal gives a very long period before the anode draws full current, which corresponds to about 1.4 mV voltage drop in the present investigation. With normal anode settings, the current will show a slow increase after 15 hours, because the standard plant practice requires that the new anode block should be set somewhat higher than the butt which is removed. It should also be noted that even after 15 hours, the anode is not fully thermally equilibrated. The higher parts of the anode reach steady state temperature only after 2-3 days.

Temperature in Newly Set Anode Blocks

The anode temperature during normal cell operation, as well as during periods when the current was shut of to that particular anode block, was discussed earlier [2,3]. Temperature variations related to anode replacement will be discussed below.

Typical temperature patterns for five different positions in a newly set anode are given in Figure 5. In accordance with the visual observations, the temperature measurements also indicate that the corners of the anode heat up fastest (positions 1 and 11). The data in Figure 5 indicate that the melting of the frozen bath layer near the centre of the anode (position 9) is manifested as a distinct increase in the rate of temperature rise, starting after about 12 hours. Hence, the visual observations, current recordings and temperature measurements all give a consistent picture regarding the heating of newly set anodes.

A common feature for all the anodes measured was that the temperature rise was faster in the part of the anode facing the centre channel of the cell, as compared to the part facing the side channel. This can also be observed in Figure 5 (positions 5 and 15, as well as positions 1 and 11). This phenomenon is probably related to the flow pattern in the cell.

Temperature Variation in an Anode Block due to the Setting of a Neighbouring Block

The temperatures were still recorded after the anode block had reached thermal equilibrium. The temperature response in the hot anode block due to the setting of a neighbouring block could then be studied.

Some typical temperature recordings for different parts of the anode are presented in Figures 6-8. The data indicate that the setting of the neighbouring block induced a temperature reduction; this effect being substantial on the side facing the cold anode (Figure 6). It should be noted that the cooling is larger high up in the anode than near the horizontal surface. Similar observations were made for several other anode settings. On the opposite side of the anode (turning away from the cold anode), the temperature reduction is small and of short duration (Figure 7). The cooling at that side probably reflects a temperature reduction in the bath. Figure 8 shows that the cooling near the centre of the anode is also found to increase with increasing distance from the horizontal anode surface. The effect of the next anode setting, 32 hours after the setting under discussion, can also be observed in this figure.

On the side of the anode facing the cold anode, the temperature response is so huge (more than 60 °C reduction) that it can not be explained by the slightly reduced bath temperature. Heat radiation from the warm anode block to the cold one can be a probable reason, however, as discussed below.

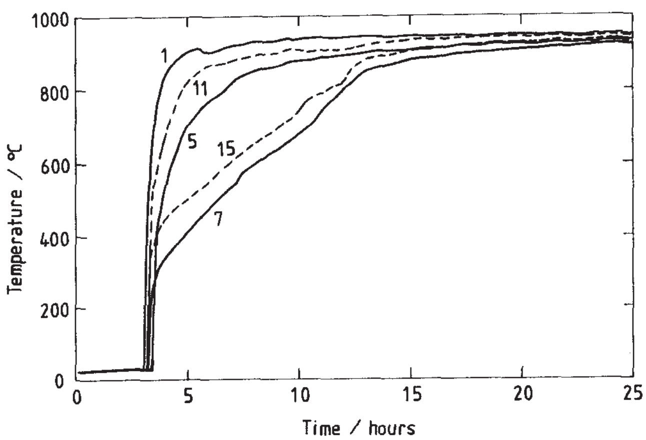

Figure 5: Typical temperature versus time curves recorded in thermocouple positions 1, 5, 7, 11 and 15 (see Figure 1) in a newly set anode block in a high amperage Hydro Aluminium prebake cell. The tip of all the thermocouples were located 2 cm from the horizontal anode surface at the time of setting.

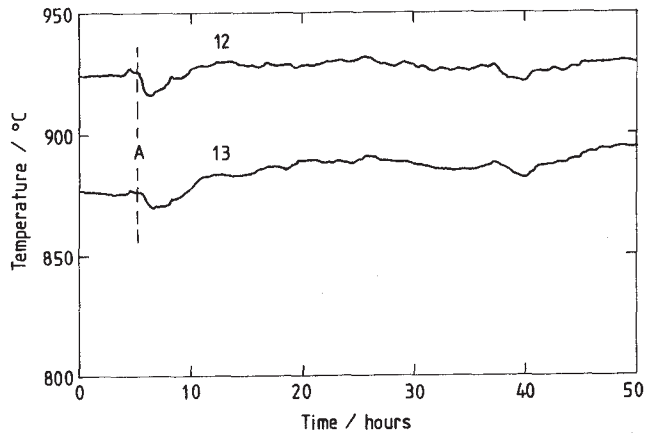

Figure 7: Temperature recordings in positions 12 and 13 (see Figure 1) in an anode block of a high amperage Hydro Aluminium cell. The neighbouring anode on the opposite side of the thermocouple positions was set at event "A". The tip of the thermocouples were located 9 and 19 cm from the horizontal anode surface, respectively, in the beginning of the time period shown in the figure.

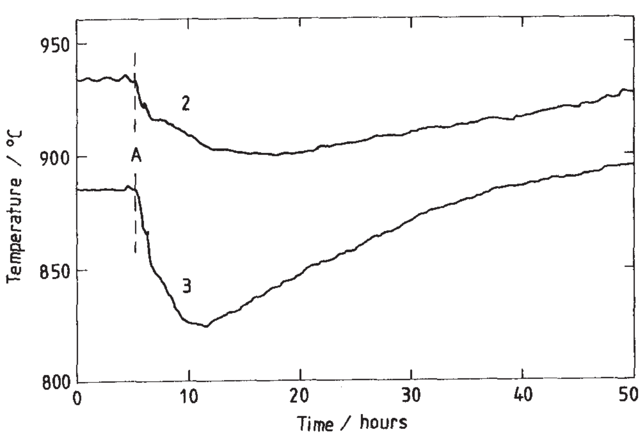

Figure 6: Temperature recordings in positions 2 and 3 (see Figure 1) in an anode block of a high amperage Hydro Aluminium cell. The neighbouring anode close to the thermocouple positions was set at event "A". The tip of the thermocouples were located 9 and 19 cm from the horizontal anode surface, respectively, in the beginning of the time period shown in the figure.

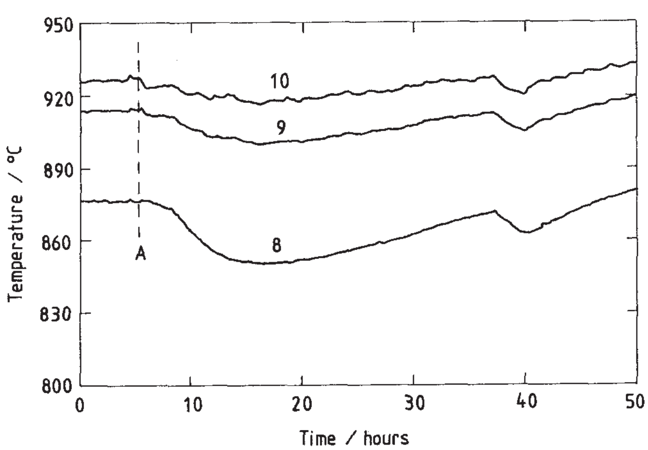

Figure 8: Temperature recordings in positions 8, 9, and 10 (see Figure 1), close to the centre of an anode block in a high amperage Hydro Aluminium cell. One of the neighbouring anodes was set at event "A". The tip of the thermocouples were located 19, 9, and 4 cm from the horizontal anode surface, respectively, in the beginning of the time period shown in the figure.

Cooling of the Anode by Heat Radiation

In industrial Hall-Héroult cells there normally exists an opening between the bath surface and the top crust. This gap may often be 5-10 cm high. When an anode butt is replaced, the new block is normally covered with a layer of crushed bath and/or alumina which will temporarily fill the space between the anodes. The heating of this cold powder will, of cause, extract some heat from the hot blocks. Due to the intense gas induced convection it is, however, reasonable to assume that the gap will be re-opened relative rapidly. This opening allows for direct heat radiation from the hot anode to the cold neighbouring anode. By using standard equations for radiation between parallel black surfaces, the heat flux is calculated to be 64 kW/m^2 when the two surfaces are at 800 °C and 400 °C, respectively. This calculation shows that the radiation from the neighbouring anodes hardly can be neglected when modelling the freeze profiles on newly set prebake anodes, even though the temperature difference between the surfaces, and hence, the heat flux, decreases relatively rapidly with increasing time of exposure. The discrepancies between the present investigation and the simulations by Grjotheim et al. [1] can probably partly be due to their assumption that radiated heat can be neglected. The effect of heat radiation will be further discussed below.

Numerical Calculations

In order to study the relative importance of various parametres such as heat transfer coefficients, heat radiation, and absence of freeze on the vertical sides of the anode, some numerical calculations were performed. The newly set anode and the neighbouring anode were modelled as sections through B-B in Figure 1. It was not intended to construct a complete model of the anode in an aluminium cell, since the calculations were performed only two-dimensionally. Two simplifications were also made, that may not be recommended for use in a more sophisticated model of the anode: 1) The heat production due to ohmic voltage loss within the anode was neglected, and 2) the thermal conductivity of the anode was assumed to be independent of the temperature. Nevertheless, the results obtained are believed to be realistic.

The specific heat capacity of the anode was assumed to vary from 0.99 $kJ \cdot kg^{-1} \cdot K^{-1}$ at 300 K to 1.93 $kJ \cdot kg^{-1} \cdot K^{-1}$ at 1300 K, in accordance with the JANAF data for graphite [6]. Other physical data used in the calculations are listed in Table I below.

Figure 9 shows the calculated freeze thickness at different positions as a function of time for situations when the vertical sides of the newly set anode block were assumed to be covered by a frozen bath layer. As can be observed, the entire surface is covered with freeze after 5 or even 8 hours, depending on whether heat radiation from the hot neighbours was taken into consideration or not. No current would be detectable during that period, and this is clearly not consistent with the findings in industrial cells, which were discussed above.

Calculated frozen bath thicknesses in situations where a frozen layer was assumed to be absent from the vertical sides of the anode are shown in Figure 10. It follows from the figure that the melting period depends on the heat transfer coefficient between bath and freeze; 1000 $W \cdot m^{-2} \cdot K^{-1}$ appears to be a more realistic value than 500 $W \cdot m^{-2} \cdot K^{-1}$. The results in Figure 10 are much more consistent with the observations in the industrial measurements than the results in Figure 9. Even though melting probably will take place somewhat faster in practice, due to the three-dimensional geometry, the results in Figures 9 and 10 indicate that both heat radiation and absence of freeze on vertical surfaces probably should be taken into account in constructing mathematical models related to the anode setting procedure.

Table I. Physical data used in numerical calculations.

Thermal conductivities;		
- anode material	6	$Wm^{-1}K^{-1}$
- frozen layer	1	$Wm^{-1}K^{-1}$
Heat of fusion, frozen layer	540	$kJ \cdot kg^{-1}$
Heat transfer coefficients;		
- at top of anode (including top crust)	8	$Wm^{-2}K^{-1}$
- at vertical anode surface, (bath-freeze or carbon)	2000	$Wm^{-2}K^{-1}$
- at horizontal anode surface, (bath-freeze or carbon)	Variable	
Ambient air temperature	200	°C
Bath temperature	968	°C
Liquidus temperature	960	°C
Anode block temp. at moment of immersion	30	°C
Anode immersion depth	0.15	m
Interpolar distance, corresponding to maximum allowable freeze thickness	0.05	m

Figure 11 shows calculated temperatures versus time in a hot anode block being exposed to a newly set cold neighbouring block. The temperatures (with radiation included) follow similar patterns as in Figure 6. The differences between Figure 6 and Figure 11 can partly be explained by the fact that the distances from the vertical and horizontal surfaces to the thermocouple were slightly different in measurement and simulation. It is probably more important, however, that the data in Figure 6 were obtained with thermocouples located close to a corner, which allowed heat to be transported to the thermocouple from two directions.

The temperature reduction in the hot block due to radiation towards the newly set anode block gradually became smaller with increasing distance from the radiating surface, and any effect of heat radiation could not be detected near the side turning away from the newly set block. This is in agreement with the observations in Figure 7 and Figure 8. The observed temperature reduction in Figure 7 is of short duration and probably due to the reduced bath temperature, which was not taken into consideration in the present modelling procedure, however.

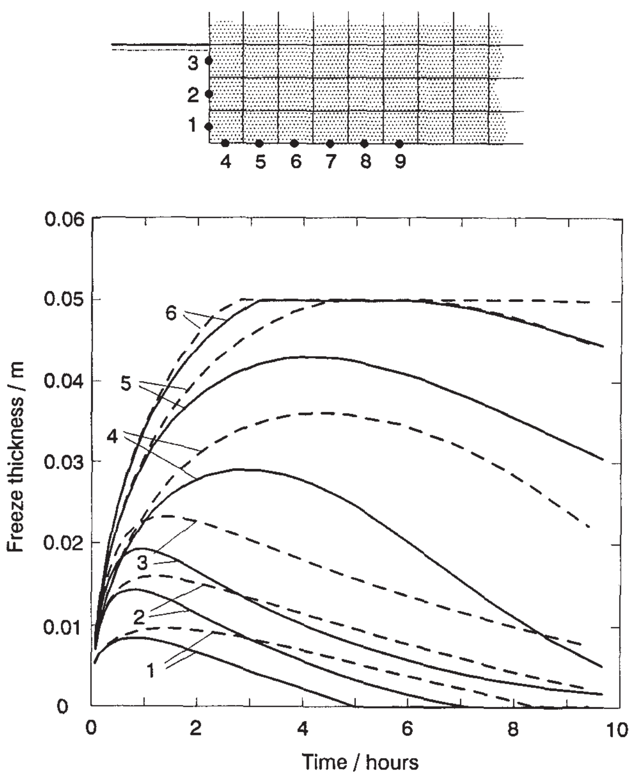

Figure 9: Calculated thickness of frozen layer as a function of time for a newly set anode block. The numbers in the figure refer to the positions shown in the upper part of the figure, which represents a section through B-B in Figure 1. Heat transfer coefficient from bath to horizontal surfaces: 1000 $W \cdot m^{-2} \cdot K^{-1}$, other data as in Table I. Full lines - heat radiation from the hot neighbouring anode blocks taken into consideration, broken lines - radiation not taken into consideration.

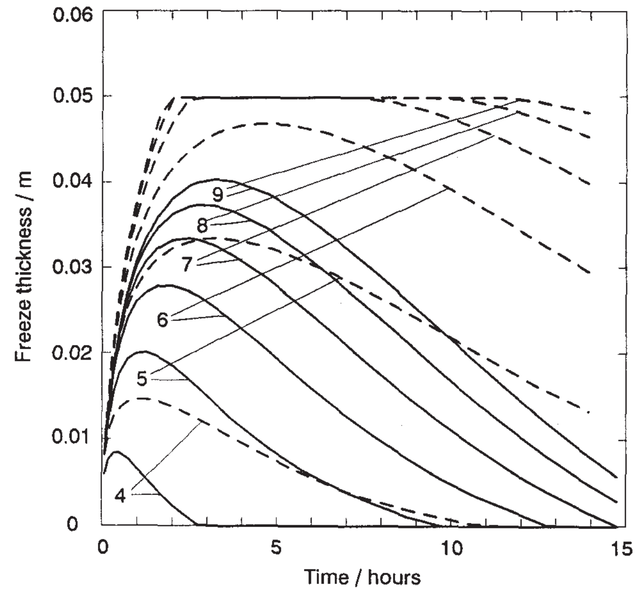

Figure 10: Calculated thickness of the frozen bath layer as a function of time for a newly set anode block. It was assumed that no formation of freeze took place at the vertical surfaces. Heat radiation from the hot neighbouring anode blocks was taken into consideration. The numbers in the figure refer to the positions shown in the upper part of Figure 9. Full lines - heat transfer coefficient from bath to horizontal surfaces equals 1000 $W \cdot m^{-2} \cdot K^{-1}$, broken lines - 500 $W \cdot m^{-2} \cdot K^{-1}$. Other data are given in Table I.

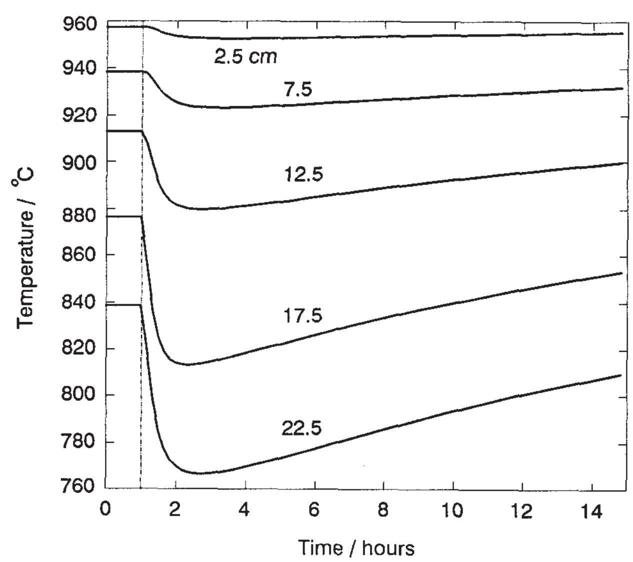

Figure 11: Calculated temperature response in a hot anode block due to heat radiation towards a newly replaced block. The results are shown for points located at line B-B in Figure 1, 7.5 cm away from the radiating surface. The distances from the horizontal anode surface are given in the figure. The heat transfer coefficient from bath to horizontal surfaces was assumed to be 1000 $W \cdot m^{-2} \cdot K^{-1}$. Other data are given in Table I.

Conclusion

Visual observations of the bath layer which freezes onto the horizontal part of newly set anode blocks in prebake Hall-Héroult cells showed that at maximum, this layer had a thickness corresponding to the interpolar distance. In the present work no frozen bath could be detected on the vertical sides of the new anodes, however. The reason for this is not clear.

The measured current pickup and temperatures in newly set anodes showed good correlation to the visual observations. At normal anode settings there was a small, but detectable current immediately after setting, which probably can be related to the observed absence of freeze on the vertical part of the anode 90 and 259 minutes after setting.

Temperature measurements within hot anode blocks during periods following the replacement of neighbouring butts showed that the newly set block induced a substantial temperature reduction in its hot neighbours. This cooling is interpreted as mainly being caused by heat radiation from the hot anode to the cold one.

Numerical calculations showed that the melting of the frozen bath layer was unrealistic slow, unless it was assumed that 1) the vertical sides of the anode block were free from frozen bath, and 2) heat was extracted from the hot neighbouring blocks by radiation.

Radiation from hot anode blocks to the newly set block should probably be taken into consideration when trying to establish the optimal anode setting procedure (i.e., subsequent setting of neighbouring anode blocks or a more random anode setting pattern). The reason for the observed absence of frozen bath on the vertical part of the anode should be investigated further, e.g., by taking out the anode blocks at shorter intervals after setting.

Acknowledgement

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References

1. K. Grjotheim, B.J. Welch, and M.P. Taylor, "Relating Operating Strategy and Performance in Aluminium Smelting Cells - an Overview", Light Metals 1989, pp. 255-260.

2. R. Ødegård, S. Julsrud, A. Solheim, and K. Thovsen, "A Study of the Electrochemically Induced Cooling of the Anode in Hall-Héroult Cells", Light Metals 1991, pp. 307-313.

3. R. Ødegård, S. Julsrud, A. Solheim, and K.Thovsen, "A Thermodynamic and Experimental Study of the Electrochemically Induced Cooling of the Anode in Hall-Héroult Cells", accepted for publication in Met. Trans. B (1991).

4. M.P. Taylor, "Static and Dynamic Energy Balance in Reduction Cells", Proceedings of the 10th International Course on the process Metallurgy of aluminium, May 27-31, 1991, pp. 14.1-14.60, Institute of Inorganic Chemistry, N-7034 Tondheim, Norway, 1991.

5. Personal communications, Potroom supervisors of Hydro Aluminium, Norway, 1990.

6. JANAF Thermochemical Tables, Third Edition (J. Phys. Chem. Ref. Data, Vol. 14, Suppl. 1, 1985).