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THERMAL EFFECTS BY ANODE CHANGING IN PREBAKE REDUCTION CELLS

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Abstract

Thermal effects caused by anode changing in prebake alumina reduction cells were studied by temperature measurements using thermocouples located at different positions inside the anodes. Anode changing caused a temperature reduction in the nearest neighbour anode of typically 20 to 40°C, as measured close to its working surface. The minimum temperature was recorded about 5 hours after the anode change, and it could take up to 24 hours before the old anode again showed a stable temperature reading. The cooling effect is due to heat radiation losses to the new anode, and thus the heat balance of the neighbouring anodes is altered significantly after an anode change. Temperatures were also measured inside the newly set anode. If the new anode on purpose was set too low by 20 mm to provoke formation of a spike on the working surface, the measured temperature inside this anode could reach as high as 1080 °C.

Introduction

Anode changing in prebake aluminium electrolysis cells is the routine operation that introduces the largest single thermal disturbance. Thus, it changes the heat balance, causing a significant energy drain at a particular location in the cell. For a modern anode weighing about one tonne, this drain amounts to about 10 kW over the anodes life span. This corresponds to 0.18 kWh/kg Al, assuming the anode will reach an average temperature of approximately 900 °C at steady state. This energy drain cannot be supported by heat transfer from the bath alone, and freezing of bath on the new anode inevitably occurs. Mathematical simulations (1,2,3) and experimental observations (*1,2*) have shown that the bottom of a newly set anode rapidly will be covered by a layer of frozen bath. At its maximum the layer of frozen bath on the horizontal part of the anode has been found to extend over the whole interpolar gap. Parts of the frozen bath can persist on the bottom of the anode for up to 24 hours after the new anode was set (1, 3).

The insulating layer of frozen bath will also affect the magnetic field in the cell causing other disturbances, i.e. local changes in bath and metal velocities and flow patterns. In addition the heat balance of the cell will be disturbed.

Ødegård et al. (*2*) showed that the thermal balance of the nearest neighbour anode was affected when a new anode was set. Thermocouples placed in various positions in an anode next to the one being replaced, revealed temperature drops of more than 60 °C in some positions close to the new anode. This drop was more pronounced at positions above the bath level. The same trend was found for the central part of the anode where a temperature drop of 10 °C was found 4 cm above the bottom, compared to 30°C observed 19 cm above the bottom of the anode. This thermal response could be explained by heat radiation in the gap between the anodes above the bath level being the dominant heat transfer mechanism between a hot anode and a newly set anode.

The observed temperature drops were much higher than the difference between the bulk bath temperature and its liquidus temperature (the superheat), thus indicating a possible formation of freeze also on the neighbouring anodes. To throw more light on these problems two series of experiments were conducted where the thermocouples were placed close to the bottom of the anode.

Experimental

The experiments were performed on 176 kA point fed prebake anode cells at the Hydro Aluminium Karmøy plant in Norway. Ready-made commercial K type thermocouples (Chromel-Alumel) shielded by stainless steel tubes were used. Inside the anode block they were protected by 10 mm mullite tubes ("Pythagoras", Haldenwanger). Measurements were performed in both old and new anodes. Fig. 1a shows the thermocouple position in the old anodes. Eight vertical holes were drilled pairwise at approximately 80 mm distance in each anode (16 mm diameter of the hole). The pairs of holes were placed symmetrically relative to the longitudinal axis on either side of the anode. Normally four thermocouples were used during each run. The depth of the holes was adjusted according to the expected wear rate of the anode, so that the thermocouples were 20 mm from the bottom of the anode when the neighbouring anode was changed. This means that one set of holes was drilled to the expected depth when the neighbouring anode on one side was replaced, while the other set of holes was drilled to a depth calculated to be 20 mm from the bottom when the anode on the other side was changed.

The thermocouple signals were recorded and stored by means of a portable data logging unit (AAC-2, INTAB, Sweden). The data were logged with 10 seconds intervals, and the average value of every three readings was stored. The thermocouples were not calibrated because we were more interested in the temperature variations rather than obtaining precise absolute values.

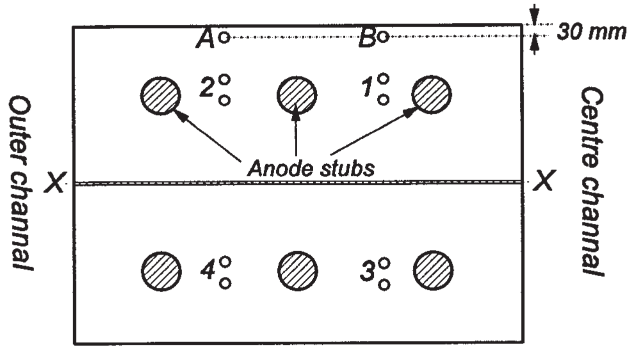

Figure 1a. Planar view of the thermocouple positions inside the old anode (see text for further details). Anodes which were split, were cut along the X - X axis.

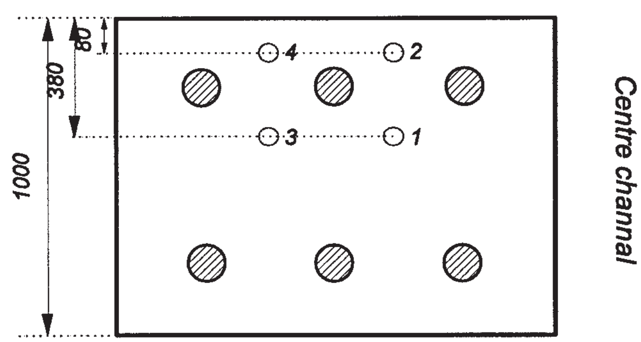

Figure 1b. Positions of the thermocouples (1- 4) in the new anode.

For measurements inside the newly set anode, the thermocouples were placed in positions 1 through 4, as shown in Fig. 1b. In this case the thermocouples were located about 50 mm above the working face of the anode.

In some experiments the current through each of the six anode stubs in the anode was monitored by measuring the voltage drop across a fixed distance on the yoke. The purpose was to determine if the current distribution within an anode was affected by the presence of a cold neighbour. This type of measurements can only be taken as rough estimates because the yoke geometry is not the same for the stubs in the corner position and the stubs in-between. Some experiments were also performed with anodes that were cut in two halves along the longitudinal plane, as shown in Fig. 1a. The distance between the two halves was either ~8 or ~3 mm.

A series of experiments was also conducted with a heat insulating plate fixed to the one side of the new anode facing the measured anode. The purpose was to reduce the radiative heat flow between the two anodes. In addition the remaining space between the anodes was filled with alumina immediately after the anode was set. Two additional holes for thermocouples were drilled parallel to the side of the anode at positions A and B, as shown in Fig. 1a. The depth of the holes was adjusted to give one thermocouple reading below the bath level at a distance of approximately half the depth of the anode immersion. The other hole ended above the bath level at approximately half the distance to the top of the anode.

Results and discussion

Measurements in a newly set anode

Fig. 2 shows recorded temperatures as a function of time after anode changing. Positions 2 and 4 close to the side of the anode had the fastest heat-up rate. After about six hours the temperature difference of these positions, compared to positions 1 and 3, was more than 200 °C. It took about 40 hours to stabilize the temperatures close to the working face of the anode, and even then the thermocouples showed slightly different temperatures.

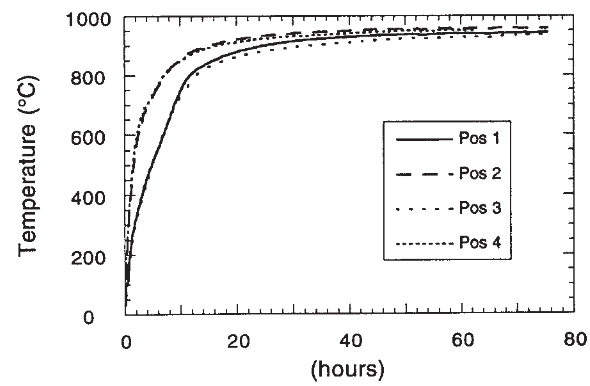

Figure 2. Temperature versus time in a newly set anode. Positions of the thermocouples are shown in Fig. 1b.

Measurements in an old anode when the neighbouring anode was changed

An anode on the "downstream" side of the cell was equipped with thermocouples, and temperatures were recorded when the nearest neighbour anode (on the side where the thermocouples were placed), was changed. The positions of the thermocouples in the old anode were identical to those shown in Fig. 1b. The results are shown in Fig. 3. The largest temperature drops, about 20°C, were recorded in positions 2 and 4, while positions 1 and 3 showed drops of only 8 to 10 °C. About 1.5 hours after anode change had occurred, the temperatures became constant for about 3 hours, before they continued to decrease. A possible explanation is that the surrounding bath then had reached its liquidus temperature, and stayed there while some bath froze on the old anode.

The minimum anode temperatures were reached after 5 to 7 hours. Fig. 3 also shows that the bath temperature, when measured at a position in the cell three anodes away from the new anode, decreased by about 5 °C immediately after the anode changing, and it took 8 to 10 hours before it became stable again. Thus, these temperature measurements may then be interpreted to indicate that some bath may freeze on the surface of the old anode when its nearest neighbour is changed. This was studied in a separate experiment, and will be discussed later.

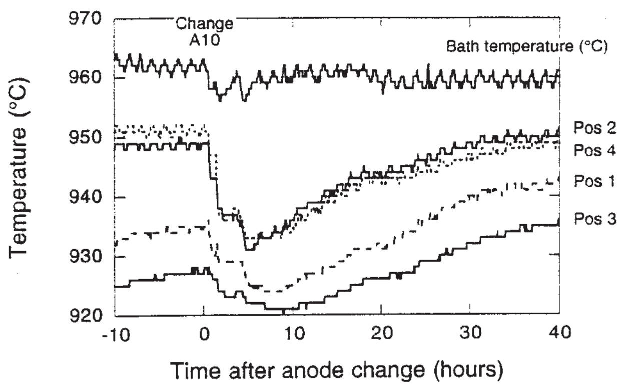

Figure 3. Temperature <u>versus</u> time in an old anode when the neighbouring anode was changed. Positions of the thermocouples were as shown in Fig. 1b. The bath temperature was also recorded.

<u>Measurements in a split anode</u>

Temperature recordings of thermocouples placed in a split anode (as seen in Fig. 1a), are shown in Fig. 4. The data are typical in the sense that they show a pronounced difference between the thermocouples placed in positions 1 and 2 (at a horizontal distance of 1/4 of the anode width from the long side facing the new anode) and positions 3 and 4 on the other side of the anode. The thermocouple readings on the cold side (nearest the new anode) dropped ~ 20°C after the new anode was set, and the minimum temperature was reached after about 5 hours. The thermal disturbance lasted approximately 24 hours after the anode changing.

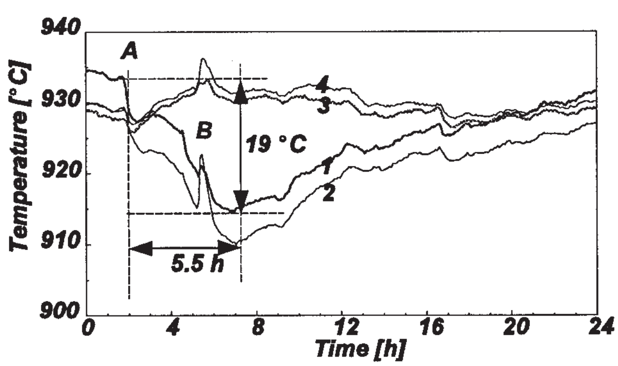

Figure 4: Temperature recordings in an anode next to the anode being changed at time A. The thermocouples were positioned 20 mm above the bottom of the anode. Positions 1 and 2 were located about 1/4 of the anode width from the side wall facing the new anode, while positions 3 and 4 were located at the same distance from the opposite side (see Fig. 1a). The event marked B is an unexpected temperature rise not found in any of the other experiments.

With a bath superheat normally in the range between 5°C and 15°C, an observed temperature drop of ~20°C only 20 mm from the bottom of the anode justifies the assumption that a layer of frozen bath had been formed on the old anode. This means that the anodic current distribution should be affected because the frozen bath would act as an electric insulator. In Fig. 5 this effect is demonstrated as the ratio between the sum of the currents passing through the stubs on the hot side and the cold side of the anode is plotted together with some the temperature data from Fig. 4. Immediately after the anode change (at time A) a shift in current distribution towards the hotter side of the anode occurred. The shift lasted for approximately 10 hours and it coincides with the period with the largest temperature difference between the thermocouples in the hot and cold side of the anode block.

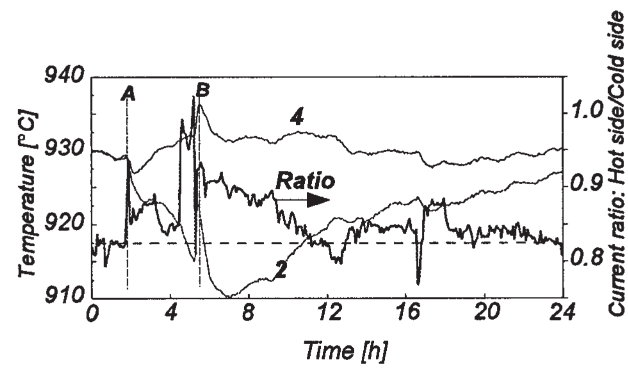

Figure 5. Data from the same experiments as shown in Fig.4. The ratio between the sum of the currents measured through the stubs on the hot side of the anode and the stubs on the cold side (right hand scale) is plotted together with selected thermocouple readings shown in Fig.4.

The event at point B in Figs. 4 and 5 is clearly manifested as peaks in the temperature curves. It is probably associated with the covering of the new anode with alumina/crushed bath. This is normally carried out four hours after the anode is changed. Except for the fact that a raise in temperature also was observed on the hot side of the anode, a detachment (scaling off) of frozen bath due to mechanical shocks caused by the anode covering operation is a possible explanation. This would mean that frozen bath adheres loosely to the anode. The temperature recordings resumed their normal trends within one hour. If the hypothesis above is correct, it means that a new solid layer was reformed during this interval. It is interesting to note that the current distribution was influenced by this event, but as long as no other series of experiments showed similar behaviour, this must be considered as speculation.

Another interesting feature in Fig. 4 is the thermal arrest observed for the thermocouples on the cold side approximately 1 hour after the anode change. Similar arrests were found in some of the other experiments (see Fig. 3), but not in all. A more distinct thermal arrest is shown in Fig. 6. These recordings were made in the same anode as in Fig. 5, but when the anode on the other side was changed. The thermocouples were placed in approximately the same positions as those shown in Fig. 4 and were numbered accordingly. The "shoulder" on the curves lasted for approximately one hour, and the thermocouple readings levelled out at a temperature 4 - 6 °C below the "stable" values recorded prior to the anode changing. The temperature drop was of the same magnitude as the normal bath superheat. As mentioned above, one explanation is that the shoulder is associated with the formation of freeze on the anode. Thus, in the period when bath is beginning to freeze out on the anode, the temperature will remain constant until a sufficiently thick layer is formed. This freeze will then block the current. Gas induced stirring will be reduced and the thicker freeze will act as a thermal barrier against heat flow from the bath to the anode. In Fig. 6 a period with constant temperature was found also for the two thermocouples in the hot side of the anode. However, only the temperatures in the cold side decreased significantly after the initial period with constant temperature. This means that similar to the experiment shown in Fig. 4, a frozen layer of bath was formed only on the part of the anode close to the new anode.

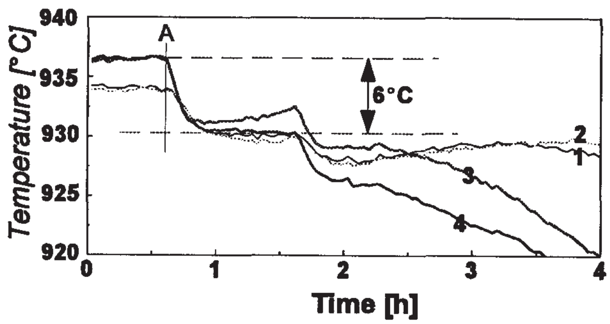

Figure 6. Temperature recordings in the same anode as shown in Fig. 4, but four days later when the anode on the other side was changed at the time A. The thermocouples were placed in approximately the same positions as those in Fig. 4.

Results from other series of measurements are given in Table 1. The temperature drop to the thermal arrest is given (if a distinct shoulder on the curve was found), together with the maximum temperature drop and the length of time to reach the minimum temperature. The temperature drop to the shoulder is around 5°C, but from the data in the table no explanation may be found why this phenomenon was observed only in some cases. Concerning the maximum temperature drop there appears to be a slight increase with decreasing temperature measured prior to the anode changing operation. This is expected assuming that the temperature measured close to the anode bottom reflects the bath temperature. One would suspect the observation of a bath temperature of 920°C prior to the anode change to be erroneous, but in this case the maximum temperature drop was very high (40°C). When normal and split anodes are compared one might expect somewhat higher temperature drop in the "cold" side when the anodes were split. However, the scatter in the present data is too large to confirm this.

It is difficult to find any correlation between the various experimental data and the dependent variables listed in Table I. Because the measurements are from different cells or from the same cell but taken several days apart, the absence of any significant correlation may not be surprising. It is possible that this reflects the range of variable conditions that can exist and affect the thermal balance within the cells.

Figure 7 shows results from an experiment where bath samples were taken in the vicinity of the anode during a period extending from approximately one hour before until approximately one hour after the anode changing operation. The temperature in the bath was measured in the same positions for comparison with the liquidus temperature of the bath. The liquidus temperatures were measured after the experiments in a special apparatus designed for that purpose (5). Fig. 7 shows that the liquidus temperatures in this period varied roughly proportionally to the bath temperature, giving a constant superheat. After the anode changing the liquidus temperature decreased to the range of temperatures measured inside the anode (~ 20 mm from the bottom). For the last bath sample three of the thermocouples showed readings above the liquidus temperature. This should rule out the possibility of any formation of frozen bath on the anode at these locations.

Table I. Results from temperature measurements in anodes next to the anode being changed. The tips of the thermocouples were placed about 20 mm above the bottom of the anode when the anode changing occurred (see text).

Split anode	Av. temp. prior to the anode changing (°C)	Age of measured anode (days)	Temp. drop to shoulder (°C)	Max temp drop (°C)	Time to reach minium temp. (h)
Yes	946	12	~5	22	4
Yes	946	20	~ 5	22	6
Yes	959	9	4 - 7	19	6
Yes	931	7	6	19	5.5
Yes	935	11	6	24	5
No	920	7	5 - 7	40	6
No	953	15	n.d.	15	3
No	950	7	5	13	7.5
Yes	951	6	n.d.	17	5
Yes	947	10	n.d.	15	3.5
Yes	940	15	n.d	19	5
n.d. = not determined			Average:	20 ± 7°C	5 ± 1h

Analyses of the bath samples showed good agreement between the measured and the calculated liquidus temperatures based on the liquidus equation given by Solheim et al. (4), as shown in Fig. 8. The samples were analysed with respect to alumina in a LECO apparatus. The AlF_3 and CaF_2 contents were collected from plant data based on routine bath analysis taken twice a week. It was assumed that the anode changing had a negligible effect on the contents of these bath components. The good agreement shown in Fig. 8 supports the assumption that the drop in liquidus temperature can be explained by an increase in the concentration of dissolved alumina caused by the anode changing. With a constant superheat as indicated by the data in Fig.7, this means that the change in bath temperature to a large extent is determined by this increase in alumina concentration

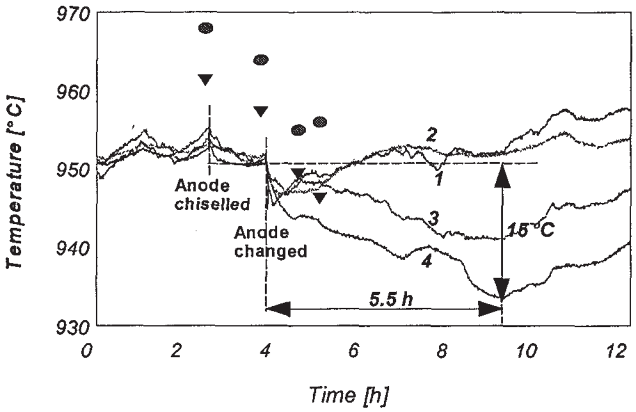

Figure 7. Identical to Figs. 4 and 5. Thermocouple positions 3 and 4 were this time facing the new anode, while positions 1 and 2 were on the opposite side. Circles show bath temperatures measured immediately before bath sampling, while triangles represent the measured liquidus temperatures of the bath samples.

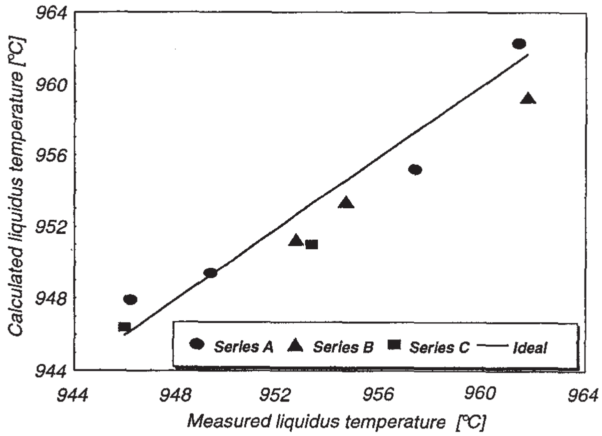

Figure 8. Measured liquidus temperatures compared to liquidus temperatures calculated from bath analysis data (5).

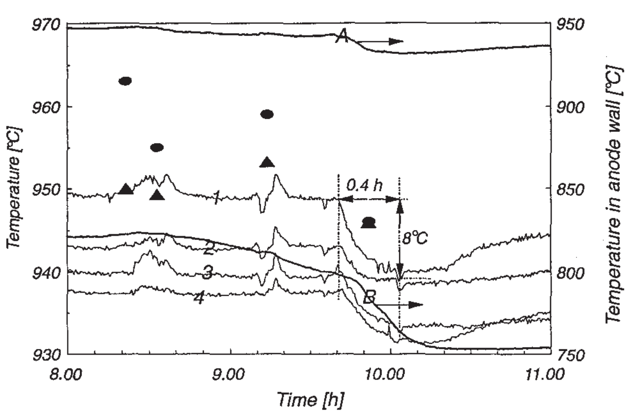

Figure 9. Measurements with an insulating plate fixed to the side of the new anode facing the neighbouring anode equipped with thermocouples as shown in Fig. 1a. Lines, A and B, represent temperatures measured in the anode side facing the new anode at a level below and above the bath, respectively (see text). Lines 1 - 4 are identical to those in Fig. 4. Other symbols as in Fig. 7.

Measurements with an insulting plate between anodes.

Fig. 9 shows results obtained with an insulating plate placed between the new anode and the neighbouring anode. It is evident that the plate reduced the heat transfer between the two anodes.

The maximum thermal drop in the neighbouring anode in this case was approximately 8 °C, which is far below the temperature drops shown in Table I. Perhaps more striking is the difference in the time needed to reach the minimum temperature. Figure 9 shows a value of about 0.4 hours for the measurements with the insulating plate, which is less than 10 per cent of the times shown in Table I. These observations indicate that a major part of the heat flux between the anodes is caused by radiation in the air gap above the bath level. The insulating plate was not insoluble in the cryolite melt and it was expected that the part extending below the bath level would dissolve rapidly. At temperatures above 800 °C in the side of the anode, as shown in Fig. 9, it can be shown that heat transfer by radiation will be dominating compared to heat transfer by convection in the "air gap" between the anodes .

The drop in bath temperature caused by the anode changing in this experiment is about the same as the for the experiment shown in Fig. 7. However, it is interesting to note that the bath temperature dropped to the liquidus temperature of the bath. As in the previous experiment bath samples were taken at the same time as the temperature was measured. In this case the liquidus temperature was higher than the temperature measured in the neighbouring anode.

Provoking formation of anode deformations or spikes

Fig. 10 shows recorded temperatures in different positions inside an anode which was purposedly lowered by 10 mm in order to provoke a deformation or spike. This anode then had been changed 16 shifts earlier. As seen from the voltage curve, the current through the anode then immediately started to vary significantly. After about 2 hours the thermocouples showed a slight temperature increase, and after about 8 -10 hours temperatures around 1000 °C were recorded by two of the thermocouples. The current through the anode increased by a factor of 2, and was rather unstable. This anode then developed a deformation, with a thickness of about 10 mm and extending over approximately half the working surface of the anode. This was observed after 15 hours when it was taken out of the cell for visual control and for milling of the working surface.

Does the bath freeze on the vertical sides of the anode?

Formation of freeze on the vertical sides of the anode has been suggested earlier in the literature (1). In order to check this, a new anode was taken out of the cell after one hour. The whole working face of the anode was then covered by a 30 to 40 mm thick layer of frozen bath, which dropped off when the anode was moved out of the cell by the crane. There was no sign of any solid bath on the vertical sides of the anode. The nearest neighbour anode was also taken out for visual inspection. There was no solid bath adhering to either the sides or the bottom of this old anode.

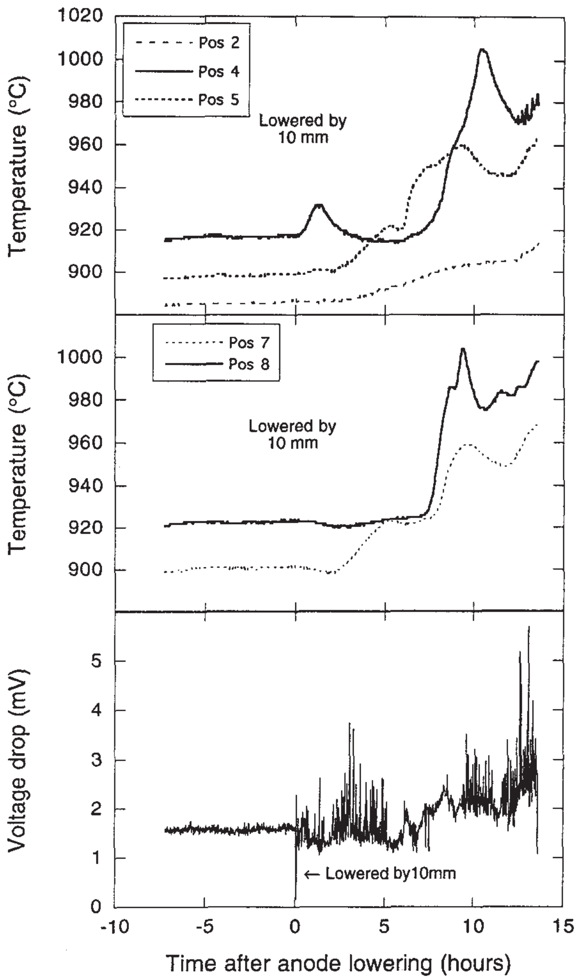

Figure 10. Temperature and voltage drop versus time for a 16 shift (128 hours) old anode that was lowered by 10 mm. An anode deformation then had developed after 15 hours.

Measurements of the current pick-up rate of new anodes showed that they start to pick up current immediately. This must mean that the current then mainly goes through the vertical sides of the anode during the first hours after changing. Full current is usually reached after 30 hours in the cell.

A possible explanation for the observation of no freeze formation on the vertical sides of a newly set anode may be that the freeze, if it is formed, is easily detached. In the initial period immediately after the anode is immersed into the bath, a relative large volume of air must escape from the pores within the anode due to the volume expansion caused by the heat-up. It seems reasonable to assume that a large part of this air will escape through the sides of the anode creating turbulence and increased heat transfer from the bath. The gas from the nearest neighbour anodes will add to this turbulence. Later the anode gas created by the steadily increasing current passing through the sides of the anode may become the dominant factor, thus obstructing formation of a freeze covering all of the sides of the anode. It should be noted that the heat transport above the bath level occurs radiatively from the neighbour anodes, and this may also be a contributing factor. A partial covering of the sides cannot be ruled out, however. This freeze would then in any case be very thin, and it would probably fall off easily due to shaking and vibration when the anode is taken out for inspection..

Summary and conclusions.

Temperature measurements at different positions inside prebake anodes gave the following results:

- In a newly set anode the temperatures can vary about 200°C over a horizontal distance of about 300 mm during heating. It may take more than 40 hours to reach stable temperatures close to the working face of the anode.

- When a nearest neighbour anode was changed, the temperatures decreased for 5 to 7 hours, and it took totally 8 to 10 hours to reach a stable temperature again in the old anode. The temperature reduction was typically 20 °C, as measured 20 mm above the working face and 90 mm from the side of the anode.

- The cooling of an old anode when a neighbouring anode was changed, is probably due to considerable heat loss by radiation in the "air gap" between the anodes. The presence of an insulating plate mounted between the two anodes reduced the temperature drop from about 20 to 8 °C, and the minimum temperature then appeared after only half an hour.

- If an old anode was lowered by 10 to 20 mm to provoke a deformation or spike on the working surface, temperatures above 1000 °C were recorded in most cases, and the highest temperature then was 1080 °C. This implies that there must be a considerable change in the current distribution inside the anode in these cases.

Acknowledgments

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