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

ANODE SIGNAL ANALYSIS – THE NEXT GENERATION IN REDUCTION CELL CONTROL

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Keywords: Anode current signals, reduction cell control

Abstract

Reduction cells have achieved excellent control capability over the past 20 years by improved acquisition and treatment of the cell resistance signal, which provides the basis for regulation of alumina feeding, thermal balance and cell stability. As cells become larger in size however, there is an increasing need for control sensors that can recognize and react to spatial variation in the cell both in terms of anode performance and alumina feed control. Monitoring of individual anode current signals can provide the 'next generation' control capability that will be necessary to ensure that very large cells can deliver the same process efficiencies as their smaller predecessors. Coincidently, anode signals can now be acquired, stored and processed with far greater convenience and lower cost than was possible in the past, making an enhanced control capability within practical reach.

Introduction

Aluminium smelting cells are controlled in real time by the continuous monitoring of the cell pseudo-resistance or normalized voltage signal[1] at an acquisition frequency typically in the range 1-20 Hz. This one signal provides the basis for the core control requirements of the cell, namely the regulation of the alumina feed rate, the regulation of the heat input, and the maintenance of magneto-hydrodynamic stability. Of necessity therefore, this one signal describing the state of the cell generates control responses which assume that the cell is homogeneous in nature. Thus, the key control responses are:

<u>Alumina feeding</u>. Alumina addition is initiated in response to tracking of the filtered resistance signal, when threshold values for resistance rise and / or slope derivatives are attained. A number of feeders are activated that are intended to disperse alumina evenly to all regions of the cell. Although the control capability exists to distribute the alumina in a non-uniform way, there is no intelligent basis for doing this as the composite resistance signal assumes that the alumina concentration is uniform throughout the cell.

<u>Adjustment of the anode plane</u>. Control of the anode-cathode spacing (ACD) is critical in maintaining cell stability, in regulation of the heat balance, and in achieving efficient production levels (Faraday efficiency, specific energy consumption and anode consumption). This control is achieved by automatic adjustment of the anode bridge, to which all anode assemblies in the cell are attached, in response to the cell resistance signal. Modern prebake cells typically contain up to 40 anodes, each in parallel electrical connection to the anode bridge. As such, the ACD for individual anodes will vary depending on the resistance of each anode assembly, which may be affected by the anode quality, the actual anode area, the resistance of the electrical connections etc. Problems with individual anodes are detected as 'noise' in the composite cell resistance, but the control response is achieved inefficiently by movement of the entire anode plane rather than by addressing the individual anode(s) that is causing the problem.

As the current rating of modern reduction cells extends to 400 kA and beyond, the ability to control the cells efficiently to a single resistance signal becomes increasingly difficult:

- The larger physical size of the cells means that the assumption of homogeneity in cell state that is implicit in the alumina feed control response must be questioned. Specifically, it becomes increasingly difficult to detect and avoid anode effects which arise as a localized cell state when the control signal is increasingly diluted by larger cell size.
- As the cell size increases, so too does the number of anodes in the cell. This increases the probability that some anodes will have defective performance, but at the same time the increasing dilution of the resistance signal means that the ability to detect problems with individual anodes is diminished.
- Large, modern cells are required to operate at lower ACD than smaller cells in order to achieve satisfactory heat balance. This places even more importance on maintaining excellent anode performance, and detecting problem anodes as they arise.

Clearly, there is an increasing need to recognize spatial variation in large, modern cells that is not achievable by use of the cell resistance signal alone. This paper demonstrates, through some specific examples from operating cells, that individual anode current signals have the potential to recognize spatial variation and offer a significantly enhanced control capability.

Background and Context

The concept of using individual anode current signals for cell control is not new [1-8]. Major companies including Alcan, Alcoa and Pechiney have all evaluated cells using anode current sensing, coupled with the capability for independent movement of individual anodes. Alcoa still use this technology in their P-225 potlines operating at Tennessee since 1972, but have not implemented the concept in their subsequent smelters. This lack of commercial exploitation would suggest that the potential control advantages from individual anode monitoring are outweighed by the additional cost and complexity of fitting cells with individual anode adjustment capability.

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[1] Pseudo-resistance $R = (V-E)/I$
Normalised voltage $V_N = [(V-E)/I]*I_N + E$
Where V and I are instantaneous voltage & current, E is the back emf (value typically used is 1.65V)

The context today is very different to when the potential for individual anode monitoring and control was first evaluated more than 30 years ago however. Consider the following factors:

- Cells are now much larger, generating spatial variation and dilution of the resistance control signal as noted above. Both factors impede efficient control.

- Anode signals can now be acquired, stored and processed with far greater convenience and lower cost than was possible in the past. Non-contact sensors based on the Hall effect allow continuous monitoring without interference from anode change operations. Bluetooth technology allows wireless transmission from the sensor to the local cell controller. The ever-decreasing cost of computer memory allows high frequency acquisition and intelligent processing of the current signals to make effective control decisions in a way that was not possible in the recent past.

- The demands on cell control are now much greater. In particular, a high cost may be assigned in the near future to the occurrence of anode effects and the greenhouse gases that they generate. Similar considerations apply to the efficient consumption of anodes.

In this modern context, it is appropriate to reconsider the value of individual anode current monitoring and how it may be applied in advanced control applications. For the control of alumina feeding, for example, it is possible to utilize the existing feeders in an intelligent way according to spatial variation in alumina concentration that may be sensed by the anode signals. In the case of ACD regulation, two application modes can be considered:

Anode Current Monitoring with Manual Anode Adjustment. This application utilizes the existing anode jacking capability, whereby the anode plane is moved as one. Independent anode movement can only be achieved by manual intervention as is currently the norm. The ability to identify anodes requiring manual intervention, and the diagnosis of anode problems, are significantly enhanced however.

Anode Current Monitoring with Automatic Anode Adjustment. This application requires that each anode stem be equipped with independent jacking capability, so that ACD may be adjusted for individual anodes in response to their current signal. The additional hardware cost and control complexity must be compensated by a higher cell performance if this advanced control capability is to be justified.

Anode Signal Acquisition

The traditional method for acquiring anode current signals was by measurement of the voltage drop across a defined length of the anode rod, Figure 1. This method has a major disadvantage in that the electrical contact to the rod must be disconnected and replaced each time the anode is changed, causing inconvenience to operators and risk of damage to wiring. Hall sensors offer the possibility for wireless contact, but at significant cost and potential for damage in the hostile environment.

To eliminate the said drawbacks we suggest a different measurement system, as indicated in Figure 2. All measurement points are on the anode busbar supporting the anode rods, where the number of voltage measurement points should be one more than the number of currents to be measured and the current to each rod can then be determined by difference calculation. A mathematical model taking into account specifics of the cell busbar arrangement, riser locations and cross-members is applied. This simple, low-cost, fixed measurement system greatly facilitates the employment of individual anode current signals into cell control algorithms.

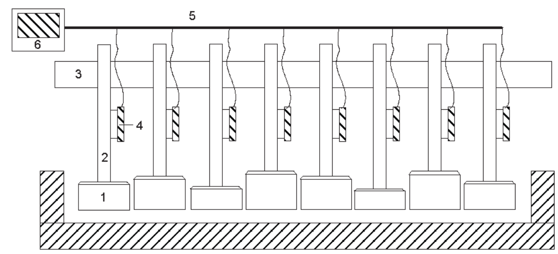

Fig.1. Typical measurement of individual anode currents.
1- anode, 2- anode rod, 3- anode busbar, 4 – voltage drop meter, 5 – data bus line, 6 – data controller, 7 – measurement points.

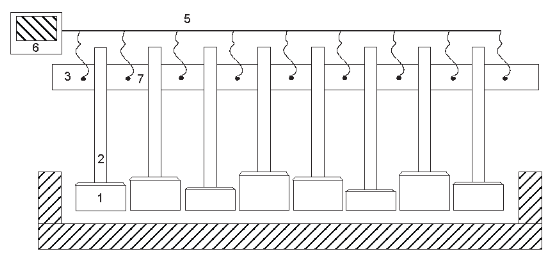

Fig.2. Preferred system for anode current measurement.

Anode Signal Characterization

Information on three process states may be derived from the anode signals:

The average current drawn by each anode. This is sensed by the relative signal magnitude of each anode in the cell over a time window in the order of minutes and hours. Differences between anodes will normally reflect differences in relative ACD, for which adjustment of outliers (anodes drawing abnormally low or high current) may be warranted. An example from an operating cell is shown in Figure 3, where the impact of anode change is also indicated. The coefficient of variation (COV = standard deviation of individual anode current values * 100 / average), excluding the newly changed anode, is typically in the range 10-15 % for good-practice smelters.

Surface motion of the metal pad. The wave motion of the metal pad creates a dynamic ACD which is imprinted on each anode current signal. Sensing at a frequency of around 1 Hz is normally sufficient to see the amplitude of the metal wave, and to differentiate between cell instabilities caused by magneto-hydrodynamic instability (often referred to as 'low frequency noise') or problems caused by individual anode problems ('high frequency noise'). Control actions would normally imply increase of the anode plane (ACD) for correction of MHD instability, or adjustment of specific defective anodes for correction of high frequency noise. An example is in Figure 4.

Bubble generation and release. CO_2 bubbles generated by electrolysis coalesce on the anode under-surface and are released in 'slugs' at around 1 Hz frequency. The bubble release appears as 'noise' imprinted on anode signals that are typically acquired at around 1Hz for current monitoring. Acquisition at frequencies to 10 Hz or higher can provide information on the performance of anode slots, or detection of some anode abnormalities such as spikes. Typical bubble noise is indicated in Figure 5.

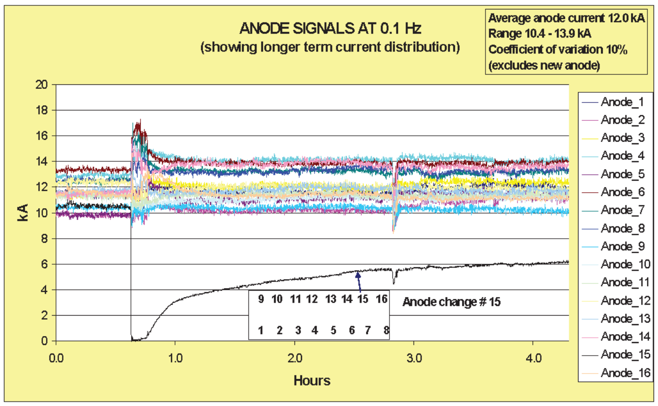

Figure 3 Anode Current Distribution

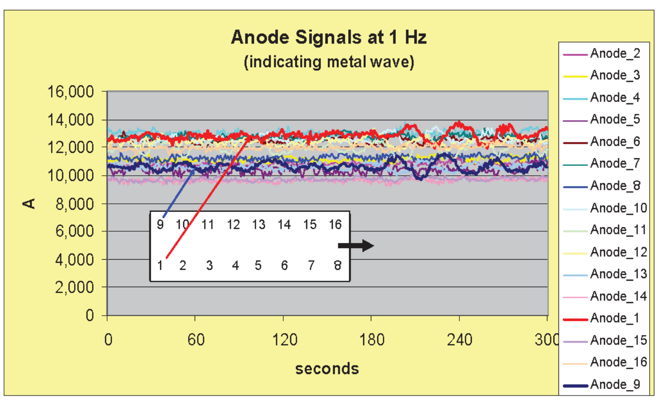

Figure 4 Anode Signals at 1Hz – Indicating Metal Pad Instability

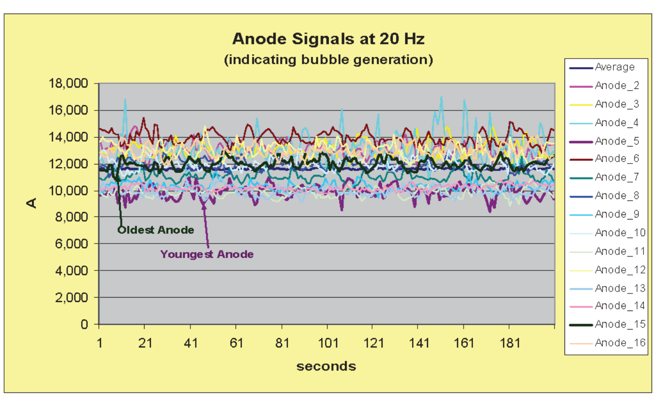

Figure 5 Anode Signals at 20 Hz – Indicating Bubble Generation

Opportunities for Advanced Control Using Anode Current Signals

1. Achieve More Uniform Current Distribution

Differences in current draw for individual anodes invariably reflect differences in ACD, which therefore infers sub-optimal current efficiency. The differences may arise from common cause variation inherent to the process, which are amenable to improvement by process redesign, or from special causes or transients that may require specific control actions on an individual basis.

Some typical causes of uneven anode current distribution are:

Common causes inherent to the process:
- Incorrect referencing of the new anode to the metal profile
- Excessive manual intervention (raising anodes too frequently or too high) to correct transient instabilities
- Inefficient anode change sequences creating excessive thermal transients

Such common causes can be identified by analysis of individual anode current distribution history from many cells, seeking correlations between anode current and the location in the cell. An example of such data is shown in Figure 6.

Special causes requiring specific control actions:
- Anode setting errors or slippage of rods
- Abnormally high anode resistance caused by, for example
  - Poor stub contact due to airburn, damaged stubs, poor casting etc
  - Poor clamp to rod contact
  - Poor anode quality due to cracking, low baking temperature etc
- Transient cathode problems (sludge and ridge) that create localized metal pad disturbances

It must be noted that a certain level of variation in current distribution is normal for the cell – reflecting changes in the anode resistance over time due to increasing carbon temperature and reduction in anode area as the anode ages. Excessive manual intervention by raising and lowering individual anodes to achieve a better current distribution is often counter-productive.

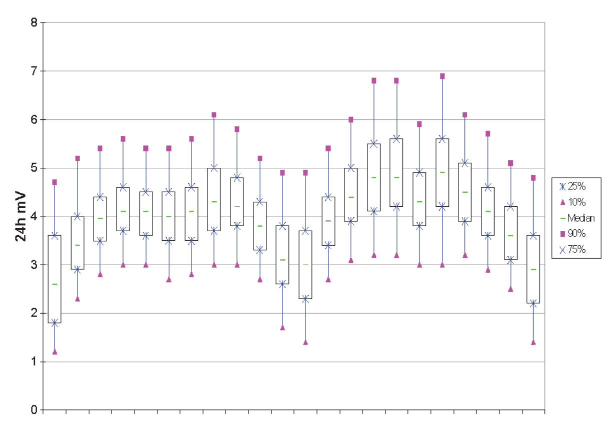

Figure 6 Example of Common Cause Variation in Anode Current Distribution by Anode Location (at 24 hours after anode change)

2. Anode Problem Diagnostics

Problem anodes are invariably associated with low ACD, either directly through positioning errors or indirectly as a result of quality problems causing high electrical resistance. In the latter case, the current draw is initially reduced resulting in lower carbon consumption, until the resulting ACD reduction for that anode rebalances its resistance with others in the cell. The net effect is that the anode will eventually take an equal share of current, but at a lower ACD which may generate instability or even transient shorting of the anode to the metal pad. When the ACD is low, the current dynamic induced by the metal pad movement is amplified, as shown in the example from Figure 7.

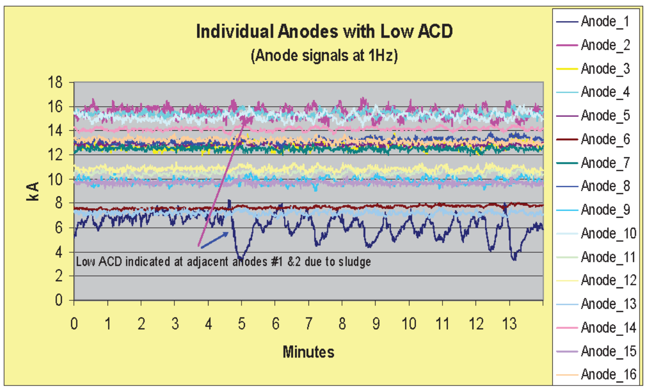

Figure 7 Individual Anodes with Low ACD

Low frequency noise, with a regular period of typically 20-50 seconds, is usually associated with thermal imbalance and MHD instability. High frequency noise, on the other hand, is typically associated with individual anode(s) shorting to the metal pad for a variety of possible reasons (slippages, cracking, spikes, burn-offs, exposed stubs creating high anode resistance etc). In both cases the typical control response is the same however - adjustment of the entire anode plane (increase of the 'ACD'). While this response is appropriate for correction of thermal imbalances and MHD instability, it is grossly inefficient and unnecessarily disruptive to the thermal balance when applied as a corrective action for an individual anode problem. In the latter case, the required action is to identify the specific anode and correct it by manual intervention. This task would be greatly facilitated if the specific problem anode could be identified from the composite resistance signal, but this is not usually the case. Specific anode problems may be easily recognized by monitoring of the individual anode current signals however.

3. Visualization of the MHD Instability

Figure 8 and 9 provide an example of a cell with MHD instability. All anode currents are fluctuating according to the metal wave, but Figure 8 indicates that the wave amplitude is higher towards the upstream end of the cell. This may indicate problems with the magnetic field intensity, or excessive ridge formation, at the upstream end of this cell. In this case, an increase in ACD for the entire anode plane is required to re-establish stability, as indicated by the increase in voltage in Figure 8.

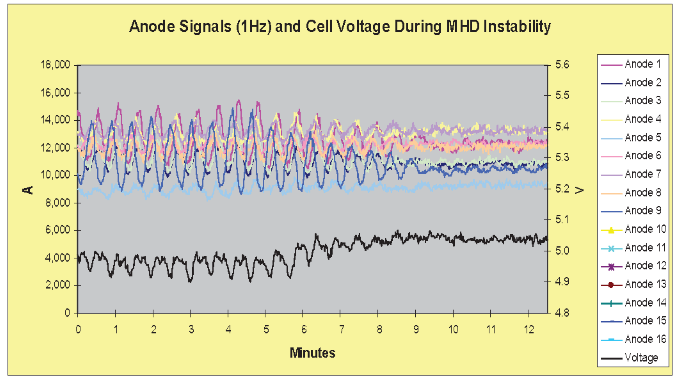

Figure 8 MHD Instability

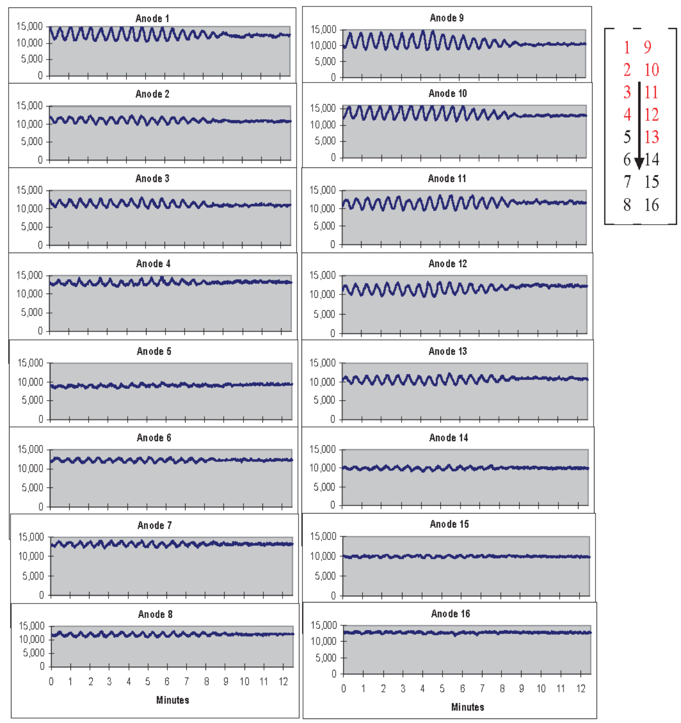

Figure 9 MHD Instability – Correlation with Cell Location

4. Improved Alumina Feeding & Avoidance of Anode Effects

The regulation of the alumina feed rate by resistance tracking is a strategy that has been universally adopted by the industry over recent decades. The trend in cell resistance as the alumina concentration diminishes is tracked using a composite, filtered resistance signal, and feeding is initiated when the resistance increment and / or its slope derivative(s) reach target values. This strategy has been largely responsible for the dramatic reduction in anode effects in recent years, but experience suggests that a different approach will be necessary in the future if 'best-practice' is to be maintained. It is already apparent that anode effect frequencies for the 300+ kA technologies tend to be higher than their smaller predecessors, but why is this so? The trend is to larger cells, operating at lower alumina concentration for increased efficiency, and at higher current density for increased productivity. In this context, recognition of the spatial variation within the cell in terms of alumina concentration becomes increasingly critical for avoidance of anode effects. The cell is equipped with alumina feeders that could respond on a selective basis to address spatial variation in concentration, but the composite cell resistance signal is incapable of sensing this variation. The composite resistance signal is clearly limiting the alumina feed control capability for modern cells, while an increasing environmental cost is assigned to anode effect emissions.

The question arises – could individual anode current signals offer a more reliable sensing of the approaching anode effect than the trend in cell resistance? In particular, is it possible to identify spatial variation in alumina concentration from the anode current signals, and implement feed orders that are specific to certain regions (feeder locations) in the cell?

Figures 10 and 11 show a typical anode effect from a cell operating at 200 kA, over time scales of 30 seconds and 13 minutes respectively prior to the anode effect. The current signals are taken at 20 Hz, although 1 Hz monitoring would be satisfactory for control purposes. The anode layout in the figure corresponds with the anode locations in the cell so that spatial effects can be observed. A declining current trend on any anode is indicative of increasing polarization of that anode due to localized depletion of alumina and subsequent generation of PFC gases. In the 30 second time scale (Figure 9), a decline in current is first observed at anode #10 about 15 seconds prior to the anode effect, followed quickly by adjacent anodes # 11 & 12. A ‘warning’ of 15 seconds is barely sufficient for control purposes to action feeders and avoid the anode effect.

Observation over a longer time scale on the same cell (Figure 11) is more instructive however. In this case, anode #4 is seen to decline in current nearly seven minutes before the anode effect, followed quickly by adjacent anode #5, and then #6. The current deficit from these anodes is redistributed primarily to adjacent anodes # 2 & 7 until #2 also becomes polarized two minutes prior to the anode effect. The current deficit from #2 is primarily distributed to the opposite anode #10, which itself led into the anode effect as noted in Figure 10. This is just one example of where anode current monitoring gives not only a clear early warning of the anode effect, but also indicating the cell region which is low in alumina concentration. The potential application for improved feed control is apparent.

Conclusion

The value of individual anode current signals as an additional sensor for efficient control of modern prebake reduction cells is clearly established. Anode signals can complement the existing control based on the cell resistance signal in the following ways:

- Differentiation between MHD instability caused by thermal imbalance or low ACD, and instability caused by defective anodes. This leads to more appropriate control actions, by automatic adjustment of the entire anode plane or by manual intervention (or automatically if independent anode jacking is fitted to the cell) to correct a specific anode problem.

- Identification of spatial variation in alumina concentration by early warning of anode polarization at specific regions, from which intelligent alumina feed actions may be initiated. This will complement the existing resistance tracking strategies and support lower anode effect frequencies.

- Improved understanding of anode performance in the cells, enabling optimization of the referencing for new anodes, adjustments for slot erosion, optimized sequencing of the anode changes etc. which will deliver improved uniformity of anode current distribution and more efficient carbon consumption.

The need for enhanced cell control using individual anode signals will become greater as the cells become larger. Fortunately, this need coincides with the increasing availability of low cost / high capacity memory chips which make acquisition and processing of anode current signals in real time a viable control proposition. In particular, sensors requiring no physical contact to the anode rod, and the possibility for wireless transmission to the controller, make signal analysis a practical possibility in the industrial environment. Such control has the potential to equal the implementation of resistance tracking of alumina feeding through the 1980’s in terms of its impact on the smelting process efficiency.

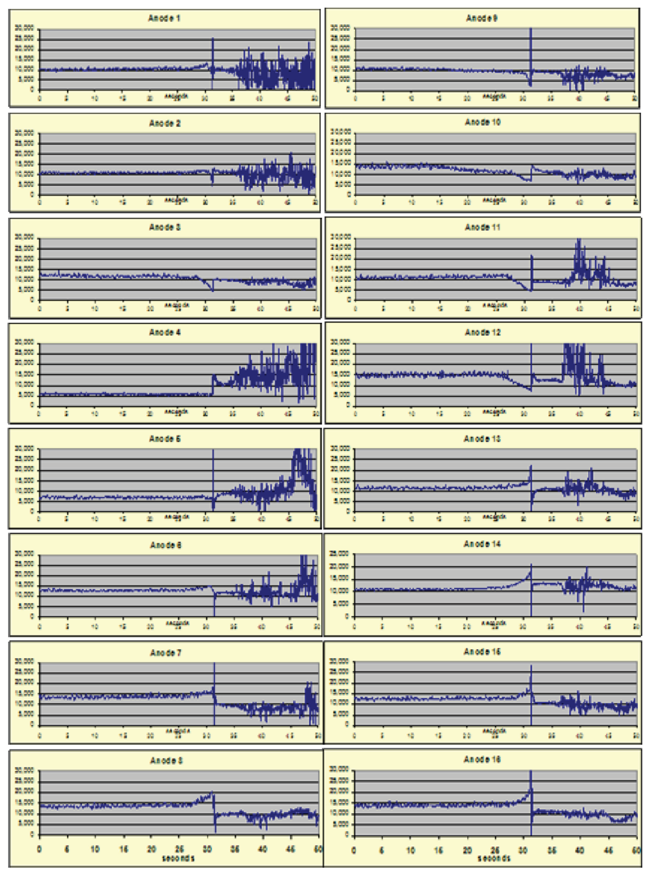

Figure 10 Anode Signals at 20 Hz through 30 Seconds Leading to Anode Effect

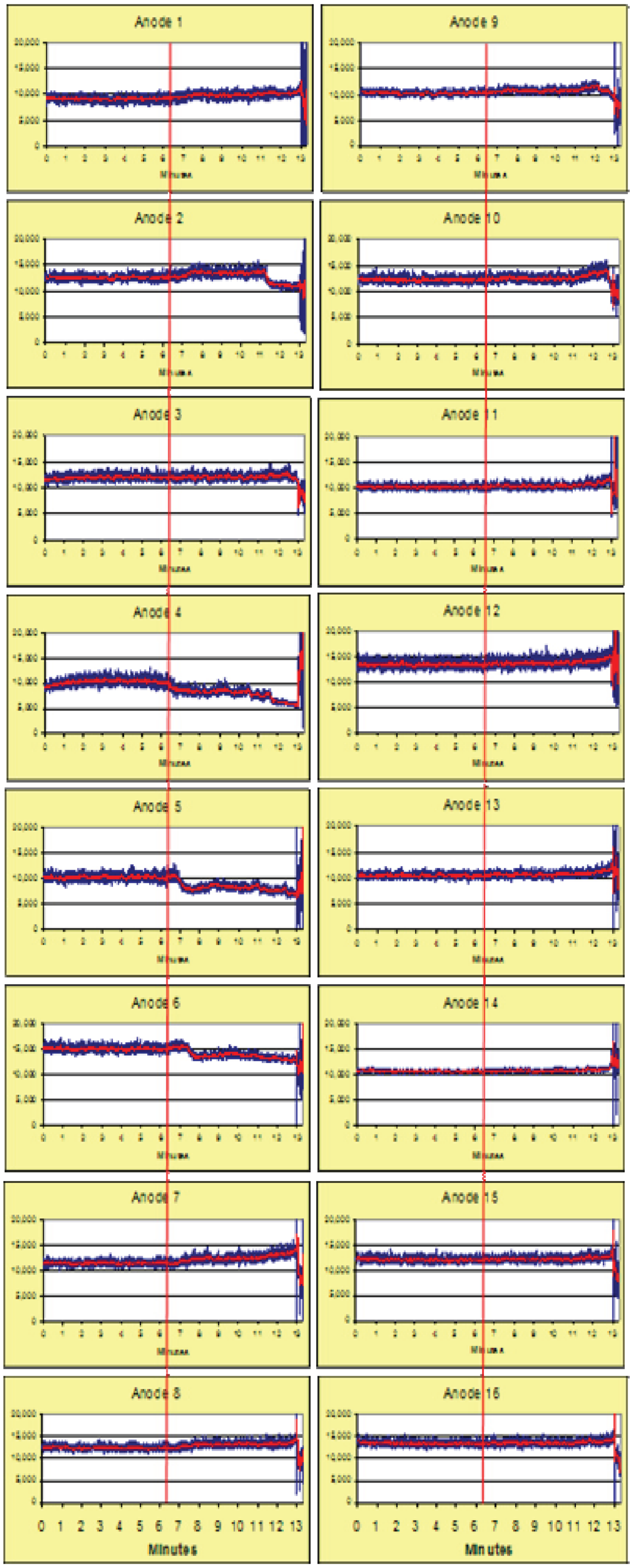

Figure 11 Anode Signals at 20 Hz through 13 Minutes Leading to Anode Effect

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