Essential Readings in Light Metals: Aluminum Reduction Technology.
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5. CONTROL

Papers on reduction cell process control have been published in every *Light Metals* volume. The control section, which includes papers from 1971 to 2011, shows that there has been a significant increase in control sophistication over this period. Greater sophistication, permitted by the development of computers and fostered by ever-increasing process knowledge, has greatly reduced operational variation. Perhaps the greatest improvement has been made to the control of dissolved aluminum concentration in the bath. From scheduled alumina feeding of the 1970s, to "on demand" feed control and then, more recently, nonlinear model based control, this evolution has greatly contributed to improving reduction cell performance and lowering environmental emissions. Indeed, the once ubiquitous anode effect, associated with low alumina concentration, has been virtually eliminated in modern cell technology.

However, compared to other chemical processes, reduction cell control has remained rather simple due largely to the distributed nature and lack of observability of the process. The impact of this can be seen in several papers dealing with aspects of cell heat balance control. Control algorithms and knowledge based systems have developed to make the most of the scant data available and, it must be said, do a reasonable job. Considerable effort has also been expended over the years on the difficult challenge of developing new sensors for control purposes. Three papers describe some fruitful attempts at this.

The first paper in the section, by Pierre Homsi et al., provides an overview of process control from 2000 that is still highly relevant today.

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OVERVIEW OF PROCESS CONTROL IN REDUCTION CELLS AND POTLINES

Pierre HOMSI*, Jean-Michel PEYNEAU*, and Michel REVERDY**

*ALUMINIUM PECHINEY - LRF - B.P. 114 - 73303 - Saint-Jean-de-Maurienne Cédex - France

**ALUMINIUM PECHINEY - 7, place du Chancelier Adenauer - 75218 Paris Cédex 16

Abstract

Hardware and software developments have led to dramatic improvements in the process control of reduction cells over the last two decades.
Process computers are used not only for cell control but also for the technical management of modern potlines.
The objectives of automatic cell process control are reviewed, including alumina feeding, cell resistance regulation (ACD control), bath chemistry and cell heat balance control. Routine operations on the cells are also accounted for.
A description is given of tools to assist potline personnel in the optimization of operations, quick diagnosis of process changes, correction of abnormal or exceptional situations on individual cells or potlines as well as work scheduling on the cells.
New developments in cell and potline control provided by the ALPSYS system are also presented.

1 - Introduction

As a result of substantial progress in computer technology, advanced and more user friendly systems have been developed and perfected for automatic cell and potline control.[1-2]

Modern cells with prebaked anodes operate with central point feeding and a sophisticated process control system. These automatic control systems use modular regulation procedures for adjusting individual cell operating variables such as anode-cathode distance, alumina concentration and aluminium fluoride content in the bath. A completely automated potline process control system, resulting from very long research and systematic development work, also ensures overall potline control and correction of abnormal or exceptional situations for individual cells or the complete potline.

Development of automated process control is closely linked to cell and potline control strategy. This paper will therefore begin by a presentation of the most commonly used potline process control philosophy and continue with an insight into the main potline operating variables and parameters.

Cell regulation procedures will then be reviewed before dealing with overall potline computer control for normal operations and the use of process control to correct abnormal or exceptional cell or potline situations. ALPSYS, the latest Pechiney system, will be briefly presented.

2 - Consistency : a Key Point in Potline Control Strategy

Keeping a well balanced potline is usually achieved by a two-level activity :

2.1 - Individual Action

Individual action on each single cell will lead to consistent potline operation, within a selective, narrow band of operating variables. This will be achieved through :

- Consistent working procedures
- Corrective make-up tables rectifying deviations in any of the important operating variables such as bath temperature and composition, metal and bath heights, cathode voltage drop, etc
- Automatic process control procedures applied to cell resistance, alumina content in the bath, cell heat balance, and any of the usual process disruptions (anode effect) or operation interference (anode changing, tapping, etc...).

Consequently, each cell will run at almost constant resistance, with limited variations in ACD, alumina content, bath composition and more generally heat balance.

2.2 - Operation of the Potline as a Single Unit

Once potline consistency is ensured, it is possible to operate it as a single unit, with adjustments made on common parameters such as the amperage or, if justified by changes in the raw materials, on the make-up tables. In this way, the overall heat balance of the potline is obtained.

3 - Monitoring of Work

To maintain consistency and good balance of the potline, exactly the same instructions need to be followed for the various cell operations.

Systematic and regular checking of all work routines by the potline shift and day work personnel will ensure that each person on all shifts around the clock follows the specified procedures.

Uniform operation is essential to enable potline personnel to evaluate the effects of any changes in work routines or operating parameters.

The most important work routines to be monitored are those that have the biggest influence on cell condition :
- anode changing,
- anode covering,
- metal and bath height measuring,
- metal and bath tapping,
- bath temperature measuring.

4 - Information Used for Process Control

Almost all industrial automatic controls are based on cell voltage and potline amperage measurements.

The only additional information is provided by the operator :

either through switches and push-buttons informing the automatic equipment of manual operations being carried out on the cell (e.g. metal tapping, anode changing)

or through data loggers which automatically feed the system with cell measurements.

Cell voltage is measured on the cell busbars. Potline amperage is general potline information to be transmitted to each Potmicro in charge of individual cell control.
Variables are measured, calculated or analyzed to characterize operation.

Parameters are the controls that can be deliberately modified to obtain corrective effects on potline operation.

4.1 - Main Operating Variables and their Variations

Bath Temperature
Frequently measured on modern cells[3], bath temperature is closely related to bath composition, and more specifically to AlF_3 excess and alumina content. It reacts strongly to process disruptions such as anode effects or operations on the cell.

It provides useful information taken in combination with other heat balance parameters.

Bath Composition
AlF_3 excess content in the bath is essential for the determination of additions through make-up tables. Keeping AlF_3 excess close to the target is a major objective. Bath composition, similarly to bath temperature, is sensitive to events occurring on individual cells such as instability or long anode effects. It also depends on the chemical purity of the alumina supplied to the potline.

It is usually a good indicator of changes in potline heat balance.

Cathode Voltage Drop and Cathode Surface Condition
Cathode voltage drop will usually slowly increase with age. Short term variations are linked to changes in ledge profile and cathode surface condition. The latter is monitored regularly by rod checks performed by experienced personnel. Corrective action aims at avoiding any detrimental decrease in the ACD. Additional target resistance is applied to cells with high cathode voltage drops.

A general increase in the potline average cathode voltage drop generally corresponds to a cooling trend (confirmed by temperature and bath analyses) and is corrected by raising the amperage, resulting in an increase in the power input to the cathode. This cathode drop increase can also be caused by a change in the quality of the alumina. In the case of cells with automatic point feeding, this requires adjustment in the feeding parameters as well as a possible change in target resistance and bath composition.

Instability
The process computer system records the maximum amplitude of variations in the instant cell resistance. Cell to cell averaged values over a shift are used as an indicator of cells with either anode level adjustment problems or cathodic problems.

Metal and Bath Heights
Metal height increases with a cooling trend. Bath height generally varies with the overall bath material balance of the cell. In the case of recycled anode crusts crushed and mixed with alumina to cover newly changed anodes, bath height variations will trigger changes to the amount of alumina in the cover. Bath height control is essential to achieve good metal purity and good alumina dissolution.

Alumina Content in the Bath
When controlled by an efficient process control system such as ALPSYS, point feeding cells operate with only small variations in alumina concentration in the bath. This is achieved by analyzing trends during successive cycles of underfeeding and overfeeding. Anode effect rates can be reduced drastically.

Point feeding performances can be characterized by several operating variables, namely : quantity of alumina added, number of underfeeding/overfeeding cycles, actual resistance slopes, tracking duration, anode effect frequency. These indicators, besides their use for adjusting alumina feeding rates, are affected by changes in the cell or potline heat balance.

Metal Purity
Iron dissolved in the aluminium can originate from various sources, including raw materials, cathode bars, metal tools or anode pins attacked by the bath. Silicon is essentially related to raw material supply and recycling of carbon and bath. Silicon levels do not depend on heat balance changes on point feeder cells with low side insulation, unless silicon carbide sidewall slabs are used.

Liquid Bath and Metal Quantities
Average liquid bath heights with standard deviations are monitored as well as quantities of transferred bath. Variations can be caused by thermal changes but also changes in raw materials, quality of work and anode cover.

Liquid metal height measurements are used to determine the quantity of metal to be tapped. Metal inventory is also regularly measured on reference cells and once or twice a year on all cells. Averages over several cells are used to monitor slow drifts that might affect potline operation.

AlF_3 consumption normally varies depending mainly on the sodium content in the alumina and the age of the cells. Any major variation over a period of one week can be an indication of a warming or cooling trend.

Table I shows a list of measurements widely used in the industry along with measurement frequency[1]

4.2 - Operating Parameters and their Effects

Amperage, AlF_3 corrections and potline target resistance are used to counteract trends in potline heat balance. It is recommended to avoid changing more than one parameter at a time.

Potline Target Resistance
Potline target resistance can be changed to act on potline heat balance. The full effect of a change can only be seen after several days.

The optimum target resistance is the lowest resistance corresponding to good stability and good current efficiency levels. It can only be optimized by very small and progressive adjustments, with only one parameter adjusted at a time and the corresponding effect carefully studied. It is possible to run the cells with automatic point feeding at a lower average ACD because of the almost constant alumina concentration leading to almost constant resistance and ACD.

Adjustment of Potline Amperage
Potline heat balance can be controlled by amperage adjustments. When changes are necessary (e.g. bath temperature too high or poor cathode surface condition), care should be taken not to make very substantial amperage adjustments at a time. Temporary action can be taken to correct accidental imbalances such as abrupt changes in weather, line stoppages, changes in alumina quality. Long term action is taken to obtain a different operating balance.

Automatic Process Control Parameters
Many parameters, specific to each process control procedure are used to adjust cell operation. In the case of cells equipped with point feeders and a modern automatic control system, adjustment of alumina content in the bath is obtained by modifying specific control parameters.

Other Parameters Allowing Action on Potline Heat Balance
To modify the potline heat balance it is also possible to act on other parameters such as : anode cover (thickness, composition), cell ventilation (depending on the design), target metal height and the fume extraction flow rate.

5 - Procedures Based on Resistance Control

Fundamental cell control procedures are based on pseudo-resistance calculations using cell voltage and potline amperage. In the case of current fluctuations due to simultaneous anode effects or restricted amperage regulation, voltage is not simply linked to amperage by the resistance but by impedance and correction is necessary for the calculation to be correct.

Table I: Types and Typical Frequencies of Control Measurements[1]

Measurement	Frequency
Widespread use	
Cell Voltage	Continuous (automatic)
Line Current	Continuous (automatic)
Observation (flame, crust, etc...)	Several times/day to daily
Bath Height	Daily to once every two days
Metal Height	Daily to once every two days
Tapped Metal Weight	Daily to once every two days
Bath Temperature	Daily to weekly
Bath Chemistry (AlF_3,, LiF, CaF_2, MgF_2)	Twice per week to two weekly
Metal Purity (Fe, Si)	Daily to weekly
Cathode Voltage Drop	Weekly to annually
Alumina-Feed Dose Weight	Weekly to occasionally
Anode Beam Position	Continuous (automatic) on some technologies
Individual Anode Currents (by Rod Voltage Drop)	Daily to weekly or exceptionally Continuously on one technology
Limited Use	
Crust Breaker Position	Continuous on point feeders
Aluminum-Fluoride Feed Dose Weight	Exceptionally
Sludge/Ridge Height	Daily (with metal height)
Sidewall Ledge Positions	Twice/week
Direct Alumina Concentration	Daily
Superheat	Daily
Sidewall Temperature	Continuously
Cathode (Collector Bar) Temperature	Continuously
Sidewall Heat Flux	Continuously

5.1- Conventional Resistance Regulation

For each acquisition of U and I values, the pseudo-resistance is calculated as follows :

$$R = \frac{U - E}{I}$$

where E is a constant value determined by the zero current intercept of cell voltage versus line amperage. Average values of R calculated for a period of a few minutes are compared with a target resistance.
Around the target resistance, there is a « no adjustment zone ». A regulating order proportional to the difference between the average and the target is calculated for values located on either side of the « no adjustment zone ». To avoid squeezing the cell unnecessarily, excessive consecutive down orders are prohibited on side-break cells. On cells with automatic point feeding, the feeding programs have priority over conventional pseudo-resistance regulation.

5.2 - Detection of Cell Instability

Comparison of the resistance elongation (difference between the maximum and minimum values over a given time) with a threshold will, when necessary, cause the Potmicro to take action to eliminate the consequences of instability.

This treatment involves additional target resistances acting on the consequences but not always on the cause : special work on the cell may be necessary. Rapid elimination of the instability is necessary to allow resumption of correct monitoring of the alumina point feeding and to avoid a decrease in current efficiency.

Several process control systems across the industry differentiate between low frequency noise linked to metal movements and high frequency noise related to anode problems.

5.3 - Automatic Anode Effect Suppression

This procedure has become a marginal control procedure on modern cells with efficient alumina feeding control and an anode effect frequency below 0.1 per cell per day. Determination of the causes of anode effects is useful for adjusting the regulation parameters. In standard anode effect treatment the anodic system is given a series of down orders followed by a series of up orders, called a loop. The anode effect squelching sequence allows for a limited number of loops followed by a resistance regulation period to successfully eliminate the anode effect. An overfeeding period matches the squelching sequence.

In some other cases, automatic air blowing beneath the anode is used.

5.4 - Procedures Linked to Manual Operations

Control procedures adjust ACD and alumina feed when manual operations are carried out on the cell. These specific procedures are used at the operator's request when carrying out operations such as tapping, anode changing, anode beam raising, feeder checking, etc...

5.5 - Monitoring of Alumina Concentration

The alumina concentration control scheme[4-5] is based on the alternation of periods when alumina is introduced at a slower rate (i.e. underfeeding) and at a faster rate (i.e. overfeeding) than the rate corresponding to normal consumption of the cell (i.e. nominal rate) : see figure 1.

The switch-over from slow to rapid feed rate occurs when the rate of variation of pseudo-resistance exceeds a set value. A slope is calculated using resistance variations during underfeeding and is compared to a low threshold.

This control strategy is based on the pseudo-resistance being, for a given anode-cathode distance, a function of alumina concentration. Below an alumina concentration of 3 %, the resistance increases significantly with the depletion of alumina in the bath.

A rapid increase in current efficiency is measured when alumina concentration in the bath is lowered, despite the corresponding increase in bath temperature (see figure n° 2). This fact has often been debated[6].

A demand feed strategy is used, in particular, on bar breaker cells. This strategy is based on a tracking procedure, where breaking and feeding are stopped until the resistance increases by a set-value, which then triggers resumption of the breaking and feeding.

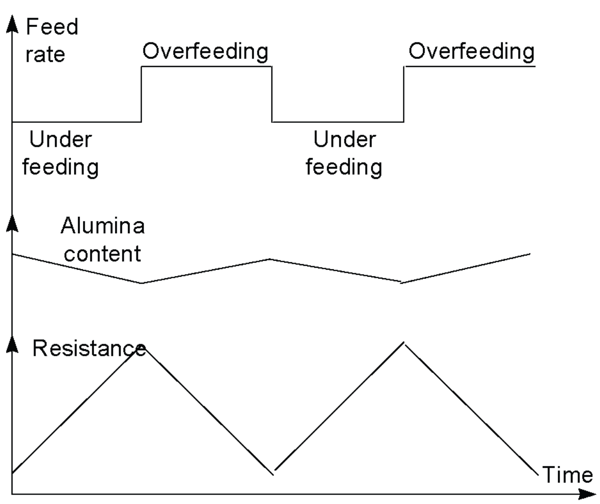

Figure 1: Monitoring of Alumina Content by Resistance Slope Calculation

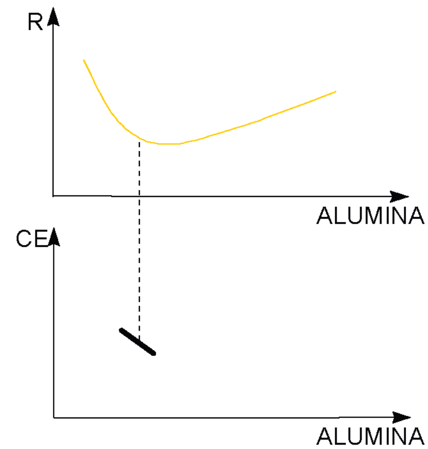

Figure 2: Optimum Alumina Content in the Bath

6 - Automatic Control of Cell Heat Balance

Modern cells designed with an AlF_3 hopper and feeder are fitted with an automatic control system managing AlF_3 corrections by determination of AlF_3 feeder shot intervals[7]. The system also introduces target resistance modifications such as additional resistance based on the cell thermal condition. On large cells designed with a crushed bath hopper and feeder, the control system monitors bath height.

Non-continuous measurements and analyses are used to carry out cell heat balance control : excess AlF_3, bath temperature, cathode voltage drop, cell age, anode changing, anode effects and fluoride content in the fluorinated alumina.

Each time a bath analysis or temperature measurement becomes available, the number of AlF_3 shots to be added in a given time is recalculated according to charts based on excess AlF_3 and bath temperature (see figure 3). These charts include a minimum and maximum amount of AlF_3 to be added to prevent rapid variations in cell heat balance and risks of excessive local cooling of bath under the AlF_3 feeder.
A bath ratio change in resistance is computed at each new calculation of the AlF_3 feeder shot interval corresponding to the introduction of an AlF_3 excess analysis or a bath temperature measurement. Each time a new cathode drop is introduced, a new cathodic additional resistance is calculated as a function of the value of the cathode voltage drop measured, possibly smoothed by one or several previous measurements of the cathode voltage drop. These additional resistances are automatically added to the target resistance used by the cell microcomputer to carry out conventional resistance control.

Other Heat Balance Control Strategies
Most technologies use heat balance control[8-9] algorithms based on AlF_3 and temperature determinations and actions on AlF_3 additions and cell resistance. The degree of sophistication may vary and the emphasis given to bath temperature versus AlF_3 analysis can be shifted one way or the other.

D. Desclaux's[10] system for example relies on bath temperature triggering AlF_3 additions.

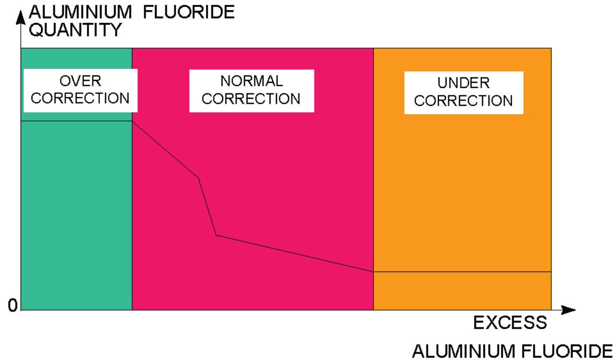

Figure 3 a: Influence of Excess AlF_3 in Bath on Quantity of AlF_3 to Be Added in One Shift

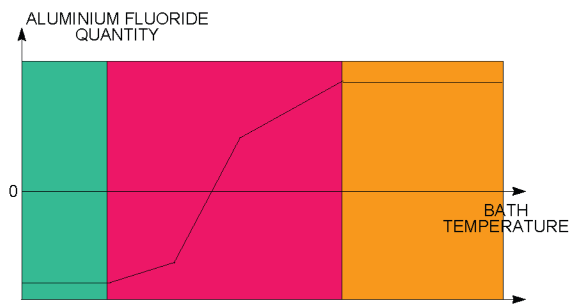

Figure 3b: Influence of Bath Temperature on Quantity of AlF_3 to Be Added in One Shift

7 - Computer Control Developments

7.1 - Computer Assistance into Optimum Operation

Supervision systems are developed and used to keep potline operation in balance, facilitate adjustments and modify target operating levels. Such systems are designed to help determine the required adjustments in potline amperage and target resistance in order to maintain steady operation. For overall potline balance, parameters such as instability, cathode voltage drop and surface condition, bath temperatures and analyses are largely used. Averages, standard deviations and trends are calculated from the potline data-base. Sets of rules are used to assist potline personnel in decision making.

7.2 - Computer Assistance in Work Organization

Numerous and repetitive tasks have to be carried out in the potline, including preventive maintenance on cell tending equipment. Computers are powerful tools for preparing work schedules at any position in the potline at any given time. They can take into account all the necessary modifications to standard scheduled work, enabling easy introduction of non-routine work.

7.3 - Process Control for Abnormal Operations

Computer control is also being developed to assist in restoring normal situations for individual cells or for a complete potline.

Abnormal Operation of Individual Cells
Cells with operating variables beyond an acceptable range (e.g. average instability, alumina consumption, average slope, etc...) are automatically identified and visual or manual checks proposed.

Automatic Adjustment of Cell Parameters After Start-Up
Careful follow-up of a pre-determined adjustment schedule is essential for cathode life and efficient cell operation. In the case of newly started cells, target voltage, alumina feed rates and bath composition are a function of age.
A computer start-up program automatically changes the parameters at the right time to accurately follow the adjustment schedule. Bath composition of young cells is adjusted by the AlF_3 automatic point feeding system, with varied feed rates according to cell age.

Potline Restart After Power is Restored
Restarting a potline after a shutdown is a difficult operation which can be assisted by automatic control using systematic and very complete procedures.
The aims of such procedures are to enable the substation to supply the current without numerous anode effects and to restore potline heat balance.

Cell preparation is performed whenever the shutdown is notified in advance.

Restart procedures include amperage monitoring as well as cell control. Duration of the shutdown determines the amperage increase schedule. Alumina feed rates are calculated as a function of the amperage and overfeeding is used for a certain period, depending on the shutdown duration, to prevent anode effects without sludging the cell. The anode bottom level is specially adjusted to avoid squeezing the cell. AlF_3 automatic corrections are temporarily canceled. It is a very useful procedure, particularly when power peak shaving is applied.

8 - AP Process Control Latest Developments : the ALPSYS System

The AP electrolysis information system has recently been totally redesigned into a new system called ALPSYS.

Innovative features include the new Potmicro with advanced alumina feeding control using the patented « parabolic slope calculation »[13] aiming at zero anode effect and higher current efficiency.

The new system has state of the art ergonomics and a user-friendly man/machine interface, with a low response time. It provides access to major real time monitoring functions and makes best possible use of graphical user interface.

Its architecture uses modern and proven client/server technology with Oracle database and tools.

An example of graphical visualization (potline mimic) is provided in figure 4, giving access to a cell history graph (figure 5) with, in addition, actual values displayed in a window.

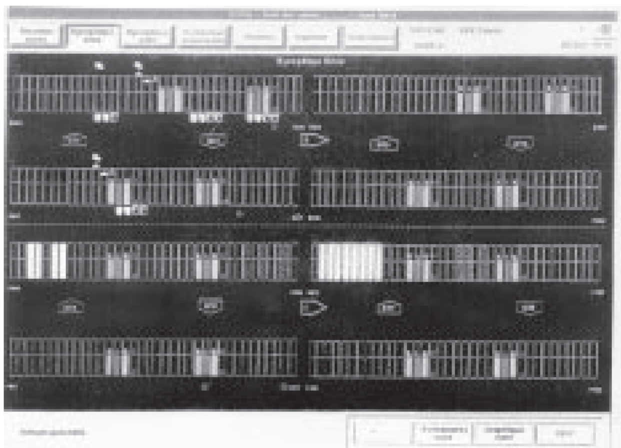

Figure 4: Graphical Visualization of Potline

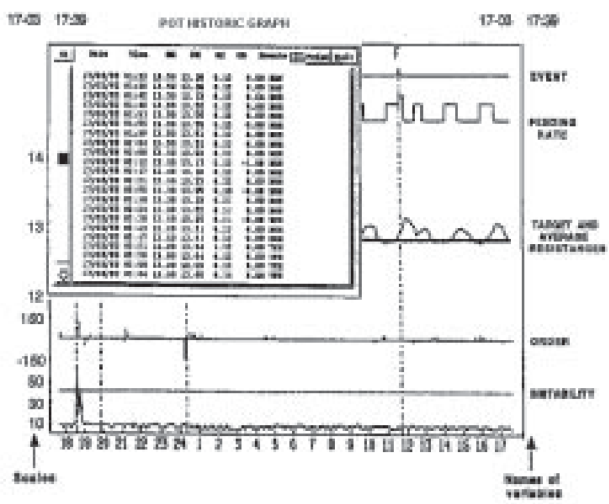

Figure 5: Pot History Graph

9 - Conclusion : Future Directions

Improved performance can be expected in the future from reduced process variations. This should allow a shift in target for process variables towards areas where current efficiency will be maximized and power consumption reduced. Bath temperature and composition are two examples of such variables. Zero anode effects is and will remain a major objective allowing a reduction in green-house gases.

Advances will be made possible by improved measurements, timely triggered by the process control system.

The bath height and temperature semi-continuous measurement device[11-12] with its interaction with the Potmicro is a good illustration.
The superheat probe[14] is another example of devices offering access to additional indicators. Quicker response for bath analysis, either through on-the-floor Raman readings or complete X-ray determinations, including alumina, giving access to superheat, offer other paths of development.

Last but not least, better understanding of the process through the use of statistical tools for data crunching will make further advances possible.

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