

Control of Temperature in Aluminium Reduction Cells - Challenges in Measurements and Variability

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Abstract

The temperature of the electrolyte is one of the key process variables in a reduction cell, as it has a strong influence on cell current efficiency. The variation in temperature, a measure of control performance, is typically higher than desired and smelter operators would generally like to see an improvement. Measurement of temperature is made difficult by a number of factors such as the corrosive nature of electrolyte, spatial and temporal variation resulting from the semi-batch, and the semi-continuous nature of the process. Difficulties also arise in the interpretation of the temperature measurement and feedback to control action, as temperature change can result from a change in excess aluminium fluoride, alumina and/or superheat. Depending upon the cause of temperature variation, the appropriate control action may vary.

Introduction

With the advances in fundamental knowledge, there has been an increased emphasis on operating cells with high aluminium fluoride concentration and at as low a temperature as possible in order to gain maximum current efficiency.

For a given cell technology and control system there is inevitably an optimum:

- temperature,
- aluminium fluoride concentration and
- average alumina concentration

in order to obtain the best cell performance.

Practically these properties vary considerably within a cell. Thus as the process control hardware and software have improved, operators have been faced with the dilemma as to whether it is more desirable to maintain these parameters within narrower bands or to attempt to move to lower temperatures and higher aluminium fluoride concentrations.

Because of the large mass of electrolyte and frozen ledge, the cell also needs to be maintained within a narrow heat balance range. Hence there are the additional needs:

- to control the superheat of the electrolyte and
 - to keep consistent flow conditions in the cell
- in order to keep the sidewall heat-flux constant and avoid variations in the amount of ledge and bath.

Due to design and heat loss mechanisms, for a stable cell at a fixed alumina concentration, calcium fluoride concentration and aluminium fluoride concentration, the superheat and bath temperature are consequential. This is because, all these parameters are inter-related in a cell and are influenced by the state of heat balance. By doing multiple regression correlations, various workers have predicted the liquidus curves of cell electrolytes and, if the cell is at its fixed target superheat (typically between 7 and 12°C) temperature changes can be used to assess changes in electrolyte composition.

The liquidus equation predicted by Solheim et al¹ is probably the most widely accepted one, although it has been shown to have limitations through impurities². This equation, when combined with the superheat, gives the following relationship for operating temperature:

$$T_{\text{bath}} = \Delta T + 1011 + 0.5F - 0.13C^{2.2} + 3.45C/(1 + 0.173C) + 0.124CF - 0.00542CF^{1.5} - 7.93A/(1 + 0.0936A - 0.0017A^2 - 0.0023AF)$$

Where F is the concentration of excess AlF₃, C is the concentration of calcium fluoride, and A is the wt% concentration of dissolved alumina.

The common average operating temperature of cells today is in the region 955 to 965°C. If the bath temperature becomes too high then adverse consequences result through:

- Decreased current efficiency.
- The crust thickness can be reduced, increasing energy losses, and accelerating the loss of volatile gases.

In contrast if the bath temperature falls below the lower limit:

- Alumina solubility is reduced, resulting in poor dissolution and sludge formation.
- Electrolyte resistivity is elevated.
- Ridge forms on the cell cathode, seriously disrupting current flow patterns, causing instability and increasing the possibility of anode spike formation.
- Routine operations such as anode replacement are made more difficult due to the increased presence of lumps and a harder crust.

Deviations from the optimum operating temperature are therefore undesirable. However due to the semi-continuous nature of the smelting process, changes in cell conditions are inevitable. For example, during anode change there is not only a redistribution of current, but also a spatial increase in energy demand. These lead to local variations in superheat, which consequentially leads to temperature changes, and variations in the electrolyte composition.

The temperature linked property, superheat, also has a desirable operating range. High superheats give rise to:

- melting of the side ledge,
- hence exposing sidewall materials to the corrosive electrolyte.
- Changed electrolyte volume
- Changed electrolyte composition

whilst low superheats result in:

- poor alumina dissolution,
- sludge formation and further operating disturbances,
- Changed electrolyte volume
- Changed electrolyte composition

Although superheat is primarily influenced by the instantaneous process energy balance, generally rising temperatures will be

associated with increases in superheat while falling temperatures will be associated with low superheats. Causes of high superheat (and the reverse for low superheat) include:

- A decrease in current efficiency
- Extra cell voltage, including noisy cell volts
- Anode effects

Accordingly, Taylor³ has proposed the operating window as given by Figure 1. This representation of the link between temperature, superheat and AlF₃ concentration does however assume that

- the CaF₂ concentration is constant, and
- the Al₂O₃ concentration is constant.

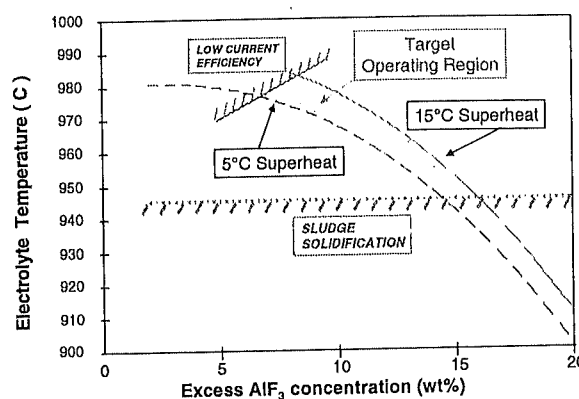


Figure 1: The operating window for good cell performance³

Over the years, the monitoring and control of reduction cells has been difficult because of the slow turnaround of chemical analyses of the electrolyte and also the difficulty in continuously monitoring these parameters. Because of the inter-relationship between temperature and aluminium fluoride concentration, when the cell operates at a fixed average alumina concentration and superheat, smelters have started using temperature as an alternative to chemical analysis because of the ease and speed of measurement.

Thus, temperature becomes an important measurement parameter, not only to ensure a cell stays within its target band, but also as a reflection of the electrolyte composition control. Smelters often use temperature measurements to predict the variation of aluminium fluoride concentration and thus for electrolyte composition control.

Temperature Measurement Issues

Current industry practice, with regards to measuring cell electrolyte temperature, is to treat the bath as isothermal, and assume that a measurement at some point in the bath is a representative temperature.

The interval with which the temperature is measured varies, typically, between once a week and once a day. Some smelters

measure the temperature at random times, others at a fixed time either before or after a cell disturbance such as metal tapping or anode setting. Inevitably, the temperature is measured at one fixed location within the cell, because of convenience or accessibility. This immediately raises the questions:

- 1) *How accurate is a given temperature measurement?*
- 2) *How representative is the temperature measurement at a fixed location for that in the rest of the cell?*

Because of the established importance of temperature it would be ideal to continuously monitor temperature as one of the process variables. However conventional thermocouples fail too quickly for this approach to be cost effective. Remote sensing devices have also presented problems because of the difficulty of maintaining a uniform sample site of electrolyte on which to focus.

In a recent article⁴, when Aluminium Pechiney developed their automatic measuring device, they opted for thermocouples with limited time of immersion, but enabling more frequent "spot" measurements:

However, this leads to the following questions:

3. *Whether short periods of continuous measurements are better than spot measurements?*
4. *What the requirements are for an automated sensor?*

To answer these questions, four temperature measurement issues are addressed in this paper. These are:

1. The type of sensors that are needed.
2. The accuracy and repeatability of individual temperature measurements.
3. The impact of current work practices on bath temperature.
4. The impact of abnormalities within the cell, which cause energy imbalances, and therefore, temperature changes.

The paper concludes by discussing the impacts of these issues when using temperature for controlling aluminium fluoride and as an auxiliary measure for advanced process control.

The data presented comes from a range of different cells and technologies, having been selected to illustrate issues rather than an integrated picture.

Sensor Requirements

Since trends in temperature give information on cell conditions, continuous measurement seems the ideal. This is supported by data of Purdie et al⁵ who performed continuous monitoring of temperatures in three locations in a point fed cell, as illustrated in Figure 2. The resultant traces show that the temperature follows

changes in alumina concentration and is, therefore, bath composition dependent. However, the value is different in different locations, and the reason for this is addressed elsewhere.

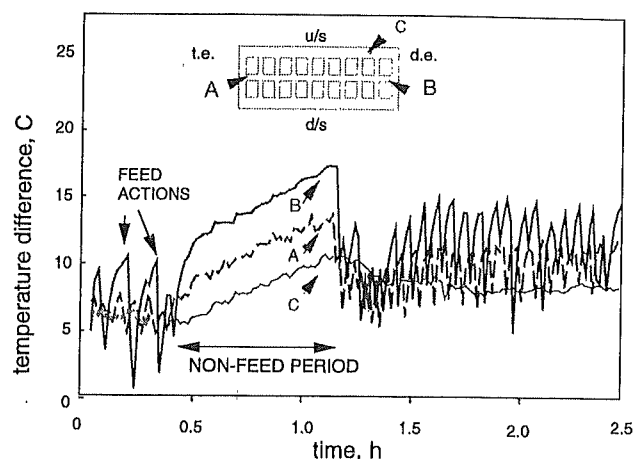


Figure 2: Continuous Measurements of Cell Temperature at Three Different Locations during Different Feeding Operations⁵

The data of Figure 2 raises questions because it indicates the temperature is not uniform within the cell. It also, raises questions as to how representative a single measurement would be, since the temperature shifts are linked with the routine operating and control practices. However, it shows that, if continuous measurement is not possible, it is highly desirable to have an automated system that can be pre-programmed and linked with the operating procedures. Based on this, a good non-continuous temperature measurement system should:

- be automatically pre-programmable and linked with the control system;
- respond quickly on immersion and then measure over a short time interval continuously, to ascertain feed and operating effects;
- be repeatable to within $\pm 1^\circ\text{C}$;
- have an accuracy within similar limits;
- and have a usable life, long enough to make its use cost effective.

Spatial and Temporal Variations in Electrolyte Temperature

Because of the link between temperature and energy balance, the temperature of an individual cell at any instance will to be influenced by:

- feeding, and presumably other routine work practices;
- extra cell voltage (including noisy voltage);
- current efficiency and,
- unaccounted for recent events (such as anode effects).

Thus, it is difficult to answer the question on how representative an individual cell measurement is, based on studies of one cell design alone. In order to address this question, a number of different technologies have been looked at - some side by side technologies with measurement at the end of the cell, others end on end, with measurement points on one side, at the centre, or elsewhere. In each case, at least 30 measurements, at the same stage of the work practice and for the same anode change pattern, have been averaged and compared against the average temperature for the samples of cells.

Such data is presented in Figure 3. It is seen that following an anode change close to the measuring point, the temperature reads below the average, whereas at extreme distances, it reads towards the maximum and above the average. Curve A is side by side cell technology and the measurement point is in the centre channel at one end of the cell. The same trend is evident for curves B and C. Here the data is taken from end to end cell technology but where the measurement point is central on one side of the cell. The data again shows that when the anode change is near the measuring point, the temperature invariably reads lower, whereas for an anode change at the other extreme of the cell, the measured temperature tends to be higher than the average. (The two curves, B and C, are for the different sides of the cell.)

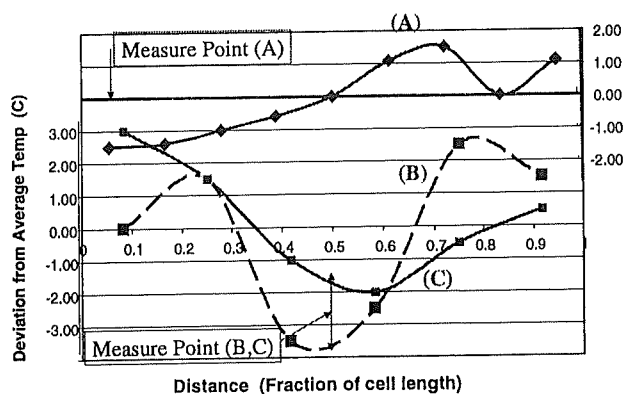


Figure 3: The deviation in measured temperature at a fixed position in the cell through recent anode changes elsewhere in the cell (X-axis refers to position of anode undergoing anode change.)

Because the anode changes for technology A compared with B and C are quite different fractions of the total carbon mass, the magnitude of the impacts are different. It should be noted that in this data there is a secondary impact from the setting pattern and the data will also be slightly influenced by the aluminium fluoride addition schedules. However, it is clear that the temperature measured at a fixed location is influenced by work practice and is not representative of the whole cell.

Whilst it is noted, in discussing Figure 3, that the anode setting pattern has a secondary impact, this is more clearly demonstrated in Figure 4, where 28 cells, taken from each of two identical potlines, are compared. In this instance, anodes were changed approximately every second day, but temperatures were measured daily. The deviation from the average potline temperature is almost exactly aligned for each group. When analyzed more closely, the minor secondary effects can be explained by the setting pattern and cell feeder locations.

The exact reflection of the work practice on temperature deviation shows that, when characterized for a given technology, a correction factor could be applied to the measurements to give the effective deviation, but the actual measurement is not representative of the cell in itself.

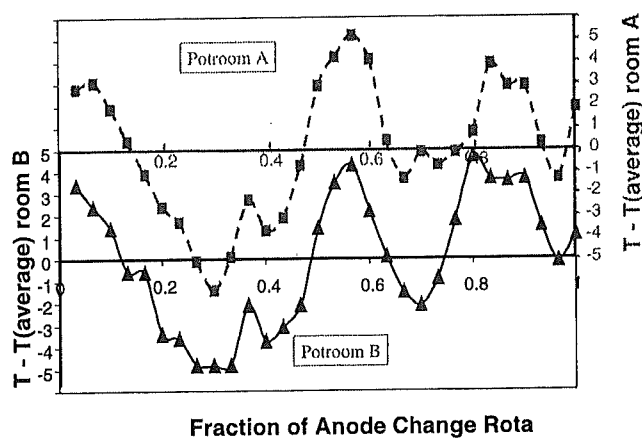


Figure 4: Illustrating the systematic link between Temperature measuring error and work practices.

The data of Figure 4 also shows that the deviations are of long time duration, much longer than that simply of the freeze growth and re-melting of the newly set anode. This is because the temperatures measured on the days between anode changes still conform with the same trend line, even though the measurements are 24 hours apart. Since feeding affects the temperature, as is evident from Figure 2, and all cells have periods of over-feeding and under-feeding in their control strategy, this is also a potential source of temperature error. This is more sensitively reflected in changes in superheat. The superheat distribution in a well-run point fed potline is given in Figure 5 where it is seen that there is a bimodal distribution. Cross checks of the feed strategy with the measured superheat showed that the group with the low superheat values are associated with the over-feed situation, whereas the other more dominant grouping, is either in base-feed or under-feed situation.

Shifts in superheat are reflected by differences in temperature and are driving forces for shifts in electrolyte composition as well.

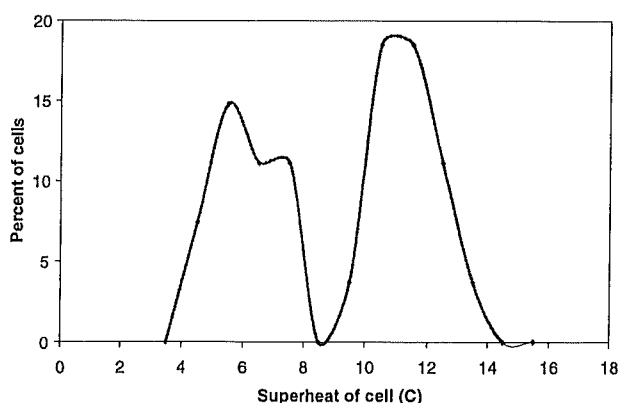


Figure 5: Superheat distribution in well-run point fed technology

Role of Cell Design

Whilst it is evident that temperatures within the cell are not uniform, and work practices and operating procedures cause variations within the cell, it is also possible that cell design impacts temperature. The data presented in Figure 6 from a specific cell study, provides an indication that this could be so. The figure presents the average of ledge profile measurements for each side of a cell. The profile for the upstream side is of significantly different thickness to that of the downstream side. This establishes that the heat flow out of either side is different. Whether this is due to higher heat transfer coefficients or, alternatively, temperature and superheat gradients, has not been established. The trends in shell temperature data are also included in Figure 6. These show that the average sidewall temperature of one side is consistently higher, but this difference diminishes below the bath-metal pad interface. Thus, it is likely that the location impacts are also influenced by cell design.

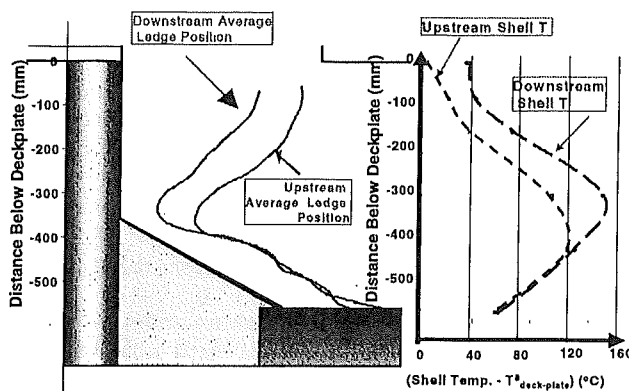


Figure 6: Illustrating differences in side-ledge profiles and side-shell temperatures for different sides of the cell.

Dynamical Variation in Bath Temperature

As discussed in the preceding section there are a number of issues regarding the measurement of temperature. From a process control perspective it is desirable to differentiate between "real" changes in temperature as a dynamic response to changes in process inputs and measurement noise or error. It is desirable that a control system should respond only to "real" change in temperature and not to the measurement noise.

The question therefore is, what component of the variation in temperature is noise and what is real variation that we would aim to control. This question should be answered, taking into consideration the frequencies of measurements and control actions.

When designing a control system, the selection of sampling frequency is crucial to the control performance. Typically the frequency response of band-limited systems is first examined, and is often used as the starting point for selection of sampling rate. The sampling rate is generally selected to be faster than the desired closed loop band-width (or frequency range) of the system. In the case of bath temperature however, measurement frequency is generally determined by practical measurement constraints. Bath temperature is typically measured manually and infrequently, once or less per day. The issue then is rather than what is the desired sampling rate, what is the frequency range of dynamical variation that a control strategy should aim to control and what therefore should be treated as "measurement noise" for control purposes.

The Nyquist sampling theorem indicates that at a sampling frequency of 1/day, then the highest frequency that can be theoretically identified is 0.5/day. If a frequency of variation can not be identified, then it cannot be controlled. Generally, to ensure good control performance, a margin of safety is needed and hence targeting control of frequencies lower than 0.2/day is suggested (ie with period > 5 days). The next question is whether this is sensible

and the answer depends on what dynamical variation is occurring at less than this frequency.

Figure 7 shows the power spectral density function (PSD) obtained for one cell technology where the temperature is measured once per day. The PSD shows that the majority of the variation in temperature is concentrated at low frequencies, for example 80% of the variance in temperature is due to frequency components below 0.25/day (corresponding to a period of 4 days). Above this frequency, the variation may be "white noise" (ie random error) as the PSD is at a fairly constant level.

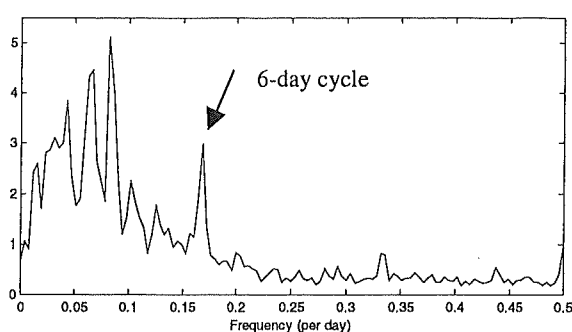


Figure 7 Power Spectra for Bath Temperature in One Cell Technology

For this cell technology with daily measurements of temperature, there is significant variation in temperature with frequency greater than 0.2/day (ie period greater than 5 days). It therefore seems to be a reasonable approach to target the control system at frequencies below this and therefore consider variation at higher frequencies to be "measurement noise".

Also observed in the PSD is a peak at 0.17/day (corresponding to a period of 6 days), with a harmonic observed at 0.33/day. These are due to the anode setting pattern; one anode is set every day for 5 days, then on the sixth day no anode is set (called a miss-shift). There is a thermal energy demand associated with raising the newly set anode to operating temperature, which impacts on the electrolyte temperature. Miss-shifts in the setting rota therefore give rise to an increase in temperature (or more correctly, don't cause a depression in cell temperature). While this variation occurs at a frequency less than 0.2/day, a feedback control system should not respond to this phenomenon as before any control action influences the temperature, another anode will have been set. The impact of the location of any anodes set in the cell was also shown earlier to have an impact on temperature in the measurement location of a cell. This variation occurs at quite low frequencies, however this probably represents a localised temperature effect and the control system should not respond to this either, given that any control action will affect the entire cell. To account for both of these setting effects, it may be advantageous to have a temperature target that varies with the anode setting rota.

As also shown earlier, the physical process of alumina feeding and also the underfeed/overfeed modes that are typical of present feed control strategies, affect the cell temperature. The variation caused

however is occurring at a substantially higher frequency than 0.2/day (ie $> 24/\text{day}$), hence this variation is measurement noise within the context of temperature control from daily temperature measurements. Ultimately it would be desirable to minimise this noise source.

While this discussion has focused on feeding and anode setting, there are other phenomena that cause high frequency or short-lived variation in bath temperature to which a feedback control system should treat as "measurement noise", for example anode effects.

Interpretation of Temperature Measurement and Feedback for Control

The question that now remains is what is causing any "real" or dynamical variation in temperature and what would be the appropriate control action?

Bath temperature can be considered as the bath superheat plus the liquidus temperature. The liquidus temperature is dictated by the chemistry of the bath and the most significant components are alumina and aluminium fluoride concentration. If only bath temperature is measured, then any variation could be due to a change in any of these three variables. Table I shows the percentage of the variation in temperature that can be attributed to each of these three components for a number for different cell technologies. In some technologies, variation in all three is contributing to the variation in temperature. The data also shows that the relative contribution can vary over time.

Table I: Percentage variation in temperature explained by variation in chemistry and superheat in a number of different cells⁶

% variation in temperature explained by variation in:	Group X	Group Y	Group Z Time Period 1	Group Z Time Period 2
AlF ₃	79	42	63	1
Al ₂ O ₃	7	22	-23	30
Superheat	10	35	77	72

What the data in Table I does not show is whether the variation in superheat, alumina, aluminium fluoride and hence temperature, is low frequency dynamical variation or whether it is high frequency "measurement noise", within the definition for these given above. Given the impact of the alumina feed control, we might expect that at least in part, the variation in temperature resulting from alumina concentration and superheat variation, might be high frequency variation and therefore should be treated as "measurement noise" for the purposes of feedback control. It is likely however that, in addition to the high frequency variation in alumina concentration due to the feed cycle, there is low frequency variation (ie period of days) in the end of track alumina concentration. This could occur due to the influence of other cell variables on alumina solubility and dissolution, sludge accumulation and back-feeding, and the alumina vs resistance curve.

Table II shows the long-term (six month average) data for a smelter that operated at different aluminium fluoride concentrations over a long period of time. The aluminium fluoride concentration target ranged from 7.8 to 10.2% over a period of approximately ten years. The calcium fluoride concentration, which is influenced by the alumina supply, is noted to change by a total of 0.5% during that time. This change in bath chemistry has an impact on the alumina solubility, and it is seen that the average dissolved alumina concentration varied over this period by 1%.

Table II Various Long Term Bath Chemistry and Temperature Relationships of a Smelter (6 month Averages)

wt% AlF ₃	wt% Al ₂ O ₃	wt% CaF ₂	Operating Temp.(°C)	Calculated Liquidus Temp.
7.8	3.9	5.5	963	965
8.2	3.4	5.6	965	966
9.0	3.3	5.8	968	964
9.6	3.6	5.4	967	961
9.5	4.2	5.4	966	958
9.8	3.8	5.5	961	959
9.8	3.2	6.0	961	961
9.8	3.3	6.0	963	961
10.0	3.0	5.9	967	962
10.2	2.9	5.6	970	962

Currently, the most widely used control action is feedback control from bath temperature measurements to AlF₃ additions. There are two potential issues with this control action.

Firstly, relating to the control objectives, some smelters aim to control bath temperature alone. Others aim to control the concentration of excess AlF₃ and have based this on the assumption that bath temperature is a good inferential variable for the AlF₃ concentration. As shown above this is not completely the case as variation in Al₂O₃ concentration and superheat also influence temperature.

The second issue is that by manipulating AlF₃ additions, we are seeking to adjust the mass of AlF₃ in the cell. Recent work⁷ has considered the possible contributors to the net consumption of AlF₃ in a cell. This work concluded that the changes in net AlF₃ consumption would normally be small, unless there is a major shift in one or more of:

- the sodium and impurity analysis of the primary alumina
- the absorbed or crystalline water of the alumina
- the amount of alumina fed to a cell, or drastic changes in the cover integrity.

Therefore, based on normal daily production and the large volume of liquid electrolyte, one would not expect to see a change in AlF₃ mass balance and hence the concentration at constant bath mass. Practically however, the variation in AlF₃ is much greater and recent work⁷ indicates that the bath mass should not be assumed to be

constant, but can change substantially with common changes in the energy balance. The impact of "disturbances" to the cell (eg newly set anode) were shown to have a significant effect on the ledge mass and hence bath mass. Changes in process variables (eg voltage, metal height) that are known to occur from one day to the next, were also considered for their impact on steady state ledge mass. For example, an increase in voltage of 250mV would cause a 30% decrease in ledge mass and a decrease in current efficiency of 4% would cause a reduction of 12%. In the cell technology considered a change of +/-20% ledge mass and hence bath mass, would cause a change of +/-2wt% excess AlF₃. Changes of this order can be observed from one day to the next in cells.

We can therefore conclude that excursions in the concentration of AlF₃ and hence temperature are most likely caused by changes in bath mass and are not due to changes in net AlF₃ consumption. Manipulating AlF₃ additions in response to changes in concentration of AlF₃ and bath temperature will therefore most likely cause variation in the mass of AlF₃ in the cell.

Is the manipulation of AlF₃ additions, and probably the mass of AlF₃ in the cell, an appropriate action as a response to bath temperature, in the face of disturbances to this single-input/single-output system from changes in alumina concentration, superheat and bath mass? The answer to that depends on the ultimate control objective:

- If bath temperature alone is considered to be the critical cell variable, then it is appropriate to manipulate whatever inputs give the best control performance, which is judged by minimum square error (ie actual less target) integrated over time. Therefore if manipulation of AlF₃ additions gives the best control performance, then it is appropriate.
- If concentration of AlF₃ alone is considered to be the critical cell variable then the same arguments apply as for the point above. If the bath temperature is used as an inferential sensor for concentration of AlF₃, then the control system may however be responding to changes in superheat or alumina concentration rather than changes in AlF₃ concentration.
- If the objective is to control concentration of AlF₃ and alumina along with superheat, then manipulation of AlF₃ additions may still be appropriate depending on effectiveness. Other inputs however will also need to be manipulated so that good control of AlF₃ and alumina concentration and superheat can simultaneously be achieved. The measurement of temperature alone however is inadequate to infer all three variables.
- If the objective is control of the masses of AlF₃, alumina and ledge/bath and of superheat, then manipulation of AlF₃ additions to the extent they generally are manipulated is probably inappropriate. Greater emphasis should be given to choosing input variables which influence the energy balance and hence ledge dynamics, along with those affecting the AlF₃ and the alumina mass balances. Once again, measurement of temperature alone is inadequate to infer all variables of interest.

Conclusions

- Spatial and “high” frequency temporal variations in bath temperature occur in cells and should be considered to be “measurement noise” for the purposes of feedback control from “low” frequency bath temperature measurements (ie $\leq 1/\text{day}$).
- An automated semi-continuous measurement system linked with operating practices and the control system would be advantageous to minimise this “high” frequency “measurement noise”.
- Variation in bath temperature results from variation in superheat and AlF_3 and alumina concentrations. It is therefore unwise to assign variation in temperature to be from variation in excess AlF_3 concentration alone.
- Variation in AlF_3 concentration is most likely due to changes in ledge mass and hence bath mass and not due to changes in net consumption of AlF_3 .
- Appropriate manipulated variables for feedback control from a bath temperature measurement depend on the ultimate control objective. This objective will also influence what other measurements may also be required.

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