CHARACTERISTICS OF *IN SITU* ALUMINA PID ORE FEED CONTROL

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Abstract

Point feeders have volumetric chambers that periodically deliver ore to cells through holes pneumatically broken into the crust layer. The period of feeder actuations is controlled by the logic employed to regulate bath alumina concentration. The time evolution of bath alumina concentration is mostly a function of the rates of alumina consumption and feeder mass charge, but is also influenced by other events such as crust seal breaks/leakages, and plugged or semi-plugged feeder holes. PID modulated *In Situ* feed logic addresses variable non-feeder ore related events to control alumina concentrations at targeted levels. Frequent underfeed and overfeed episodes are avoided. The *In Situ* ore feed concept has been successfully tested in the Dyna/Marc cell simulator at a targeted 2.30 % alumina concentration demonstrating both increased current efficiency (CE) and decreased kWh/kg compared to presently employed methodologies. Anode/cathode distances (ACD) can also be accurately measured using *In Situ* % alumina predictions.

Introduction

An *In Situ* feed control methodology has been proposed [1, 2, 3]. Its distinguishing feature is marked by point feeder actuation periods that maintain within reasonable and acceptable limits targeted alumina concentrations. Every few hours an *in situ* % Al_2O_3 routine is called during which ore feed is restricted for 5 minutes or so in order to force a small decrease in alumina concentration. The rate of change in the ACD corrected predicted voltage (V_P) is then used to compute an estimated *in situ* % Al_2O_3 which can be subsequently tracked by V_P. The *in situ* % Al_2O_3 prediction is not especially sensitive to small variations in other bath parameters. After collecting a 5 minute raw voltage/amperage data array a new *in situ* % Al_2O_3 is first computed, a new secondary calibration curve is then computed from 2 established primary calibration curves which are exponential fits of (% Al_2O_3 - % $Al_2O_{3 \, (anode \, effect)})^{-1}$ versus V_P (see Figure 1).
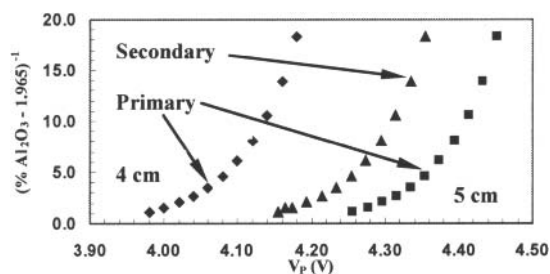

Figure 1 Two primary calibration curves (ACD's of 4 and 5 cm) and a secondary calibration curve

The two simulated primary calibration curves in Figure 1 are based upon ACD's of 4 and 5 cm [4]. Once computed the secondary calibration curve permits *in situ* % Al_2O_3 levels to be accurately tracked vis-à-vis the V_P variable until the elapse of several hours before a new *in situ* measurement routine is called. The 3 calibration curves in Fig. 1 can be also employed to compute the ACD by use of a simple interpolation technique. Prior to each 5 minute ore feed restriction, the ACD can be adjusted to a target value as necessary. It is important to note that the raw V_P must be continuously adjusted based upon the voltage change caused by the estimated change in ACD determined by the difference in rates of metal pad build up and anode carbon burnoff. That is the principal reason why periodic *in situ* routines to measure % Al_2O_3 are necessary as the result of unavoidable error in this estimate.

Current Efficiency Losses

The *In Situ* ore feed method is a departure from present control tactics which cycle between underfeed and overfeed modes and which in some instances may also include a period of nominal steady state ore feed. Present control techniques can result in significant alumina concentration fluctuations. During the overfeed period especially the available superheat reservoir can become increasingly more depleted. As a result, the time for complete alumina dissolution increases since there is insufficient superheat remaining for the endothermic alumina preheating and dissolution requirements during the short period before the next ore addition [5]. At the end of the overfeed period it is reasonable to expect increased levels of some form of bath dispersed or undissolved alumina. Multiple studies of alumina dissolution behavior in cryolite have shed important light on key factors [6, 7].

It is reasonable to expect current efficiency losses to be initiated at the cathode surface. It is assumed that virtually 100 % Faraday cathodic Al deposition initially occurs at this surface. Secondary non-electrolytic reactions which subsequently decrease CE mostly have their origins in Al diffusion processes initiated within the adjacent cathodic diffusion layer.

A simplified example to shed light on some of the driving forces that partially account for CE losses can be made for a 95% CE 300 kA cell with 10000 kg molten bath with a Na content of 610 ppm and a metal pad with a Na content of 100 ppm. There is a CE loss of metal production in the amount of 121 kg/day. Any Na produced at the expense of Al at or near the metal surface diffuses into either the metal pad or the adjacent bath. Of this loss about 0.09 kg/day of Al (Na equivalent) is accounted for by the Na produced and extracted into the metal pad. It is a negligible amount. The principal source of the loss of about 119 kg Al/day starts by Al diffusing into the adjacent bath diffusion layer. The fate of Al within the diffusion layer could be twofold: 1) subsequent escape into the bulk bath as a dissolved or dispersed

species; 2) exothermic reactions of diffused Al that produce free Na and/or subvalent Al species. The heat produced by these reactions result in a convective heat flow causing a rapid localized transfer of Al, Na and reduced Al species into the bulk bath. These bath species can subsequently react with CO_2 as they diffuse into the anode bubble zone. Some can escape, especially the more volatile Na, into the anode off gas stream. Any pronounced yellow flame seen emanating in the off gas is a sign of elemental Na and as such is correctly diagnosed as the sign of a "sickly" or low CE pot.

Many of the slowly dissolving dispersed alumina particles produced during the overfeed period can be cryolite impregnated agglomerates of different sizes [7]. A fraction of these cryolite encapsulated particles can then settle for a time on the bath/metal interface thereby penetrating and often in effect expanding the narrow diffusion layer. Localized resistance heating can be produced within this expanded diffusion layer containing an elevated dissolved Al concentration. Within this highly Na^+ enriched cathodic diffusion layer, in the presence of an increased concentration of Al at an elevated temperature, exothermic reactions involving dissolved Al can produce a combination of free or elemental Na and subvalent species such as AlF, AlF_2^-, and AlF_3^- [8]. Rising convective thermal currents can then rapidly sweep the localized dissolved metal (Al and Na) and subvalent species into the bulk bath to form dissolved as well as dispersed non-dissolved species since equilibrium solubility amounts can be exceeded. The rate of Al diffusion from the metal pad is thereby commensurately increased because of the increased rate of depletion in the diffusion layer. It is acknowledged that this explanation is not a fully tested hypothesis, but represents an effort to stimulate additional thinking and investigation on this thought.

Higher Na concentrations in bath (up to 1800 ppm) have been shown to be statistically linked to lower current efficiencies [9]. A careful study has documented that under laboratory conditions typical potline bath has a Na solubility limit near 610 ppm (exposure to ambient air was assiduously prevented) [8]. This information suggests that potline bulk bath can have a metal content up to 3X the equilibrium level (actually it could be higher since any exposure of lab bath samples to ambient air would react to some degree with free or elemental Na). This metal excess suggests a possible reason why potline bath is not transparent but rather the translucent liquid it is. Potline bath is not a true solution since any metal content exceeding the equilibrium amount forms some type of light diffusing medium. True solutions are transparent. The translucence of bath is most likely the result of suspended or dispersed/undissolved solids, liquids, or gases due mostly to undissolved alumina agglomerates, free metals exceeding the equilibrium amount, and CO_x's including small amounts of HF and H_2.

Other reactions contributing to current efficiency losses at the bath/metal interface include those between Al and any residual LOI content of settled dispersed alumina and which produce HF and H_2. It is difficult to argue that dispersed alumina/alumina agglomerates which have settled onto the metal surface are not harmful to production efficiencies. Likewise it is difficult to argue that any ore feed methodology which decreases the amount of bath dispersed alumina/agglomerates is not likely helpful to the production process.

The semi-continuous action of point feeders periodically deliver a finite mass of alumina, which upon contact with bath dissolves in a finite period of time. Point fed alumina dissolution can be fast under optimal conditions, but is not an instantaneous process. Bath temperatures decrease after each alumina addition and thermally recover at a finite rate. If the rate of alumina addition is close to the steady state rate, especially when the bath alumina concentration is low, then full superheat recovery before the next alumina addition is more assured when compared to the effect overfeed rates have on superheat levels. During the overfeed mode of present feed methodologies, the formation of dispersed alumina is accelerated. If a cell were to be fed ore at or near the steady state rate maintaining a low alumina concentration, then it is far more likely that dispersed alumina levels will be kept to minimal levels. *In Situ* ore feed methodology assiduously avoids overfeed periods.

A cell's CE is typically acknowledged to be linked to alumina concentration. Lower alumina concentrations are accompanied by increased CE's in the presence of high bath metal concentration [5]. However the highest CE's seem to be slightly positively correlated with alumina concentration in the presence of low bulk bath metal concentrations. *In Situ* feed control is designed to significantly decrease the formation of dispersed alumina by targeting % Al_2O_3 at low levels. Under such conditions it is reasonable to expect significantly lower dissolved bulk bath metal concentrations.

If *In Situ* controlled point fed alumina dissolves more quickly within the anode bubble zone at lower alumina concentrations, then the LOI content of alumina is less likely to react with bath dissolved metal and instead preferentially reacts to form HF. It is accordingly reasonable to expect that the accumulation of dispersed alumina at the bath/metal interface layer can be largely avoided if point feeders deliver ore at a rate close to the steady state rate at all times and which maintains a sufficiently low targeted alumina concentration that avoids anode effects. This is precisely the aim of *In Situ* ore feed logic.

Unpredictable Variations in the Amount of Ore Contacting Bath

The mass of alumina delivered by point feeders and which subsequently contacts bath can vary unpredictably over time for a number of reasons. Some of these reasons include changing ore bulk density, an occasional plugged or semi-plugged feeding hole, or at times a leaky point feeder. It is also possible that during normal operations a crust seal break at some location may produce extraneous leakage of unknown amounts of non-feeder alumina at unpredictable times. Accumulated alumina around a feeder hole may suddenly slough into the bath. It is not realistically possible to constantly and accurately monitor all of the factors that contribute to the actual mass of ore making bath contact at any given time. The instantaneous CE is also not precisely known and therefore the real time rate of alumina consumption cannot be accurately tracked. These are the reasons why historically any attempt to control alumina concentrations by simply monitoring and setting point feeder actuations at a constant rate based upon an assumed ore shot mass have predictably failed. However it has now become possible to monitor on a real time basis both the *in situ* alumina concentration and ACD using processed conventional cell voltage/line amperage data. Armed with this basic information when coupled with *In Situ* processing logic,

point feeders are controlled at variable rates close to the steady state rate that maintain a targeted alumina concentration within an acceptable error band. The targeted alumina concentration can in fact be tailored to the optimal level for any given pot to maximize production performance. For some pots maximal performance might be had at a low of 2.20 % and for others possibly at a high of 2.70 %. It is also now possible to subject the targeted alumina concentration to the ore quality being received at smelter site. Poorer quality slower dissolving ore would argue for lower operating targeted alumina concentrations. *In situ* ore feed logic is equipped to probe this opportunity.

In Situ PID Control Details

The dynamics of cell operations are such that changes in dissolved alumina concentrations have immediate effects on cell voltage levels. The predicted voltage variable (V_P) has been statistically demonstrated to be superior to pseudo-resistance (R_P) to describe the thermodynamic state of a cell [1, 2]. One of the speakers during the aluminum plenary session at the 2011 TMS San Diego meeting and who is a well known and highly respected authority admonished attendees by stating that it was time for the smelting industry to return to basics when he insisted that "electrochemistry is electrode potentials or voltages" and that "resistance simplifications can go wrong" [10].

Accurate real time *in situ* % Al_2O_3 is computed using V_P. V_P is the expected voltage computed at a constant reference line amperage and as such filters out voltage changes from variations in line amperage. The ACD drift corrected V_P can therefore be reliably employed for computing real time *in situ* % Al_2O_3 by computing the V_P slope (mV/min) during a no feed period spanning about 5 minutes or so. It is expected that *in situ* % Al_2O_3 predictive measurements typically need to be repeated every 3 hours or so under normal undisturbed operations. The principal reason for periodic *in situ* alumina concentration measurements is the possible presence of a small voltage drift as the result of the difference between metal pad build up and anode burn off rates which change the ACD. This slowly changing voltage drift can be estimated to correct the raw V_P computation which is used to track % Al_2O_3 and ACD. Over time any small error in this corrective estimate slowly becomes magnified. Hence a 5 minute recalibration routine becomes necessary every few hours where a no feed restriction decreases the alumina concentration by about 0.15 %.

In Situ Ore PID Modulated Ore Feed Simulation Runs

The nature of *in situ* ore feed control makes it a candidate for PID (Proportional, Integral, Derivative) modulation. This may be a novel application for PID control since point feeder actuation period changes are executed every 5 minutes or so instead of on time intervals of seconds. Four cell simulation runs were generated where a feedback loop was used to compute cell voltage levels based upon a voltage offset term in the 4 cm ACD exponential primary calibration curve, i.e. (% Al_2O_3 - 1.965)$^{-1}$ versus V_P [4]. The PID feed rate is computed by the equation:

$$FR = SSFR * [1 - (P_{gain} * (\Delta\%Al_2O_3) + I_{gain} * \Sigma(\Delta\%Al_2O_3) + D_{gain} * d(\Delta\%Al_2O_3)/dt)]$$

Where: FR is the point feed rate (kg/hr)
SSFR is the nominal steady state feed rate (kg/h)

P_{gain} is the proportional gain
$\Delta\%Al_2O_3$ is the difference between *in situ* % Al_2O_3 and the target % Al_2O_3 (i.e. the error term)
I_{gain} is the integral gain
$\Sigma(\Delta\%Al_2O_3)$ integrates $\Delta\%Al_2O_3$ terms (%)
D_{gain} is the derivative gain
$d(\Delta\%Al_2O_3)/dt$ is the rate of change of $\Delta\%Al_2O_3$ (%/min)
$P * \Delta\%Al_2O_3$ is the P component
$I * \Sigma(\Delta\%Al_2O_3)$ is the I component
$D * d(\Delta\%Al_2O_3)/dt$ is the D component.

The feed period (s) is subsequently computed from the feed rate:

$$FP = 3600 * SM / FR$$

Where: FP is the feed period (s/ore shot)
SM is the nominal shot mass (kg/ore shot)

The four simulation runs were based upon the following parameters: 10,000 kg of bath, 10 % excess AlF_3, 5 % CaF_2, 94% CE, 300kA, P_{gain} = 6.0, I_{gain} = 0.3, D_{gain} = 3.0. It is important to avoid integral windup by setting appropriate min/max levels for the integral component, $I * \Sigma(\Delta\%Al_2O_3)$.

The first data array in each simulation run imposed an initial 5 minute no ore feed restriction in order to compute the *in situ* % Al_2O_3. If necessary subsequent 5 minute data arrays were subject to continued ore feed restriction as a larger *in situ* measured concentration approached the target level. Included as an option in the simulations was an ore offset term which could be varied as desired at different times. The ore offset term represents the unknown and variable amounts (±) of ore which contact bath for reasons previously described. Fast ore dissolution was assumed in the first two simulation runs where no dispersed alumina is present.
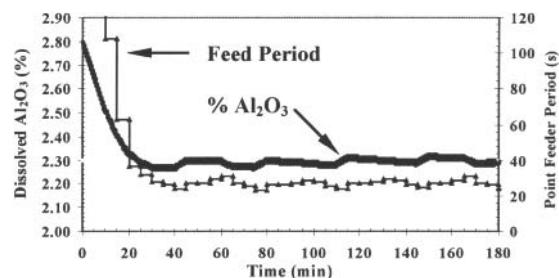

Figure 2 First simulation run: % Al_2O_3 (actual) and Point Feeder Actuation Period (Target % Al_2O_3 = 2.30)
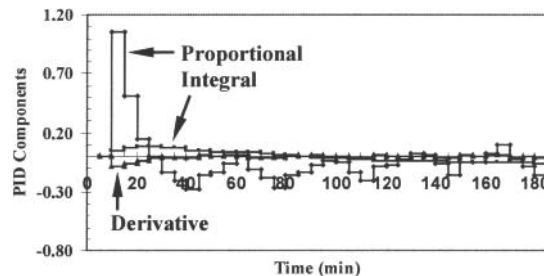

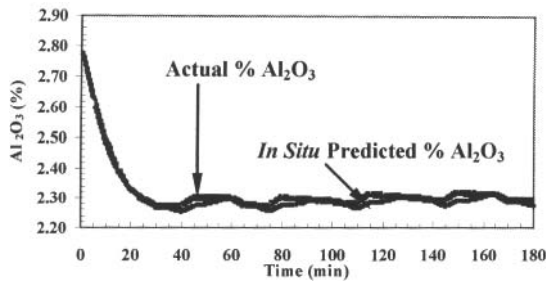Figure 3 First simulation run: PID Components versus time

Figure 4 First simulation run: Actual vs. *In Situ* % Al₂O₃

Figures 2 - 4 represent the first 3 hour simulation run (no impressed amp/voltage random noise but 2 impressed voltage cycles of 3.3 and 2.1 mV of periods of periods 35 and 15 seconds respectively) and no ore offset episodes. The target % Al$_2$O$_3$ was 2.30%. Ore feed was restricted for a total of 15 minutes until the *in situ* alumina prediction was within about 0.20% of the target value (at 15 minutes the *in situ* prediction was 2.528% and the actual % Al$_2$O$_3$ was 2.564%). Within 30 minutes the alumina is thereafter controlled to the 2.30 % target level within a band of 2.267 to 2.319% (see Figure 2). In Figure 3 the proportional component is initially very high since the alumina level is higher than target. The integral component in Figure 3 is also initially positive but then slowly decreases as the proportional term becomes slightly negative. The derivative component in Figure 3 remains at a very low level throughout and the control soon collapses to mostly PI. Over time all 3 components decrease and approach 0. If there had been no impressed voltages cycles, then the plots in Figure 2 would have not varied after the 20 minute mark.

A second simulation run is shown in Figures 5, 6, and 7 where a +42 kg ore offset representing a uniform ore leakage was impressed during the 60 - 80 minute time segment.
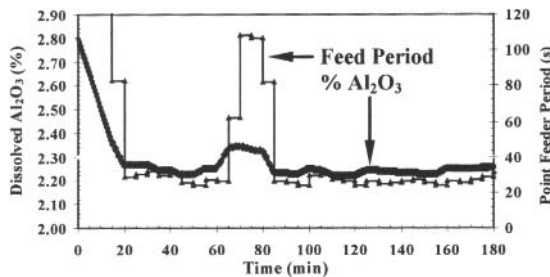

Figure 5 Second simulation run: % Al₂O₃ (actual) and Point Feeder Actuation Period (Target % Al₂O₃ = 2.30)
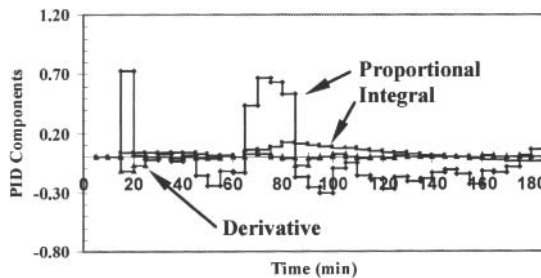

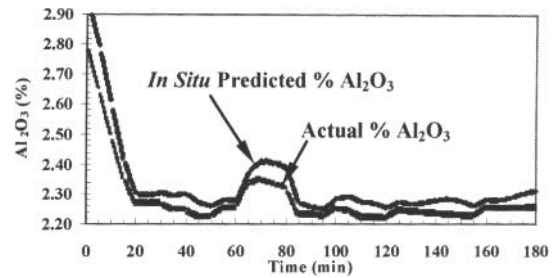Figure 6 Second simulation run: PID Components versus time

Figure 7 Second simulation run: Actual vs. *In Situ* % Al₂O₃

At the 60 minute mark there is additional ore mass of 42 kg uniformly starting to leak into the bath during the next 20 minutes. There is a timely detection of an increase in alumina concentration as shown in Figure 5 where the feed period is swiftly increased to counteract the increasing alumina level. The *in situ* response halts the increase in alumina content after an initial rise from about 2.27 to 2.34 %. Otherwise the alumina concentration would have risen to more than 2.70 %. In Figure 6 the sharp increases during the 60 to 80 minute time period in the proportional and integral components are clearly seen. When the ore leakage stops at the 80 minute mark, these terms appropriately decrease as the control returns close to the target level. It is easy to notice the small alumina "bump" in Figure 7 which was prevented from growing much larger by PID control. For this simulation run the ACD was computed at 4.60 cm versus the actual value of 4.64 cm.

The previous 2 simulation runs were based upon no bath dispersed alumina loading. The third simulation run displayed in Figures 8 - 11 is based upon an initial dispersed alumina load of 0.45 % where the dissolution rate is given by: $d(M_{DA})/dt = k \ M_{DA}$(% Al$_2O_3$ - % Al$_2$O$_3$ (saturated)) where M_{DA} represents the mass of dispersed alumina, the dissolution constant k = 0.8, and % Al$_2$O$_3$ (saturated) = 7.3. It was assumed that 25 % of any given ore shot dissolved within seconds with the remainder becoming undissolved dispersed alumina which subsequently dissolved as determined by the rate equation. Additionally, randomized noise levels were impressed upon this run (± 0.05 % for amperage and ± 0.15 % for voltage).
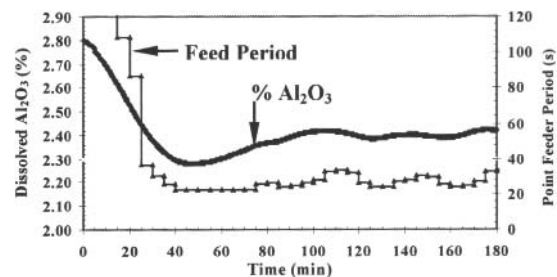

Figure 8 Third simulation run: % Al₂O₃ (actual) and Point Feeder Actuation Period (Target % Al₂O₃ = 2.30)
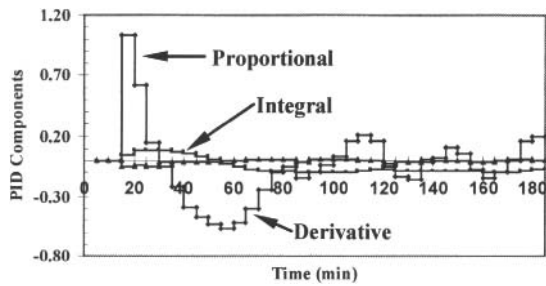
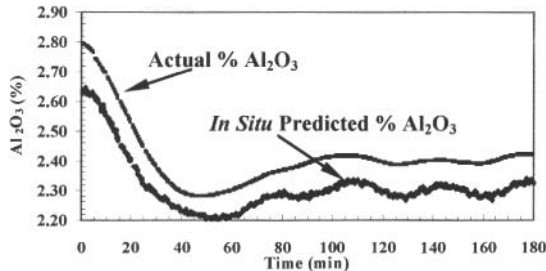Figure 9 Third simulation run: PID Components versus time

Figure 10 Third simulation run: Actual vs. *In Situ* % Al_2O_3

In Figure 8 the time to reach target alumina concentration approximately doubles from 20 minutes to 40 minutes because of the dispersed alumina dissolution rate. The alumina concentration is somewhat off the 2.30 % target after the 40 minute mark (2.279 to 2.420 %) but still renders acceptable control in spite of less than ideal performance. The decrease in dispersed alumina loading in Figure 11 during the first 20 minutes is the result of the continued imposed no ore feed restriction.
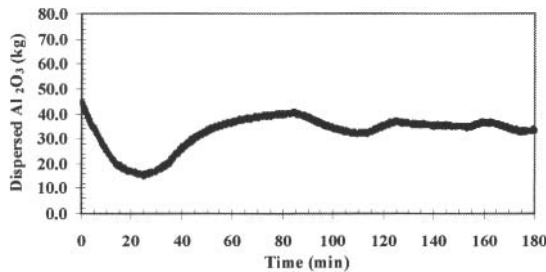

Figure 11 Dispersed alumina versus time

A potentially more serious situation can occur if any extraneous ore leaks into the bath during the 5 minutes of restricted ore feed when the *in situ* alumina concentration is being measured in addition to the presence of 0.45 % dispersed alumina. The consequence of two serious situations results in a decreased V_P slope which produces a positive error for the *in situ* % Al_2O_3 prediction. This leads to alumina control which sinks below the targeted level. In Figures 12 to 14 there was a simulated leak of alumina amounting to 5.0 kg during the no feed period when 15.2 kg of alumina was being consumed (a purposely large simulated leakage). The *in situ* measured alumina is 2.274 % while the actual level is 2.208 %, an error of + 0.066. The ACD was measured by interpolation at 4.71 cm while the actual value was 4.64 cm. Figure 12 shows that after the 20 minute mark the alumina is being controlled at about 2.13 % which is considerably

lower than the targeted level of 2.30 %. Figure 13 shows the less than ideal PID responses. Figure 14 illustrates the significant gap between the measured *in situ* % Al_2O_3 and the actual values. However in this type of situation anode effects can be avoided as long as the target % Al_2O_3 is not set too low. It is reasonable to expect that pots prone to dispersed alumina formation will eventually become much less prone to this phenomenon.
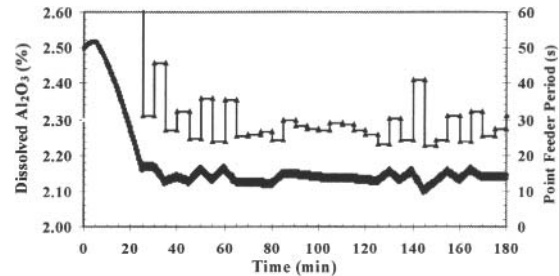

Figure 12 Fourth simulation run: % Al_2O_3 (actual) and Point Feeder Actuation Period (Target % Al_2O_3 = 2.30)
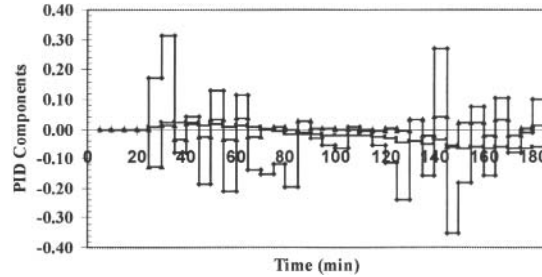

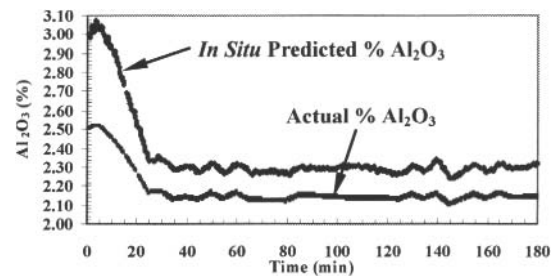Figure 13 Fourth simulation run: PID Components versus time

Figure 14 Fourth simulation run: Actual vs. *In Situ* % Al_2O_3

Conclusion

It has been shown in simulation runs that PID modulated *In Situ* feed control logic makes a reasonable case for improved alumina concentration control that maintains a targeted level within acceptable limits in spite of unknown and unpredictable events which can affect the amount of ore dissolving in the bath during normal operations. A case has been made for a significant decrease in dispersed alumina formation. *In Situ* feed control is expected to work optimally at the highest targeted alumina level where the formation of bath dispersed alumina does not occur. Operating experience will dictate the uniquely optimal target maximum for any given cell.

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It may now be possible to take up the challenge of genuine continuous ore feeding that dribbles alumina at a variable controlled rate of about 1 -2 g/s through small holes in slotted anodes as controlled by *In Situ* feed methodology. The bath agitated region where alumina particles would make contact would ensure fast ore dissolution. It is also possible that significant surface moisture would be driven off prior to bath contact if there is off gas entrainment for a short duration within the slot. Another important benefit would be alumina pre-heating that enhances the dissolution rate and which also provides a more uniform alumina distribution.

Acknowledgement

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