

ACTIVE POT CONTROL USING ALCOA STARprobe™

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Abstract

To run an aluminum smelting cell, routine bath sampling and subsequent chemistry analysis are required along with pot temperature measurement. The sampling and analytical process is lengthy, tedious, and very often results are delayed as long as 24 hours. In addition the results are not coupled to other critical information (e.g. noise, automatic resistance adjustments, etc) at the time of the sample. Alcoa STARprobe™, which was previously described (1), corrects these deficiencies while providing a means to more efficiently and effectively control a smelting pot. This paper presents the background philosophy for an advanced control that has been enabled by the new measurement technique. The control method has been applied in multiple plants and demonstration of improved performance will be shown.

Introduction

In a previous paper, Alcoa STARprobe™ was described as a real time measurement tool for active pot control (1). The motivation for developing the STARprobe™ is obviously to improve the efficiency of the operation. Since the probe allows a coordinated real time measurement of superheat, temperature, ratio (acidity), and alumina concentration, this information is easily coupled with the other known pot operating conditions such as noise, voltage modifiers, and state of feed control. This paper shows a detailed comparison of STARprobe™ and traditional sampling analytical results on a plant scale in routine production and the principle of an advanced control algorithm which has been enabled by the new integrated technique.

Deficiency of Bath Chemistry Control

Bath chemistry and cell operating temperature are controlled to achieve optimal current efficiency and energy efficiency. Specific chemistry targets and the corresponding operating temperatures are commonly dependent on cell technology. Typically, control of these relies on traditional bath sampling/analysis and separate temperature measurement. The bath chemistry control is done by manipulating chemical additions (AlF₃ or soda ash) (2 to 4), while pot temperature control is achieved by maintaining a specific resistance target (5, 6). The two controls are usually carried out independently with very little coordination. As illustrated in Figure 1, chemical additions (AlF₃ or soda ash) drive bath ratio to target, and pot resistance (voltage) adjustments drive the pot temperature to its target. Usually this approach is good enough as long as both bath chemistry and temperature are operated within targeted operating ranges. During a transition period when a pot

temperature changes from low to high, bath ratio control attempts to maintain the target ratio which will at least lead to sub-optimal operation and at worst a pot failure. It is also true for cases where a pot temperature transitions from a high to a low. Ultimately the bath chemistry control, no matter how sophisticated the algorithm, produces unfavorable conditions due to lack of real time analysis and lack of integration with the rest of the system. Eventually this negatively impacts energy efficiency.

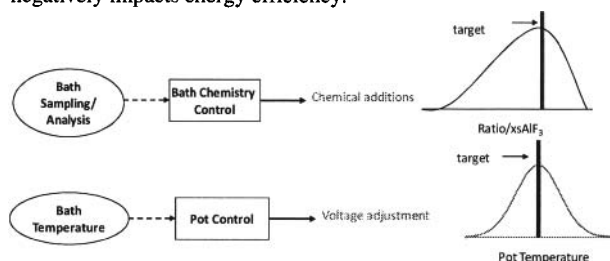


Figure 1: Traditional pot ratio and temperature control.

Another deficiency is when a pot suffers problems from anode or cathode issues, raw material changes, or operational upsets (unplanned maintenance). Conflicting decisions between bath chemistry and temperature control can be made that produces an unfavorable condition with excess high superheat. For the worse cases, excess high superheat results in:

- Loss of side ledge and potential pot failure
- Loss of current efficiency (7) that generates extra heat
- Loss of bath cover with loss of alumina control and high emission.

Some advanced control algorithms try to overcome the deficiency by using various models to get both bath chemistry and temperature under control in an operating target zone. However, due to lack of key links between material and thermal balances, inefficiency still exists from the inability to control bath chemistry and temperature in a closely coordinated manor.

Dynamic Link Between Material and Thermal Balances

Material (chemical) and thermal (energy) properties are continuously in a balanced but dynamic state. Pots under normal operating conditions usually have a fairly consistent heat balance and the heat flow through the pot side and end walls stays fairly constant (8). The relationship of heat flow to and from the sidewall at the bath zone may be approximated by

$$\begin{aligned}
 Q &= Q \text{ (to ledge)} = Q \text{ (from ledge)} = Q \text{ (away from shell)} \\
 &= h_{B-L} \cdot A_L \cdot (T_{\text{bath}} - T_{\text{liquidus}}) \\
 &= h_{B-L} \cdot A_L \cdot \Delta T
 \end{aligned}
 \tag{1}$$

where Q = heat flow rate through side-ledge

- h_{b-l} = heat transfer coefficient: bath to ledge heat transfer
- T_{bath} = bath temperature
- $T_{liquidus}$ = liquidus temperature of bath
- A_L = cross-sectional ledge area
- ΔT = bath superheat ($T_{bath} - T_{liquidus}$)

The heat flow to ledge interface is driven by bath superheat $[\Delta T]$, if a constant superheat can be maintained during pot operation, the heat flow through sidewall would remain constant and:

$$T_{bath} - T_{liquidus} = \text{Constant} \quad (2)$$

The liquidus temperature is impacted by bath chemistry (constituents) (9):

$$T_{liquidus} = C_0 + C_1 \cdot \text{Ratio} + C_2 \cdot \%CaF_2 + C_3 \cdot \%Al_2O_3 + \dots \quad (3)$$

Combining (2) and (3), relationship can then be easily derived:

$$\text{Ratio} = C' + C'' \cdot T_{bath} \quad (4)$$

Equation (4) is the ratio (XS AlF_3) variation purely due to pot thermal change as expressed by bath temperature. Figure 2 shows an example of bath ratio and %XS AlF_3 as a function of bath temperature at a constant superheat of 10°C. As the temperature increases due to increasing voltage or resistance, a part of the side ledge will melt whereby the bath ratio increases (%XS AlF_3 decreases). It is operationally impossible to run a pot at an exact constant superheat, but it is not impossible to target a range. Figure 3 shows an example of a pot operated at a superheat range of 5 and 15°C. The bath ratio increases as bath temperature increases when the superheat is within this range. In this case, the acidity change is from the freezing and thawing of cryolite in the ledge and not from neutralizing Na_2O from alumina during the electrolysis process. Fundamentally, when a pot is in thermal balance its ratio can be known purely based on the temperature and this relationship can be used to judge how well and efficiently a smelter is operated.

Pot operation is all about maintaining a thermal and material balance. A dynamically well-kept pot (both material and energy are maintained well balanced) is at peak operating efficiency when the ratio, temperature, and superheat are at the optimal condition.

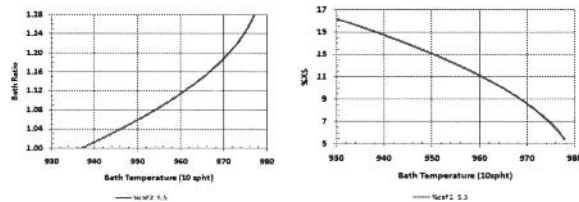


Figure 2: Ratio (XS AlF_3) as a function of temperature for a thermal and material balanced cell at 10°C superheat.

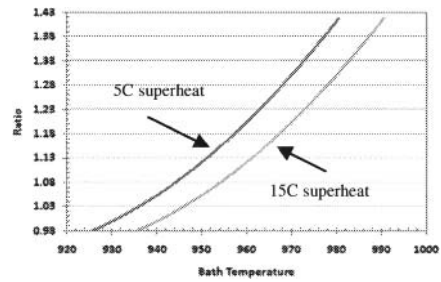


Figure 3: Relationship between ratio and temperature at a superheat between 5 and 15°C.

The Alcoa STARprobe™ based control package establishes both thermal (power) and material (chemical) balance at a constant superheat to enable and, more importantly, maintain a high operating efficiency. Figure 4 illustrates the strategy of Alcoa’s STARprobe™ pot control: STARprobe™ results are transmitted to a database where proprietary control algorithms will tie the STARprobe™ results together with pot running status (historical and current) and give operation control orders to the potroom floor for chemical alumina and power adjustments. These adjustments will achieve the maximum current efficiency and minimum power requirements.

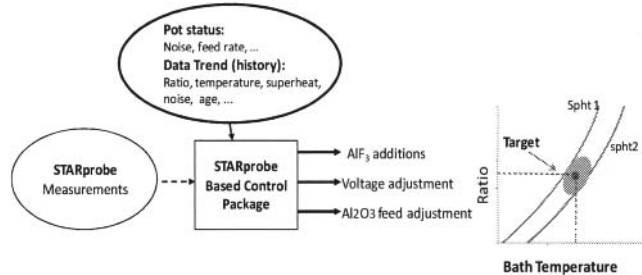


Figure 4: Alcoa Proprietary STARprobe™ pot control.

Results and Discussion

The STARprobe™ is deployed by carrying out plant wide “side by side” comparison to the traditional analytical method to assure a smooth transition to the STARprobe™ method of operation. Then, after the measurement technique has been proven, STARprobe™ control is phased in as a second step. To date, Alcoa STARprobe™ has been successfully deployed in eight Alcoa smelters. The longest time the first smelter starting to use STARprobe™ for pot control has been over 3 years (by the time this paper was written).

Comparison of STARprobe and Conventional Methods

Smelter A:

Figure 5 shows the comparison of %XS AlF_3 results from two of typical daily measurements. Bath samples were taken and

analyzed by pyro titration while STARprobe™ was used to make measurement for the same pots. The %XS AIF₃ typically varied from a low of 6% to a high of 15% and varied randomly from pot to pot without specific order/pattern. The %XS AIF₃ by the two methods overlapped and agreed well.

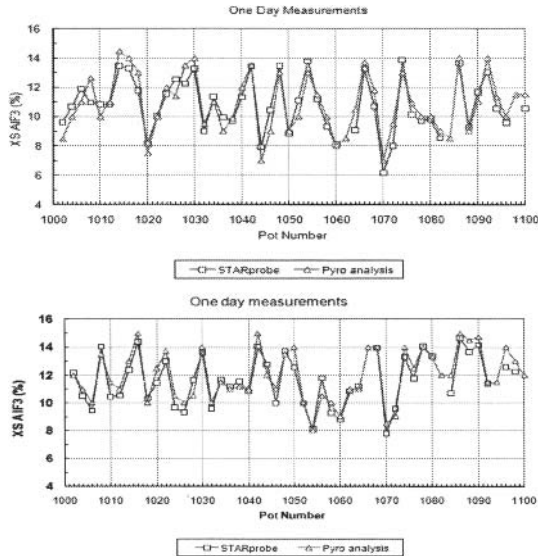


Figure 5: Comparison of %XS AIF₃ as measured by STARprobe™ and sampling/Pyro analysis method.

Figure 6 shows the %XS AIF₃ by pyro titration vs. STARprobe™. The distribution is exactly as expected indicating STARprobe™ gives a non-bias analysis against the pyro titration. There was no statistical difference between the two methods. The average %Xs AIF₃ by STARprobe™ was 10.55% with a standard deviation of 1.98 compared to an average of 10.66% with standard deviation of 2.02 for the pyro titration method.

Fewer comparisons were made for alumina due to limited availability of the LECO analyzer. Figure 7 shows the %alumina results as measured by STARprobe™ and LECO analysis. The STARprobe™ trended the %Al₂O₃ well compared to the LECO but the accuracy is not as good as the ratio measurement. The typical correlation (R²) between the two alumina concentrations was 75% with a typical standard deviation of 0.5%.

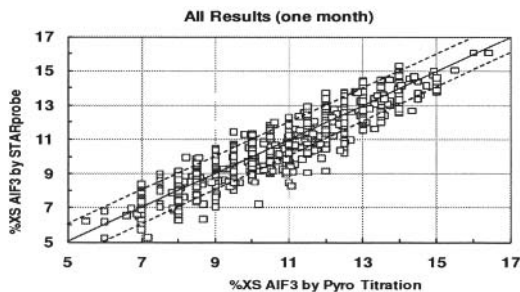


Figure 6: %XS AIF₃ as analyzed by pyro and STARprobe™

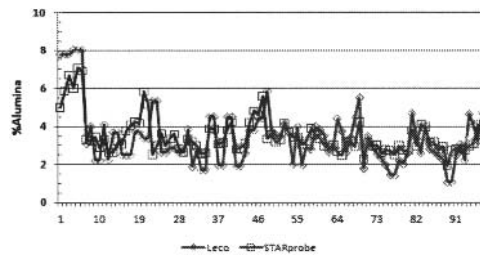


Figure 7: %Al₂O₃ as measured by Leco and STARprobe™

Figure 8 shows the typical bath temperature and superheat distribution by STARprobe™ during the period of “side by side” comparison before the new control algorithm was used.

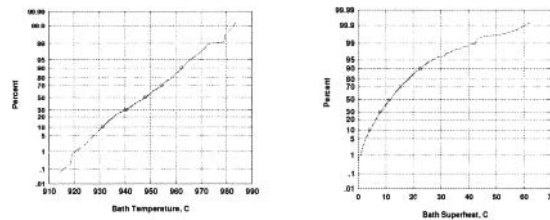


Figure 8: Distribution of bath temperature and superheat in smelter A before new control algorithm was deployed.

Plant B:

A similar measurement comparison campaign was carried out in smelter B for one month to make sure the measurements were capable prior to turning on the new STARprobe™ control. The campaign was also used to determine the superheat distribution during the normal pot control conditions

Figure 9 shows a comparison of typical daily measurements while Figure 10 summarizes the results for the month long campaign. The bath ratio ranged from a low of 1.04 to a high of 1.22. Generally, the STARprobe™ agreed well with XRD analysis. Minor differences were due to the fact that bath sampling and STARprobe™ were not exactly carried out at the “same” time. Bath sampling was done in batch mode taking about one-half hour to one hour while STARprobe™ measurements were done over a period of four hours. During this four hour period some pots experienced some operational activities that caused a bath ratio change. During the month long measurement campaign, STARprobe™ measured an average ratio of 1.1239±0.036 vs. an average ratio of 1.12435±0.031 by bath sampling/XRD method. Thus, there was virtually no difference between the two methods.

Figure 11 shows the comparison of %Al₂O₃ on a limited number of pots. Just as before, STARprobe™ could not match the accuracy of LECO analysis but it did trend with the LECO.

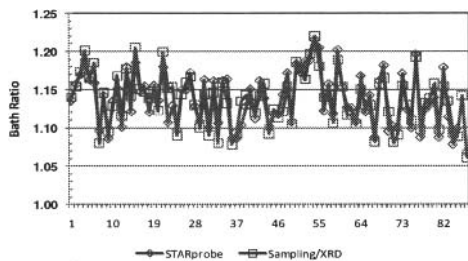


Figure 9: Daily ratio in “side by side” sampling campaign.

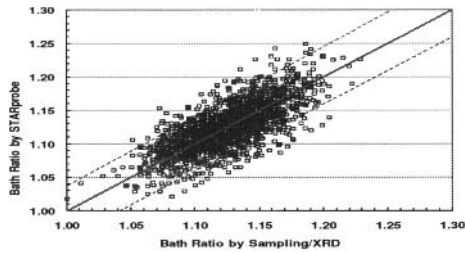


Figure 10: Ratio comparison in one month campaign.

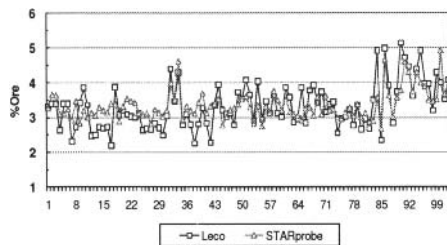


Figure 11: %Al₂O₃ by STARprobe™ and LECO.

Plant C:

A third large scale “side by side” capability study was carried out in smelter C before STARprobe™ was deployed. Figure 12 shows the results from a group of measurement (66 pots). The acidity results by STARprobe™ and sampling/XRD method matched well except for two pots as indicated in Figure 12. After further examination, it was found that bath samples were switched during preparation for XRD analysis. After the correction, the two results all matched well as shown in Figure 13.

The results of the overall comparison are shown in Figure 14. Again, with the smelter’s typical operating range from a low of 5% to a high of 13.5% XS AIF₃, the STARprobe™ agreed well with the bath sampling/XRD analysis method.

Alumina concentration in bath was compared with XRF and shown in Figure 15. Again, the STARprobe™ agreed with sampling XRF analysis method fairly well.

Pot Behavior Profiling

During an operational disturbance such as tap, anode change, cover application, feeding change or instability, the pot energy

and material states are likely to change. The energy change will result in a change of pot temperature while the material change will result in a change of bath chemistry (ratio). Either change individually or combined will either increase or reduce the superheat. If the perturbation is large, a new energy and material balance state is represented by a different bath chemistry and pot temperature. Pot control is aimed at maintaining a targeted energy and material balance to minimize operational impact, which means that the superheat needs to be controlled and maintained to achieve the maximum efficiency.

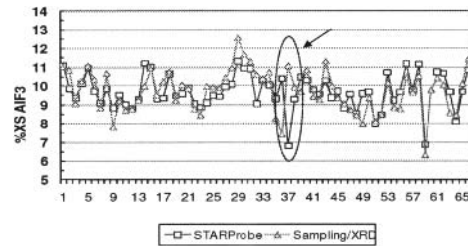


Figure 12: %XS AIF₃ from a shift of sampling campaign.

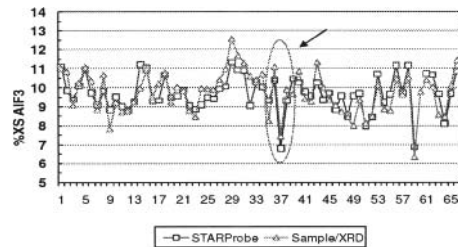


Figure 13: %XS AIF₃ after correction of the mixed bath samples.

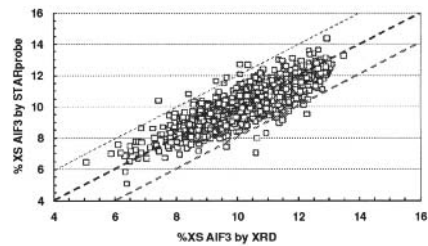


Figure 14: %XS AIF₃ comparison in month long campaign.

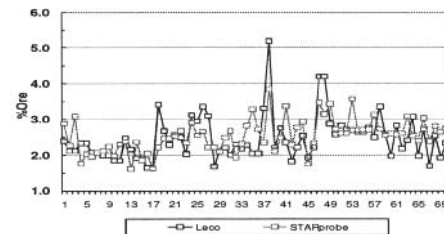


Figure 15: %Al₂O₃ by STARprobe™ and sampling XRF method.

Figure 16 shows profiles of temperature, liquidus, and superheat over a short period of 5 hours during which there were no major operational activities. During this period of normal operation the

pot temperature varied from a low of 938°C to a high of 956°C. The liquidus generally followed the temperature and varied from a low of 930°C to a high of 942°C. The superheat varied from a low of 6°C to a high 13°C, a normal operating range – not high enough to melt excessive ledge while not low enough to cause any operational problems.

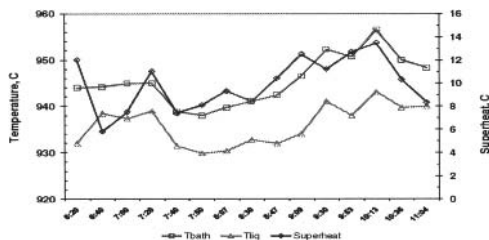


Figure 16: Variation of bath temperature and liquidus.

Figures 17 and 18, respectively, show variations of temperature and bath ratio, and temperature and superheat in a pot for a 42 hour period. During this period, the pot underwent chemical additions, metal tapping, anode setting, and other operations. The pot temperature varied from a low of 935°C to a high of 958°C while the bath ratio varied from a low of 1.03 to a high of 1.11. Superheat changed from a low of 5°C to a high of 20°C.

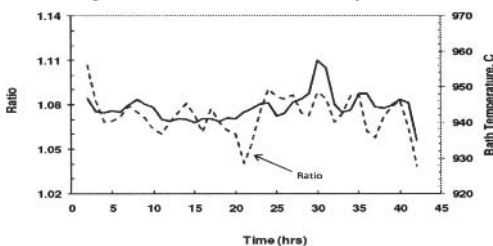


Figure 17: Bath ratio and temperature variation within 42 hours.

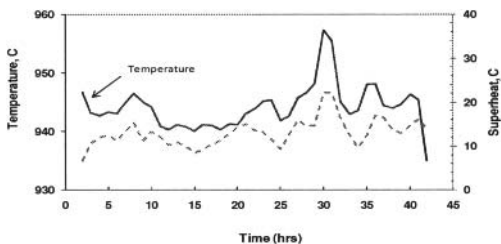


Figure 18: Temperature and superheat variation within 42 hours.

Figure 19 shows another pot survey across a smelter including pot temperature, bath ratio, and superheat in a specific time period of operation. Optimal operating ranges for both bath ratio and bath temperature are also shown. As can be seen, a considerable amount of cases (pots) are out of the targeted ranges, indicating that there is a high potential for improvements if we are able to move both bath ratios, temperatures, as well as bath superheat to optimal operating zones (tighter ratio and temperature operating range with optimal superheat so that maximum pot performance

can be achieved). In other words, by actively taking the correct measures, a correction can be made to bring the pot back into the optimal multi-dimensional performance condition. This is achieved by factoring in STARprobe™ information along with all the information available about the condition of the pot when it was sampled and its most recent historical performance.

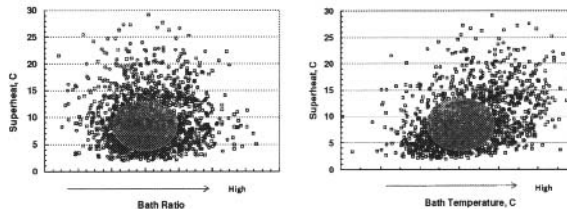


Figure 19: Bath superheat vs. 1) bath ratio, and 2) pot temperature.

STARprobe™ Based Active Pot Control - Performance

An example is given below for one of Alcoa smelter locations where STARprobe™ based control is deployed.

Figure 20 presents voltage behavior for a period of 5 months in a 66-pot scale trial at this smelter. 33 pots were controlled using the new control algorithms while the other 33 pots were used as standard control group. STARprobe™ measurements were applied to all pots. The average pot voltage of the test group was reduced by at least 15 mV while the voltage of the control group increased by almost 10 mV. Paired t-test of the periods before and during test has a p-value much lower than 5%, which means that the pot voltage reduction is statistically significant. This improvement was consistent in all phases of the trial. One important observation was that the reduction on voltage did not create pot instability.

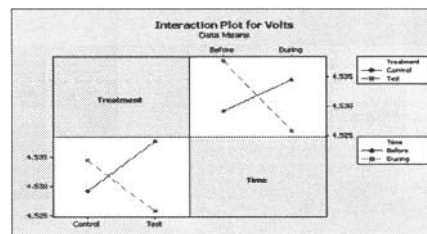


Figure 20: Voltage reduction in a 5-month period trial.

Figure 21 presents the overall pot voltage trend before and after the implementation of the control algorithm using STARprobe™. The pot voltage first experienced a gradual reduction and then stabilized after a few months of deployment. During this period, a voltage reduction of about 50 mV was achieved. It should be mentioned that the settings in the control algorithm were still being fine-tuned after the deployment while at the same time pot operation was being adjusted to maintain thermal balance.

The new control algorithm also minimizes over-control in bath chemistry (undershoot or overshoot of chemical (AlF₃) additions). The end result is that the overall fluoride (AlF₃) consumption is

reduced. This can be seen in Figure 22 that shows the AlF_3 addition change before and after the implementation of STARprobe™ based control. The estimated net reduction on the AlF_3 consumption is estimated about 5%.

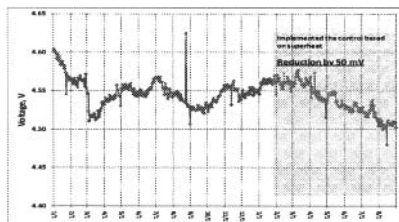


Figure 21: Voltage trend before and after the active pot control.

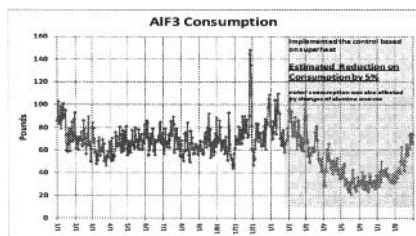


Figure 22: AlF_3 consumption before and after the active control.

Probably the most important pot performance indicator is current efficiency. Figure 23 shows the current efficiency (plant monthly average) prior to and after deployment of both STARprobe™ and the STARprobe™ based control algorithm. The detail values are also listed in Table I.

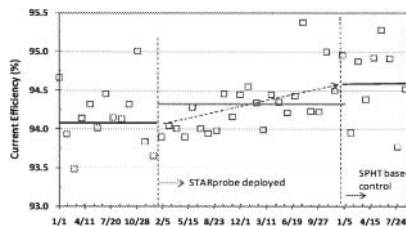


Figure 23: Average current efficiency prior to and after STARprobe™ deployment and control.

Table I: Pot Performance Comparison

	Amperage (A)	Pot Volts (V)	CE (%)
Baseline (13 months)	240185	4.551	94.2
STARprobe™ only and partial control (12 months)	240414	4.586	94.3
STARprobe based control (6 months)	240887	4.575	94.6

The current efficiency (13 month average) under previous pot control prior to STARprobe™ deployment was 94.1%. The current efficiency was steadily improved after STARprobe™ deployment with an average over 94.5% (12 month period). The increase was mainly due to: 1) Daily manual interventions on

those pots identified with excess high superheat ($>15^\circ\text{C}$), and 2) Automatic parameter adjustment based on the integration of the STARprobe™ measurement with the pot status information for all those pots that were operated under sub-optimal conditions. After deployment the current efficiency was maintained at an average of 94.6% for over a 6 month period during which at times there was a significant raw material degradation. The increased current efficiency was primarily obtained with reduced pot voltage and increased line amperage during this time.

Summary

Alcoa STARprobe™ has been successfully deployed in Alcoa's plants to replace the traditional bath sampling/analysis methods and pot temperature measurement practice. The detail comparisons of measurement results on plant scale for several smelters further verified that STARprobe™ measures bath ratio (acidity) as accurately (if not better) as the analytical methods. A constant superheat based control algorithm was developed and deployed for pot control to take advantage of the real time STARprobe™ measurement results. Higher pot performance, meaning a reduced pot power consumption, a reduced chemical consumption, and an increased current efficiency, has been achieved by using STARprobe™ and the integrated STARprobe™ based pot control.

Acknowledgement

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