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EXPERIMENTAL STUDIES OF THE IMPACT OF ANODE PRE-HEATING

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Abstract

The adverse impact of anode setting on the current efficiency (CE) is well known in the aluminum industry, although few published studies exist. When a cold anode is lowered into the bath, it immediately quenches a layer of frozen bath on the bottom surface that may extend to the metal pad. It takes time, energy, and bath motion to melt this layer. Until then, the anode current distribution is uneven and the bath motion is disrupted around the newly set anodes. These effects are hypothesized to lead to higher noise and lower CE.

The paper summarizes experiments, conducted at Alcoa Warrick, during which anodes pre-heated to 480-510°C (bottom surface) were set in a few pots over 60 days. The studies suggest potential to double the rate of load up, reduce energy consumption by 40 kWh/mt, and increase CE by 0.5-1%. Approaches to supply hot anodes are discussed.

Introduction

The adverse impact of anode setting on the current efficiency (CE) is well known in the aluminum industry, although few published studies exist. In one such study, by Poole and Etheridge [1], a current efficiency loss of 2.2% was reported due to the setting of presumably cold anodes, which is far beyond the loss required to make up the anode sensible heat at smelting operating temperatures. These results can only be explained by other effects of anode changes on cell behavior that reduce process stability beyond simply thermal effects.

Previous work developed for understanding cell stability can be divided in two main branches. First, control models aimed at detecting process abnormalities from variables monitored at the pots were developed for real-time correction of processing conditions. Owing to computational speed requirements, such models currently use the simplest possible mathematical constructs – as expressly recognized by Yurkov and Mann [2]. More elaborate process control models have been presented on the same line, using elaborate statistical methods to cope with phenomenological complexity [3]. It is, nonetheless, interesting to notice that none of the recent authors reports temperature measurements of pot input materials as part of their explanatory variable sets.

A second group of researchers ascribes pot instability mainly to perturbations of the metal pad due to electromagnetic effects. Numerous models have again been presented to describe the action of Lorenz forces on the metal pool, which is believed to cause wave motion and provide for uneven anode-cathode distances. One of the most prominent aluminum cell modeling efforts was presented by Zoric, Rousar, and Thonstad in a series of two publications [4, 5]. In their attempt at explaining the electrical current distribution in aluminum pots, Zoric, Rousar, and Thonstad [4, 5] calculated the change in shape of an anode block after anode setting until a steady profile was achieved. They concluded that anode shape, and consequently current distribution, reaches steady state in 6 to 9 days after a new anode is placed in the pot. They also concluded that about 15% of the electrical current flows through the anode sides at steady state. The modeling work of Zoric, Rousar, and Thonstad [4, 5] assumed, however, a flat metal pool at the bottom of the cell. Severo et al. [6] explored steady state and transient cell conditions using commercial finite difference codes and were able to provide more insight into metal pad stability. Indeed, these authors stressed the role of anode changes with regards to metal pad stability, pointing out that several hours should be required before magnetic fields and metal pad contours return to steady state. More important, the authors point out that large horizontal currents are induced in the metal pad during anode changes and may lead to severe pad instability. Unfortunately, no direct estimates of current efficiency losses or results of simulations with different starting anode temperatures were presented.

In conclusion, absent models or previous experimental work that could be used to assess the impact of setting pre-heated anodes on the process, an experimental campaign was executed at the Alcoa Warrick smelter. In the next section, the design and commissioning of an anode pre-heating station are presented. This is followed by a description of the experiments conducted and the key findings. The subsequent section tackles the question of how to supply hot anodes to the pots. Findings from experiments conducted at another Alcoa smelter to "fast track" anodes from the baking furnace to the pots are presented. Conclusions and recommendations for future work are presented in the final section.

Design and Commissioning of the Anode Pre-heating Station

The design of an experimental pre-heating system started with the definition of minimum anode throughput and pre-heating temperatures. Based on inputs from the Warrick smelting technical team, a test bed of four experimental pots and four control pots was defined as sufficient for the exploratory study with anodes pre-heated to a maximum temperature of 500°C (maximum limit permissible due to carbon air burn). This way, the design criteria utilized defined a system capable of pre-heating six anodes per day to a maximum temperature of 600°C, so that enough anodes would be available to supply two experimental pots each day. At the plant, anodes are set at the pots in alternating days. In order to keep the design as simple as possible and gain agility in the development, construction, and commissioning phases, electrical heaters were allowed in the design specifications in place of combustion systems.

An engineering firm was engaged to help design and fabricate a pre-heating station within the given specifications of temperature, anode throughput, and energy source. A number of different designs were proposed for the pre-heating system and discussed with Alcoa representatives, resulting in the choice for a system with resistance heaters capable of delivering up to 30 kW of power – owing to the uncertainty in heat losses in a completely untried prototype, a safety margin of 10 kW more than the theoretical minimum required was allowed. A photograph of the final pre-heating station is shown in Figure 1.

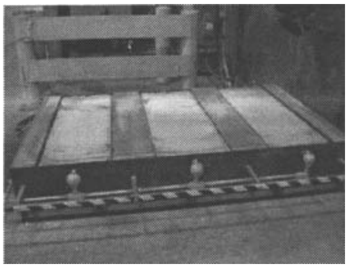


Figure 1: Anode pre-heating stations built for plant trials at Warrick

Two pre-heating stations such as depicted in Figure 1 were built and delivered at the Warrick plant. After delivery, the stations were tested in two configurations as part of commissioning. The first configuration tested was the original design, where steel shields are present in front of the heaters to protect them from debris. In the second configuration, the shields were removed to allow radiant heat flow directly from the heaters to the bottom surface of the anodes. The tests were done in order to ascertain the capability of the stations to deliver hot anodes at a rate sufficient for the tests. To this end, thermocouples were placed in holes drilled into the anodes (10 inches from the top surface) and the temperature monitored after starting up power. The temperatures measured during these tests are presented in Figure 2.

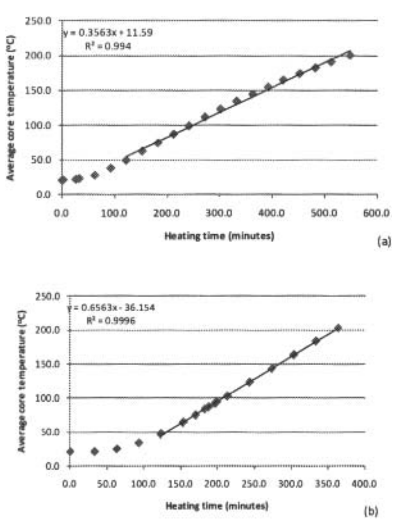


Figure 2: Results of commissioning tests. (a) heaters with steel covers, (b) heaters without steel covers.

The heating rates measured indicated that a target core temperature of 200°C could be achieved in approximately 6 hours without steel shields, and 9 hours with the protective shields. Whilst both heating rates should suffice to provide an adequate throughput of hot anodes, personnel availability required that the heat up time be as short as possible resulting in the option to operate without steel shields. A comment is due regarding the target core temperature of 200°C. As mentioned previously, a number of models were developed to aid in the planning and interpretation of the work. In station commissioning, a finite difference model of the anodes was developed to describe the transport of heat along the anode axis. This model was combined with the experimental measurements in Figure 2-a to determine the heat transfer coefficient heater-anode and estimate the temperature at the bottom of the anode according to the temperature measured at the reference point (10 inches down from the anode top). Figure 3 shows a comparison of results from this model with experimental data points along with the calculated temperatures at the bottom of the anode. Based on the results in Figure 3, it was decided to use a 7 hour heat up time as target for the anode pot setting tests, providing for anode bottom temperatures between 484°C and 512°C – temperatures around the maximum anode permissible to avoid air burn.

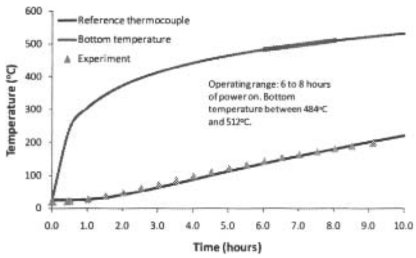


Figure 3: Determination of heating station operating range without steel shields

One more special system was required by the tests of anode pre-heating at the pots: devices to measure the difference in electrical current pick-up in cold and pre-heated anodes after setting in the pots. To this end, special data-loggers Omega OM-CP-Volt101 were acquired and mounted to clamps attaching to the anode rods. The data-loggers continuously measured the voltage difference between their connecting wires so that plenty of data can be acquired from each single test. The data loggers are, however, quite sensitive to temperature, and were enclosed in a refractory cloth to withstand service at the pots.

Lastly, specific written procedures and control sheets were prepared for the heating station, hot anode setting routine, and data record keeping. The commissioning of the two pre-heating stations, delivery of the voltage data logger system, and development of the experimental procedures concluded the commissioning of hot anode setting tests and Phase 2 of the research program.

Experimental Findings from Setting Pots with Heated Anodes

The experimental campaign, aimed at verifying the benefits of setting hot anodes in smelting pots, involved a number of different experiments supported by the pre-heating station and engagement from the Warrick team. The main line of experimentation consisted of continuous operation of pots setting hot anodes with quantification of (i) gain in electrical current pick-up in hot anodes, and (ii) gain in current efficiency due to hot anode setting. A number of extra ad-hoc tests were used to peremptorily check the experimental methods and speculative propositions regarding the effects of hot anode setting. Such tests included the manual measurement of rod voltage drops to verify the reproducibility of measurements with automated data loggers, tests with varying anode pre-heating temperatures, tests of extra resistance added to pots by anode setting (bridge-locking experiment), and tests to optimize setting practices with hot anodes (changing anode off-set). Each of the tests will be discussed in subsequent paragraphs.

Eight smelting pots served as test bed for the experimentation: four receiving only pre-heated anodes, and four receiving only cold anodes. Pots receiving pre-heated anodes only were termed "experimental", and pots receiving only cold anodes were designated as "control". These two groups were used for all performance comparisons between hot and cold anode setting. By advice from the veterans in the Warrick team, pots 45, 52, 70, and 74 were used as experimental. Pots 44, 51, 66, and 72 were used as control. The overall test schedule comprised two full anode rotations. Load pick-up tests were executed during the first half of the test, based on the belief that the pick-up of current by a given anode shows stronger dependence on the condition of the anode itself than on conditions of the overall pots. Tests to quantify current efficiency gains were reserved for the final weeks of the campaign since current efficiency is known to depend strongly on pot operating parameters.

The first series of tests belonging to the mainstream plan aimed at determining the gain in electrical current pick-up between cold and hot anodes after set. In these tests, the automatic data loggers deployed during commissioning were attached to the anode rods immediately after set. The data acquired was collected daily for comparison between anodes set hot and anodes set cold. In total, data from over 38 experiments was collected for later comparison between the two groups.

A comparison of the electrical current pick-up between anodes set hot and anodes set cold was done by taking the average rod voltage drops in each group measured at given discrete times of 2, 4, 6, 12, 18, and 24 hours. Figure 4 presents the results of this comparison. As can be seen in this Figure, pre-heated anodes showed a consistently higher rod voltage drop than anodes used cold. A pronounced difference was found shortly after set. At one hour after setting, hot anodes registered an average voltage drop 25% higher than cold anodes (using the cold anode measurements as a basis), the largest difference in averages occurring 2 hours after set when hot anodes show an average drop more than 40% higher than cold anodes. After 4 hours, the differences between hot and cold anodes are in the range of 11 to 15%. These observations were consistent with all measurements of rod voltage drops taken at later dates and confirm that hot anodes do show a faster rate of electrical current pick up. As will be clear from the discussion of current efficiency tests, a faster rate of current pick-up adds to process stability by improving the distribution of current over all the anodes in the pot.

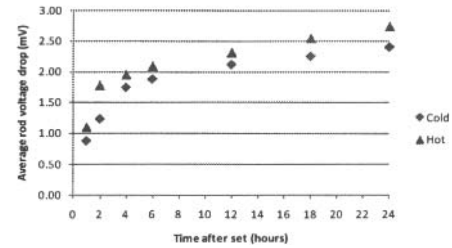


Figure 4: Results from anode electrical current pick-up after setting

During the last month in the campaign, the experimental pots being stably operating with hot anodes, data on the current distribution around all anodes in the experimental and control pots was manually collected to quantify the potential gains in current efficiency. These data were combined with the plant routine measurements of pot bath ratio, pot temperature, and pot noise to determine current efficiency. Bath ratio is simply defined as the mass ratio of sodium fluoride (NaF) to aluminum tri-fluoride (AlF_3) and is very commonly used to control aluminum smelting pots. At Warrick, this ratio is routinely monitored by the operators on a weekly basis. Bath temperature, on the other hand, is monitored daily and used as an early-warning sign for pot control. Lastly, pot noise finds no easy definition, being related to the stability in current and voltage at each pot – it is automatically calculated by the computers controlling the pot lines and kept in an electronic archive. Current efficiencies (CE) for the experimental and control groups were calculated based on the correlation previously developed by Sorensen [7] from data on silver dilution experiments:

$$CE = f(N, R, T, s) \qquad (3)$$

where N is the pot noise, R is the bath ratio, and T is the pot temperature (°C). Here, s represents the relative dispersion in current distribution among all anodes in a given pot, and is calculated from:

$$\bar{s} = \sum_{\substack{All \\ anodes}} \frac{|i_a - \bar{i}|}{\bar{i}} \qquad (4)$$

where i_a is the electrical current through each individual anode and $\bar{i}$ is the average current among all anodes (not the total cell current).

Figure 5 shows a comparison of the daily average current efficiencies in the experimental and control pots during the last month of experimentation. Unlike electrical load pick-up, the experimental pots did not show an overwhelming and consistent gain in current efficiency as measured through Sorensen's formula. Indeed, Figure 5 shows estimates of current efficiency in control pots sometimes higher than in experimental. Clearly, other sources of process variability associated with anode setting (crust breaking, pot voltage modifiers, alumina covering) could have played a major role in detriment to the current efficiency, precluding the clear identification of an obvious gain. Overall, considering all the experimental measurements, a difference of 0.3% exists between the average current efficiency in experimental and control pots. At the confidence levels warranted by the data, it is estimated that the actual difference between the control and average pots is in the interval of 0.5% and 1.0%, the probability of a difference higher than 0.5% being estimated at 0.77 whilst the probability of a difference higher than 1% being 0.04. Other experimental techniques, especially tracer studies (silver, sodium) were considered to add more confidence to this result, but ruled out due to the time and expense involved.

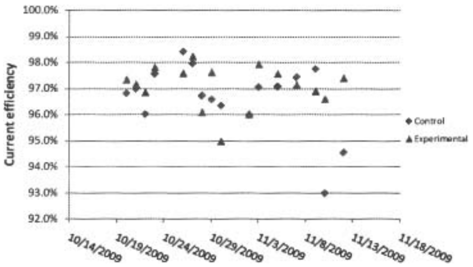


Figure 5: Average current efficiency measurements in experimental and control pots

As previously mentioned, a number of ad-hoc experiments were developed in searching for phenomenological explanations of gains in electrical current load up and current efficiency: (i) varying anode pre-heat temperature, (ii) measuring extra pot resistance from anode setting, and (iii) changing anode off-set.

The first set of ad-hoc experiments was aimed at defining the minimum anode temperature necessary to avoid freezing of bath under the anodes after setting. In theory, thermal energy from the molten bath contributes to bringing anodes up to pot operating temperatures, with the collateral effect of freezing bath under the anodes. In turn, frozen bath hinders the flow of electrical current, thereby disturbing pot operation. This way, in order to determine the validity of this theory and the minimum required anode temperature to avoid such process disturbance, an experiment was done with a set of three anodes at different temperatures. The anodes were set in the pot and lifted after 2 hours of immersion for visual inspection. Figure 6 shows the observation from this experiment and a comparative picture of anodes set cold. As can be seen in Figure 6, an anode initially pre-heated to a bottom temperature of 500°C did not show any frozen bath two hours after set, whilst anodes charged at 300°C or less show considerable frozen layers. These experiments support the theory and provide a potential phenomenological explanation for the gain in load up rate measured during the mainstream experimental program.

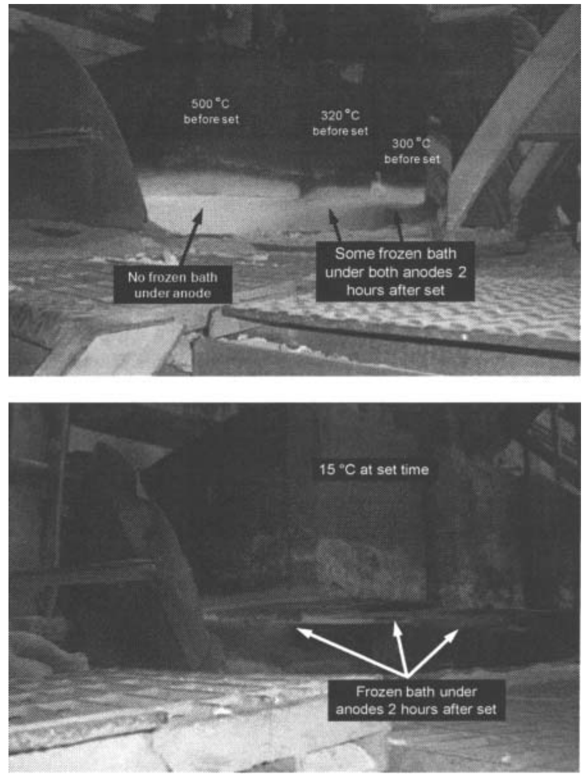


Figure 6: Determination of minimum anode pre-heat temperature to avoid bath freezing

The second set of experiments intended to quantify the extra power associated with anode setting immediately after setting, and compare the difference between anodes set hot and cold. To this end, the pot bridge was locked in place in preparation for anode setting in order to prevent the control system from introducing unnatural variations – the control system is programmed to react to anode setting by automatically moving the bridge up, which increases anode-cathode distance and provides more thermal energy to compensate for losses associated with anode setting. Electrical data (pot voltage, current, and resistance) from the pot control system was collected and later used to calculate the energy input to the pots during the process of anode setting. The incremental energy due to anode setting was then estimated taking the power input to each pot five minutes before setting as a baseline, resulting on the estimates of additional pot power input presented in Figure 7.

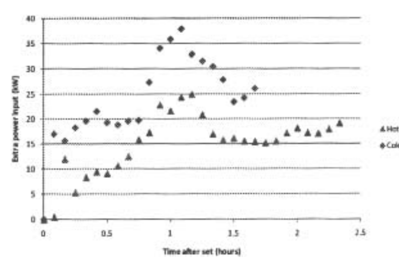
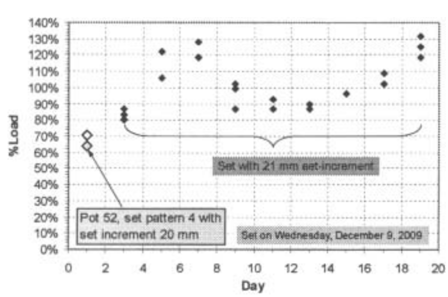
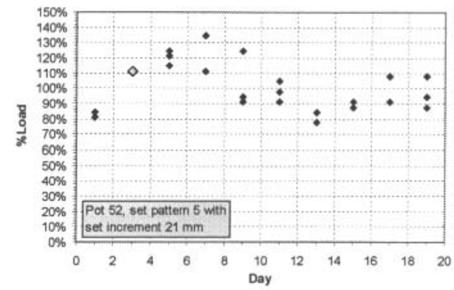


Figure 7: Power input to test pots

Again, as observed in the experiments of electrical current load-up, a clear dominance exists in Figure 7; at all sampled times, the pot charged with cold anodes required more power input than the pot charged with hot anodes. On average, 25.0 kW of extra power were required at the pot charged with cold anodes, whilst only 15.4 kW extra were required at the pot charged with hot anodes over the time of the experiment. The extra energy associated with anode set events can be estimated from these extra power measurements and the disturbance time after set. As previously described in the experiments with voltage meters, large differences in load up between anodes set cold and anodes set hot is found in the first four hours after set. Therefore, considering a disturbance time of 4 hours, it can be estimated that a pot receiving cold anodes should require 100 kWh (4 hours x 25 kW) to overcome the disturbances associated with anode setting. It should be noted that, at Warrick, each pot daily produces very close to 1 metric ton of aluminum and suffers one anode setting event (i.e., the units kWh/mt of Al and kWh/anode set are rather equivalent in the Warrick context). In turn, the extra energy input associated with anode setting events in pots receiving hot anodes can be estimated as 62 kWh, showing that about 38 kWh/mt of Al can be saved with hot anode setting. Hence, the hot anode setting saves 38 kWh/mt. This does not take into the energy needed to preheat the anodes, since the underlying premise for this work is that the hot anodes could be delivered either from the bake furnace or that the anodes could be heated by reusing waste heat collected from the smelter.

The last set of ad-hoc experiments was devised to assess the potential for reducing the incremental distance between the bottom plane of new anodes and the bottom plane of anodes already in the cell (anode off-set) made possible by anode pre-heating. In these tests, the main object of concern is that the anodes sat with a different off-set may carry excessive load in comparison with anodes sat at standard heights. Therefore, to the end of testing the maximum current carried by the anode after setting, a pair of anodes was set at one of the experimental pots with an increment of 20 mm instead of the standard 21 mm. The voltage drop in the anode rods was then monitored daily and used to calculate the relative electrical current flowing through the anode, as shown in Figure 8 for different days after setting. These experiments showed that anodes with a different off-set did not carry excessive load (usually taken as over 115% of the average current in the pot) up to six days after setting.





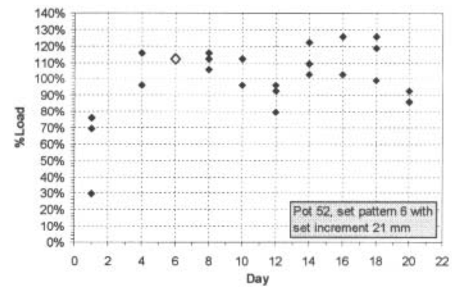


Figure 8: Stability of anodes sat with different increment (20 mm instead of 21 mm).

Delivery of Hot Anodes to the Pots

Efforts are underway to develop approaches that are technically, operationally, and economically feasible to deliver hot anodes to the pots on a routine basis. Preliminary data from these efforts will be presented here.

Figure 9 shows the main steps each anode goes through along with the time taken for the step at an Alcoa smelter. It can be seen in Figure 10 that even though the anodes can be extracted at a relatively high temperature from the bake furnace, the temperature decays rapidly as the anode sits in the storage area highlighted in Figure 10. The core temperature drops from over 400°C to under 200°C within 6 hours.

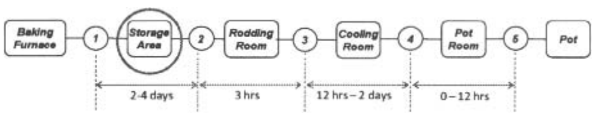


Figure 9: Current state – Process flow from the "Removal of the Baked Anode" to "Setting the Pot" at an Alcoa smelter

A "fast track" experiment was conducted to bypass the storage area and the waiting area where rodded anodes are waiting to be transported to the pot rooms. This experiment allowed us to show that hot anodes can be delivered from the baking furnace to set in the pot within 110 minutes, as shown in Figure 11. Depending on the position in the baking furnace from where the anodes are extracted, the core temperatures ranged between 275 and 430 °C. It was possible to limit the temperature decay during rodding and the transport to the pot room to within 10 °C. Core temperature of the anodes delivered to the pots ranged between 260 and 375 °C.

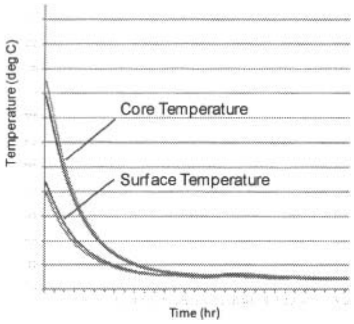


Figure 10: Temperature decay of the anodes while in the storage area

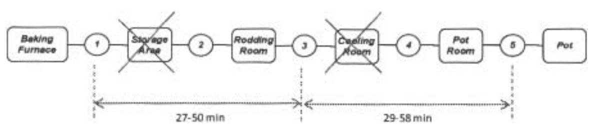


Figure 11: Approach for the "Fast Track" experiment

By reorganizing the activities / work schedules and with minimal capital outlay, it may be possible to operate in the "fast track" approach for at least 50% of the anode sets. The implications are currently being studied.

Other approaches under consideration are the utilization of the heat from the spent anodes and waste heat recovered from the pot rooms. These approaches, however, would require capital investment to implement, operational changes in the pot rooms, and may limit the temperature to which the anodes can be heated.

Conclusions

The experimental studies showed that pre-heated anodes do provide for improved electrical current pick up in anodes immediately after setting, with gains between 0.5 and 1.0% in current efficiency. Ad-hoc experiments provided phenomenological support to the theories in support of anode pre-heating. Questions regarding the efficacy of methods available for measuring current efficiency gains do, however, remain, and further experimentation appears prohibitively costly. More work is needed to detail out approaches to deliver hot anodes to the pot rooms. The most promising approach in the near term appears to be to pursue changes to the anode flow path – from the bake furnace to the pot rooms, thus retaining the sensible heat in the anodes. In the long run, it may be possible to combine the operational changes with ways to utilize waste heat collected from the smelter; more work is needed to develop innovative approaches that are viable technically, economically, and operationally.

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