Optimisation of the Performance of Cathode Risk Pots

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Abstract

The initial response in a smelter which suffers from multiple damaged cathode pots was to increase metal levels to cool cathodes and reduce the chance of pot failure. However this strategy led to reduced performance as cooler cathodes led to dissolution problems, higher sludge formation, increase in cathode voltage drop (CVD), and high heat dissipation from the sidewall requiring higher voltage to maintain heat balance. An optimisation plan was carried out on six test pots over a year which included improved anode change/cavity cleaning practices and more accurate liquid level measurements. In addition to improved work practices, a revised process control strategy was tested, including a new cryolite ratio (CR) control regime and use of data from multiple pot parameters to perform weekly analyses of heat balance on individual test pots. This weekly analysis led to decisions aimed at maintaining heat balance and improved pot performance. During the program, metal level on test pots was reduced gradually in order to reduce heat dissipation from the sidewall, improve alumina solubility and prevent the increase of CVD; this measure, in conjunction with voltage optimisation, CR control and new operational practices, offered an improved performance in terms of energy consumption, stability and high current efficiency (CE).

Keywords: Aluminium electrolysis cells; heat balance analysis; CR control; liquid levels measurement.

1. Introduction

An aluminium reduction smelter in China was started in October 2013. Following this potline initiation, the majority of the pots showed different levels of cathode damage, mostly as transverse cracks in the carbon block upper surface (Figure 1) and high concentrations of iron (Fe) and silicon (Si) in the molten aluminium metal (Figure 2).

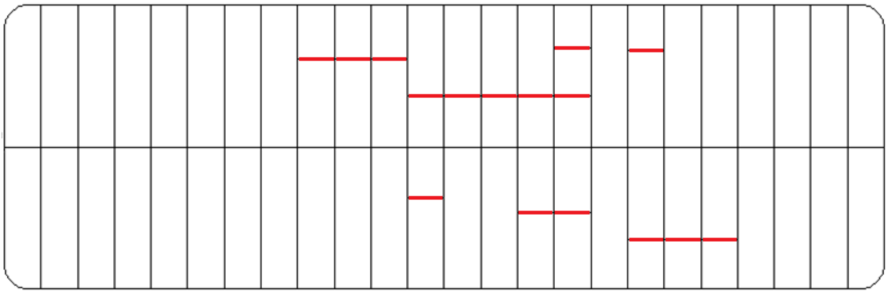


Figure 1. Diagram of the cathode surface with transverse cracks (shown as horizontal red marks).

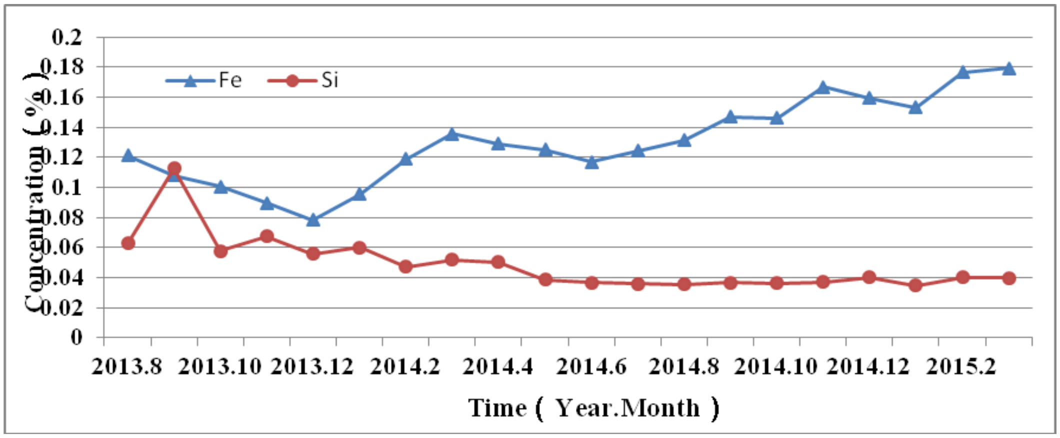


Figure 2. Average Fe and Si % concentration in metal in a section of pots.

Any pot with obvious cracks and high Fe and Si content is defined as a damaged pot. Each section has 19 – 46 % damaged cathode pots, which adds up to 35.5 % of the entire potline (as seen in Table 1). Because all the pots in the potline share the same design, building method, material, baking-start up process and management technology, the remaining 64.5 % of pots are considered as pots with high potential of developing cathode damage.

In order to reduce risk of further damage to cathode and metal leaks / tap outs, the smelter raised metal level gradually a few months after the stat up from the original design level of 25 cm to 30 – 33 cm. By doing so, more heat is dissipated from the sidewall, which causes longer ledge toe and cooling of the cathode surface, which prevents cathode failure. In addition, the higher metal level made the liquid aluminium pad more stable hence increasing the current efficiency (CE). Figure 3 shows metal and bath levels trends in a section of pots since the potline started.

Table 1. Number of cathode damaged pots per section.

Section	No. damaged pots	% pots
1	7	19
2	17	46
3	17	46
4	11	30
5	12	32
6	11	30
7	16	43
8	14	38

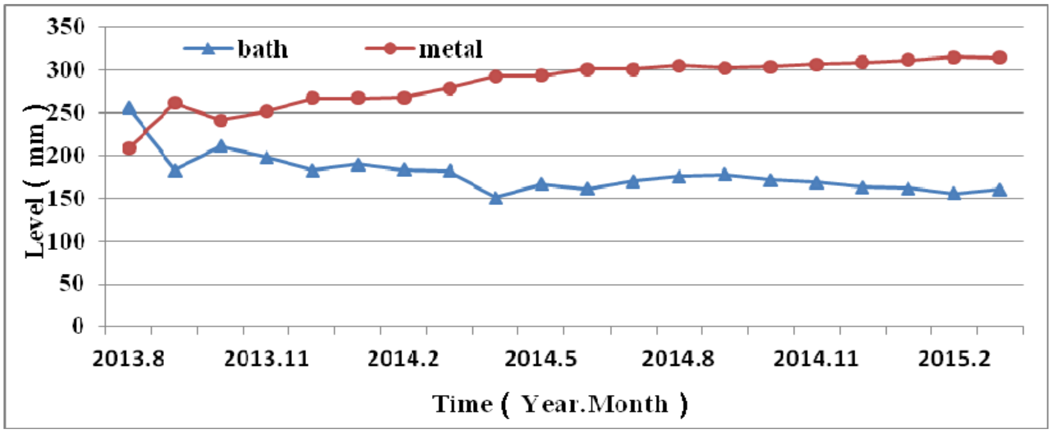


Figure 3. Average metal level (red) and bath level (blue) on a section of pots from section start-up.

Operating at high metal level leads to many disadvantages:

(1) Higher heat dissipation from the sidewall reduced the bath temperature in the pot cavity, especially on the cathode surface, and more energy input is required to compensate for the heat loss.

(2) The bath level had to be lowered as a result of higher metal level in order to accommodate the total liquid volume within the pot cavity, as illustrated in Figure 3.

The reduced bath volume and bath temperature can create difficulties in alumina dissolution [1 - 2]. The low solubility in the bath causes accumulation of undissolved alumina, which can form hard build-up of ridge and sludge on the cathode surface as it sinters into corundum. This ridge and sludge electrically insulates the cathode which will force the current to flow to less resistance areas of the cathode surface, causing current distribution problems (as illustrated in Figure 4). This problem is more prominent around the pot corners where more heat is dissipated, resulting in excessive ledge toe being formed. Furthermore, sludge increases cathode voltage drop (CVD) and as shown in Table 2, the average CVD of some pots was 356 mV. However, according to the original design, the CVD value for these cathodes age should be in the range of 300 – 320 mV, indicating that the cathodes are not performing to their full potential.

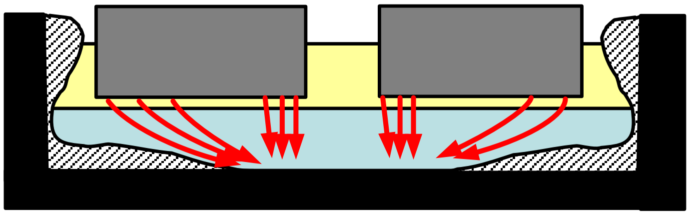


Figure 4. Abnormal current direction caused by formation of longer toe.

Table 2. Cathode voltage drop (CVD) of some pots in September 2015.

Pot Number	**CVD (mV)**
1	370
2	340
3	365
4	352
5	349
6	358
mean	356

The formation of high sludge, long ledge toe and non-uniform current distribution led to further damaged pots and higher energy consumption. Hence a project aiming to optimise energy consumption without reduction in CE and further damage to pots cathode was done on a group of 6 pots and results of various parameters was compared to a group of 6 reference pots from the same section.

2. The Strategy and Method for Optimised Performance

In order to tackle the problems mentioned above, a project had started that include collaboration of teams from GAMI, Light Metals Research Centre (LMRC) and the smelter over a span of a year to try and optimise the performance of the pots which suffer from high cathode damage risk. Despite the issues mentioned above, the CE of pots in the potline was relatively high with an average of 93.5 %, hence the focus was on optimising the energy consumption without causing any reduction in CE and further damage to the cathode blocks.

The strategy taken was to optimise energy consumption by controlled reduction of metal level followed by reduction in pot voltage while maintaining the pot's stability on a group of 6 test pots and compare their performance to a group of 6 reference pots from the same section. The main precondition to metal level reduction is stable pots, which was confirmed by weekly review of pot condition (referred to as a heat balance review, Section 2.4). Other preconditions included:

- Improved and standardised anode change procedure to reduce pots noise.
- Maintain heat balance by improved cryolite ratio (CR) and metal level control using statistical process control methods.
- Increase accuracy of liquid levels measurement by changing the method and design of new tools.
- Monitor the effects of metal level changes via the heat balance review.

In order to gauge the performance and progress of the project, the performance of the section was analysed over 3 months prior to the initiation of any measures of improvement and was referred to as baseline performance. Once all the preconditions were met and the new improvement measures were implemented successfully the performance of the test pots were analysed over 4 months and was referred to as test period.

2.1 Noise reduction by improved operations

A new anode change procedure was applied to reduce noise levels by better cleaning of pot cavity. Prior to anode removal, the crust in the pots are broken by the crane jackhammer from all 4 sides around the spent anodes instead of 2 sides as it was done previously, which prevented very large pieces of crust on the unbroken side falling into the cavity.

Prior to introduction of the new procedure, the pacman was used only once to clean the cavity even though there was enough crust material remaining in the cavity to fill another scoop of the pacman. The pot cavity was only cleaned once near corner anodes, despite many issues with long ledge toe reported. No carbon dust skimming was done and carbon pieces that fell into the cavity were fished out manually using a long hook. Two pacman operations per anode change were applied during the test period. The first pacman collected the crust pieces from the bottom of the cavity, and the second pacman scoop skimmed the carbon dust that floated on the bath surface.

The new anode change practice was written as a standard operating procedure (SOP), with detailed step-by-step instructions. Each step includes photos to make it visual and as clear as possible for every operator, especially for new operators that join the team. Potential hazards and safety gear were listed in the beginning of the document and hazards and safety measures are written for every step of the procedure.

2.2 Reduction in heat balance variations

Cryolite ratio (CR) and metal level are some of the main factors that influence pot temperature. Hence stable temperature depended on stable CR and metal level. A statistical process control (SPC) method was used to control AlF_3 feeding and metal tapping. The strategy, method and results of the SPC-based AlF_3control is described in detail in another paper by Luo et al. [3].

2.3 Accurate liquid levels measurement

Metal tapping by SPC control needs to be based on accurate liquid levels measurement. Before the project started, traditional "bottom-up" method was used to measure liquid levels (shown in Figure 5). Sludge and cathode problems in different pots can cause large measurement errors when using the "bottom-up" method, which can negatively affect the tap strategy (as illustrated in Figure 5). In order to avoid such problems, the liquid levels measurement was changed into a "top-down" method which reduced the interference of artificial factors in the measuring process.

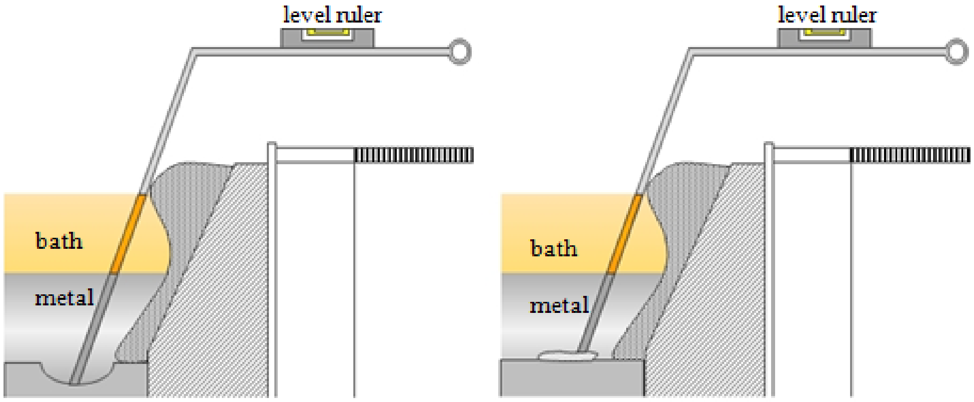


Figure 5. Bottom-up liquid levels measurement method with its associated disadvantages, e.g. cathode erosion at the tap hole (left) and sludge/ridge on the cathode (right).

A new set of tools were made for the top-down measurement method which eliminated the need to use a spirit level (previously used to ensure the tool is horizontal) and the measurement could be done accurately by a single operator compared to the need of two operators in the previous method. To verify the measurement accuracy of the new tool, a Gauge R&R statistical analysis was done comparing measurement done by the new tool to the older tool. For this analysis, only the metal level was analysed although both metal and bath levels were measured and recorded.

The results of Gauge R&R test show a reduction in variation between operators from 1.77 cm for the old method and tools to 0.7 cm for the new method (as seen in Figure 6 'R chart'). The Gauge R&R results of the new vs. old tools and the results from measurement done in several other smelters are shown in Table ***3***.

The result of the old tool show that 57.7 % of total variations are due to the measurement system while the new tool the variations of the measurement system are only 43.9 % of total variations. It indicates that the accuracy of the new measurement system is much better than the old tool. When comparing the results to other smelters, it can be seen that the new measurement in this smelter is better than in other smelters where Gauge R&R tests were conducted on metal level measurements previously. However, the new tool and method are still considered unacceptable as the total variations of the measurement system should be below 10 % to be considered as good measurement and can considered acceptable if the total variations (sums of repeatability and reproducibility) are below 30 % hence, there is room for improvement.

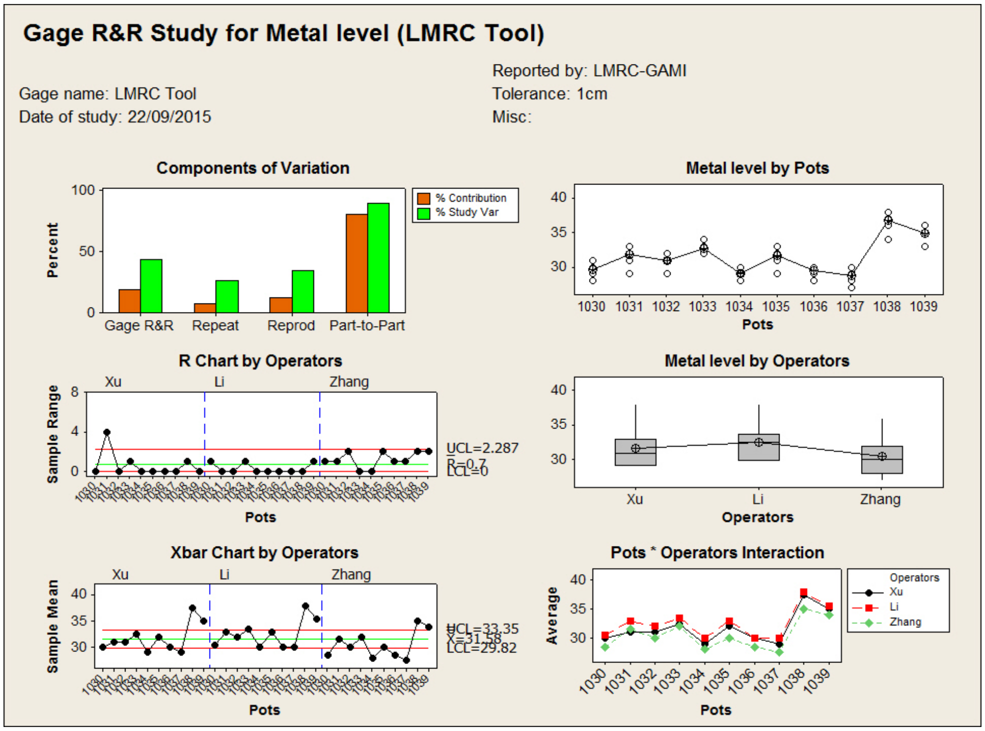


Figure 6. Gauge R&R test results for the new tools and method.

Table 3. Gauge R&R results for different tools in this smelter and results from different smelters.

	This Smelter		Other Smelters			
Smelter	**Using *new* tool**	**Using *old* tool**	**Smelter A**	**Smelter B**	**Smelter C**	**Smelter D**
Gauge R&R acceptability	43.9 %	57.7 %	70.77 %	55.08 %	56.08 %	60 %

2.4 Heat balance review

Reviews of the heat balance (HB) and individual pot condition were conducted on a weekly basis. The purposes of these weekly HB reviews are to:

1) Review of trends in various parameters across the section using a statistical analysis tool known as “4 plots” (Figure 7);
2) Monitor the heat balance and pot condition of each individual pot using “9 plot” chart (Figure 8);

3) Identify abnormal pots or pots with issues, analysis of root cause of any issues and decide on a response plan to resolve these issues;
4) Monitor pot performance and influence of the new process control strategies;
5) Consider whether long term targets on stable pots can be further optimised (e.g. lowering metal level and voltage).

Furthermore, changes in systematic factors (those that affect multiple pots, e.g. a section, a potroom or a potline) could be observed by section-wide analysis using the 4 plots tool, which contained statistical analysis such as: Xbar S charts, boxplot by date or by pot and histograms of almost 20 parameters such as average voltage, CR, temperatures, and so on. The analysis of factors that affect the entire section was useful, because it allows the smelter to distinguish the systematic factors from factors that affect specifically individual pots.

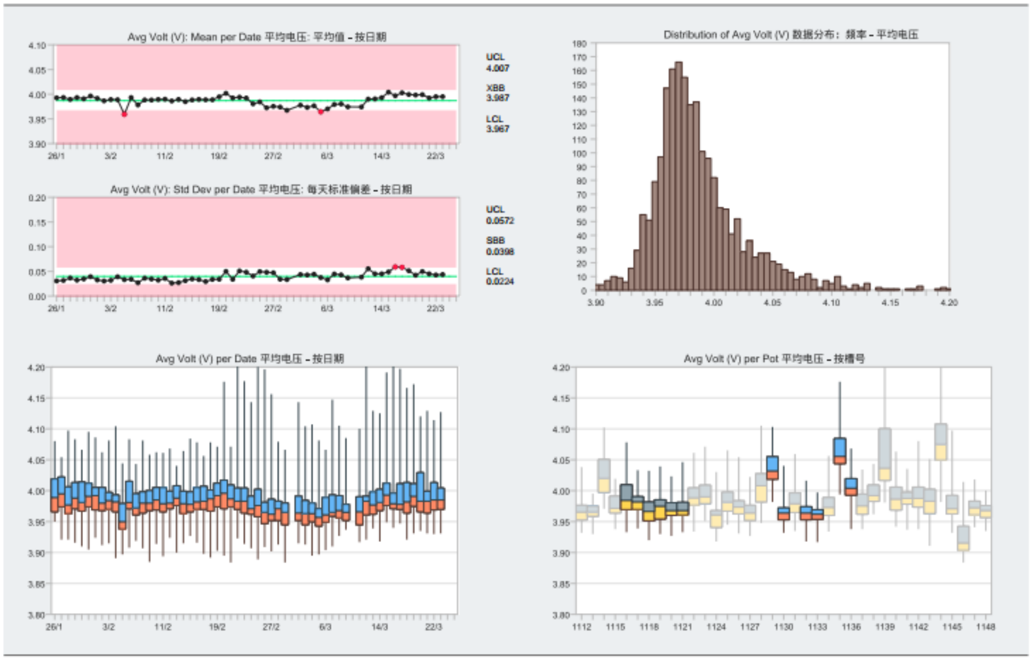


Figure 7. 4 plots showing Xbar S-chart, boxplot by day and by pot and histogram of various parameters (average voltage in this case) across entire section.

Heat balance reviews of individual pots are conducted by analysing the trends of 19 different parameters over a two months period, using a set of "9 plots" (example for pot 1130 in Figure 8).

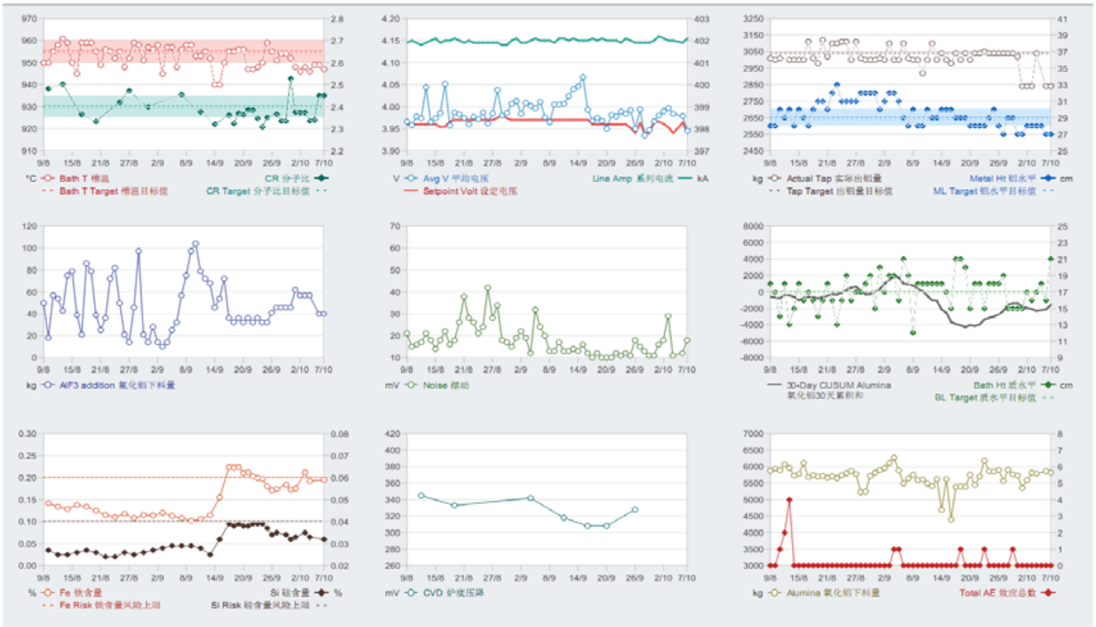


Figure 8. 9-plots showing the trends of 19 parameters for specific pot over 2 months span.

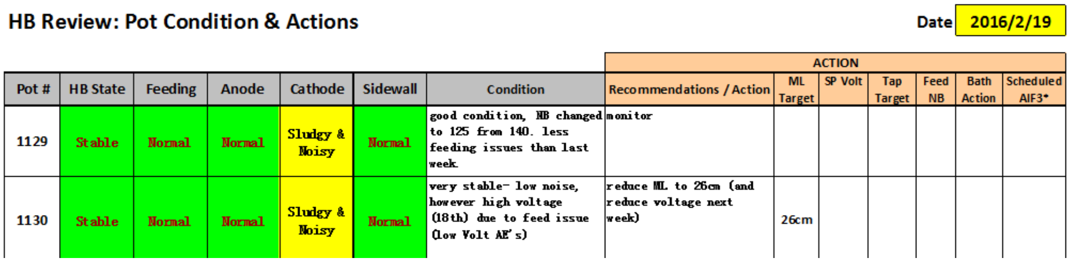
These charts which depict the trends of various parameters of the pot in the same time frame can be used not only to assess the current heat balance condition of individual pots, but also to evaluate the effects of past decisions on the pot.

Through a heat balance analysis, an informed decision making process, which includes the actions needed to be made on each pot in order to maintain the heat balance and improved pot performance can take place. An example of the outcome from one heat balance review of the test pots is shown in Figure 9. This includes:

(1) A colour-coded status of the current condition of each pot in terms of heat balance, feeding condition, anode health, cathode health and sidewall condition. Colours used are green (normal), yellow (abnormal) and red (high risk);

(2) Summary of issues currently present on pot and recommended actions to identify and resolve the root cause of issues;

(3) Record of recommended changes to pot targets (voltage, metal, AlF_3, etc.).



HB Review: Pot Condition & Actions

Date 2016/2/19

							ACTION						
Pot #	HB State	Feeding	Anode	Cathode	Sidewall	Condition	Recommendations / Action	ML Target	SP Volt	Tap Target	Feed NB	Bath Action	Scheduled AlF3*
1129	Stable	Normal	Normal	Sludgy & Noisy	Normal	good condition, HB changed to 125 from 140. less feeding issues than last week.	monitor						
1130	Stable	Normal	Normal	Sludgy & Noisy	Normal	very stable- low noise, however high voltage (18th) due to feed issue (low Volt AE's)	reduce ML to 26cm (and reduce voltage next week)	26cm					

Figure 9. Example of outcomes from one HB review on two test pots.

A metal level reduction of 0.5 - 1.0 cm was considered, based on the following conditions:

1) Pot temperature was stable for more than 2 weeks, varying within the control limits;
2) Pot noise has been below 20 mV for more than 2 weeks;
3) Collector bar temperatures were maintained at normal range for more than 2 weeks;
4) Fe and Si concentration in metal did not increased significantly for 2 weeks.

3. Results and Discussions

During the test period, the metal level of the 6 test pots was decreased by 3 – 5 cm. This was the result of applying the measures mentioned in Section 2, i.e.: heat balance review, new anode change procedure, SPC method for controlling CR and metal level, and top-down method for measuring liquid levels. Applying these measures led to the following improvements:

- Improved CR and temperature control
- Improved Key Performance Indicators (KPI) such as Energy Consumption and CE compared to reference pots.

However the success of the new measures on the performance of the pots was hindered due to a change in raw materials quality as described in the next few sections.

3.1. Improved CR stability

The new AlF_3 control regime led to reduction in AlF_3 feed variations. The AlF_3 feed's standard deviation of reference pots was 28.39 kg while that for the test pots was 18.59 kg, meaning 35 % less than the reference pots. The reduced variation in AlF_3 feed led to reduced variation in CR by 37 % compared to the CR variations of the reference pots. The temperature stability is one of the KPIs of the pots; it was also influenced by the improved stability of the bath chemistry, and the test pots showed 14 % less variations in bath temperature compared to the reference pots. These results shows that the strategy taken to reduce variation on the test pots was correct, making the pots more stable which opened the possibility for metal level and energy consumption optimisation (for a more details on the AlF_3 feed control that was applied on the test pots refer to the paper by Luo et al. [3]).

3.2. Improved Key Performance Indicators (KPI) for test pots

The performance of all the pots in the potline was reduced when comparing the baseline period to the test period. The CE of both test pots and reference pots were decreased by 1.13 % and 1.51 %, respectively (Figure 10 left) and the DC consumption was increased by 160 kWh/t Al and 176 kWh/t Al respectively (Figure 10 right). Compared to the reference pots, the average CE of test pots was 0.38 % higher, but the average energy consumption per tonne aluminium of test pots was 29 kWh higher.

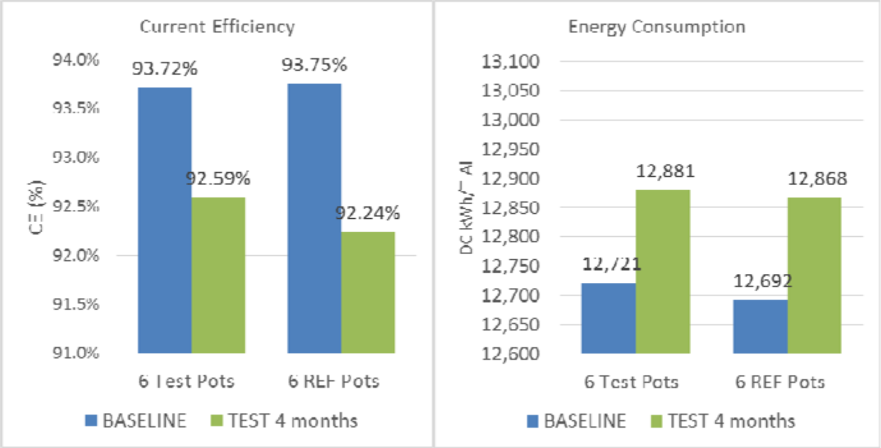


Figure 10. KPI's for test and reference pots comparing 3 months baseline to 4 months test period.

The main reason for the reduction of performance across the potline is change in alumina quality from change of supplier. The new alumina supply led to a reduction in solubility and the average alumina concentration in the bath was decreased from 1.7 % at the baseline period to 1.1 % in the test period as seen in Figure 11.

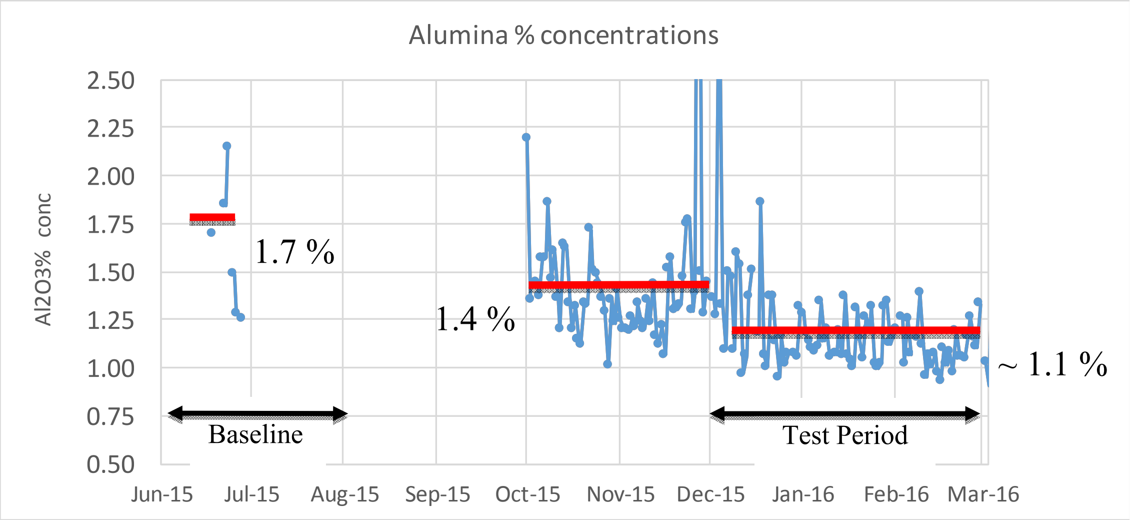


Figure 11. Average daily alumina concentrations on 6 test pots over the baseline and test period.

The change in alumina supply can be seen in Figure 12 which shows the alumina shipments by supplier, changing from suppliers B and F as dominant suppliers before December 2015, to E and G being dominant suppliers after December 2015. The 4 months of the test period is also indicated in Figure 12. During these months the reduced alumina solubility and performance can be allocated to the two sources of alumina coming from supplier E and G. These results show the effect of contaminants in the raw material on the reduction process performance and the need for high quality raw materials to maintain high pot performance.

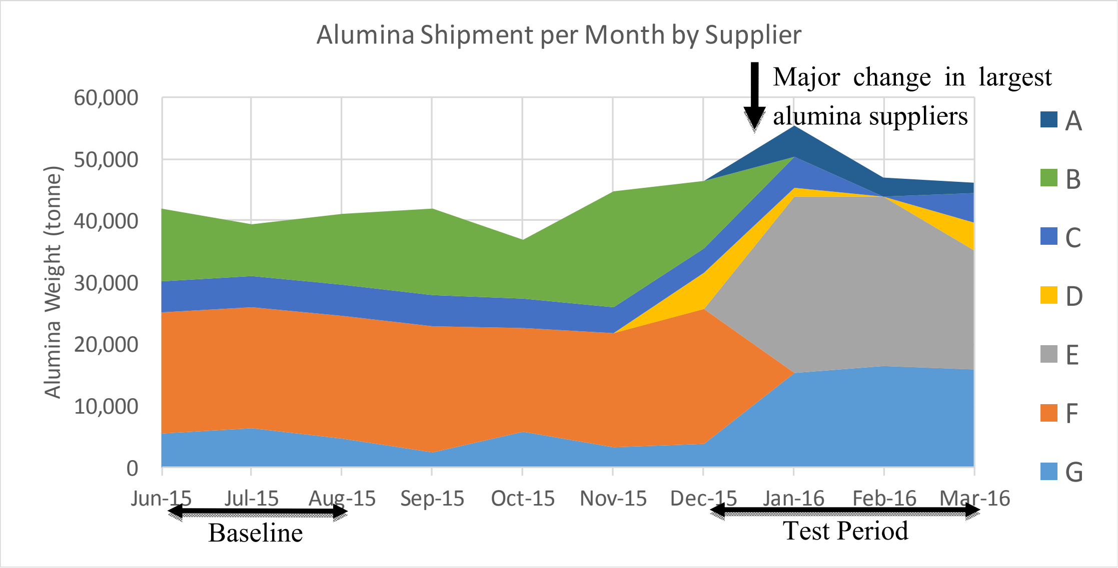


Figure 12. Alumina shipments (tonnes) by supplier during the baseline and test period.

While the KPI in Figure 10 shows the average performance of the test pots compared to the average performance of the reference group, the performance of each individual pot provides further understanding on the differences between the two groups. Figure 13 shows the CE of the individual test pots (left) and reference pots (right). The CE of reference pots were uniformly distributed from 91.52 % to 92.96 %, however the test pots had two pots with low CE (pots 1129, and 1133) and four pots with CE higher than 93 % or even 94 % (pot 1132).

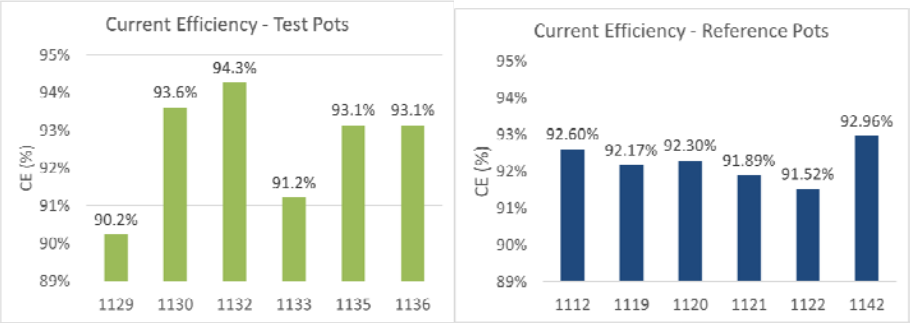


Figure 13. Average CE of individual pots during the 4 months test period, test pot CE (left) and reference pots CE (right).

The average voltage of each pot (Figure 14) shows similar distribution to the CE, the voltages of reference pots were uniformly distributed between 3.968 V and 4.005 V, while the test pots had two pots with significantly higher voltage than the rest of the group (pot 1129 and pot 1135). These two pots had cathode damage. The voltages of these pots could not be decreased quickly due to their condition. It is worth mentioning that pots 1112 and 1142 from the reference pots group were also classified as damaged cathode pots however their performance was similar to the other pots in the group.

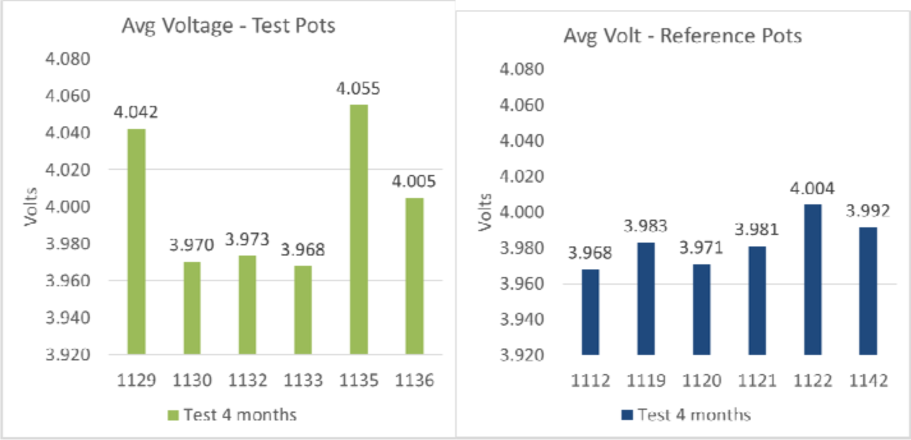


Figure 14. 4 months average voltage of individual pots from the test group (left) and reference group (right).

The DC power consumption of the corresponding 12 pots is shown in Figure 15. It reflects the data shown in Figures 13 and 14 - the DC power consumption of reference pots were uniformly distributed from 12 769 kWh/t Al to 13 036 kWh/t Al, while for the test pots, those with low CE and high voltage also showed high power consumption (pots 1129, 1133 and 1135). The DC power consumption of pots 1130 and 1132 was the lowest.

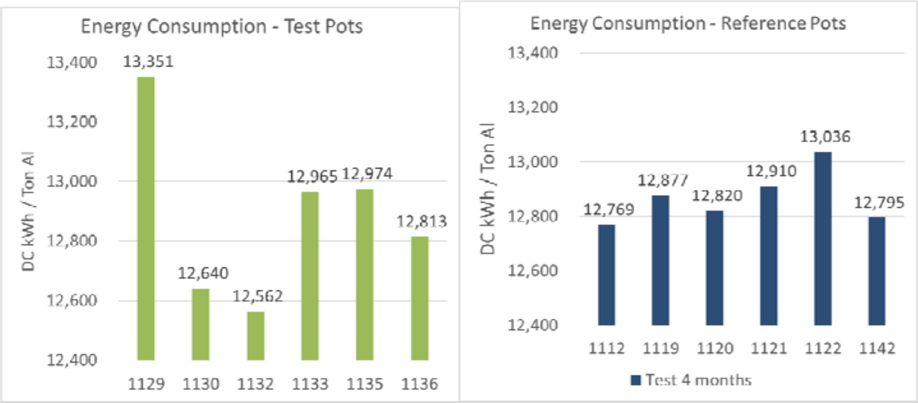


Figure 15. DC energy consumption of individual pots from the test group (left) and reference group (right).

From the data shown in Figures 13 - 15, it can be seen that the performance of the reference pots was uniform however the test pots had 2 pots (pot 1129 and pot 1133) that had lower performance compared to the rest of the group. Pot 1129 had cathode damage prior to the test period, which caused higher noise and voltage levels (Figure 16) and CVD, hence reduction in metal level could not be done as fast as other pots and it had low performance throughout the test period.

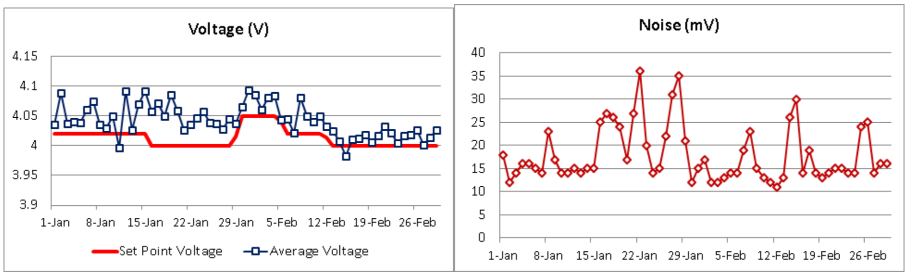


Figure 16. Voltage and noise levels over two months span on pot 1129.

Pot 1135 had damaged cathode during the test (as seen in Fe and Si levels in Figure 17 right) but recovered later. However the metal level could not be reduced in order to prevent further cathode damage.

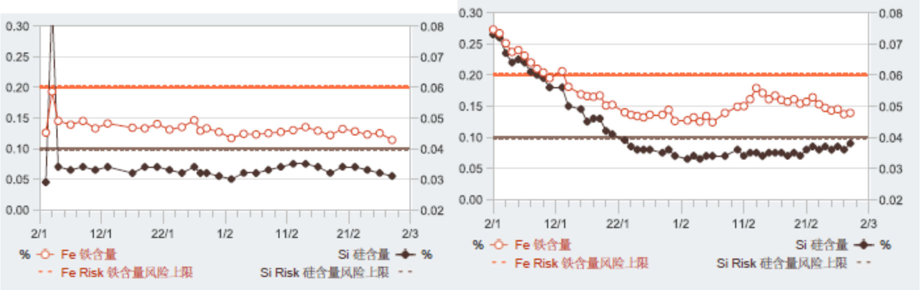
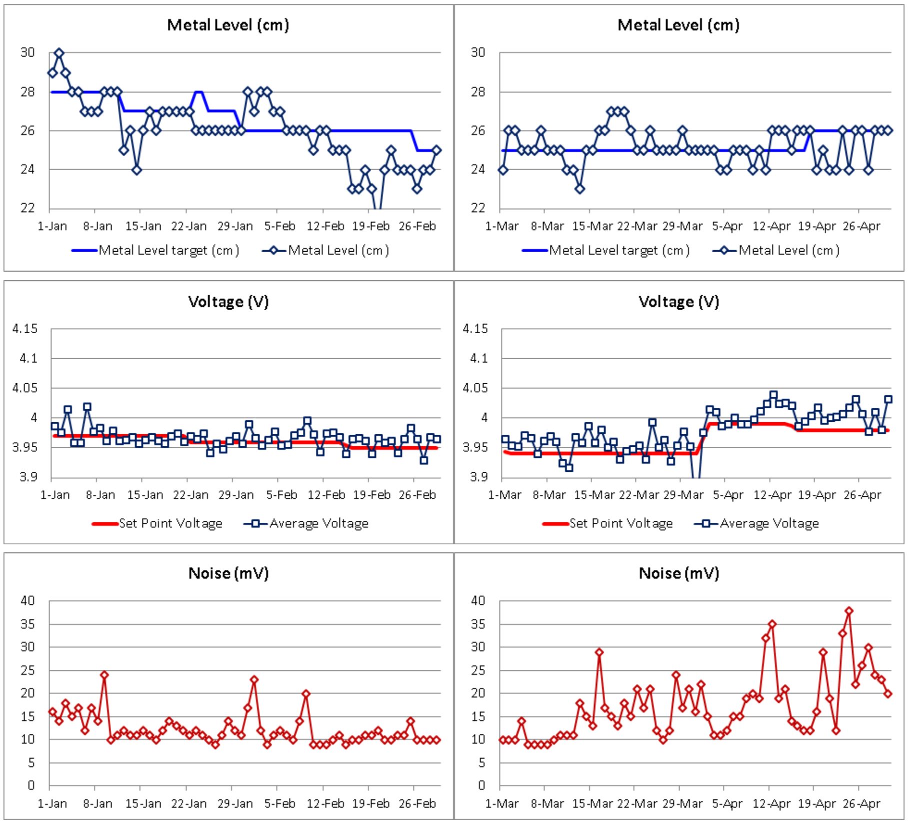


Figure 17. Fe and Si levels – on cathode damaged pot 1129 (left) and pot 1135 (right).

Pot 1133 had stable operation in terms of noise levels and voltage for 4 months, hence its metal level was decreased to the lowest level in the group (25 cm), as can be seen in noise and voltage trends on Figure 18 left. However, it had low metal inventory (initial inventory was 4 tons lower compared to other pots and was further reduced by 4 tonnes during the test period), and when the metal levels reached 25 cm and lower, signs of instability such as high noise and voltage started to appear (Figure 18 right). Hence, the metal level had to be increased to increase pot stability, meaning that 25 cm of metal level was actually breaching the optimum level for this pot.


Pot 1133 – Jan-Feb 2016

Pot 1133 – Mar-Apr 2016

Figure 18. Metal level, voltage, and noise trends on pot 1133 prior to reaching optimum point (left) and after passing optimum metal level (right).

The reduced performance on pot 1133 due to low metal inventory and metal level indicated that sufficient metal inventory is a precondition for optimisation of metal level.

If pots 1129 and 1133 are excluded from average KPI calculations, the performances of the other 4 good test pots are higher than reference pots as seen in
Table 4. The average CE of 4 good pots was 1.29 % higher than the average reference pots, and the average DC energy consumption was 93 kWh/t Al lower than the reference pots.

Table 4. KPI results of 6 test pots and 4 test pots compared to the reference pots during test period.

KPIs taking into account changes in metal inventory	**6 Test Pots**	**4 Test Pots**	**6 Ref Pots**	**Difference (4 Test vs. 6 Ref Pots)**
Current Efficiency (%)	92.59	93.53	92.24	**+ 1.29**
Energy Consumption (DC kWh/t Al)	12 884	12 747	12 840	**- 93**

4. Conclusions

The test results showed that the strategy and method used to optimise the performance of pots which suffer from high risk of cathode damage were correct. Reduced variations in AlF_3 feed with combination of improved operational procedure and better informed decision making process leads to more stability and offers the ability to optimise metal level and reduced energy consumption while maintaining high CE when compared to other pots in the section. However, as seen in the case of pot 1129, pots which already had cathode damage created challenges to optimise their performance as their noise levels were higher than other pots and there was a need to keep their metal level higher as a safety measure. Additionally, as a lesson learned from the performance of pot 1133, metal inventory had critical effect on pot stability and the ability to reduce metal level, hence sufficient metal inventory is precondition to successful optimisation of metal level and energy consumption. The effect of changed alumina supply and alumina purity led to a decrease in CE and increase in DC energy consumption over the entire potline which illustrate the need of high purity raw material to maintain high performance.

5. Acknowledgements

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6. References

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