Smelter Power Modulation in China and Application on High Amperage Reduction Cells

Nicholas B. Depree[1], Yashuang Gao[2], Cui Xizhong[3], Mark P. Taylor[4] and Zhang Wenmu[5]
1. Chief Technology Officer
2. Senior Process Engineer
EnPot, Invercargill, New Zealand.
3. Vice General Manager, Aluminium Sector, Technical Centre Director
Shandong Weiqiao Pioneer Group, China
4. Professor of Chemical and Materials Engineering
University of Auckland, New Zealand
5. General Manager
Binzhou Beihai Huihong New Materials, Binzhou, China
Corresponding author: nickd@enpot.co.nz
https://doi.org/10.71659/icsoba2025-al009

Abstract

The EnPot system for power modulation of Aluminium smelting cells was developed over many years of research and plant trials at the Light Metals Research Centre. The system uses ducted suction air and patented Shell Heat Exchangers, the airflow through which can be increased or decreased to selectively insulate or cool the pot shell. This allows power modulation of smelters on demand, or for deep modulation operation. This can give great advantages to smelters operating with varying power prices or power availability, which has been seen with increasing regularity around the world. The rapid increase in power price volatility in China and global demand for low-carbon Aluminium has driven demand for modulation, resulting in successful EnPot installation on 6 high amperage cells at a Chinese smelter. Initial results are shown in this paper, demonstrating the potential for both cooling and insulation of large cells, while maintaining operational stability and safety.

Keywords: Power modulation, Demand side response, Heat exchangers, Energy saving, Plant trial.

1. Introduction

The EnPot system was installed in February 2025 at the Binzhou Beihai Huihong New Materials Co. Ltd. Smelter ('Beihai Smelter') on 6 x 440 kA pots. The goals of this trial installation are to prove safety and effectiveness on much larger pots than previously installed, and to gauge the upper and lower operating windows i.e. the power modulation range of operable heat balance. This trial process will necessarily take some time to complete, however data presented in this paper shows the installation and commissioning success, and initial trial results showing safe substantial heat balance changes.

1.1 System for Sidewall Cooling and Insulation

The EnPot system was developed over many years of fundamental and industrial research at the Light Metals Research Centre, University of Auckland, New Zealand. Initially designed to maximise shell heat transfer for large amperage creep, it was further developed to enable potline current modulation both upwards and downwards using the insulating ability of the patented Shell Heat Exchanger (SHE) units [1, 2]. It has been trialled at many smelters of varying design and line current around the world, and is currently in operation on a full potline at Trimet Essen smelter [3]. The installation at Beihai Smelter represents the largest pot it has been installed on, and very relevant to future industry needs especially in China. A schematic of the system arrangement is shown in Figure 1.

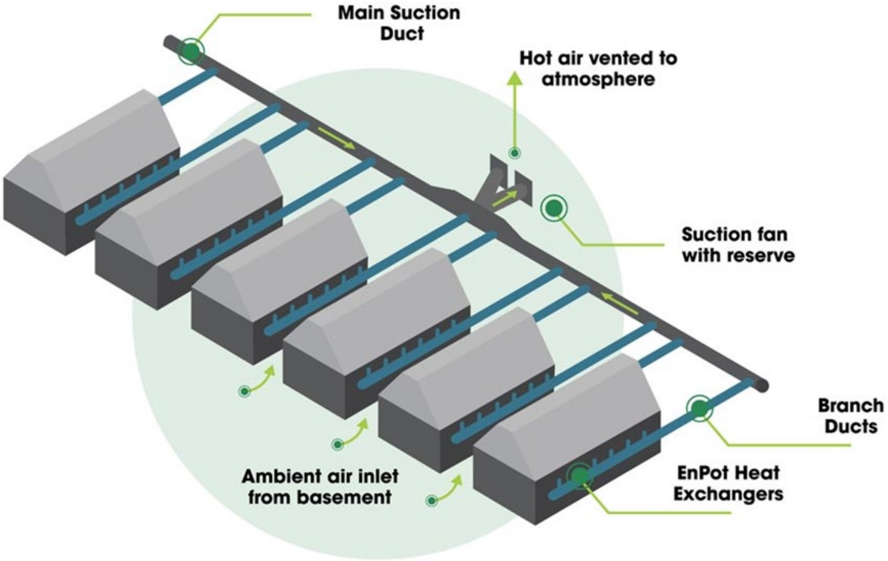

Figure 1. EnPot system schematic diagram.

1.2 Smelter Power Modulation

The ongoing challenges for power supply to Aluminium smelters around the world are now well established, including varying power price and availability over time scales from hourly variations to seasonal or yearly shortages. While the uncertainty of availability and price of power supply is a clear risk for smelters, it can also be seen as an opportunity to take advantage of varying pricing in future, as well as potential for decarbonisation by moving from fossil fuelled power to variable renewable energy, where the smelter provides a highly valuable firming service to the power grid [4, 5].

These challenges exist worldwide, of different complexity and opportunity in every country and for each individual smelter. This is especially true in China, where multiple factors are already at play, with further changes coming in future. These challenges include [2]:

- Government mandates to use more renewable energy in smelting, and to reduce power consumption and emissions [6].
- Changing national capacity caps now allowing for new production or capacity creep at existing smelters [7].
- Regional capacity caps where smelting capacity has been physically moved from coal-fired power regions to those with hydro power.
- Seasonal shortages in hydro power generation affecting capacity caps [8].
- Tiered power pricing based on energy efficiency (DC kWh/kg Al) [9].
- Daily variable power pricing being introduced based on renewable availability.
- Introduction of carbon emission taxes and trading schemes e.g. EU's Carbon Border Adjustment Mechanism (CBAM) [10]

Multiple pricing challenges can now be faced by any one smelter, giving new stimulus in the industry to look to flexible production, as well as other possible benefits such as decarbonisation or even enabling pots to run with lower energy use, as well as capacity creep in some areas where production caps and licences are now in excess. This has directly led to the installation of the first EnPot system in China at Beihai Smelter.

2. System Design, Installation and Commissioning.

The EnPot system consists of patented stainless-steel Shell Heat Exchanger (SHE) units mounted on the upper sidewall of each cell as shown in Figure 2, covering a large surface area to maximise heat transfer control. These units are connected via stainless ducting to under-pot suction manifold boxes, each connected to suction branch ducts via airflow control valves, as shown in Figure 3. In the case of Beihai Smelter, there are 48 SHE units divided into 5 manifold boxes on each side of the pot. The branch ducts per pot are also connected via airflow control valves to the main outside suction duct and fan system shown in Figure 4, such that each pot can be controlled independently, and airflow around the pot can be balanced to improve pot thermal condition. The system is substantially instrumented, with pot shell thermocouples mounted under SHE units at one location for each manifold, as well as end walls, and duct air flow and temperature measurement. The system was designed by EnPot and customised to the Beihai pot shell, with all pot-side hardware manufactured in New Zealand. The branch ducting, main ducting, fans, electrical and instrumentation equipment were supplied locally by Beihai Smelter contractors, including site installation labour.

Figure 2. Sidewall mounted SHE units and connection pipes.

Installation supervision and system commissioning and calibration were performed onsite by EnPot engineers. Following whole-pot installation, the airflow control valves were adjusted to reduce temperature variation around the pot as shown in Figure 5. This shows great potential of the EnPot system to create more regular pot-side heat transfer, reduce ledge thickness variation, and potentially allow more efficient operation at lower energy consumption or higher current efficiency. This effect was also demonstrated in the system at Trimet Essen [11]. Airflow balance was adjusted several times, as shown in Table 1, where the existing, pre-install (without SHE) measured variation of shell thermocouple readings was 120 °C, and by changing airflow control valves could be reduced to 80 °C and then further to 50 °C.

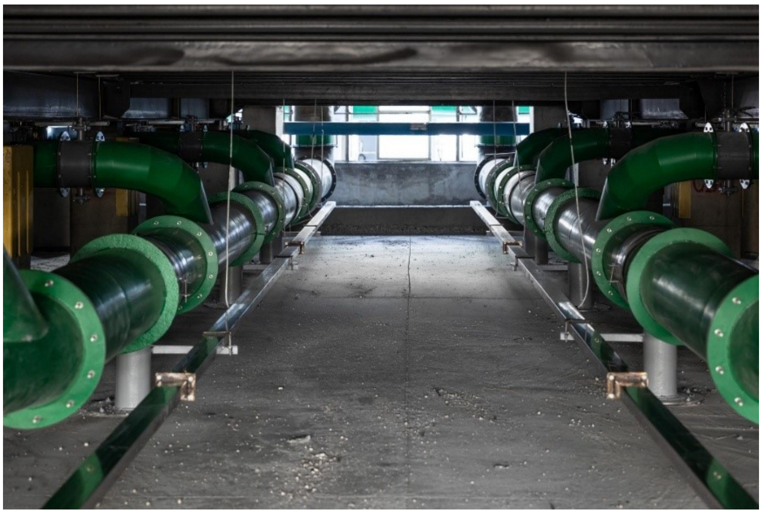

Figure 3. Under pot ducting.

Figure 4. External ducting and fans.

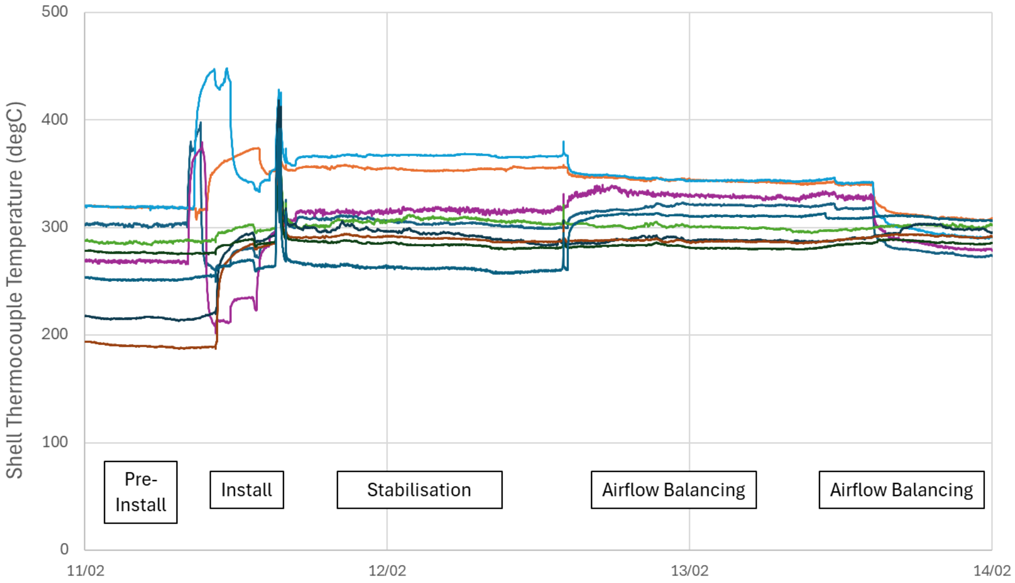

Figure 5. Shell thermocouple temperatures pre-install, during, and post-install with airflow balance adjustment.

Table 1. Shell thermocouple temperature pre-and post-SHE install.

Period	Min (°C)	Max (°C)	Range (°C)
Pre-Install	200	320	120
Post-Install	250	360	110
First Adjustment	260	340	80
Second Adjustment	260	310	50

3. Commissioning Tests

Initial commissioning tests were conducted to confirm the cooling and insulating ability of the system. Beyond the temperature rise when SHE were installed seen in Figure 5, a further test was conducted by partially reducing airflow to pot branch ducts from approx. 40 % valve opening to 10 % (nearly closed) and observing the shell temperature rise in Figure 6. This shows the shell temperature response rate, where the average thermocouple measurements increased from 300 °C to 384 °C, of which rise 80 % occurred in 30 minutes, and 87 % in 60 minutes. A similar response was found on return to normal cooling, with 82 % of the drop occurring in 30 minutes. This shows easy ability for EnPot to insulate the shell and increase shell temperature and eventually ledge thickness. The shell temperature responds very quickly to airflow changes; however internal changes will be substantially slower. Further insulation is certainly possible by completely closing the airflow valves or stopping the suction fan.

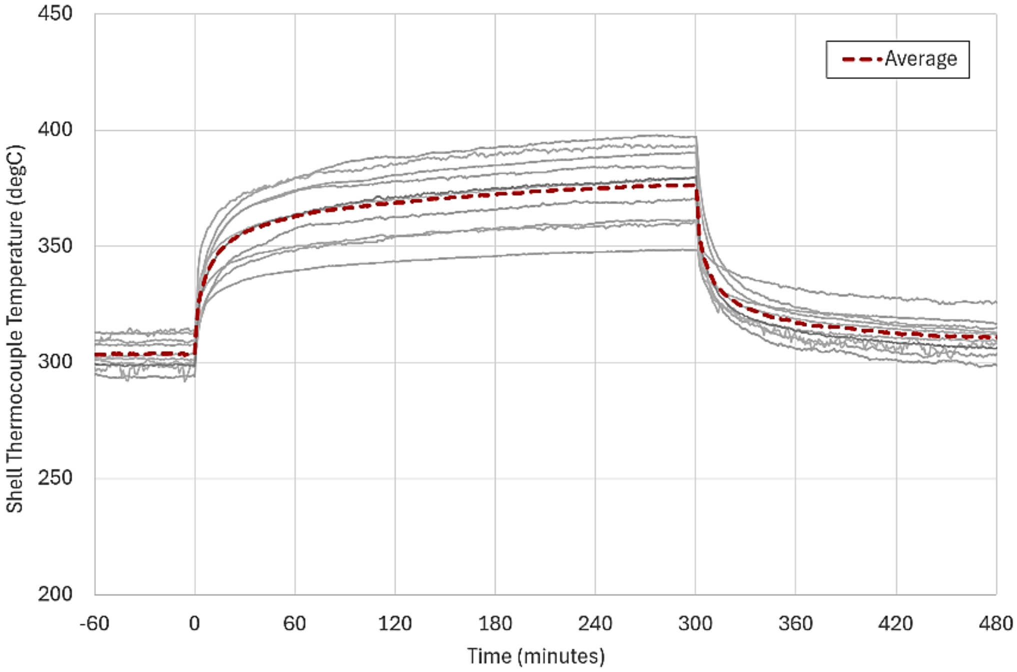

Figure 6. Shell temperature during partial insulation test.

An opposite test was performed to demonstrate cooling, by opening airflow valves and increasing fan speed via variable speed drive from 22 Hz at normal calibrated operation to 50 Hz for maximum cooling. In this case, as shown in Figure 7, average shell temperature dropped from 307 °C to 190 °C after 55 min, of which 93 % (-109 °C) occurred by 30 minutes, and when cooling was returned to normal, recovered by 83 % (+97 °C) within 30 minutes, and 91 % within 60 minutes. Further substantial tests were performed for a range of operational scenarios, especially considering shell temperature measurement via thermal imaging, and comparing the temperature of the uncooled shell adjacent to the SHE units and comparison with thermocouple results. Following commissioning the system was allowed to rest approximately 1 month to reduce pot disturbance before initial trials began.

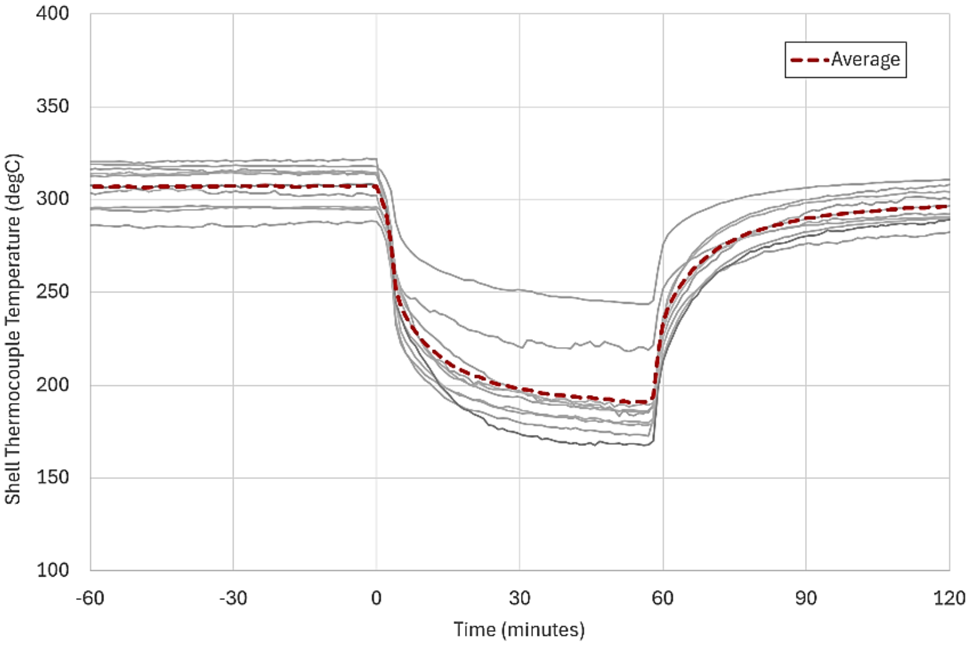

Figure 7. Shell temperature during cooling test.

4. Initial Trial Results

A wide range of tests were developed to quickly gain understanding of the basic behaviour of the system and effectiveness on the large high-amperage pots, compared to previous installations [11]. While operational changes and process control learnings for long term system performance necessarily will take many months, initial trials have been highly successful in generating information in a short time period, with initial results presented here.

Early tests involved power increases by adding pot voltage (anode-cathode distance (ACD) increase) and monitoring shell temperature over time periods ranging from 8 hours to 4 days. In each case, very little observable shell temperature change occurred, such that shell temperature is easily controlled by the EnPot system, and power changes inside the pot take longer than this to have any effect on shell temperatures or to give a signal to change cooling rates. Similarly, decreases in line current by 10–20 kA for up to 8 hours duration have no observable effect on shell temperature. The tests possible were limited by effects on other pots, with no booster group available to control line current independently, but remaining a possibility for future work.

One key test undertaken was a full shutdown, where smelter staff followed their normal procedure using shunt switches to cut out one pot, taking bath temperature measurements every 30 minutes until pot restart, with full sidewall insulation by closing the EnPot branch duct valves, and stopping pot top draught. It was observed that superheat largely disappeared after 30 minutes, followed by a steady cooling rate of approximately 4 °C per hour. The pot was restarted with bath temperature of 930 °C, extended from previous 4 h limit to 6 h, with some potential for longer. This shows increased survivability of a potline with unplanned outages, or to extend the ability to offer full-shutdown power modulations as a paid service to the power grid [5].

The main test reported here is a longer increase in heat generation, given the very slow response of pot shell temperatures. Voltage equivalent to +10 % added heat dissipation was added to 3 pots, as per Table 2, and maintained for 2 weeks, with further additions beyond this to +12.5 % and +15 % heat dissipation in the following 2 weeks. It should be noted that adding voltage is not equivalent to adding line current, as voltage adds all additional heat directly into the bath, whereas line current spreads this partly across anodes and cathode, as well as increasing anode current density, busbar temperature, and possibly metal velocity and magnetic forces. This trial was aimed at proving the potential to dissipate significantly greater heat generation - however to prove that the rest of the smelter can operate at +10 % or more line current also involves significant work investigating anode condition, bus bars, GTC (Gas Treatment Centre) scrubbing capacity etc. Some of these may be easily tested in future with possible addition of a booster rectifier on these pots, and informs part of the business case for smelter modulation if upgrades are required [12].

Table 2. Trial parameters for added heat generation.

Parameter	Value	Unit
Voltage	3.995	V
Current	440	kA
$V_{reaction}$	2.03	V
Heat Dissipation	864	kW
Added Voltage	0.2	V
Added Heat	88 (+10 %)	kW

A key result of the trial is the identification of the importance of individual pot differences, as shown in Figures 8–10, where one pot (Pot 2) had a small initial rise in bath temperature and remained very stable, whereas Pots 1 and 3 had larger initial rises, followed by downward swings due to compensatory actions by the smelter including larger increases in AlF_3 addition to reduce cryolite ratio following initial ledge melting shown in Figure 11. Operational conditions of these 3 pots were different at the start of the trial. Pots 1 and 3 were already on upswings in cryolite ratio, and adding voltage at that time exacerbated the increase, whereas Pot 2 was more stable and easily absorbed the increase. In the best case of Pot 2, the bath temperature stabilised after 1.5 days of added voltage and sidewall temperature reduction, but Pots 1 and 3 continued to increase for 4 days until the temperature peak. The shell cooling was also increased over the first two days, as the required amount of cooling was not known a priori. Cover condition and operator work practices are also extremely important to ensure good regularity of pot behaviour, one of the factors needed for a ‘deep modulation package’ and also including standardisation of top heat losses [13, 14].

Safety of the power increase was monitored carefully, including greatly increased sampling rates of bath temperature, liquid levels, bath chemistry, and extensive thermal imaging of pot shells, and anode stubs. The EnPot system has great potential for safe increases in heat dissipation as shown in Figure 11, where ledge thickness was maintained largely stable through the trial, following an initial small reduction. This is consistent with previous modelling [1] where higher power generation matched with sidewall heat extraction results in a stable, operable heat balance at higher superheat and thinner ledge position.

The initial ledge melt however does introduce chemistry and liquid level control challenges when combined with the varying initial state of pots. The initial effect of a large power increase will be an immediate bath temperature and superheat rise, across a few days as seen in Figures 8–10, whereas the changes in shell cooling may take a week or more to affect pot internal temperature and reach stability. The immediate temperature and superheat rise is also consistent with previous work [11]. This suggests that large changes in input power are better staged slowly over some weeks rather than in one step change, or that short term modulations e.g. hourly or daily will result in the pot being in a transient thermal state for a lot of the operating time, which must be carefully managed.

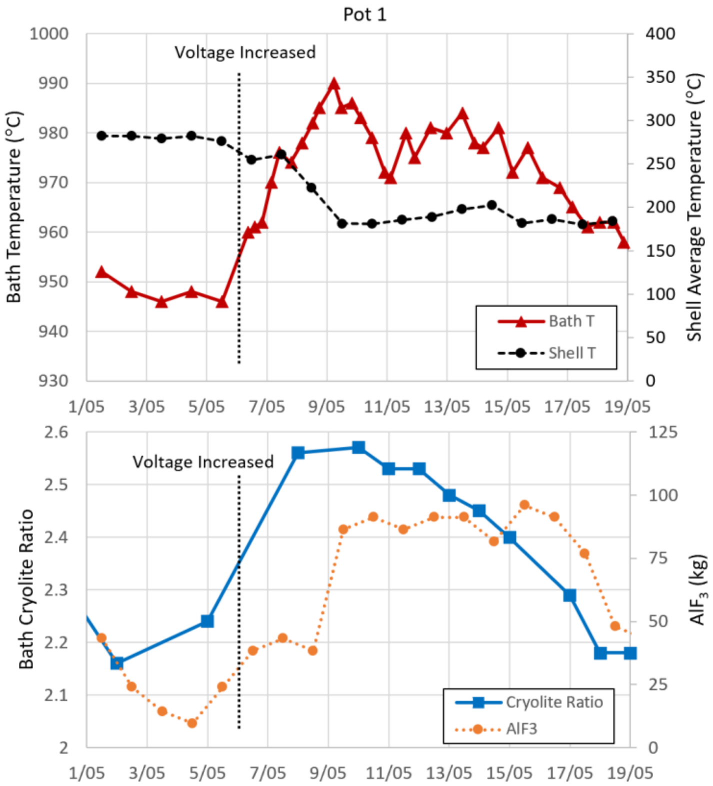

Figure 8. Pot 1 changes following 200 mV addition.
Top: bath and shell temperature, Bottom: cryolite ratio and daily AlF_3 addition.

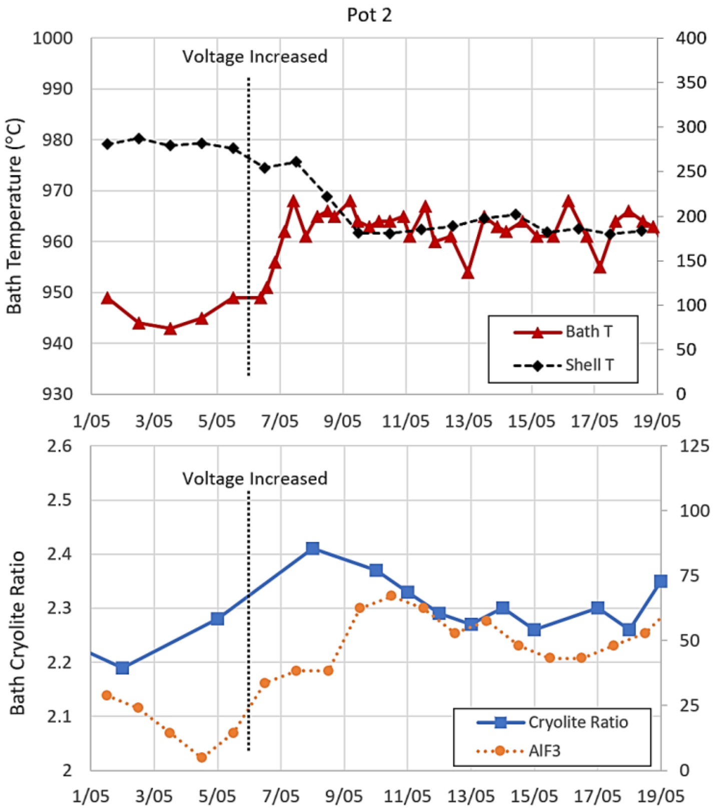

Figure 9. Pot 2 changes following 200 mV addition.
Top: bath and shell temperature, Bottom: cryolite ratio and daily AlF_3 addition.

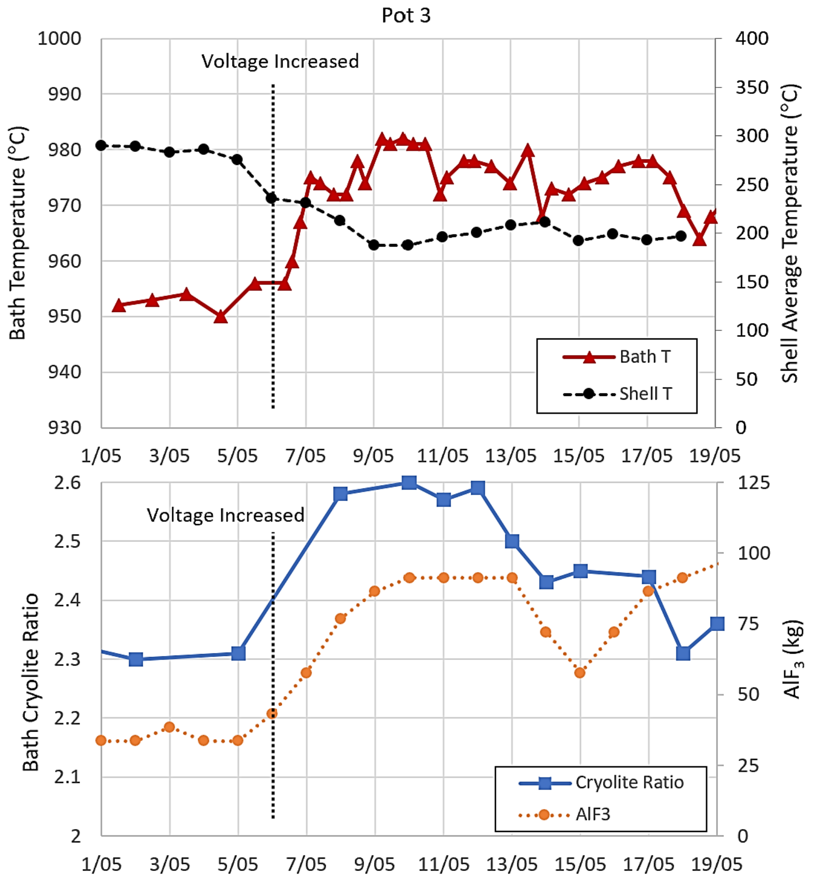

Figure 10. Pot 3 changes following 200 mV addition. Top: bath and shell temperature, Bottom: cryolite ratio and daily AlF_3 addition.

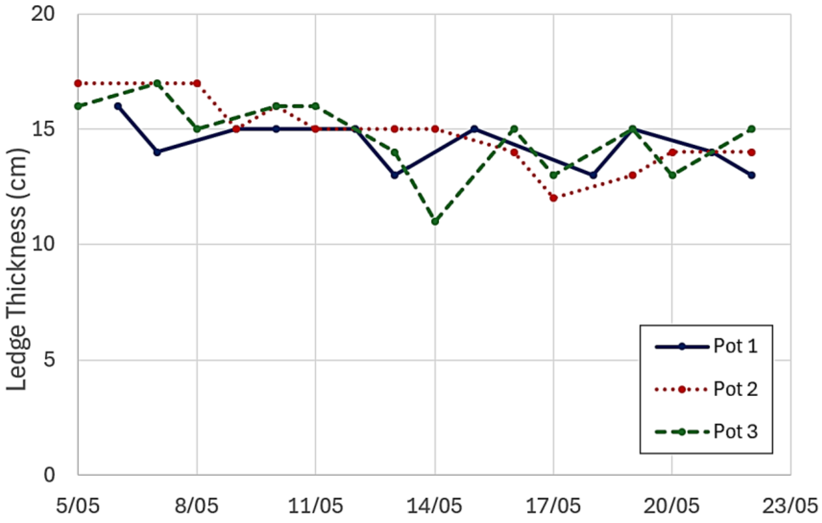

Figure 11. Ledge thickness measurements following 200 mv addition.

Because shell cooling affects the pot internal state very slowly, and the initial internal temperature increase was large in some pots, the required shell cooling is effectively an educated guess to be refined over long term operation. Adding cooling rapidly decreases shell temperature within 1–2 hours, and the airflow and heat extracted in the suction air can be only roughly matched to added heat generation, as up to 50 % of heat naturally also leaves through the top cover [2]. The shell temperature ranges are shown in Figure 12 for one pot, where it can be assumed that approximately correct cooling is achieved when there is no long term upwards or downwards trend, or drift in temperature spread. Reaching pot stability faster should be achieved by applying the full cooling at the time of, or in advance of voltage adjustment. Cooling stability may also be improved in the system control, where average shell temperature can be adjusted via fan speed automatically, or motorised valve adjustments could be made, but the internal heat balance will certainly take days or more to stabilise in any case.

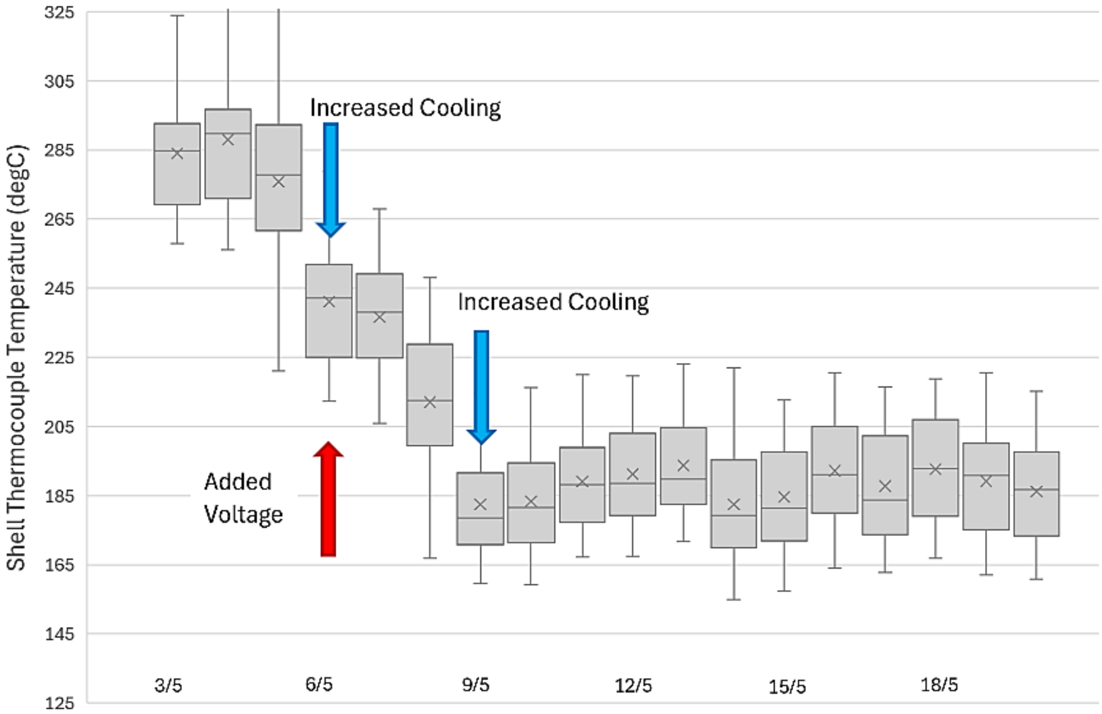

Figure 12. Change in shell temperature ranges with added cooling.

All 3 pots responded well to +10 % heat generation once stabilised, with generally excellent pot performance, including very low noise, and good feeding and voltage signals, after an initial period of back-feeding on pots with elevated temperature. Increasing up to +15 % heat generation did find thermal limitations on the pot ends however, where SHE units were not installed. The Beihai pots are common in China by being designed for insulating operation at low voltage, with a thick layer of alumina cover, as well as added physical insulation on the shell ends. There is great potential to increase modulation capability beyond +10 % simply by changing cover methods and significantly reducing cover thickness [15] and removing shell insulating materials. This should be sufficient to achieve +15 % heat generation, or perhaps 15 % line current contingent on balance of plant capabilities at higher amperage. Even further current increase should be possible by retrofitting SHE panels to the pot ends, which can be simply added to the system as installed.

Concurrent tests on the other 3 pots demonstrated low-power operation by simple ACD squeeze coupled with added shell insulation. Voltage reduction tests show significant room on these pots before magnetic instability occurred. This means that increasing line current in future can also be compensated by some ACD squeeze, or at base line current, the ACD can be reduced using EnPot insulation to reduce DC kWh/kg Al consumption, as was also shown previously [11].

5. Conclusions and Further Work

The key outcome is the successful demonstration of safe operation at significantly increased heat generation using EnPot sidewall cooling. The important information gathered is the slow response time of large 440 kA pots. These tests imposed a one-time large magnitude change in heat generation, with attendant process control challenges. In a situation where long-term amperage creep is the goal, or seasonal power modulations, this can be more easily achieved by a slow ramp of power change to ease process disturbance. The ability for short-term modulation e.g. for hourly power price changes needs further study on process control and stability, as the pot will often be in a transient thermal state which must be managed carefully.

A complete demonstration of potline modulation using EnPot will require a booster group installation, or extension to a full potline in future, in order to test the effects of increased current density on any particular cell design, and to identify other smelter limitations. The thermal balance appears achievable however at +10–15 % power consumption with the system as designed, or may be extended further using end wall SHE units for higher heat dissipation needs.

6. Acknowledgements

The authors wish to acknowledge the essential contributions made by dozens of researchers over 20 years who have worked on the shell heat exchanger technology. The authors make special thanks also to the team at Beihai Smelter, especially hard-working potline operators and potline manager Mr. Tang Weifeng who had daily oversight of the project, Mr. Yang Mingran and the equipment supply team for delivering the system, technical leaders Mr. Chen Shenglian, and Mr. Hu Hongwu, as well as executive team of Weiqiao Pioneer Group especially Mr. Cui Shilei and Mr. Li Quanlin.

7. References

1. Pascal M. Lavoie et al., Increasing the power modulation window of aluminium smelter pots with shell heat exchanger technology, *Light Metals* 2011, 369-374. https://doi.org/10.1002/9781118061992.ch66
2. Nick B. Depree et al., Evolution of power modulation technology in response to changing market conditions worldwide, *Light Metals* 2025, 540-548. https://doi.org/10.1007/978-3-031-80676-6_70
3. Roman Düssel, Albert Mulder and Louis Bugnion, Transformation of a potline from conventional to a full flexible production unit, *Light Metals* 2019, 533-541. https://doi.org/10.1007/978-3-030-05864-7_68
4. Martin Iffert, Aluminium Smelters as Catalysts for the Energy Transition: Empowering Renewable Energy Transport and Advancing Grid Decarbonization. Keynote presentation at the *153rd TMS Annual Meeting*, Orlando, Florida, 3–7 March 2024
5. Nick B. Depree, David P. Thomas and David S. Wong, The contribution and economics of demand side response towards decarbonizing the aluminium smelting industry, *Light Metals* 2022, 560-570. https://doi.org/10.1007/978-3-030-92529-1_74
6. The People’s Government of Fujian Province, Outline of the 14th five-year plan (2021-2025) for national economic and social development and vision 2035 of the People's Republic of China, June 2021. https://doi.org/10.22617/brf210192-2 https://www.fujian.gov.cn/english/news/202108/t20210809_5665713.htm
7. Andy Home, As China nears peak aluminium production, what next?, Reuters, 2024. https://www.reuters.com/markets/commodities/china-nears-peak-aluminium-production-what-next-andy-home-2025-04-24/?utm_source=chatgpt.com

8. China's green aluminium ambitions hit by erratic rains, power cuts, *Reuters* 2024, https://www.reuters.com/world/china/chinas-push-greener-aluminium-hit-by-erratic-rains-power-cuts-2024-05-10/
9. China presses aluminum sector on energy saving, carbon emission cuts, *MySteel* 2024. https://www.mysteel.net/news/5058800-china-presses-aluminum-sector-on-energy-saving-carbon-emission-cuts-
10. China plans to include steel, cement and aluminium in its carbon market in 2024, *Reuters,* September 9*,* 2024, https://www.reuters.com/markets/carbon/china-plans-include-steel-cement-aluminium-its-carbon-market-2024-2024-09-09/
11. Nick Depree et al., The 'virtual battery' – operating an aluminium smelter with flexible energy input, *Light Metals* 2016, 571-576. https://doi.org/10.1002/9781119274780.ch96
12. David S. Wong et al., The Australian energy crisis, its impact on domestic aluminium smelting and potential solutions, *Light Metals* 2020 791-802. https://doi.org/10.1007/978-3-030-36408-3_106
13. Malcolm Derek Gadd, Aluminium smelter cell energy flow monitoring, PhD Thesis, *University of Auckland*, 2003, http://hdl.handle.net/2292/26479
14. Nick B. Depree et al., A method of cell heat balance control to enable variable power usage by aluminium smelters, *Light Metals* 2024, 419-426. https://doi.org/10.1007/978-3-031-50308-5_54
15. Mark P Taylor, Anode cover material–science, practice and future needs, *Proceedings of 9th Australasian Aluminium smelting technology conference,* Terrigal Australia, 4-9 November 2007, Paper 11.