Casthouse Refractory Methods for Risk Control and Quality Assurance

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Abstract

Casthouse operations require the use of various types of refractory materials along the entire value chain that need to be properly maintained. Indeed, refractory maintenance operations in aluminium casting furnaces can expose workers to a variety of severe health and safety risks, such as exposure to hazardous substances, falling objects or contact with heavy machinery. Additionally, improper process control during the refractory dry-out and furnace start-up phases can create dangerous conditions (e.g. steam explosions). Business risks such as premature failure can also stem from insufficient quality assurance during shutdown planning and execution. While these risks have long been recognized, they were in the past managed trough administrative controls, which are inherently fallible and have led to several incidents. In the last five years, Rio Tinto has used new technology and novel techniques to implement engineering controls for risks created by refractory maintenance in casting furnaces. These innovations have led to a safer work environment for refractory maintenance crews and in certain cases have eliminated risks associated with legacy work practices.

Keywords: Refractory maintenance, Casting furnace, Steam explosion, Health and safety, Casthouse risk reduction.

1. Context and Present Situation

Rio Tinto currently operates 28 aluminium casting furnaces within its Atlantic Operations division, while an additional 4 furnaces are currently at the design or construction phase. Most of these furnaces consists of tilting units, with an average capacity around 100 tonnes. All furnaces rely on a monolithic refractory lining for metal confinement and major components of such linings typically require replacement every 12 to 36 months (the exact frequency and extent of repairs depends on process conditions and furnace design). For Atlantic Operations, this translates into 6 to 8 major shutdowns per calendar year, during which around 2 000 man-hours are required in each furnace for refractory maintenance.

Refractory maintenance in casting furnaces can be a hazardous task. For example, during most steps workers are routinely exposed to crystalline silica dust, which is a known carcinogenic substance [1]. Other specific tasks such as demolition and work inside chimneys involve additional risks: the former involves working in very close proximity to heavy machinery, while the latter exposes employees to falling pieces of refractory or debris from great heights. Because of process risks, even steps where no manual labour is involved can be dangerous to nearby personnel. The penultimate stage of a furnace shutdown is the dry-out, during which new refractories must be carefully brought up to temperature following a precise schedule. If the schedule is not strictly adhered to, a steam explosion within the new lining may occur. Such an explosion can also occur during the first batch in the furnace if molten metal penetrates the lining through expansion joints or cracks and contacts trapped residual water from the dry-out. Although rare, severe steam explosions in casting furnaces can be quite destructive, as shown on Figure 1.

Figure 1. 100 t furnace severely damaged by a steam explosion in 2015 during dry-out [2].

2. Challenges or Required Expected Improvements.

This paper will focus on safety improvements in three separate steps of furnace refractory maintenance: refractory tear-out (i.e. demolition), stack maintenance and dry-out. Since each area presented unique challenges, they will be separated henceforth to simplify the text.

2.1 Challenges with Demolition Machinery

Until recently, refractory tear-out was performed using conventional excavation machinery, like the backhoe shown on Figure 2. This figure clearly shows the main problem with this type of equipment: the operator sitting in the cab is too high to have a direct line of sight on many areas inside the furnace (roof, front ramp, floor, etc.).

Figure 2. Typical backhoe used for furnace demolition (author's image).

This issue mandated the use of a spotter to guide the backhoe operator when tearing out components invisible to the operator. Unfortunately, to be able to see the jackhammer while visually communicating with the machine's operator, the spotter had to stand extremely close to the backhoe's swing arm. Figure 3 shows a spotter near the machine.

Figure 3. Example of a spotter guiding a backhoe during roof demolition (author's image).

This level of proximity placed the spotter at great risk of being hit by or crushed by the swing arm against the furnace in case of operator error. The vehicle itself was also a considerable risk, as the backhoe frequently had to be repositioned during demolition and the spotter was often standing in a blind spot. Even though internal safety requirements mandate a safe separation distance between heavy machinery and personnel on foot, it could not be always implemented during refractory tear-out due to the necessary visual communication.

Serious safety concerns were far from the only problems with conventional excavation machinery. Poor tool articulation angles as well as thermal limitations meant that “heavy” demolition was a long and inefficient process, sometimes stretching well past 48 hours after furnace burner shutdown. Another major issue caused by the lack of tool articulation was that some areas could not be reached at all and had to be demolished manually with compressed air-powered rivet busters. This was an extremely physically demanding task, which not only was very time-consuming but also dangerous. Multiple injuries were caused by hands getting crushed between rivet-busters and adjacent surfaces.

2.2 Challenges with Stack Refractory Inspection and Maintenance

Most aluminium casting furnaces operated by Rio Tinto in Canada have stacks lined with refractory. Typical dimensions are around 35 m in height, 1m in internal diameter and 75 mm in refractory thickness. This refractory layer is essential in maintaining the asset’s integrity; without it, the steel structure would not only overheat, but would also be exposed to corrosive gases. Periodic monitoring of the refractory’s condition is required, otherwise issues will only be detected once they become serious. Figure 4 shows an example of advanced degradation that could have resulted in collapse of the stack and catastrophic damage to the casthouse.

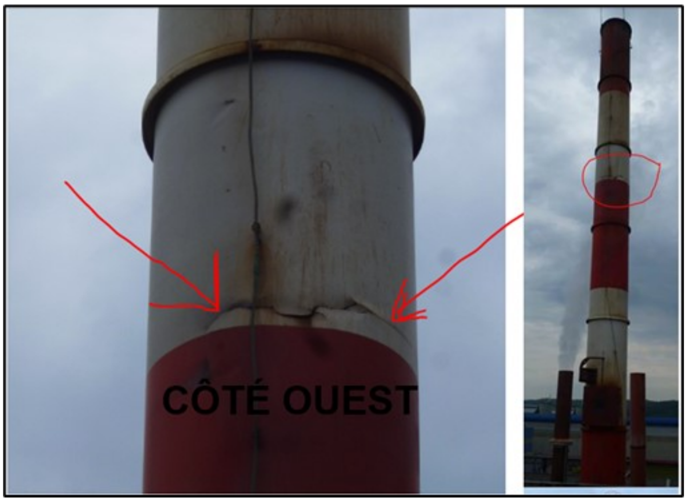

Figure 4. Shell buckling on a free-standing stack in 2013 [3].

Thermal imagery and visual inspections (interior and exterior) are adequate to assess the condition of a stack's refractory, however until recently these methods could not be used to their full potential without exposing inspectors to considerable working at height and confined space risks. Unless taken from a man basket suspended by a crane close to the stack, resolution of thermal images tended to be poor because of the great distance and view angle separating the stack from an inspector standing in front of the casthouse. A man basket or scaffolding erected from the ground up could be used to send an inspector inside the stack to inspect the refractory but given the small internal diameter and confined space requirements neither were easy to do. At the same time, the main safety concern with stacks was workers entering the base for repairs. The area most often repaired is the transition between the flue duct from the furnace (sometimes called the "elbow") and the stack. Personnel working at the base of the stack are at great risk should pieces of refractory or debris fall from high above.

2.3 Challenges with Steam Explosions Following Dry-Out

Considerable progress was made in the last decade in casthouses operated by Rio Tinto in Canada with regards to dry-out control. Until 2019, furnaces were dried out using their own burners, which caused wide temperature fluctuations because of poor control at low power settings - these temperature excursions sometimes led to steam explosions. Usage of external dry-out burners and specialized crews started in 2019 and addressed most issues related to steam explosions. However, one remained: liquid water dripping out of a furnace once the dry-out chart is completed. This situation occurred regularly (especially with larger units) and left technical teams with difficult questions to answer, such as: if water is dripping out of the furnace, can it safely be charged with molten metal? If not, when will the water stop coming out?

During dry-out, water is pushed by the thermal front inside the refractory towards the cold face. Liquid water can get trapped in colder regions or in very porous materials used for insulation (e.g. ceramic fiber boards). During the initial filling of a furnace after a refractory overhaul, molten aluminium will infiltrate expansion joints and cracks that have not been fully closed with thermal expansion. Evidence of this phenomenon is routinely found during demolition of old furnace linings. In a properly designed and built refractory system, freeze line placement will prevent metal from infiltrating joints and cracks too deep. However, under certain circumstances during start-up (incorrect alloy selection, premature charging of molten metal, excessive bath temperature, etc.) molten metal can travel far enough in the refractory to reach the steel shell.

Consequently, if residual water is trapped between the shell and the refractory is in contact with molten metal, there is a high risk of explosion.

Therefore, it is much safer to postpone the charging of the furnace until no more liquid water is dripping from underneath it, even if the dry-out procedure recommended by the refractory supplier has been finished. Delays of up to 48 hours were occasionally required to completely remove water, causing significant challenges for shutdown coordinators and resulting in substantial production losses.

3. State of the Art

3.1 Demolition Machinery

Evolution of demolition machinery was mainly constrained by business reasons. Over the years, local contractors made improvements to some of their excavation machinery to adapt it to furnace work. For example, one company had a dedicated backhoe equipped with some thermal shielding and a modified jackhammer with increased vertical articulation. However, because excavation contractors seldom perform furnace work in a year, there is little incentive for them to modify multiple machines. Thus, when the only suitable backhoe experienced breakdowns during a furnace shutdown, no replacement was available, and production losses inevitably followed. The same constraint also applied to the spotter issue: while the risk was recognized, it was managed through administrative controls, as contractors considered engineered solutions (such as cameras on the backhoe swing arm for the operator) as too expensive for their annual usage – such systems are not required for conventional excavation jobs. More affordable solutions like radio and phone communications were tried but were found to be unsatisfactory due to the delay for radios and due to the complexity of explaining verbally how to effectively position machine tools inside a furnace.

Having worked in other heavy industry sectors, the author was aware that remotely controlled machinery could be used to tear-out refractory linings, even in very hot vessels. For various reasons, prior to 2021 Rio Tinto had rarely used this type of equipment in Canadian aluminium casting furnaces. It was considered unproven for large demolition jobs and riskier than conventional excavation machinery. Moreover, companies with experienced personnel and machines suitable for hot work in casting furnaces are rare in Canada and none were based near Rio Tinto’s smelters.

3.2 Stack Refractory Maintenance and Inspection

In Rio Tinto’s Canadian aluminium smelters, thermographic inspections of stacks had traditionally been performed by high voltage maintenance personnel, since these teams were the first to receive infrared cameras decades ago and were very competent in their usage. However, the results were not always optimal. In order to avoid using cranes and man-baskets, thermographic inspections were almost always conducted from the ground with cameras that were not well suited for inspections at long ranges. In most plants, furnace stacks are located close to the center of buildings. Due to their height, this means the thermal camera operator is forced to stand quite far away from the stack when trying to capture infrared images. Since most thermal cameras found in plants cannot be fitted with a telephoto lens, this translated into poor picture resolution. As a result, it was easy to miss small hot spots on stacks. Figure 5 shows a typical stack infrared image, where anchors weld points are barely visible on the top portion of the stack.

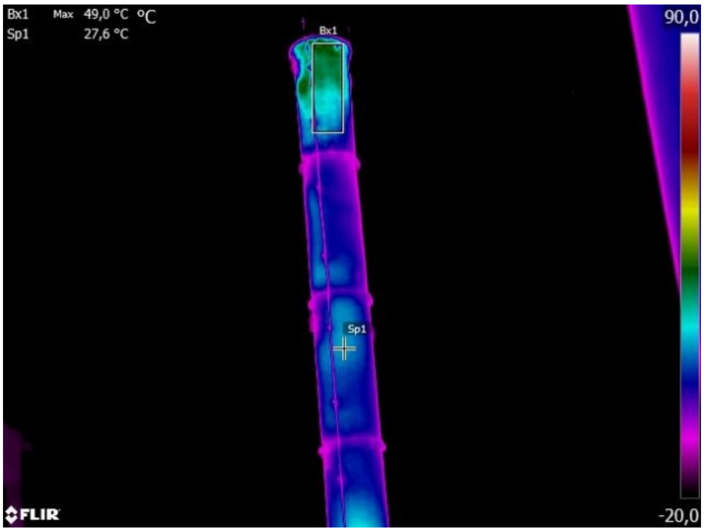

Figure 5. Typical stack infrared image [4].

When it came to personnel entering the stack for inspection or repairs, the risk of falling refractory and slag was managed through engineered controls. Unfortunately, these controls were found to be fallible. Up until about ten years ago, scaffolding and layers of 25 mm plywood were used to create a temporary protective roof over workers at the base of a stack. This method was believed to be sufficient, until falling pieces of refractory pierced through all layers of plywood during a shutdown in Laterrière. Thankfully, the incident occurred while workers were on break, resulting in no injuries.

Following this event, a large high-pressure lifting air bag was utilized instead to seal off the stack. However, its effectiveness relied on inflation pressure, requiring constant monitoring. Additionally, one worker was still exposed to falling debris until the air bag was fully inflated. Due to the inability to prove the airbag method safe, all work in stacks ended up being prohibited in 2023 until the cleanliness and structural integrity of the refractory could be guaranteed.

3.3 Steam Explosions Following Dry-Out

Monitoring the presence of liquid water and steam beneath furnaces at the end of the dry-out process has long been part of standard operational practices at Rio Tinto. Furnaces were not loaded if excessive amounts of water were detected, however the definition of “excessive” was open to interpretation. In situations where there was clearly too much water still coming out of weep holes, there was limited ability to expedite the process. Occasionally, fully tilting the furnace helped move trapped water towards warmer regions, but this was not always effective. Slightly increasing the holding temperature could also help, although there were limits on how high it could be raised. In essence, there was no effective method to accelerate the process or to predict when the water flow would cease.

4. Experimentation for Improvement: Work Description

Innovations in all three sub-fields were made in the same manner: each one was first trialled in a specific shutdown, evaluated, then improved and replicated in subsequent shutdowns.

4.1 Work on Demolition Machinery

Small scale trials with remote-controlled demolition machinery were initially conducted in 2020. These trials were carried out in collaboration with a local contractor who owned two small units from the Swedish manufacturer Brokk. They were first used to tear out hard-to-reach furnace components, such as lower wall sections located behind ramps. Figure 6 depicts a small unit in operation within a furnace:

Figure 6. One of the first trials with a small Brokk unit in 2020 (author's image).

Once these trials proved successful, the author initiated discussions with potential business partners in order to find larger robots that could efficiently replace conventional machinery. The first full-scale trial took place in Alma in early 2021. During this trial, two 115-tonne furnaces were completely stripped of their refractory lining using only demolition robots. Given the size of these furnaces, much larger machines were required; Brokk 400 units were utilized for both demolition and debris removal tasks. The difference in unit size can be seen in Figure 7.

Figure 7. Brokk 400 at work in a 115-tonne furnace (author's image).

While results of this first full-scale trial will be discussed in the next section, it is worth mentioning at this stage that demolition robots immediately replaced conventional machinery after this trial.

4.2 Work on Stack Refractory Maintenance and Inspection

In order to reduce the usage of man-baskets for stack inspections, drones were first trialled in April 2022. The drones used were large commercial quadcopters, modified and operated by Torngats, a Quebec-based company specialized in non-destructive testing and remote 3D scanning. The drones were equipped with high-resolution cameras, thermal cameras and 3D scanners. Initially, the drones were used only to inspect the exterior of stacks, but they were soon also utilized to visually inspect the refractory inside. In the latter case, the drone does not actually enter the stack; instead, it lands on top of the chimney and lowers a 3D camera and lights inside, using a motorized winch.

Figure 8. Drone operations at Rio Tinto's Grande-Baie smelter in 2022 (author's image).

These inspection methods have been used in every major shutdown since 2022 and are still under development, as discussed in Section 6.

4.3 Work on Steam Explosions Following Dry-Out

The first step in reducing the amount of water dripping out of furnaces after the completion of dry-out was to identify where it could accumulate. Observations revealed that some furnaces required additional weep holes below sidewalls, as water tended to pool in these areas. Additionally, it appeared that fibrous materials used for the insulation of sidewalls could act as "sponges", as areas insulated with this type of product often released water or steam well after other parts of the furnace.

In 2021, the author conducted a quick experiment to investigate this further. The conditions to which fibrous insulation is exposed during dry-out were recreated in a simplified manner. A 160 × 60 × 25 mm piece of insulating board (Superwool© Plus made by Morgan Advanced Materials) weighing 100 g was immersed in water at 50 °C for 30 minutes, weighed again, then placed in an oven at 120 °C. The sample was taken out of the oven and weighed at regular intervals for over five hours, to see how long it would take to return to its initial weight. As shown in Figure 9, this type of refractory material can hold a significant amount of water for a long time. Due to the low thermal conductivity of 0.6 W/m·K of the material at this temperature [3], a considerable amount of time is needed to evaporate all the water it can absorb, even when heated from all sides. This indicated that in a furnace, such materials could indeed act as "sponges" and release their water content only when heated for an extended period.

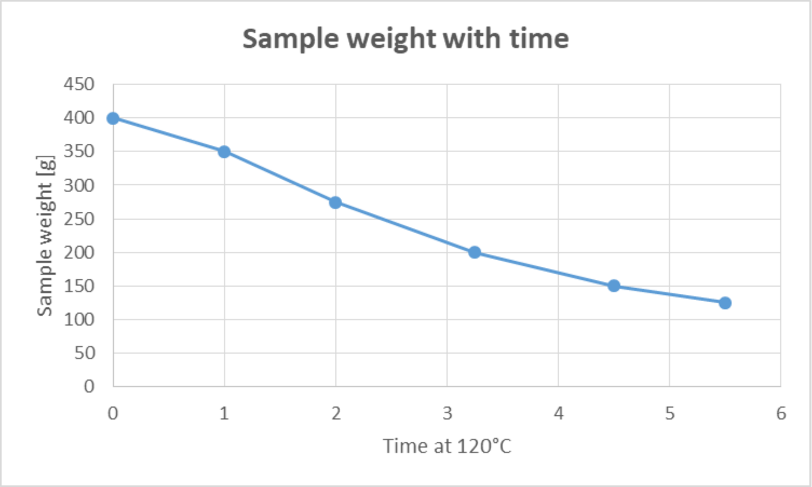

Figure 9. Insulating material weight decrease during heat soak at 120 °C, after 30 minutes immersion in water.

Unfortunately, in casting furnaces fibrous insulating materials are also often used as thermal expansion zones to compensate for volume changes in other refractories. Eliminating them would require a complete redesign of most linings, so alternative solutions were sought. When discussing the issue with a contractor specialized in furnace dry-outs, the possibility of using a vacuum pump to suck out moisture was mentioned. This company also specializes in heat treatment and they had adapted a vacuum pump (originally designed for maple syrup production) to draw in hot, moist air and condense the water it contained for another industrial application. They thought it might work with weep holes on a casting furnace, but were unsure if the air flow through these holes would prove too much for the pump, both in terms of quantity and temperature. If it worked, steam would be removed much faster from the furnace and most importantly, it might prevent it from condensing and getting trapped in cold furnace regions. A full-scale trial was conducted with a prototype in 2022: the pump was connected to over 100 weep holes on a 115-tonne furnace and left running for the duration of the dry-out. Another identical furnace was being dried-out at the same time, but without the vacuum system. The prototype hose network and manifold setup are shown in Figure 10. While technical challenges were encountered, results were promising as discussed below in the next section. The system has since been greatly enhanced and is now used in every furnace shutdown where substantial refractory work is undertaken.

Figure 10. Vacuum hoses and manifolds used during the full-scale trial (author's image).

5. Results and Discussion

5.1 Demolition Machinery

The main safety risk posed by traditional excavation machinery during furnace tear-out was contact between the machine and the required spotter, as they had to work in unacceptably proximity. The introduction of remote-controlled robots has greatly reduced this risk, as a worker no longer must position himself in the "line of fire" to guide the driver. Since Brokk robots are operated with a wireless remote, the machine's operator can stand far away from the "line of fire". However, the crushing risk has not been fully eliminated for two reasons: the first is that in certain circumstances, the Brokk operator must still stand close to the machine in order to get a good field of view. This means the operator could be struck or crushed by the robot, should they make a mistake with the controls or if there were a malfunction. This type of situation is shown in Figure 11.

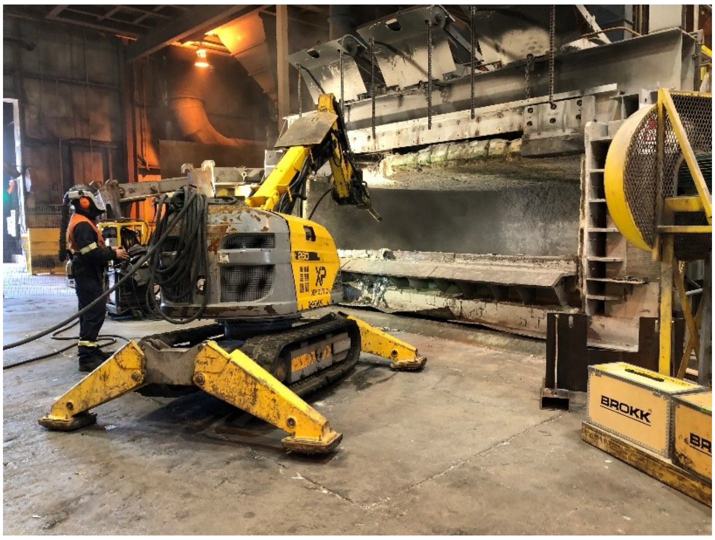

Figure 11. Operator standing close to a Brokk robot (author's image).

The second reason is the coactivity in the work zone. Other workers often need to enter the work zone during tear-out, specifically to remove full debris bins. Demolition robots can move faster than conventional machinery and the operator is often hidden by the machine, which prevents visual contact with other workers. Therefore, it is important to maintain a wide exclusion zone for pedestrians around these remote-controlled machines and use a spotter when moving them in and out of the work zone.

These machines also provided other benefits in safety and production. By significantly reducing the time required to tear-out furnace linings, they decreased the exposure of nearby workers to dust and excessive noise levels. Benchmark demolition times for 90-t tilting furnaces went from 36 hours in 2020 with a backhoe to 16 hours in 2021 with Brokk robots. As a result, overall shutdown durations were reduced, allowing for increases in production.

5.2 Stack Refractory Maintenance and Inspection

Man-baskets and cranes were often used in the past to visually inspect stacks. Lifting personnel with cranes is a risky operation, especially when conducted inside a stack. The introduction of drones has eliminated the need for man-baskets for most types of inspection; only ultrasound steel thickness measurements are still carried out with a crane (although trials are ongoing to do this with drones). The level of precision and the quality of pictures obtained are far better than in the past, enabling the detection of smaller anomalies. This improvement is easily seen when comparing. For infrared images, this improvement is evident when comparing Figure 5 with Figure 12.

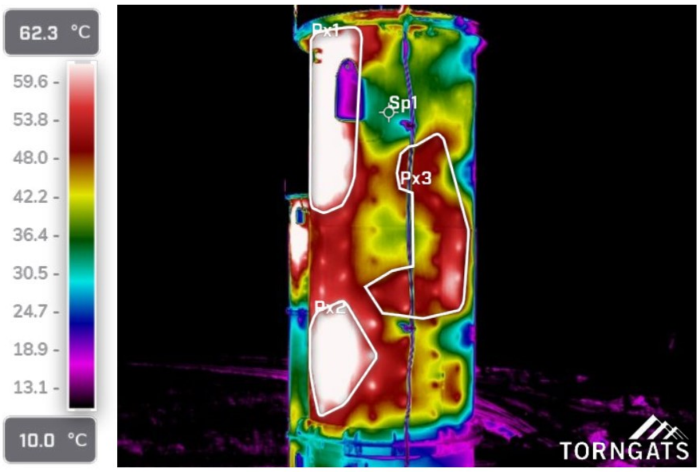

Figure 12. Infrared image taken by drone [6].

The high-resolution images and immersive videos of the refractory inside stacks enables the assessment of their condition without needing to send personnel inside using a man-basket. They are now an essential component of the new procedure to enter stacks: a full inspection is first performed using drones and if no major anomalies are found, industrial climbing specialists rappel down inside the stack to clean it and remove any loose material creating a risk. Once this procedure is complete, workers can safely enter the base of the stack for refractory repairs.

Other unexpected benefits for asset integrity risk evaluation have emerged with the usage of drones. They can easily identify damage to lighting protection devices (such as ground straps or lightning rods) that previously went unnoticed for long periods. Additionally, if equipped with the necessary equipment, drones can accurately measure the verticality of stacks in minutes. This parameter is essential for proper guy-wire tension adjustment and structural integrity.

5.3 Steam Explosion Following Dry-Out

The first full-scale trial of the vacuum system immediately revealed the potential of this technique. The "control" furnace dried out without the vacuum pump experienced water dripping out of weep holes beyond nominal dry-out duration, while the furnace under vacuum did not. Since 2022, no furnace where the vacuum pump was used has experienced dry-out prolongations due to the presence of liquid water.

Not only was moisture sucked out of furnaces in much greater quantities and more reliably than expected, but it was also quickly realized that by measuring the amount of water being drained out of the pump's tank every hour, monitoring of the flow rate of moisture could be done almost in real-time. As shown in Figure 13, when plotted against time and temperature it enables a new type of dry-out analysis.

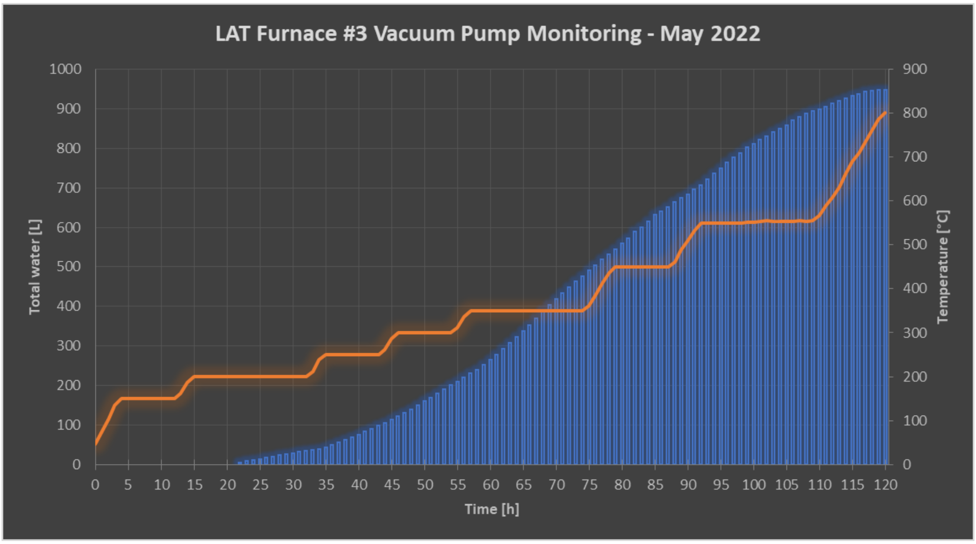

Figure 13. Plot of water output against time and temperature for Laterrière furnace #3 in May 2022.

As shown above, in this case the water output rate decreased once the temperature exceeded 700 °C and almost stopped at 800 °C. This suggests there is little moisture remaining in the refractory lining and the furnace can be safely charged. Figure 13 also highlights a problem that plagued the vacuum system during the first year of usage: the temperature trend does not extend beyond 800 °C and 120 hours, even though the furnace was maintained at that temperature for another 12 hours. This is because some components overheated at higher temperatures, causing them to melt or collapse on themselves, disabling the system. Several design iterations were required before the pump and hoses could be function for the entire dry-out.

Unfortunately, water output from the pump cannot yet be used as a precise "go/no-go" criterion for safe furnace charging. On larger furnaces (exceeding 100 tonnes) with very thick linings (> 500 mm of total thickness), pump output tends to be more variable. While it does drop significantly during the final 800 °C hold, it seldom plateaus as neatly as shown on the chart above. In such cases, no liquid water is usually observed when the vacuum lines are disconnected, which serves as a qualitative indicator that the furnace can be safely charged. However, a quantitative indicator would be more reliable, and work is ongoing to achieve this with pump output.

6. Conclusions and further work

Since 2019, Rio Tinto has successfully implemented new methods and tools to reduce risks associated with refractory maintenance in casting furnaces. Some improvements were achieved using off-the-shelf technology adapted to the needs of aluminium casthouses, while others required. These successes were made possible through partnerships with highly specialized and competent contractors. The introduction of demolition robots has resulted in a decrease in hand injuries among refractory workers. Drones have minimized personnel exposure to height-related risks and falling objects, while vacuum pumps have reduced the likelihood of steam explosions during furnace start-up.

Despite these reductions in risk, further work is needed to fully harness the potential of these new tools. For instance, tasks currently performed from a man-basket suspended from a crane could potentially be carried out by a drone if the technology allowed. As for the vacuum pump system, additional cooling enhancements are required to use the system for extended periods above 800 °C. Twin pumps for simultaneous dry-outs are also considered, as the current use of a single large pump prevents output analysis as the water coming out from both furnaces ends up in a single tank.

Further work is also required to reduce the environmental impact related to the disposition of spent furnace refractory materials. Rio Tinto currently recycles in-house a portion of the refractory waste generated by the maintenance of casting furnaces, thanks to its unique spent pot lining (SPL) treatment plant. However, this plant cannot accept refractories with imbedded metallic components, such as anchors or stainless steel fibres; these refractories must be landfilled. New technologies are required to facilitate the sorting of refractories containing metallic components, as well as to extract these components from recyclable materials.

7. Acknowledgements

The authors would like to express their heartfelt gratitude to the personnel at Rio Tinto and the external partners involved in implementing these new technologies in our casthouses. Their unwavering support, collaboration and innovative mindset have been crucial in developing these new tools for refractory maintenance. This progress would not have been possible without the commitment and expertise brought to the table by these stakeholders.

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