

Hearth Temperature Control at USS Blast Furnace No. 14

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INTRODUCTION

Blast Furnace No. 14 (BF14) is the largest blast furnace at U. S. Steel Corporation. The current hearth design was implemented in 2010 and features a micropore carbon block construction with graphite installed in the taphole area between the cold face of the micropore carbon and the steel shell. The hearth is well instrumented with over 500 thermocouples installed. Hearth wall thermocouples are positioned at 4, 12 and 20 inches from the carbon block cold face. The BF14 hearth construction and hearth thermocouple placement can be seen in Figures 1 and 2. Further details on the BF 14 design and operation are available from the AIST Blast Furnace Round-up.¹

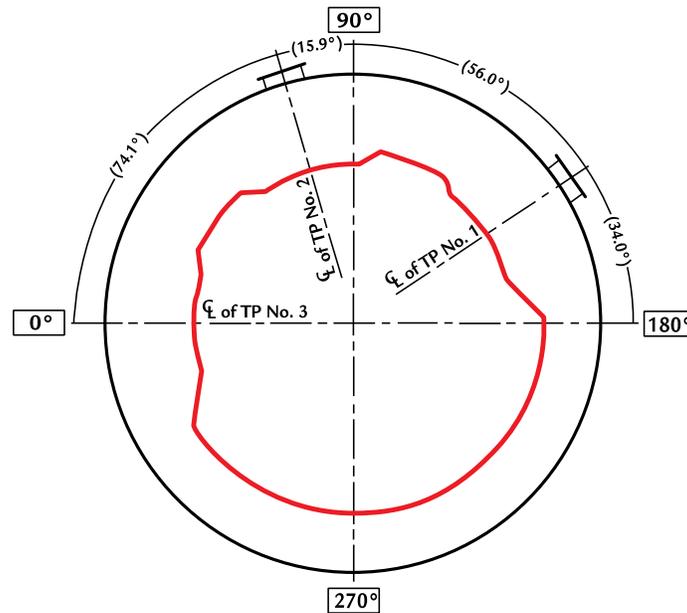


Figure 1. Blast Furnace 14 taphole location and hearth wall profile

In 2016, six years after the hearth was installed, BF14 experienced rapid hearth wall temperature increases under all three tapholes. The HW3 20-inch thermocouples immediately below the graphite layer at each taphole began to exhibit temperatures >1425 °F. At this alarm temperature, immediate planned stops are required to protect the BF14 hearth wall per U. S. Steel hearth protection procedures.

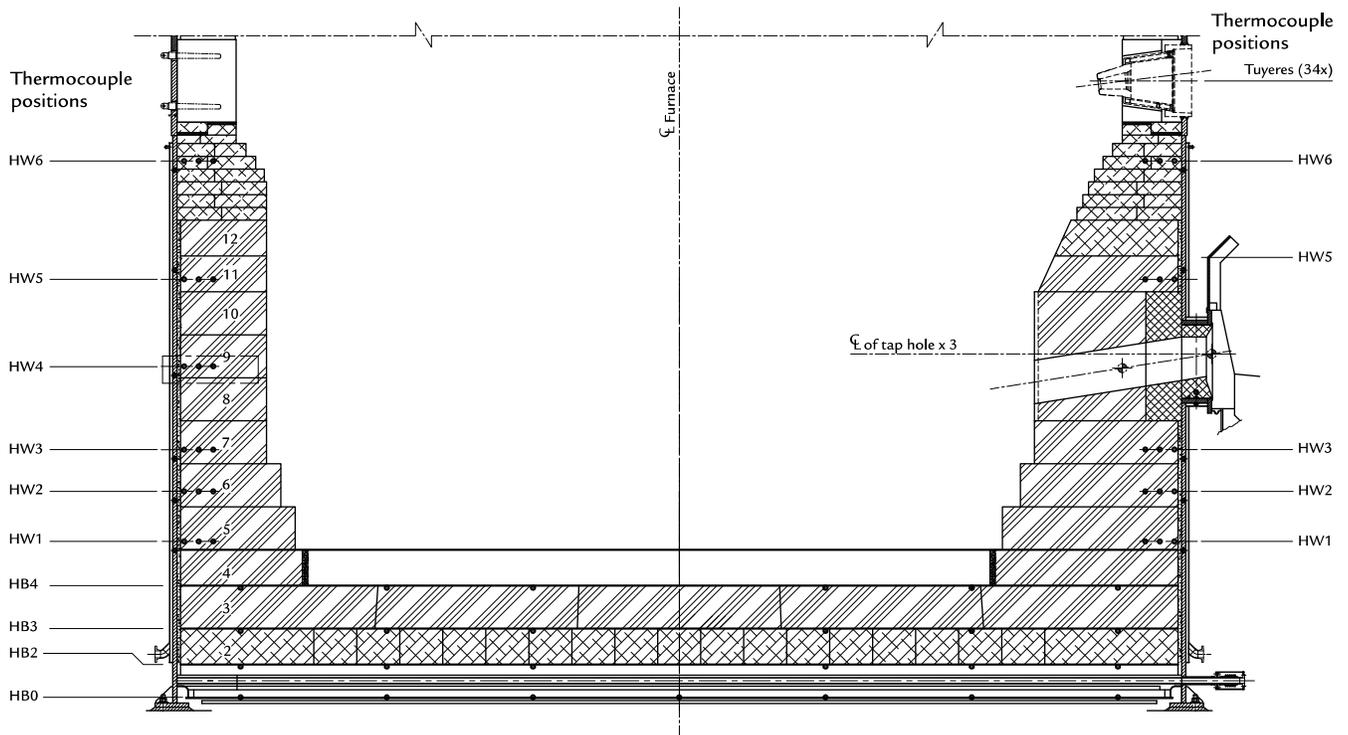


Figure 2. Blast Furnace 14 hearth refractory arrangement and thermocouple locations; section through taphole 3

In February 2017, U. S. Steel and Hatch embarked on an exhaustive root cause analysis of the hearth cooling system, force balance assessment and a process parameters review using big data advanced analytics. Various countermeasures were developed and implemented including actions to promote floating of the deadman, improved leak detection methods, innovative temperature visualization techniques, and ilmenite point charging. Hearth temperature control improved, refractory temperatures moderated, and production was increased as the countermeasures were deployed and refined. Details of the approaches used, and results achieved are described.

HEARTH TEMPERATURE MANAGEMENT STRATEGIES

As documented by S. Street at al., blast furnace operators will adopt concurrent strategies to lower hearth refractory temperatures and protect the hearth – Street named this ‘polytherapy’.² At BF14, several initiatives were started in 2017 including:

- Hearth wear and heat transfer analysis
- Refractory temperature visualization
- Casting practice improvements
- Deadman positioning and fuel strategies
- Increased tuyere velocity
- Rapid water leak detection
- Improved hot metal temperature control
- Coke quality review
- Ilmenite point charging

As these practices were applied, refractory temperatures moderated and by early 2018, hearth temperature related stops and production cut-backs were virtually eliminated. Details are provided in the subsequent sections.

Hearth Design, Wear and Heat Transfer Analysis

The BF14 hearth diameter/sump depth is on a critical line identified by Voegelpoth, Still and Peters where the deadman is floating or resting, see Figure 3.³

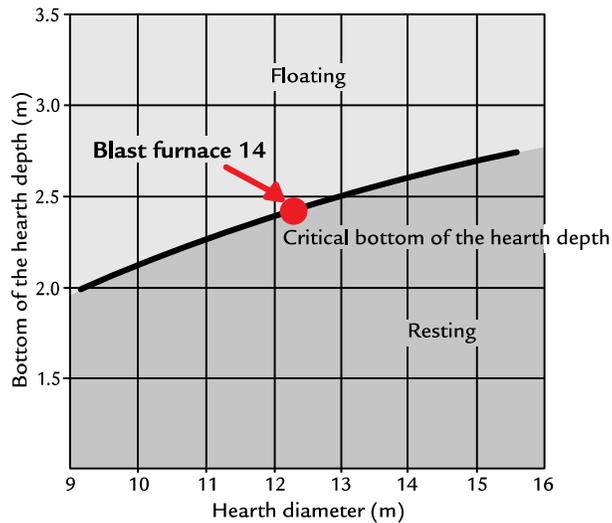


Figure 3. The Blast Furnace No. 14 hearth sump depth is on the critical line between a floating and resting deadman³

Wear of the BF14 hearth bottom increases the opportunity for the deadman to partially or completely float if other conditions warrant. Skull build-up on the refractory walls can decrease the effective hearth diameter which will also promote the deadman to float. In early 2017, detailed heat transfer analysis characterized the BF14 refractory wear and skull topography. Most but not all the ceramic pad was worn away. Bottom wear was estimated at each taphole, and local sumps were identified where the ceramic pad was lost. A large skull was estimated on the hearth wall opposite the tapholes as well as less bottom wear, Figure 4.

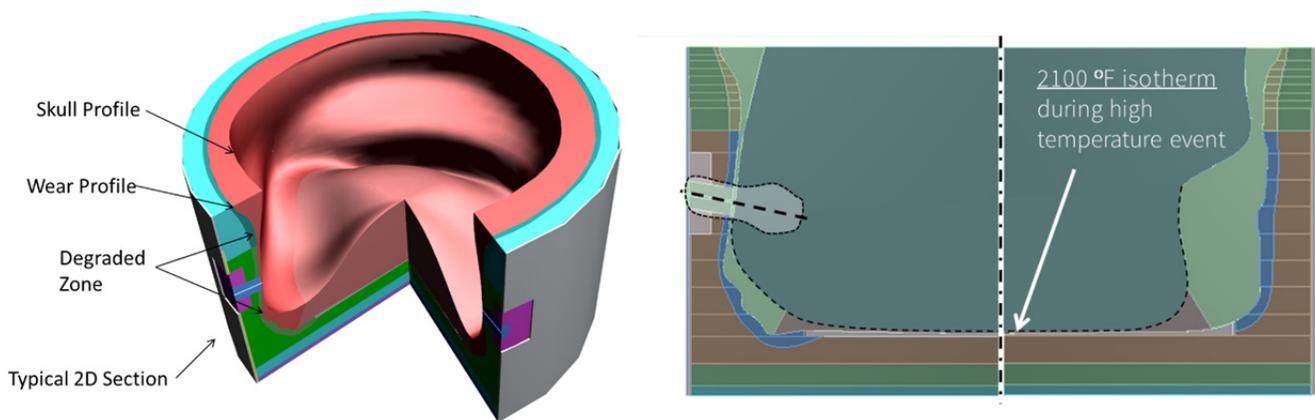


Figure 4. Hearth wear, skull position and hearth topography of BF14 in early 2017 based on heat transfer analysis. Section view on the right is from Taphole 2 to the opposite wall

With the BF14 hearth dimensions being on or near the critical transition between deadman resting and floating, floating of the deadman was challenging. Bottom temperature spikes indicated deadman floating events, but these events were not sustainable, Figure 5. The progressively increasing peaks in bottom temperature spikes shown in Figure 5 were considered a sign that the hearth ceramic pad was wearing. The distance from the flowing hot metal to the hearth bottom thermocouples located under the ceramic pad was decreasing, hence greater temperature spiking was observed. The deadman position was unpredictable and challenging to control. Actions were taken to better understand these trends and ultimately manage the deadman position.

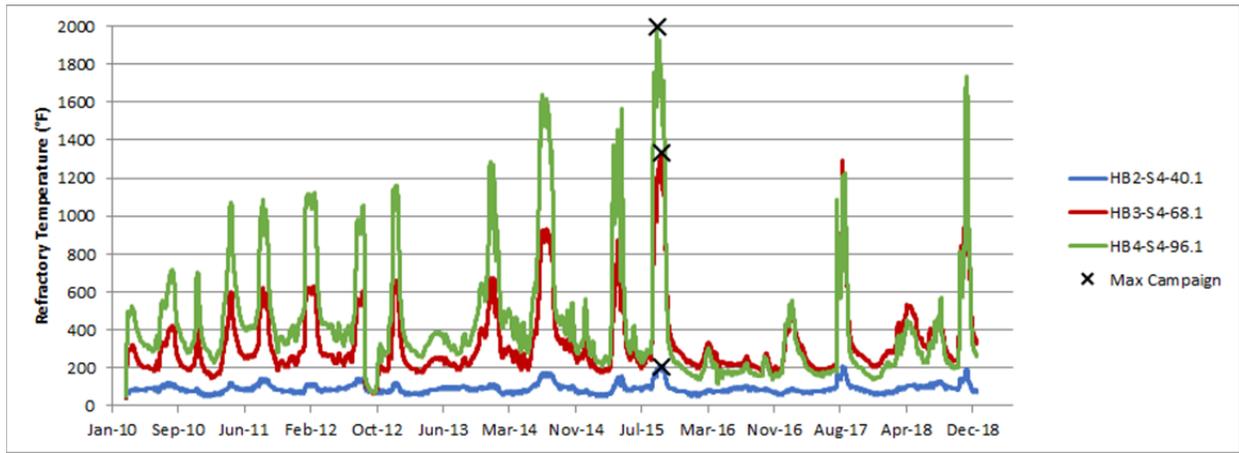
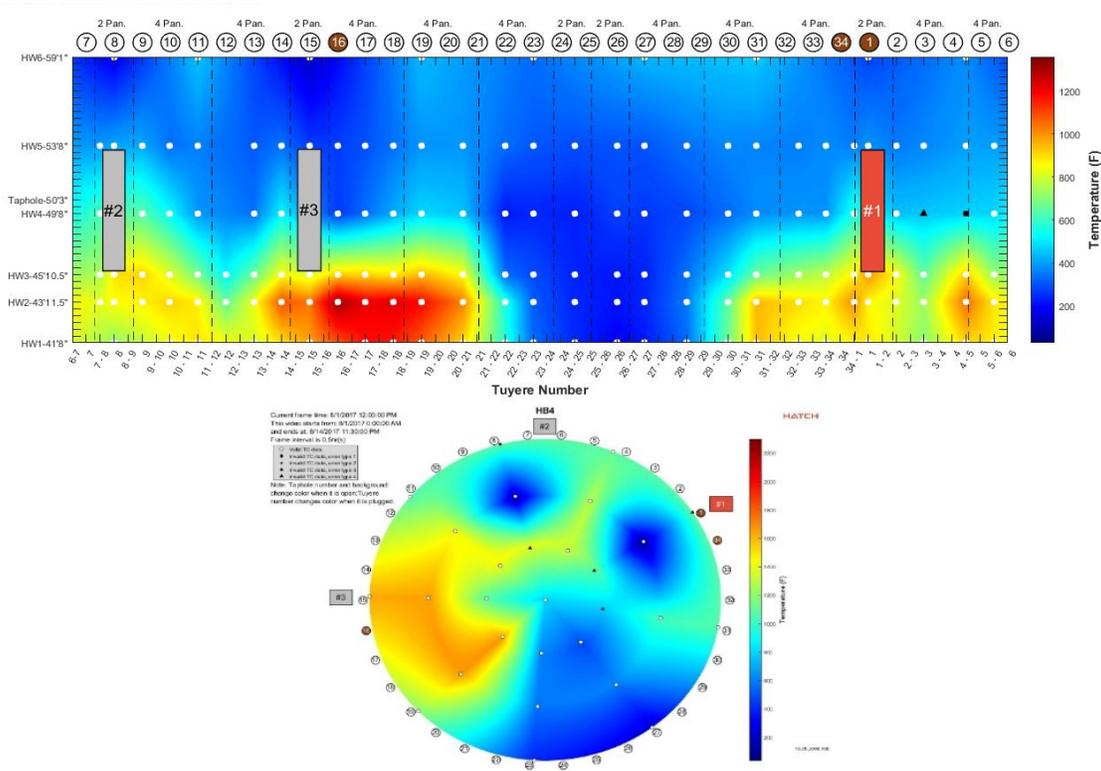


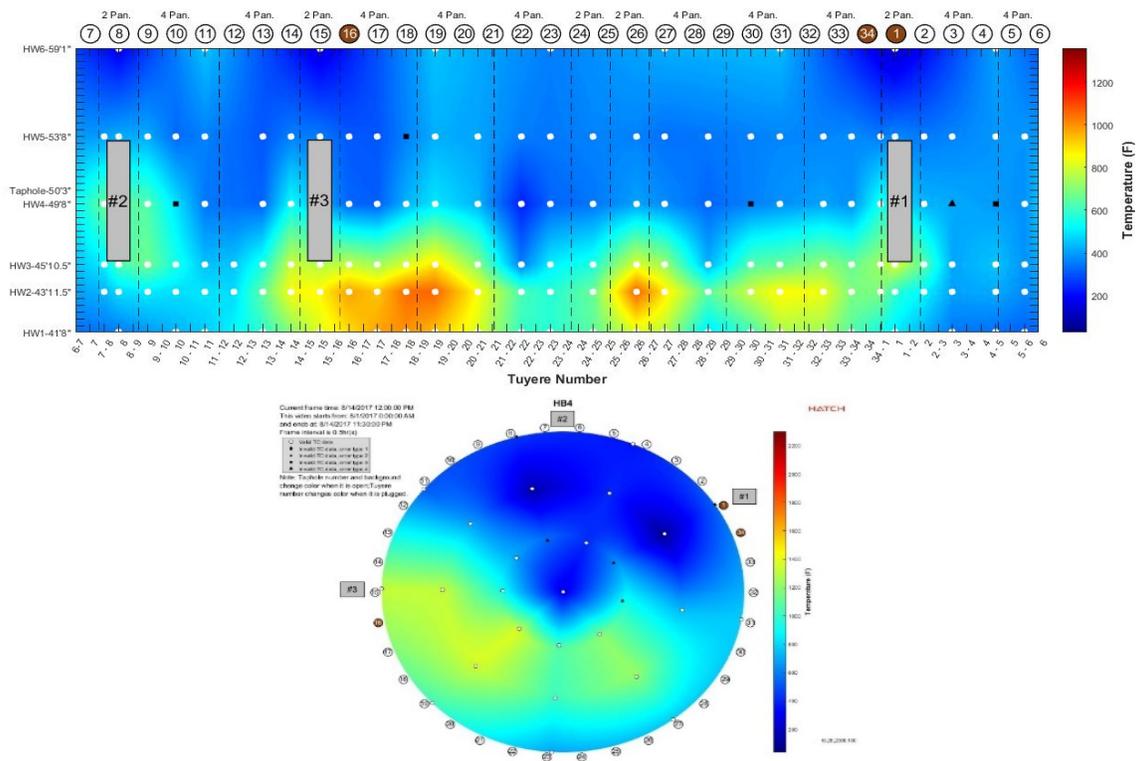
Figure 5. Spiking of the selected BF14 hearth bottom thermocouples from 2010 to 2018. These were identified as deadman floating events

Temperature Visualization

To better understand the interrelationship between hearth wall and bottom temperatures, detailed temperature maps and 'hearth temperature movies' were created by interpolating between measuring points. This allowed long term temperature trends to be reviewed in a few minutes. Casting events and plugged tuyeres were added to the movies to allow observation of temperature changes with casting and tuyere practice. Frames from selected movies may be seen in Figure 6 during a period in August 2017 when local elevated temperatures were evident at taphole 3 (TH3).



(a) Hearth refractory temperatures on 2017-08-01 during a period with elevated temperature by TH3.



(b) Hearth refractory temperatures on 2017-08-14 showing higher bottom temperatures away from the tapholes.

Figure 6. Hearth wall and bottom temperature maps showing tuyeres and taphole locations. Screenshots from August 2017 review

The hearth movies helped the team recognize and understand a range of refractory temperature conditions and identify parameters that maintained lower refractory temperatures under the tapholes. Later, an Excel based program was implemented to generate the daily temperatures profiles. The Excel program can take a snapshot at a point in time or compare temperature changes between two periods. This was useful to assess the merits of ilmenite charging as we will see later in the paper.

Casting Practice Improvements

In early 2017, the casting practice was a two-taphole operation with a short gap between casts. In mid-2017, a focussed effort was made to implement a fully dry hearth practice with a short casting overlap to reduce the velocity of liquids flowing in the hearth. Due to concerns over the BF14 force balance and general deadman cleanliness, coal (PCI) injection was halted in December 2017 in favor of higher rates of natural gas injection. Slag drainage improved significantly in 2018 as illustrated by a more consistent slag granulating rate, Figure 7.

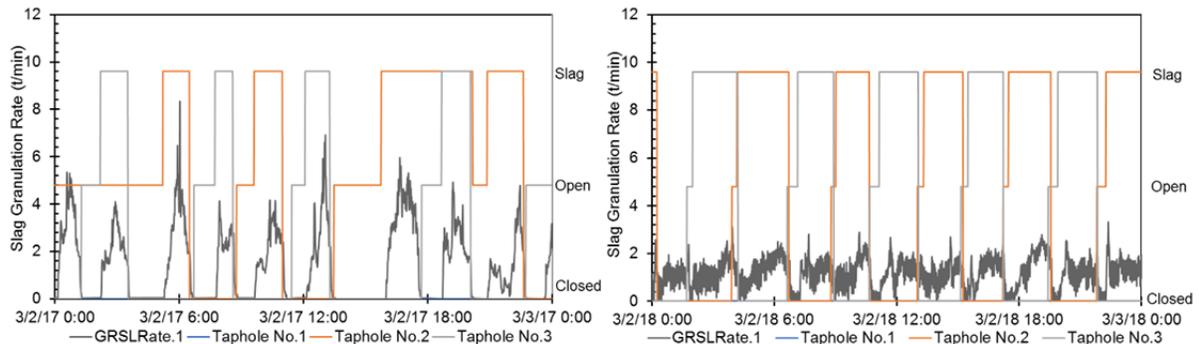


Figure 7. Comparison of the typical casting performance in March 2-3, 2017 (left) and in March 2-3, 2018 (right). Note the more consistent slag granulation rates as hearth permeability improved

Casthouse improvement efforts led to a significant improvement in the slag casting time, expressed as the percentage of the cast where slag was flowing. Slag came much earlier, and slag surges were significantly reduced a further indicator of improved hearth permeability, Figure 8.

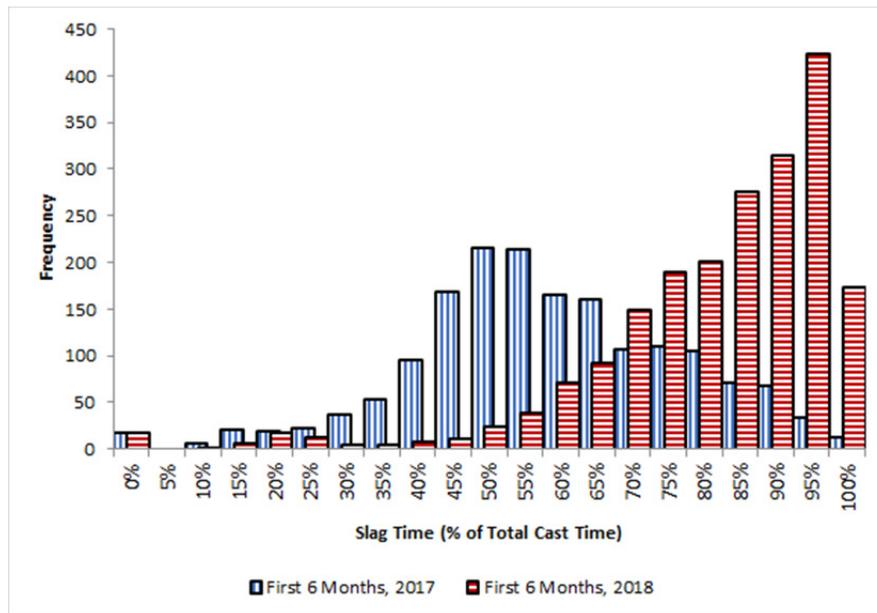


Figure 8. Slag casting time (% of cast with slag flowing) comparing the first 6 months of 2017 and 2018. The slag flow ratio improved with changes to the casting practice and other actions to improve hearth permeability

Deadman Positioning and Hearth Permeability

The deadman position can greatly influence hearth drainage and refractory temperatures. To better understand the loads imposed on the deadman, a force balance model was developed, Figure 9.

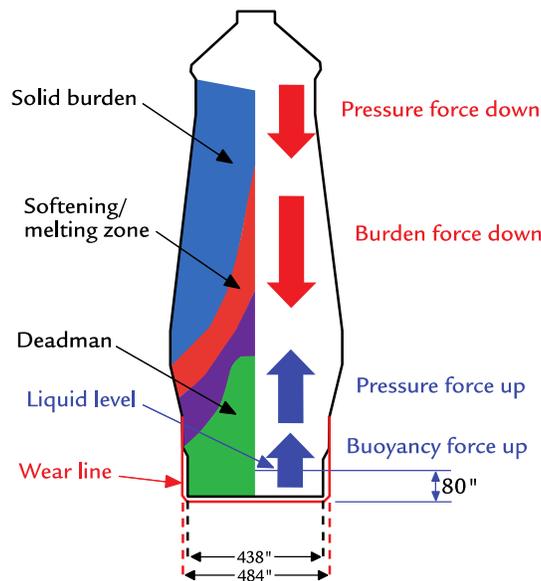


Figure 9. Force balance model developed for Blast Furnace No. 14

Using the force balance model, various scenarios were studied comparing past operating conditions and to assess counter-measures that could lessen the downward forces on the deadman.

Calculations were completed for the following scenarios:

- All-coke operation
- Natural gas at 160 lbs/nthm
- PCI at 180 lbs/nthm and NG at 40 lbs/nthm
- Lowering the stockline by 2 feet
- Lowering the top pressure by 1 psi

Changing the fuel injection practice to natural gas or an all-coke operation reduced the downward force on the deadman to the greatest extent. Reducing stockline and top pressure were considered to facilitate PCI injection and a low coke rate. The analysis confirmed that even with these changes, the downward forces on the deadman were greater than a natural gas injection practice offered.

In December 2017, BF14 switched to natural gas injection as a countermeasure to lift the deadman and increase the amount of transverse versus peripheral flow of hot metal in the hearth. The objective of this change was to increase hearth bottom temperatures and reduce hearth wall temperatures. Hearth bottom temperatures increased moderately but hearth wall temperatures remained high. While these efforts to lift the deadman were helpful, they did not immediately eliminate the high hearth wall temperature events. Production stops were still needed to build a sustainable hearth skull under the three tapholes.

Rapid Water Leak Detection

Water leakage can compromise the protective skull on the hearth wall, and in extreme cases oxidize the carbon refractory. Using a focused data mining exercise, Hatch and U.S. Steel developed a soft sensor to rapidly identify water leakage from the tuyere nose cooling circuits. The soft sensor was extremely reliable and improved the response time to tuyere leaks. Details are provided in a separate paper presented at AISTech 2019.⁴

Tuyere Velocity

Increased tuyere velocity was implemented to improve deadman permeability. Baoshan had reported that greater blast energy produced a higher hearth bottom temperature, a sign of improved hearth permeability.⁵ In 2018, the BF14 tuyere velocity was increased from about 690 to 740 feet per second (fps) on two occasions, Figure 10.

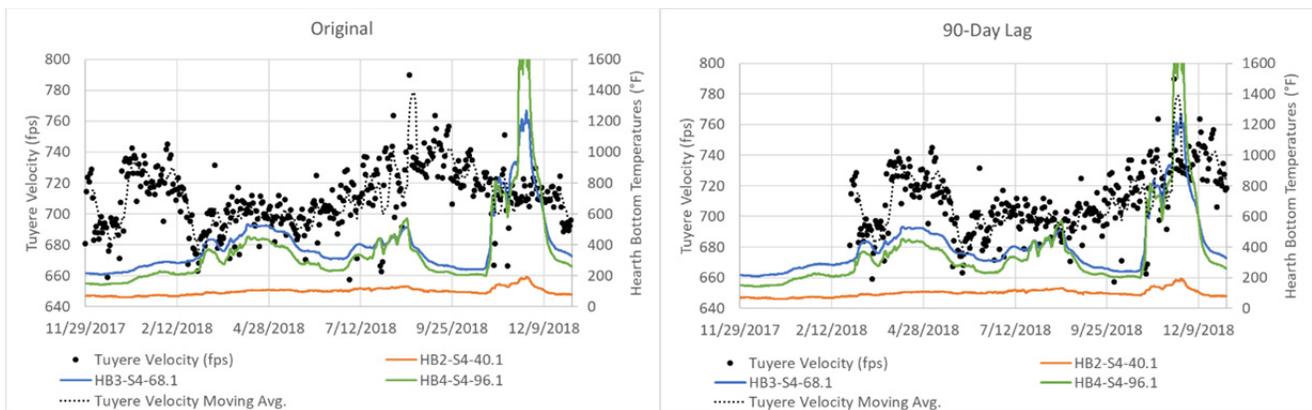


Figure 10. Tuyere velocity compared with selected hearth bottom thermocouples. The correlation to rising bottom temperatures improved when the tuyere velocity was lagged by 90-days

Baoshan reported a time lag of 17-days when comparing the change in blast energy to hearth bottom temperatures. For BF14, a longer lag of 90-days was needed to align tuyere velocity with increases in bottom temperature. Increased tuyere velocity appeared to help increase bottom refractory temperatures, but the response time was slow. A higher tuyere velocity, >720 fps, may be part of a future operating strategy to maintain elevated hearth bottom temperatures.

From September to October 2018, tuyere velocity was reduced to 700-720 feet per second as a countermeasure to worn/leaking copper staves in the lower stack.

Coke Quality

While a variety of factors can impact the deadman, coke quality is a leading factor associated with deadman fouling. Defining the appropriate coke quality for a specific blast furnace and related operating practice can be challenging, especially related to hearth wall and bottom temperature impacts. Coke quality charged to BF14 on a railcar-by-railcar basis was collected for an

extended period and compared to the observed hearth bottom temperatures. Using principle component analysis, the coke strength after reaction (CSR) best correlated to the hearth bottom temperatures using a 17-day lag. During the 9-month review period in 2018, CSR varied from 60.5 to 69.2. Hearth bottom temperatures appeared to decrease when the CSR was <64 for a sustained period and increase when CSR>64, also for a sustained period, Figure 11.

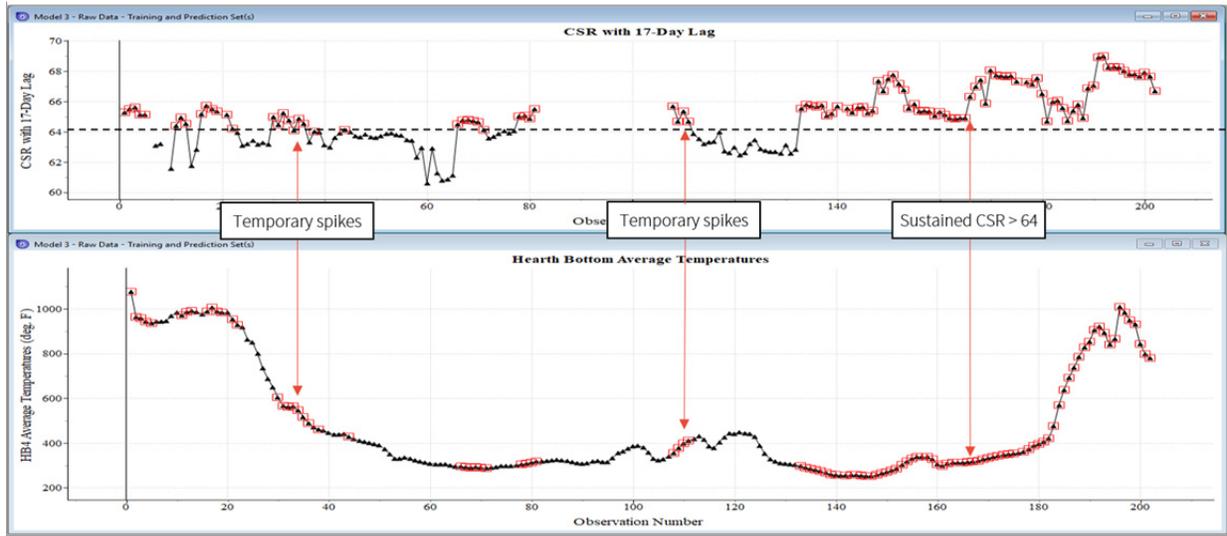


Figure 11. Comparison of the Coke Strength after Reaction (CSR) with a 17-day lag to the BF14 hearth bottom refractory temperature. Daily data from April to October 2018

The trends in the hearth bottom temperatures also coincided with the tuyere velocity changes cited in Figure 10. Additional analysis is planned to better understand the impact of coke quality and specifically CSR on the BF14 hearth refractory temperatures. The response of the hearth bottom temperatures to changes in coke CSR and tuyere velocity is slow, making it challenging to impact hearth temperatures over a brief period.

Improved Hot Metal Temperature Control

A modified thermal control model was implemented to reduce hot metal temperature variations. Control of hot metal temperature was selected over hot metal silicon content as hot metal temperature data was more readily available. The aim was to reduce the contribution of elevated hot metal temperature to hearth wall refractory heating. The natural gas injection rate was adjusted based on the instantaneous production rate calculated from the top gas analysis and hot metal chemistry rather than charged production rate. Statistical process control methods were used to better assess the hot metal temperature trends and subsequent natural gas injection rate changes needed to meet the target temperature. During October 2018, the first full month using the modified model, hot metal temperature range and aim decreased as the model tightened the control based on a moving control target, Figure 12.

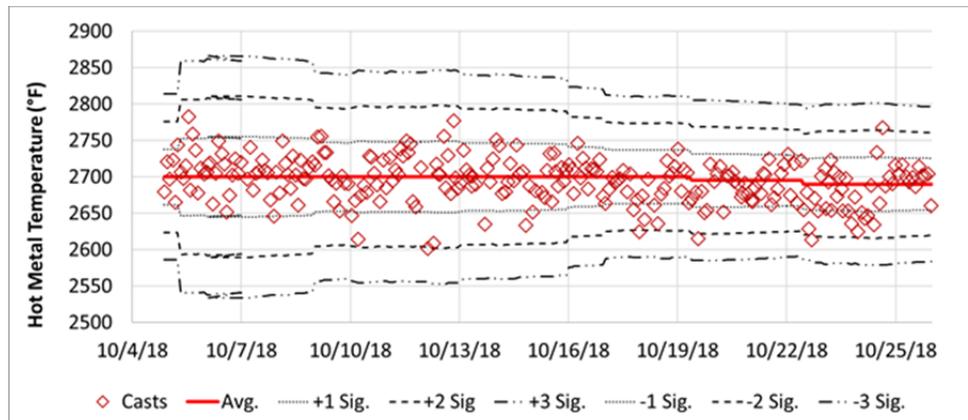


Figure 12. Improved hot metal temperature control during October 2018, the first full month using the modified thermal control model

The modified thermal control model showed promise to reduce hot metal temperature variations. Additional development work is planned for 2019 to build on the early successes using the instantaneous production rate and further refine the natural gas fueling practice.

Ilmenite Point Charging

The use of titanium bearing minerals is a well-known strategy to reduce hearth refractory temperatures. Bulk additions and individual tuyere injection are used by many blast furnace ironmakers when faced with high hearth wall refractory temperatures.^{2, 3, 5, 6} Conceptually, the titanium in the hot metal forms Ti (C, N) particles that precipitate and then deposit onto the refractory wall. The success of employing ilmenite is tied closely with the concentration of Ti in the hot metal. A concentration of >0.07% Ti in hot metal is necessary to achieve sufficient precipitation of Ti (C, N) particles. This criterion makes using ilmenite as a standard burden material challenging. A high dosage rate would be required to ensure that a sufficiently high Ti concentration is achieved throughout the entire area of the hearth. The granulated slag TiO₂ concentration would exceed the 0.75-1.0% TiO₂ limit set by the cement industry clients.

AK Steel, Dearborn, developed a point charging practice where the bell-less top is used to charge ilmenite above specific locations where high hearth wall temperatures are evident.² In principle, point charging provides a concentrated ilmenite dose over a small area that is experiencing elevated temperatures. In late 2017, the BF14 bell-less top was programmed to point charge ilmenite. Point charging trials started on January 1, 2018 to alleviate the high hearth temperatures experienced below the tapholes. Three ilmenite point charges per day were implemented, with each charge being 10,000-15,000 lbs, depending on the hot metal production target. The point charging rate considered the slag TiO₂ limit of 0.75% daily. The location of the ilmenite point charging was adjusted to target the hearth thermocouples that were experiencing elevated refractory temperature readings.

In Figure 13, the accuracy of the ilmenite point charging practice is illustrated.

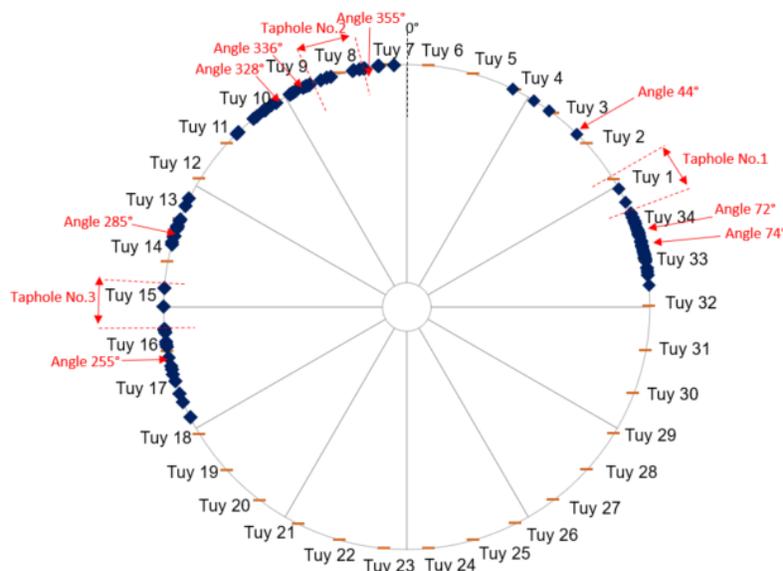


Figure 13. Ilmenite point charging experience

Point charges were within +/- 10° of target angle, an excellent result. For reference, the inter-tuyere spacing is 10.5°. Point charges could be reliably achieved between tuyeres to avoid depositing the ilmenite directly over a tuyere where the material could interact with the blast air and be pushed away from the wall. Early experience showed that point charging reduced high hearth wall temperatures. Additions made over Taphole 3, for a 4-week period provided immediate relief and sustained lower refractory temperatures as production increased, Figure 14.

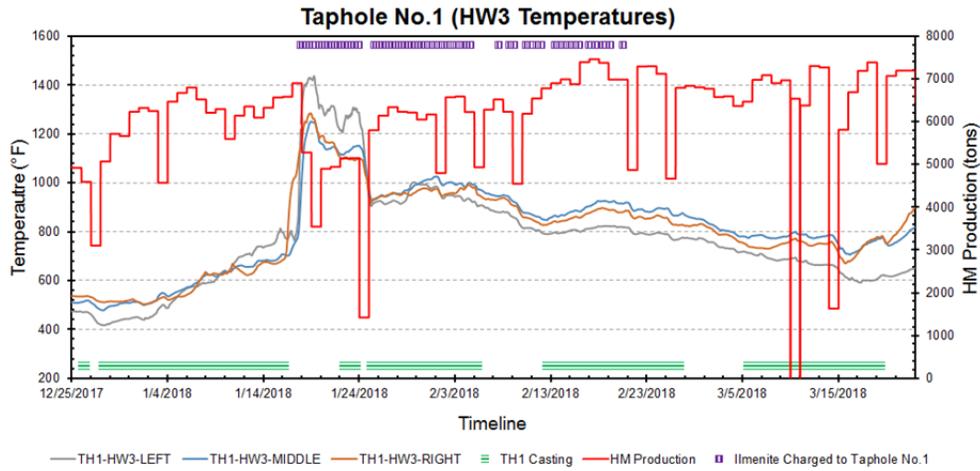


Figure 14. Impact of ilmenite point charging over Taphole 3 on the hearth wall 3 refractory temperatures

Plots comparing the hearth wall temperatures between periods were developed to assess the effectiveness of the point charging practice. In Figure 15, the differential refractory temperature between two periods are compared before and after point charging was implemented over TH1. This provided more evidence that the point charging had a desirable local effect. A similar change was observed at the other tapholes.

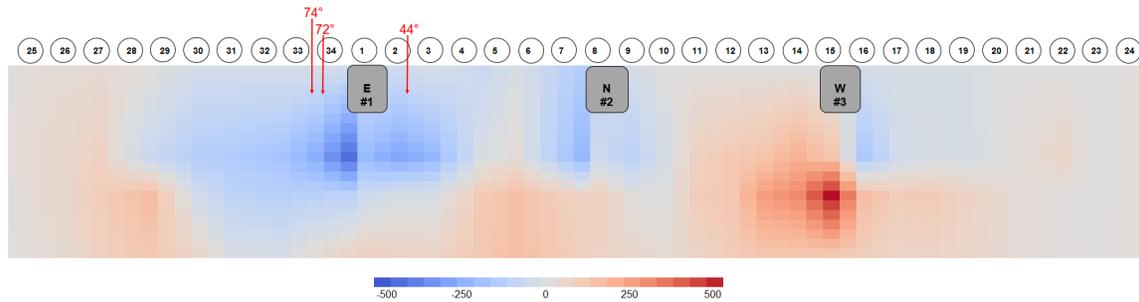
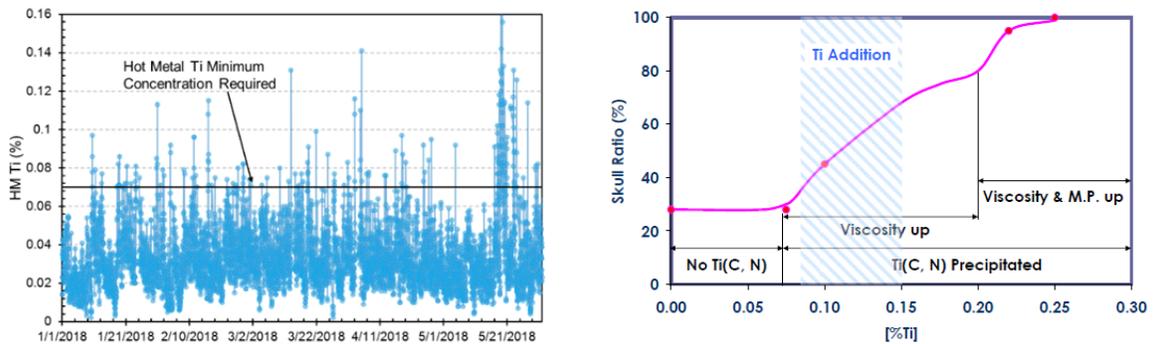


Figure 15. Change in hearth wall refractory temperature comparing January 18-20, 2018 to February 26-28, 2018 with point charging over Taphole 1 at angles 44°, 72° and 74°

The point charging practice resulted in spikes in the hot metal titanium concentration. Individual torpedo car analysis had titanium concentration $>0.07\%$ Ti needed for Ti (C, N) precipitation. Due to the nature of point charging, the local concentration of Ti may have been greater than that measured in individual torpedo cars. The individual torpedo car assays and the %Ti in hot metal needed for precipitation may be compared in Figure 16.⁶



(a) Hot metal Ti content for Blast Furnace No. 14 on an individual torpedo ladle basis.

(b) Target hot metal Ti content to create a process skull per Y. F. Zhou.⁶

Figure 16. Comparison of BF14 hot metal titanium content when ilmenite was point charged to concentrations needed to precipitate Ti (C, N) particles

IMPROVED REFRACTORY TEMPERATURE CONTROL

In 2018, the HW3 temperatures were all maintained below 1400 °F. The HW3 temperatures were maintained between 600-1000 °F for sustained periods, Figure 17.

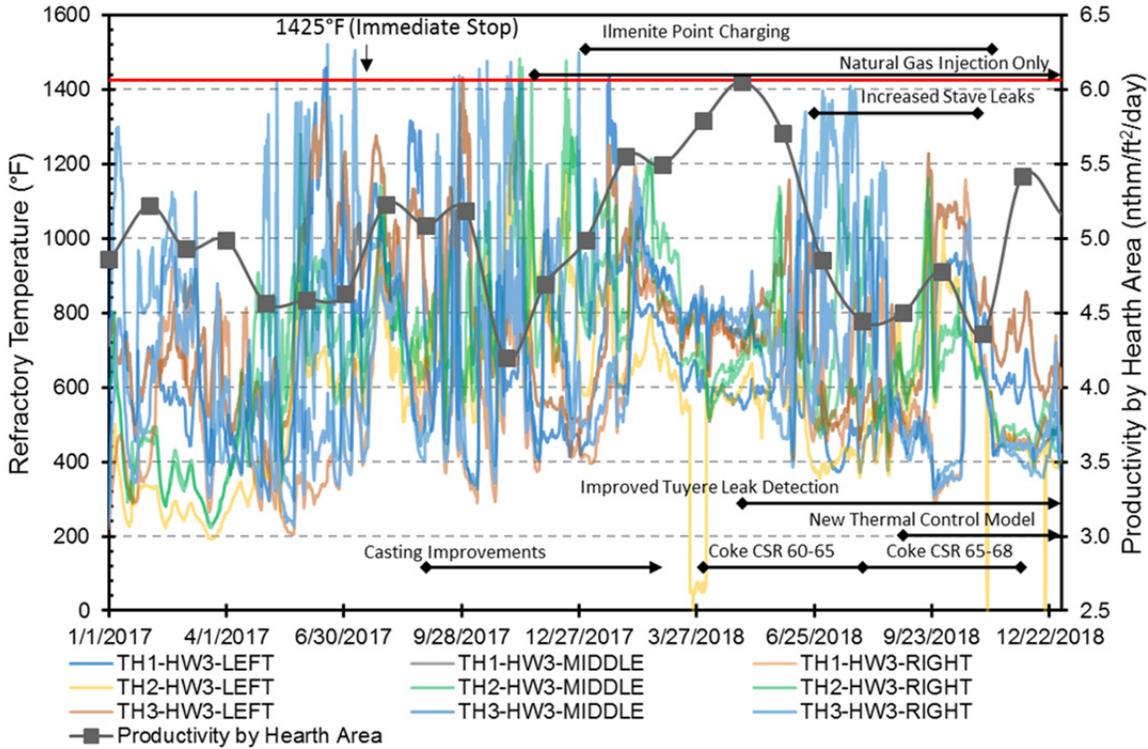


Figure 17. HW3 temperature trends to the end of 2018. Temperatures decreased as various countermeasures were implemented. (Note: BF14 hearth is 38 feet, 6 inches in diameter)

The rate of hearth wall temperature increases for HW3 and HW2 located below the tapholes greatly reduced comparing 2018 to 2017. Active refractory thermocouples, >800 °F would climb at about 1-2 °F per hour in 2018 compared to 2-8 °F per hour in 2017, Figure 18.

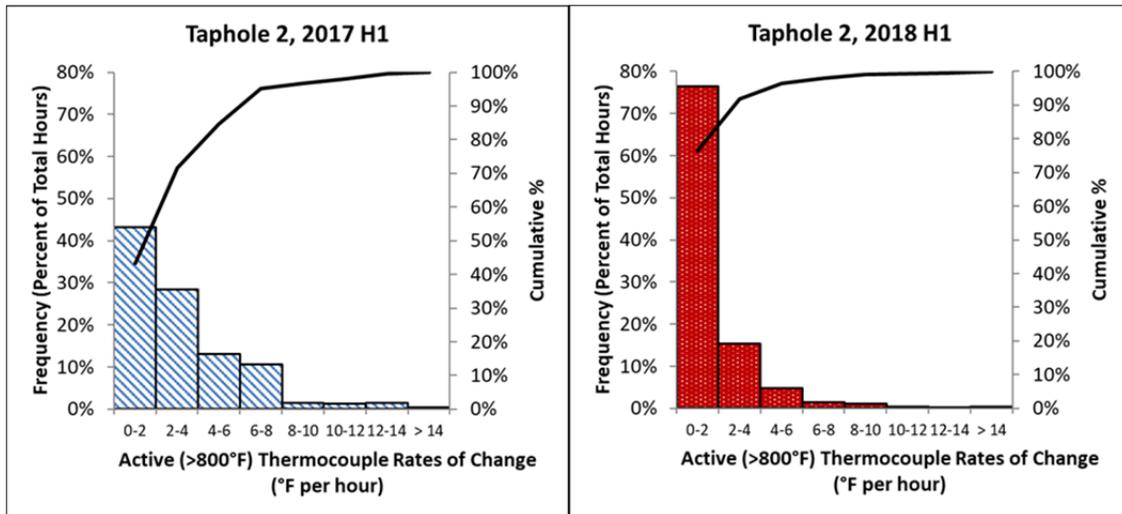


Figure 18. Comparing HW2 and HW3 hearth wall refractory temperature rates of change under the taphole 2 for high-activity events (TCs > 800°F) comparing the first 6-months (H1) of 2017 and 2018.

Similar trends were observed on tapholes 1 and 3

Hearth wall refractory temperatures were reduced, and rapid temperature increases/spikes dampened due to:

- Reduced local hot metal velocity and heat load under the tapholes because of i) casting improvements that minimize liquid accumulation and high slag tapping rates, and ii) less downward force on the deadman by using natural gas injection and a higher coke rate.
- Deposition of a local Ti (C, N) bearing skull with lower thermal conductivity than a hot metal skull over the vulnerable thermocouple positions under each taphole. The process skull appeared to be more insulating than a simple hot metal skull.

SUMMARY

Using a focussed and systematic approach, improved control of the Blast Furnace 14 hearth wall temperatures was accomplished. Production stops in response to high hearth wall temperature alarms were virtually eliminated in 2018. Close control of the deadman position, improved hearth drainage and reduced local heat load in the critical taphole zones contributed to the lower hearth wall temperatures. Ilmenite point charging reduced peak refractory temperatures under the tapholes without compromising hot metal and granulated slag qualities. Detailed process data and heat transfer analysis, coupled with advanced visualization and data interpretation were key to understand trends and the impact of countermeasures employed. Team work under challenging conditions was paramount to managing the hearth temperatures while meeting the Blast Furnace 14 production requirements.

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