Conference Paper

Use of Non-distractive Testing AU-E Technology to Evaluate Hearth Conditions at CherMK–SEVERSTAL

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Abstract

Intensive operation of blast furnace allows increase in production of hot metal and profitability of Iron & Steel Works. However, blast furnace life could be sacrificed if no measures are taken to protect refractory lining and to build stable accretion. CherMK and Hatch developed a systematic approach to monitor conditions of BF hearth lining using Acousto Ultrasonic-Echo (AU-E) non-destructive testing developed by Hatch. Multiple testing of blast furnaces revealed problematic areas with accelerated refractory deterioration and minimal thickness, formation of elephant foot, extent of accretion and speed of refractory wear, cracks and other anomalies. Improvement in coke quality, periodical staves washing, the addition of titania, grouting, etc., were recommended and implemented to prolong furnace life while maintaining the intensity of furnace operation.

Keywords: blast furnace inspection and monitoring, non-destructive testing (NDT), refractory deterioration, blast furnace campaign

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1. Introduction

Intensive operation of a blast furnace (BF) allows for an increase in production of hot metal and profitability of iron and steel operations. However, intensive operation can compromise blast furnace structural integrity if no measures are taken to protect refractory lining and to build stable accretion. This article outlines how Non-Destructive Testing (NDT) was used at CherMK blast furnaces to monitor and reduce refractory wear in the hearth while maintaining intensive operation.

Cherepovets Metallurgical Combine - Severstal (CherMK) is a Russian Iron & Steel giant, producing 12.5 million ton of steel annually. The plant has 4 operational blast furnaces: their design and operating parameters are presented in Table 1. All furnaces operate with in-plant sinter and pellets from Kostamuksha pellet plant, which also belongs to Severstal Group, charged in different proportions to each blast furnace.

Table 1 shows that CherMK blast furnaces operate with comparatively high total iron in fluxed metallic burden, with values in the range of 59.93–61.21% (highest total iron in metallic burden of Russian Blast Furnaces). Additionally, the furnaces operate with high levels of oxygen enrichment (26.84–31.39%), moderate rates of coke and supplemental fuels, and blast temperatures above 1,150 °C. As a consequence of high total iron, the furnaces have comparatively low slag volume in the range of 232 to 288 kg/thm. The smelting process is quite intensive with specific productivity ranging from 2.77 thm/m^3/day for the largest in Russia and Europe BF #5 and 3.54 thm/m^3/day for BF #1.

Table 1: Design and Operating parameters of CherMK's blast furnaces*.

Parameter	BF 1	BF 2	BF 4	BF 5
Last major reline, year	2,017	2,010	2,005	2,006
Furnace useful volume, m^3	1,007	1,033	2,700	5,500
Furnace working volume, m3	865	913.5	2,466	4,648
Hearth diameter, m	7.65	7.65	11	15.1
Metallic burden Fe_{total} (fluxed), %	60.04/59.6	59.93/59.72	60.38/59.83	61.21/61.26
Coke rate (dry), kg/thm	406.0/420.4	412.6/426.5	404.6/407.3	402.5/385.8
Natural gas rate, Nm^3/thm,	142/132	144/140	100/106	117/111
Oxygen enrichment, % in blast	31.39	31.29	26.84	30.15
Blast temperature, °C	1,156 /1,141	1,164/1,149	1,220/1,211	1,172/1,195
Average daily production, thm/day	3,062/2,952	2,925/2,954	6,881/6.940	12,871,12,884
Specific productivity, thm/m^3/day (WV)	3.54/3.41	3.202/3.23	2.895/2.92	2.77/2.772
Specific productivity, thm/m^2/day (hearth Ø)	66.65/64.26	63.67/64.31	72.44/73.06	71.91/71.982
Slag rate, kg/thm	283/288	288/291	279/293	232/229
*Numerator = 2015 data; denominator = 2017 data.				

Blast furnace #4 is the oldest in service with its campaign reaching 13 years. Blast furnace #1 was relined last year and the service life of blast furnaces ## 2 and 5 is 6 and 10 years, respectively, after last major reline. Blast furnaces ## 1, 2 and 5 have complete cast iron cooling system. BF #4 hearth is equipped is cooled with cast iron staves while copper plates are used for the cooling of the low stack area. The bottom of the blast furnaces ## 1 and 2 hearth is lined with domestic carbon blocks, while blast furnaces #4 and #5 use imported carbon blocks. Walls of the hearths of all furnaces are lined with high alumina mullite -corundum blocks and blast furnace grade fire clay bricks. Intensive operation of blast furnaces requires careful monitoring of refractory lining conditions in the furnace hearth. This monitoring allows for the application of timely preventive measures to retard premature refractory wear and to create a stable protective accretion on the walls of the hearth, preventing chemical and thermal attack by hot metal.

Blast furnaces ##4 and 5 are equipped with embedded thermocouple and have thermal models to estimate the remaining lining profile (thickness of refractory plus accretion). However, over time many thermocouples have been damaged, leaving none or sometimes only one thermocouple in the given area. Blast furnaces #1 and 2 are without any thermocouples. This lack of information makes the estimation of refractory wear and accretion extent difficult.

In 2003 CherMK first time employed the AU-E non-distractive technique for estimation of remaining refractory thickness for blast furnace ##2 and #5. Results of measurements prompted shutdown of blast furnace #2 for hearth capital repair. After furnace cooling refractory lining was photographed and remaining refractory lining thickens was reconstructed based on these images and compared to AU-E results. These comparisons revealed a similar trend in estimation of cracks position in carbon blocks (Figure 1).

In 2013 CherMK decided to engage Hatch for non-destructive testing of CherMK blast furnaces using Hatch's patented Acousto Ultrasonic – Echo (AU-E) technology [1] initially for blast furnace #1 and starting from 2015 for all 4 blast furnaces. Results of each inspection are thoroughly discussed with plant management and operators, and subsequent measures were implemented to retard or stop further refractory deterioration and to prolong blast furnace campaign lives.

2. AU-E Method of Non-destructive Refractory Testing

AU-E is a stress wave propagation technique that uses time and frequency data analysis to determine refractory thickness, and detect anomalies such as cracks, gaps or metal penetration within the refractory lining. The principles of AU-E technique are illustrated in Figure 2. During the measurement, a mechanical impact on the surface of the structure (via a mechanical impactor) generates a stress pulse, which propagates into the refractory layers. The wave is partially reflected by the change in material

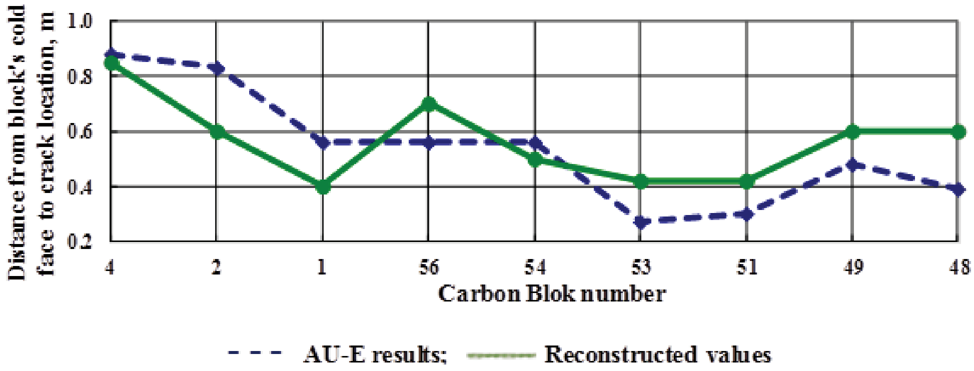

Figure 1: Comparison of AU-E results with reconstructed location of cracks (BF#2, 2003).

properties of each layer of the refractory lining, but it also propagates through the solid refractory layers all the way up to a brick/brick or brick/gas or brick/molten metal interface. The compressive waves (or *P*-waves) are received by a receiver and the signals are analyzed for refractory quality and thickness assessment.

The main details of the AU-E method are presented in this article. A more detailed description of the AU-E method is presented in several other articles [2–4].

The field data collected in the time domain is extremely complex, containing numerous frequencies and multiple reflections, diffractions, and refractions from body and surface waves. Converted to the frequency domain, the results are much better defined. A lower reflection frequency corresponds to a greater distance to the signal reflection interface. The distinct peaks in signal amplitude correspond with the boundaries between liquid metal and accretion, accretion and refractory and the locations of anomalies (crack, oxidized carbon, etc.) Therefore, position of the first distinct amplitude at lowest frequency is associated with boundary between accretion and hot metal, the second distinct amplitude at higher frequency characterizes boundary between accretion and refractory blocks/bricks and the third distinct amplitude at the highest frequency would show the position of a crack or anomaly.

The thickness of the layer of material for the AU-E technique is estimated by the following governing equation:

$$T = (\alpha\beta V_p)/2f_p, \tag{1}$$

where *T* is the thickness or depth of the reflecting surface; fp is the *P*-wave frequency; Vp is the propagation speed of *P*-wave in the material; α is the temperature correction factor; β is the shape factor.

The shape factor β, accounts for the reduction in velocity due to various furnace shapes, such as cylindrical or rectangular. For blast furnaces where lateral dimensions are at least six times the thickness of the lining, the β factor is 0.96. The thermal correction factor, α is the ratio of refractory Young's modulus of elasticity under service conditions (Ex) to the modulus of elasticity at room temperature (Eo): α = Ex/Eo. In most cases it is assumed that the Young's modulus of elasticity of the refractory changes linearly between the hot and cold face as a function of temperature.

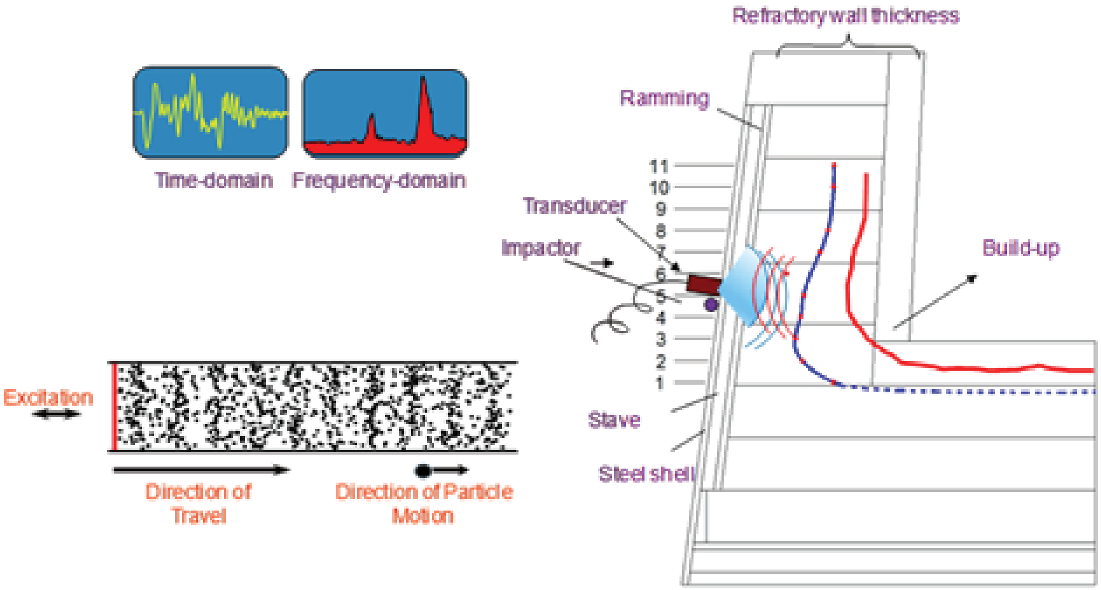

Figure 2: Illustration of AU-E method.

For a multilayered section such as a furnace hearth, the thickness of the final refractory layer (Tn) is calculated based on the following equation:

$$T_n = \frac{(V_p)_n \, \alpha_n \beta_n}{2} \left[\frac{1}{f} - \sum_{i=1}^{n-1} \frac{2\,T_i}{(V_P)_i \, \alpha_i \beta_i} \right], \tag{2}$$

where n – refers to specific layer of the hearth lining; f is the resonance frequency for the thickness of the nth layer; i – refers to initial and known thickness of layer of refractory.

Prior to the collection of field data, the apparent *P*-wave speed of each brick layer is determined by calibrating representative brick samples at room temperature. The wave speed calibration measurements must be carried out on all the materials that the wave propagates through. The α factor can either be calculated experimentally, by heating brick samples and measuring the wave speeds at the desired temperatures, or it can be calculated by the particular brick's elastic and thermal properties. The β factor can be calculated upon measuring the dimensions of the testing area.

If sample bricks are not available (e.g., in the case of CherMK) Hatch uses the information on properties of similar brick received from vendor catalogues or measured during previous projects to estimate apparent *P*-wave speed. This approximation brings some uncertainties into the accuracy of refractory thickness estimation which is an integral part of the overall measurement error of 4–7%. The estimation of the thickness of accretion is less accurate (error is about 15%), since the properties of accretion are seldom known and can vary substantially.

3. Examples of Measurements

The first round (after 2003) of remaining refractory thickness measurements at CherMK was performed in February 2013 for BF #1. Follow-up measurements of the furnace were performed every subsequent year. This furnace was selected as the most aggressively operating furnace at blast furnace shop and previous problems with sparks in heat loads.

Typical AU-E results for blast furnace #1 are presented in Figure 3 for four vertical cross-sections. The results correspond to the last inspection in July 2015 in comparison with AU-E measurements in September 2014.

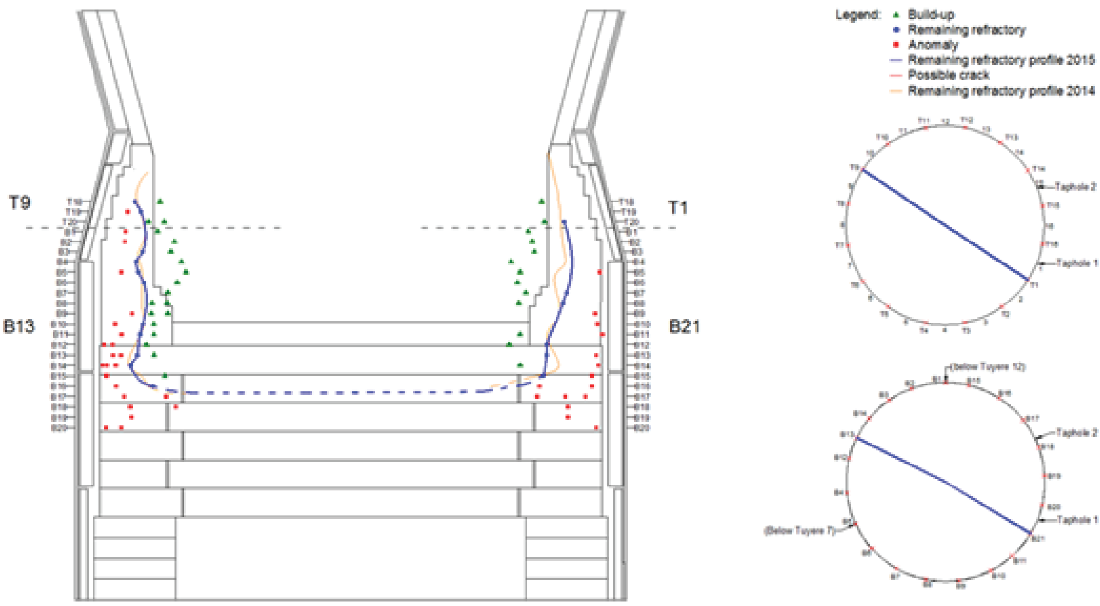

Figure 3: Results of AU-E testing of the hearth and tuyere region of BF #1.

The test results showed significant increase of wear of the walls of the low hearth over time and the formation of the 'elephant foot'. Formation of 'elephant foot' in the blast furnace sump can be attributed to the conditions of the 'dead man' which forms the flow of the metal in the low hearth region. The 'dead man' should be floating and permeable for the hot metal to avoid excessive high velocity peripheral flow of the hot metal and erosion of refractory lining. Shallow sump of blast furnace #1 does not create good floating conditions for the 'dead man'. In this case the quality of coke becomes even more critical.

Results of Figure 3 and other measurements for BF #1 lead to the following conclusions:

i. The ceramic layer and the first carbon slab layer of the hearth bottom were worn. The second bottom slab layer was partially worn.

ii. The average remaining refractory was 768 mm in July 2015, with the original average refractory thickness of 1170 mm. This was equivalent to a remaining refractory thickness of 58%. There was a 2% reduction in remaining thickness since July 2014.

iii. The minimum remaining refractory thickness detected was 280 mm or 27% of original thickness of 1035 mm.

iv. There was uneven wear in the hearth's walls with more intensive wear at left side of taphole 1 and also opposite side to this taphole. An average of 695 mm (49% of the average original remaining refractory) was detected in these areas.

v. Aligned anomalies located within the remaining refractory are likely connected (i.e., a single lengthy crack measured at more than one location) possibly forming the type of cylindrical anomaly (or crack). If any molten metal penetrates through the gaps/cracks, or any movement at the crack may cause the front of the block to fully separate along the crack. This sudden event can cause thermal spikes. These regions should be thermally monitored to identify the thermal spikes.

vi. On average, the remaining refractory thickness was greater than 30% of the original build and had not yet reached the absolute acceptable minimum of 200–250 mm.

vii. Stable accretion was formed on the hearth walls protecting it from further intensive deterioration.

viii. The average remaining refractory thickness at tuyere level was 552 mm, about 65% of the original average thickness of 843 mm.

ix. All the sections of tuyere level showed thickness of partially worn. The minimum remaining refractory detected was 290 mm. The original average refractory thickness was 843 mm.

Blast furnace #2 was tested first time in July 2015. Results of AU-E measurements for blast furnace #2 are very similar to those for blast furnace #1. However, this furnace is in better conditions with minimum refractory thickness of 640 mm and 380 mm. for furnace heart and tuyere regions, respectively.

A sample of AU-E results for BF #4 tested in July 2015 are presented in Figure 4.

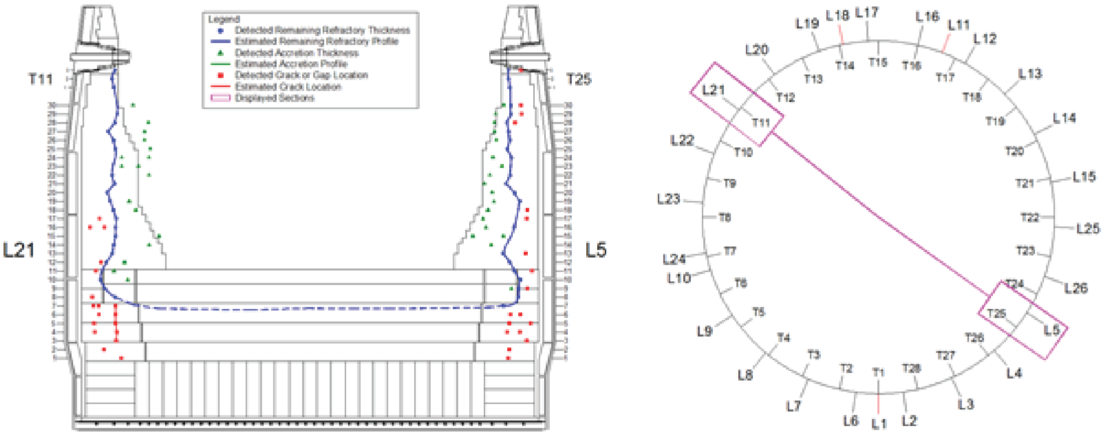

Figure 4: Results of AU-E testing of the hearth of BF #4 (July 2015).

Analysis of AU-E results for BF #4 leads to the following conclusions:

i. The first and second layers of the furnace hearth slabs were worn out. Wear had started at the third layer of the hearth slab.

ii. There were possible aligned cracks within the refractory at elevations below the third layer hearth slab.

iii. The overall average remaining refractory thickness was 860 mm, about 52% of the original average thickness of 1664 mm.

iv. The minimum detected remaining refractory thickness was 380 mm.

v. Stable accretion was formed on the hearth walls protecting it from further intensive deterioration.

vi. Possible aligned cracks were found in the hearth's walls. Continuous thermal monitoring at these possible crack regions was recommended for the detection of any thermals spikes, which would indicate the spalling of material at the hot face of the crack or metal penetration.

vii. Test results showed the formation of the 'elephant foot' in the furnace sump mainly surrounding the taphole regions.

viii. The average remaining refractory thickness in tuyere region was 650 mm (77% of the average original thickness of 843 mm).

ix. The minimum remaining refractory thickness at tuyere region was 380 mm (47% of the average original thickness of 843 mm).

All the aforementioned conclusions show that refractory lining of BF4 was in workable conditions and comparatively far from reaching absolute critical thickness of 200–250 mm.

Similarly, BF #5 was tested in July 2015 and the AU-E results are discussed further. A sample of the results for BF# 5 is presented in Figure 5.

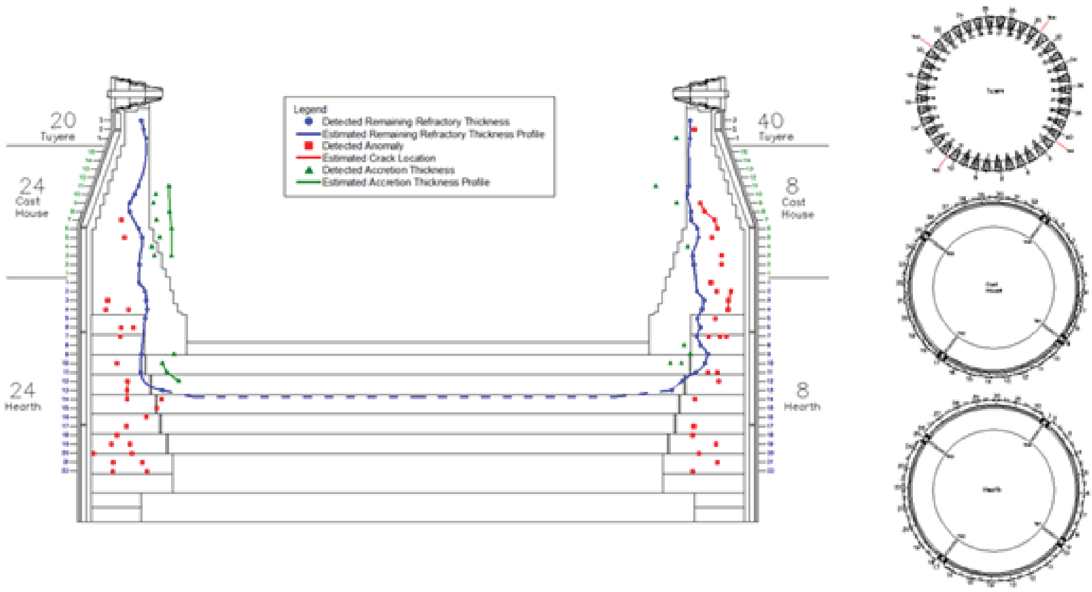

Figure 5: Results of AU-E testing of the hearth of BF #5 (July 2015).

Analysis of AU-E results for BF#5 lead to the following conclusions:

i. No ceramic layer was detected at the top of the hearth slab. The first and second layers of the furnace hearth slabs were worn out. Wear had started at the third layer of the hearth slab.

ii. The overall average remaining refractory thickness was 1391 mm, about 50% of the original average thickness.

iii. There was uneven wear in the furnace walls. In some regions of the hearth's walls the average percentage of remaining refractory was less than 40%.

iv. The minimum remaining refractory thickness was 760 mm. This thickness was about three times greater than the absolute acceptable minimum thickness of 200–250 mm.

v. Stable accretion was formed on the hearth walls protecting it from further intensive deterioration.

vi. Some of the bricks in the hearth were possibly cracked. Signals were reflected from shallower region. Ongoing temperature measurements at these cracked regions should be monitored frequently to observe any progressive thermal anomalies.

vii. It was noted that anomalies/cracks which are aligned are likely connected (i.e., a single lengthy crack measured at more than one location). Likely anomalies form some kind of cylinder around the furnace hearth. These regions should be thermally monitored to identify the thermal spikes.

viii. Test results showed the formation of the 'elephant foot' in the furnace sump in area opposite to the tap holes.

ix. Cast house level had an average remaining refractory thickness of 1110 mm, about 78% of the original average refractory thickness of 1413 mm.

x. The minimum remaining refractory thickness at cast house level was 550 mm.

xi. In general, this level was in good condition and no maintenance was required at this stage.

xii. The average remaining refractory thickness at tuyere level was 584 mm (85% of the original thickness of 690 mm).

xiii. The minimum remaining refractory thickness was 450 mm.

All the aforementioned conclusions show that the refractory lining of BF #5 was in workable condition and comparatively far from reaching absolutely critical thickness of 200–250 mm.

4. Accuracy of Refractory Thickness Estimate

The accuracy of the AU-E measurements was demonstrated to CherMK based on results of other HATCH work for Novo-Lipetsk metallurgical combine (NLMK), Russia during preparation for the hearth reline and after cooling of blast furnace #5 in March 2015 [5]. Upon NLMK's request Hatch performed measurements one week before the blast furnace shutdown. Core drilling was performed on the still hot furnaces. After the furnace was drained and cooled, physical measurements of the remaining thickness were made by tape measure. This was done by blast furnace personnel.

The core drill result revealed remaining refractory thickness of 530 mm whilst AU-E measurements indicated a refractory thickness of 500 mm. This generates a difference of 6%.

A further comparison of the AU-E results and the physical measurements confirmed that AU-E accuracy is about 4 to 7%. The error is largely due to the approximation of the refractory properties is absorbed within this range.

5. Extension of Blast Furnace Campaign Life

The trends of refractory deterioration for blast furnace #1 are presented in Figures 6 and 7.

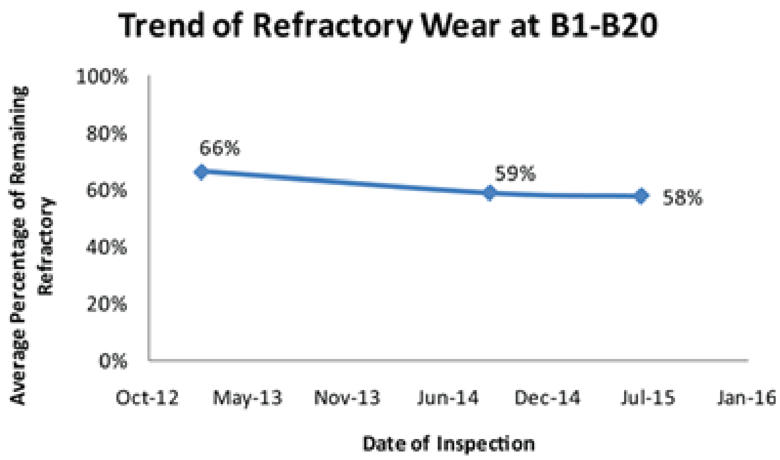

Figure 6: Blast furnace #1 average refractory wear trend in the hearth region.

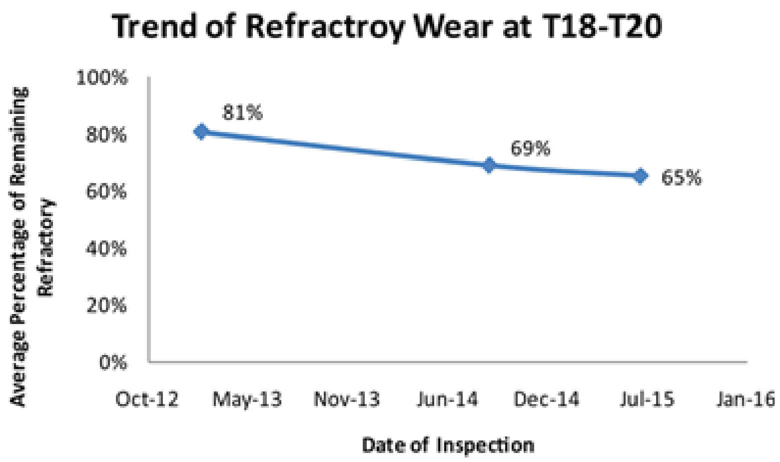

Figure 7: Blast furnace #1 average refractory wear trend in tuyere region.

Figures 6 and 7 show that between first and second AU-E testing of the blast furnace #1 the average refractory wear progressed by 12% and 7% for tuyere and hearth regions, respectively, which corresponds with the average refractory wear rates of

0.71% per month and 0.4% per month. As a result of protective measures applied by CherMK the average wear rate for the period of time between July 2014 and July 2015 for hearth walls refractories was about 4.7 mm/month for this twelve months period.

To retard refractory deterioration and to create a stable accretion CherMK and Hatch proposed and CherMK selectively implemented the following measures to prolong the furnace campaign:

Addition of titania containing materials in amount of 7–10 kg TiO_2/thm. TiO_2 forms titanium carbide and titania nitrides, which precipitates on a hearth walls.

Installation of cigar or Hatch finger coolers for local cooling and forming of accretion in critical points could be recommended to prolong the furnace campaign life.

Grouting in critical points of low thickness of refractory could be another approach to repair lining without a long period of furnace shutdown

Improvement in coke quality from CSR 45–55% to 63–65% and reduction in CRI – from 31–34% to 23–24%. In addition to other benefits, this improvement allowed for an increased permeability of the 'dead man' and a reduced circumferential velocity of hot metal which promotes the formation of 'elephant foot'. The CSR index should be high to avoid destruction of coke and allow the formation of permeable 'dead man'. The CRI index should be kept as low as possible to shift the solution loss reaction to the higher temperatures, but at the same time should be in the range which guarantees satisfactory carburization of hot metal.

Stave washing allows the removal of scale from water pipes, thereby improving the heat transfer efficiency. This helps to create stable accretion.

Periodical slower run of the blast furnaces to form accretion on the hearth's walls.

All of this allowed continuation of the furnaces campaign while maintaining their intensive operation.

In August 2017 CherMK - Severstal and Hatch compared the NDT results with physical measurements taken during shutdown of BF1 for scheduled reline (Table 2). In this table 'at the point' means that NDT measurements were performed at the same point as physical measurement and 'average' means average thickness at given elevation.

Results of this comparison shows, that the results of AU-E non distractive testing are within maximum 10% discrepancy as compared to physical measurements.

Table 2: Comparison August 2017 physical measurements with April 2017 NDT results.

Location		Physical Measurements	NDT Measurements	Comparison	Difference
Line	Point	August 2017 (mm)	April 2017 (mm)	April 2017 – August 2017 measurements (mm)	%
T12	19	570	590 at the point	20	3.5
T12	20	580	610 at the point	30	4.9
B3	4	640	640 average	0	0
B3	5	700	630 average	−70	10
B3	6	690	680 average	−10	1.45
B3	7	700	680 average	−20	2.86
B3	8	670	690 average	20	2.9
B3	9	700	760 at the point	60	7.9

6. Conclusions

Intensive operation of the blast furnace requires careful control of the hearth refractory lining conditions. The case studies at CherMK showed that AU-E is a reliable technology which enables the estimation of the thickness of refractories, accretion and location of cracks or anomaly within the accuracy of 4–7%. The application of AU-E technology for CherMK blast furnaces revealed conditions of the refractory lining, formation of accretion and the most worn regions in the furnaces. This allowed CherMK and Hatch to develop and implement preventive measures to prolong furnace campaign and continue safe furnace operation. These measures include (but are not limited to) the addition of titania materials, stave washing, grouting and utilization of higher quality coke. All of these allow CherMK to carefully control blast furnace conditions while maintaining their intensive operation.

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