REFRACTORY WEAR AND LINING PROFILE DETERMINATION IN OPERATING ELECTRIC FURNACES USING STRESS WAVE NON-DESTRUCTIVE TESTING (NDT)

A. Sadri[1], P. Gebski[2], E. Shameli[3]

[1] Hatch Ltd., 2800 Speakman Drive, Mississauga, Ontario, Canada L5K 2R7; asadri@hatch.ca
[2] Hatch Ltd., 2800 Speakman Drive, Mississauga, Ontario, Canada L5K 2R7; pgebski@hatch.ca
[3] Hatch Ltd., 2800 Speakman Drive, Mississauga, Ontario, Canada L5K 2R7; eshameli@hatch.ca

ABSTRACT

Effective maintenance practices improve safety of the operating unit, enhance safety during maintenance periods, increase operating up-time and decrease the overall maintenance costs. This paper outlines the application of Hatch's furnace condition monitoring program. Emphasis is placed on Acousto Ultrasonic-Echo (AU-E), a manually operated, non-destructive testing and evaluation (NDT & E) measurement system, which determines the thickness and physical properties of the installed refractory components. The system is used to identify the refractory wear profile and to determine the positions of cracking, metal infiltrations and other anomalies, such as gaps and discontinuities within the linings. When the AU-E system is used after the rebuild and at regular time intervals, the results can be used to determine the degree and extent of the refractory deterioration. Moreover, data analysis and interpretation algorithms have been developed in order to identify areas of hydration, based on the AU-E results. Throughout the campaign, this information is applied to schedule the shutdowns, and to determine the extent of the repair.

In this article, we are discussing the main principles of the AU-E technique and its application, particularly for determination of hearth, sidewall, taphole and roof refractory conditions. In addition, two case studies are presented to demonstrate application of the AU-E technique in an electric furnace and a flash furnace.

1 INTRODUCTION

Refractory wear and deterioration is one of the primary reasons for the termination of an electric furnace campaign. Knowledge of the current refractory thickness and quality is therefore essential for determining the campaign life of the furnace. In the past, apart from visual inspection or external surface temperature variation, there was no way of knowing where and when the refractory was deteriorating. Today, thermocouples and various mathematical models are commonly used to estimate the remaining thickness of the refractory in the furnace although many furnaces still operate without these models. The use of thermocouples and mathematical models for determining refractory thickness is an indirect approach that relies on numerous assumptions. Limitations in the number of temperature measurement points, coupled with the complexity of modeling the entire refractory lining, especially the hearth, call for an alternate method of more directly measuring the condition of the refractory lining.

To meet this need, an acousto ultrasonic propagation technique has been developed by Hatch to determine the thickness of the remaining refractory lining in operating furnaces. The AU-E technique works based on the reflection of broadband stress wave signals from the hot face of the refractory, where the contrast in acoustic impedance causes partial or full reflection of the signals. One of the advantages of AU-E technique is its capability of detecting poor bonding, delamination and joints within the lining. Wherever the thermal data are available, AU-E is used to complement the thickness calculations, and wherever there are no thermocouples, AU-E can be used to map the inner thickness of the vessel.

The purpose of this paper is to review the application of the acousto ultrasonic-echo (AU-E) method, including the fundamental relationships of wave propagation in refractories. This is followed by discussion on the basic elements of the AU-E method and the factors affecting the measurements. The paper concludes with a summary of the AU-E capabilities.

2 PRINCIPLES AND APPLICATIONS OF AU-E

When stress is released on an object, the stress wave propagates in three different modes: P-, S- and R-waves. The Predominant wave, P-wave, travels in the direction of particle motion of the material. The P-wave velocity can be calculated from Equations 1 and 2 below,

$$V_P = \frac{T}{t} \tag{1}$$

$$V_P = 2Tf_P \tag{2}$$

where $V_P(m/s)$ is the P-wave velocity, $T(m)$ is the distance that the P-wave propagates between source and receiver, $t(s)$ is travel time as measured from the initiation of the stress wave to the receipt of the reflected wave, and $f_P(Hz)$ is the P-wave resonance frequency between the top and bottom of a two layer solid system.

Combining equations (1) and (2), the remaining refractory thickness $T(m)$ in and operating furnace can be obtained as:

$$T = \frac{V_P}{2f_P} \tag{3}$$

For an infinite, homogeneous and isotropic material, the P-wave velocity $V_P(m/s)$ can be computed as:

$$V_p = \sqrt{\frac{E_d(1-\upsilon)}{\rho(1+\upsilon)(1-2\upsilon)}} \tag{4}$$

where $E_d(Kg/s^2/m^2)$ is the dynamic modulus of elasticity, $\rho(Kg/m^3)$ is the mass density and υ is the Poisson's ratio of the material. Although refractory and refractory castables are heterogeneous and anisotropic media, and the application of equation (4) may not be strictly applied, the P-wave velocity can still be seen to be strongly influenced by the material stiffness.

For refractory materials, temperature affects the modulus of elasticity and density [2]. The change in density by temperature depends on the degree of porosity and permeability of the refractory materials. The change in modulus of elasticity is dependent on refractory matrix bounding and material composition. This change in elasticity and density affects the P-wave speed. As both the temperatures and material properties vary uniquely for each layer of the furnace refractory lining, the change in P-wave speed must be computed for each layer of the refractory lining. The temperature effect is corrected by the temperature correction factor α, which is a function of the elastic properties of the refractories. The α factor is unique for each type of refractory, at each range of temperature. If the change in the elasticity over a continuous temperature range is given as $E_d(T)$, the temperature correction factor α can be calculated as:

$$\alpha = 1 + \left(\frac{\int_{T_1}^{T_2} E(T)dT}{E_o} \right) = \left(1 + \frac{\Delta E_d}{E_o}\right) = \left(1 + \frac{E_{d2} - E_{d1}}{E_o}\right) \tag{5}$$

The terms E_{d2} and E_{d1} correspond to the elasticity of the refractory material at respective first and second temperatures (e.g. on a hot face and cooler face, respectively, of a refractory brick), whereas E_o corresponds to the elasticity used to first calculate the uncorrected velocity V_p, which is the room temperature value of E_d.

As the P-wave propagates and reflects between the two layers of the solid, it causes excitation of the thickness mode of vibration. This mode is represented as alternating expansion and contraction, which varies with the shape and dimension of the structure. The β factor is defined as the ratio between the actual and theoretical wave speed value and is computed based on finite-element and laboratory experimentations. Considering both the temperature and shape factors, the simple AU-E equation becomes:

$$T = \frac{\alpha\beta V_P}{2 f_P} \tag{6}$$

Since electric furnaces consist of numerous layers of refractory, equation (6) should be modified to compute the thickness of the hot face refractory lining. For an n-layer system, the remaining thickness of the n^{th} layer i.e. the remaining thickness of the hot face refractory can be obtained from:

$$T_n = \frac{(V_P)_n \alpha_n \beta_n}{2}\left[\frac{1}{f} - \sum_{i=1}^{n-1} \frac{2T_i}{(V_P)_i \alpha_i \beta_i}\right] \tag{7}$$

where $f(Hz)$ is the resonance frequency for the remaining thickness of the n^{th} layer. Equation (7) can be used to determine refractory lining thickness on the hot face, if the wave speed $(V_P)_i$, thermal correction α_i, shape correction β_i and the thickness T_i of the layers prior to the innermost layer are known. Equation (7) assumes that the stress wave generated by a controlled impact source contains suitable energy to reach the inner most layer of the lining and resonates back and forth between the two faces in order to create a desirable P-wave thickness frequency.

3 DATA ACQUISITION AND INTERPRETATION PROCEDURES FOR THE ACOUSTO ULTRASONIC – ECHO

An AU-E system requires a broadband vertical displacement transducer that is designed to function at high temperatures (200°C), a multi-diameter spherical tip impactor, preferably with controlled impact energy, and finally a rugged computer with flexible digital data acquisition system. The AU-E system at its current version is handheld. As a more advanced unit, a fully automatic system could be installed on the areas of interest for continuous and remote monitoring of refractory changes.

3.1 Equipment Calibration

Calibration procedures are typically carried out on three (3) representative refractory samples, for each type of refractory used in the furnace in the area to be tested. Two (2) examples of the sample signals in frequency domain that were recorded for calibration purposes, are shown in Figure 1. The dominant peak is used to compute the stress wave velocity in the tested sample. The corrections for temperature and shape effects are taken into consideration, using the mechanical properties of refractory and the furnace temperatures. The apparent wave speeds are then determined for use in thickness measurements and for locating the anomalies within the refractory layers in the furnace.

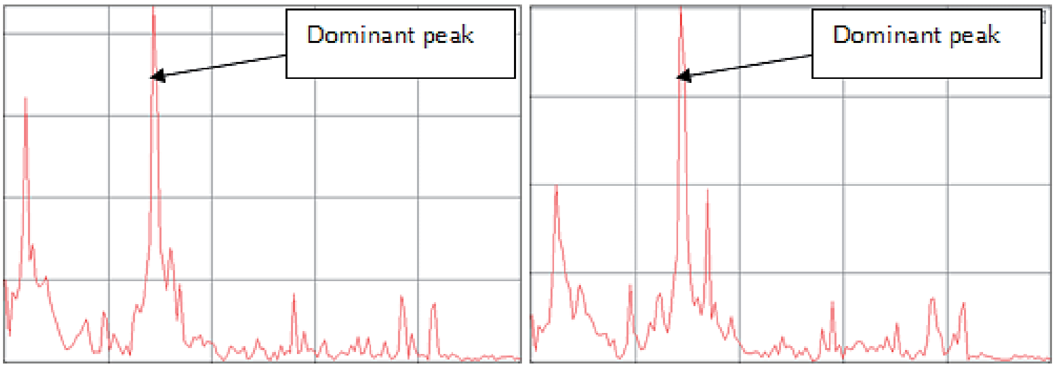

Figure 1: Sample calibration data

If the variation of the wave velocities is significant, then more samples are tested and the statistical distribution of the results is computed. Based on this information, the accuracy of the measurements is determined prior to the actual survey.

All the wave speed data for every type of refractory tested is stored in a database. Often, the sample bricks are not available for calibration. In such case the archive database is used to look up the results using identical or similar bricks parameters. With this archive updated frequently over many years, Hatch is capable of testing virtually any furnace, regardless of the refractory types used for construction.

3.2 Data Acquisition

The Acousto Ultrasonic-Echo (AU-E) utilizes time and frequency data analysis to determine the thickness of coarse-grained material, such as refractory and castable materials in operating furnaces [3]. A mechanical impact on the surface of the structure (via a hammer or a mechanical impactor) generates a stress pulse, which propagates into the furnace layers. The wave is partially reflected by the change in refractory layer properties, but the main pulse propagates through the solid refractory layers until its energy dissipates. The signal is primarily reflected by the refractory/molten metal interface, or alternatively, by the build-up/air, or molten metal interfaces that are formed between internal layers or at external boundaries. A receiver placed beside the impact area detects surface displacements caused by reflections from internal interfaces and external boundaries. The signals are analyzed both in time and frequency domain, where the controlling factors include changes in thickness, temperature, dimensions, and wave speed. The data collection activities performed by a Hatch NDT crew are shown in Figure 2.

Figure 2: AU-E survey of the furnace hearth

With this methodology, the principal stress wave captured and analyzed for quality assessment is the Predominant wave (P-wave), also referred to as the compressive wave. The compressive wave speed is affected by the density, thermal gradients, shape and dimension factors, and elastic properties. A drastic change in density and/or in elastic properties of the material results in partial or total reflection of the waveform. In addition, stress free zones, such as cracks and discontinuities, will result in partial or full reflections. Figure 3 shows two (2) sample signals in frequency domain. For the upper signal (a), the dominant frequency peak indicates full thickness of the furnace hearth. The lower signal (b), reveals the dominant peak at higher frequency, which indicates the wall thickness reduction.

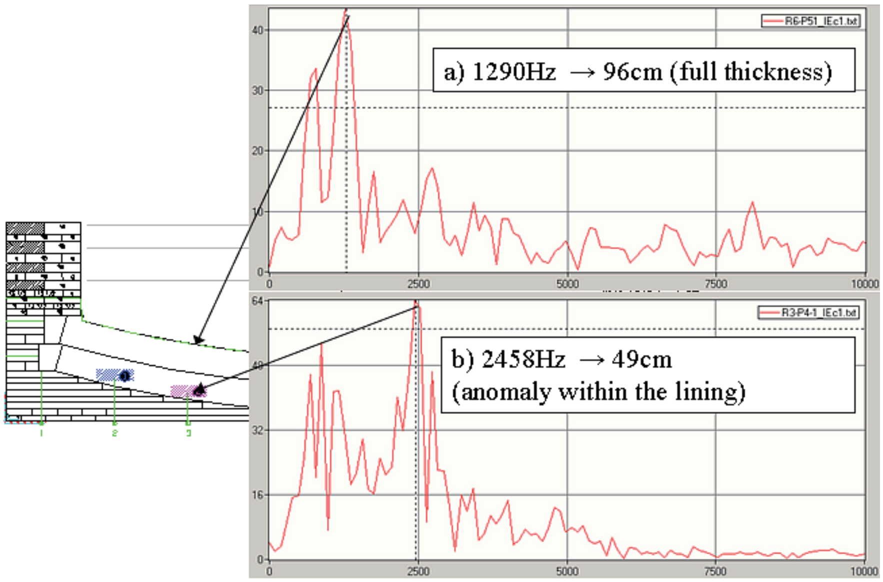

Figure 3: Thickness measurement and anomalies detection by the AU-E technique

3.3 Detecting Hydration, Metal Penetration and Cracking

Once the signals are reflected from various interfaces, the wave speed, shape, and thermal corrections can be used to determine the thickness of the refractory layer. When there are discontinuities or multiple instances of cracking, the signals tend to reflect at higher frequencies, and at higher numbers. The peak frequencies can then be used to determine the position of any cracks and discontinuities [4].

The method for detecting hydration differs from the above, because the degree of hydration has a significant influence on the reflected signals. The time-domain signals will show high frequency components and very high attenuations as the higher degree of hydration results in proportionally higher signal attenuation. Nonetheless, the best indicator of hydration remains the evaluation of the wave speed. With advanced stages of refractory hydration, wave speeds will be dramatically lower than what can be measured in a normal brick; therefore, when sending signals into the refractory lining, the presence of hydration can be determined where the lining is measuring thicker than what it is supposed to be.

Another possibility where "thicker than normal" lining sections can be observed is in regards to matte or metal penetrations. Normally, AU-E can identify matte penetrations within the hearth lining layers; however, they will not be detected when the penetration is smaller than the signal "half wavelength", since the AU-E cannot detect the layer boundary, and will instead register the additional matte thickness as part of the lining.

3.4 Detecting Refractory Wear and Impregnation

Refractory wear is identified as sections of the refractory that are either de-bonded or extensively "impregnated" by molten metal. Impregnation occurs when the molten material infiltrates into the refractory matrix, as in, for example, a copper smelting furnace where the copper eventually impregnates the matrix of the magnesia chrome-based working layer. In either case, this results in a severe change in the refractory material properties; therefore, the signals are extensively reflected at their interface with the good brick.

4 FURNACE CONDITION MONITORING PROGRAM

Hatch has designed a comprehensive Furnace Condition Monitoring Program, as a module of a more general Furnace Audit Program. The Furnace Condition Monitoring Program has been developed to meet the requirements of all the Hatch's major clients. The scope of work can be tailored to the needs of each individual furnace. It can comprise of periodic inspections, long-term refractory evaluation, and continuous monitoring of selected key furnace components (tapholes, coolers, etc.).

Although the focus of this paper is on the refractory thickness measurements by the AU-E technique, it is important to list all the major components of the Furnace Condition Monitoring Program, which includes:

- Refractory thickness measurements and anomalies detection
    - Refractory quality assessment prior to the furnace construction
    - Baseline inspection
    - Periodic inspections to minimize risk of failure and to improve the relining schedule
    - Emergency inspections
    - Continuous monitoring (under development)
- Taphole Acoustic Monitoring System
    - Continuous monitoring of the taphole refractory and the tapblock to minimize the risk of failure
- Furnace Integrity Monitoring System
    - Continuous furnace integrity evaluation through the measurements of the steel shell deformation
- Cooler monitoring
    - Detection of wear in copper coolers
- Leak detection system
    - Continuous monitoring of the furnace cooling systems

The refractory thickness measurements and anomalies detection are accomplished using the AU-E technique. For optimal results, it should begin with the refractory quality assessment. This provides the information about the exact wave velocity of the original bricks, critical for the future AU-E surveys, and provides the additional benefit of identifying defective bricks installed in the furnace. This baseline inspection provides the ideal reference for the future AU-E measurements, defining all the measurement parameters and identifying all markers (interfaces) critical for the future NDT inspections. Periodic inspections at regular time intervals then allow detection of emerging changes in the furnace refractory before they create any serious threat to the furnace integrity. Regular inspections also create an opportunity for tracking the trends regarding the refractory wear. The wear rate can then be estimated with accuracy and used for scheduling maintenance activities.

Hatch has developed a database for archiving all the information about the integrity of every furnace tested to support the furnace operators by providing them comprehensive results regarding the current and past condition of the furnace. A set of software tools has been developed for data acquisition and analysis, an example of which is shown in Figure 4.

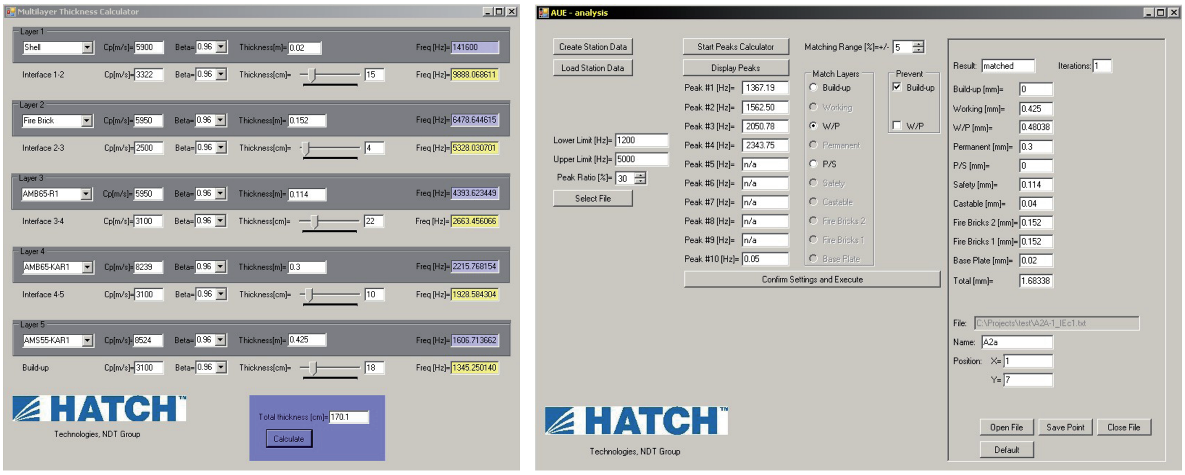

Figure 4: Screen captures of the Hatch data analysis software for furnace condition monitoring

5 CASE STUDIES

Two case studies are discussed below, presenting sample findings and results obtained by the Hatch NDT Group using the AU-E technique for refractory condition monitoring.

5.1 Hearth Lifting in a Flash Furnace

Prior to the restart of the furnace, and prior to the start of the AU-E inspection, the hearth was core-drilled in several locations to verify the presence of lining and to determine the extent of lifting in the hearth. Following the restart, Hatch NDT specialists conducted two series of the AU-E inspections of the hearth, with the objective of determining any changes within the lining and ultimately to identify if any sudden lifting of the hearth refractory lining occurred. The restart resulted in movements within the hearth lining, causing additional matte penetration and gap formations. These physical changes were detected by the AU-E system.

The core-drilling showed lifting of the hearth and matte penetration between the refractory layers. The thickness of the matte penetration was measured to be in the range of 400 to 560 mm. The accuracy of the AU-E measurements compared to the physical measurements is shown in Table 1. The progression of the hearth lifting over less than six months (as detected by AU-E) is also presented.

Once the AU-E survey results had been validated using the core drilling findings, the 3-dimensional sketch of the profile of the entire furnace hearth was generated based on the NDT data, as shown in Figure 5. The thickness (shape) up to the top of the Working layer is shown (not to scale). It does not include any build-up on top of the Working layer, even if such was detected. The bulge related to the matte penetration, mainly between the Safety and Permanent layers, is clearly seen in the central section of the hearth and is the highest between Buckstays 4 and 8. The original surface of the hearth is also shown in Figure 5, in gray.

Based on these results, a model was developed showing that the penetrated matte is causing floatation of a portion of the Permanent and Working hearth layers. The matte penetration and presence of discontinuities on top of the Safety lining is most significant between buckstays 2 to 9 at the centre of the hearth.

The results of the AU-E inspection confirmed the maintenance schedule for the next furnace reline. Eventually, the above mentioned furnace was shut down and relined after four months.

Table 1: Errors of the Matte Penetration calculations by AU-E validated based on the physical measurements and the change in Matte Penetration thickness

Drill #	Error of the AU-E measurement compared to the physical measurement [%] as measured in April 2007	Penetrated matte layer thickness change [mm] measured by AU-E from April 2007 to September 2007
1	0%	+30
2	4%	+30
3	5%	+30
4	0%	+20
5	0%	+20

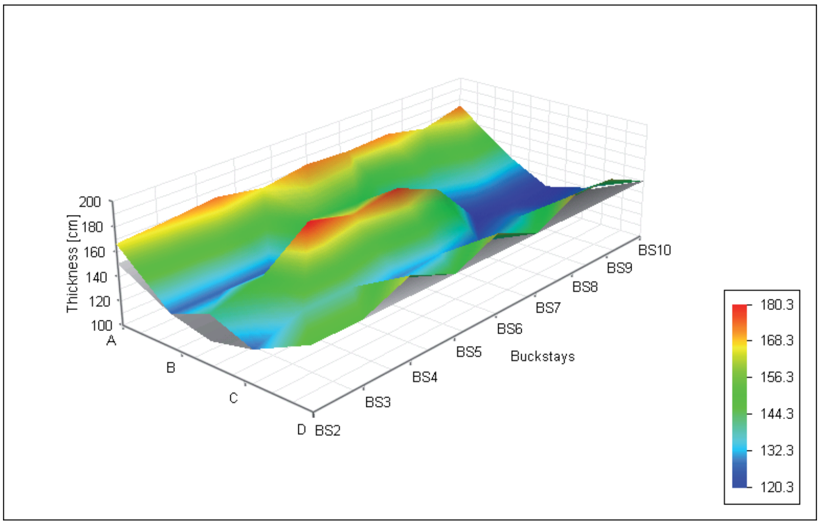

Figure 5: Hearth shape generated based on the AU-E results (not to scale)

5.2 Hearth Deterioration in a Circular Electric Furnace

Due to a series of incidents, this electric furnace was severely damaged and experienced a run-out. During the demolition of the furnace, several types of anomalies were observed, including lifting of the working lining and the hearth shaping lining, as well as metal and slag penetration between the refractory layers. This triggered a serious concern regarding the condition of the Client's other furnace, identical in design to the damaged one. In order to evaluate the conditions of that furnace AU-E technology was applied. The survey included calibration of the AU-E equipment with the brick samples and the other furnace undergoing demolition. This allowed identification of the signature signals for the types of anomalies that were of the biggest concern for the furnace operators. During the survey on the operating furnace, the search for similar patterns of anomalies was conducted. As a result, the following signs of deterioration of the furnace hearth were identified through the course of the NDT measurements:

- High concentration of the anomalies (delaminations) below the skew bricks were observed in the metal tapping zone.
- Large volume of the magnesia infill bricks, especially at the north-east portion of the furnace (near the north east slag taphole), exhibited signs of crack or separation-related anomalies.
- Anomalies directly under and directly above the safety lining bricks were spread all over the hearth. This indicates delamination in the vicinity of the safety layer that could potentially create conditions for metal penetration, or areas where partial metal penetration has already occurred.
- Evidence of wearing or cracking in the working lining bricks, or metal impregnation into the working layer, especially in the central portion of the hearth. However, these anomalies were not severe, and a significant portion of the working layer remained in sound conditions. For the north-

east portion of the hearth the results for the working lining were not available for a majority of the test points, due to full reflection of the stress wave from the lower layers.
- Evidence of the possibility of hearth lifting was found in the center portion of the hearth and towards the east. It was estimated that the hearth lifted by up to 290 mm.

The greatest concert was the possibility of hearth lifting, as a similar phenomenon was observed in the demolished furnace. The hearth lifting mechanism is illustrated in Figure 6. The top of the safety layer was detected by the AU-E technique, and was used as a known marker (at 1532Hz). Instead of the top of the working lining (expected at 1480Hz), another interface was detected, causing the partial reflection of the stress wave. The top of the working layer was indicated by the wave reflection at 1223Hz, which results in the full thickness of 134cm, including 18cm of metal penetrated between the safety and working bricks. The same methodology was used to determine the thickness of the penetrated material at other tested locations. These results were validated by the sounding conducted at selected locations from the furnace roof.

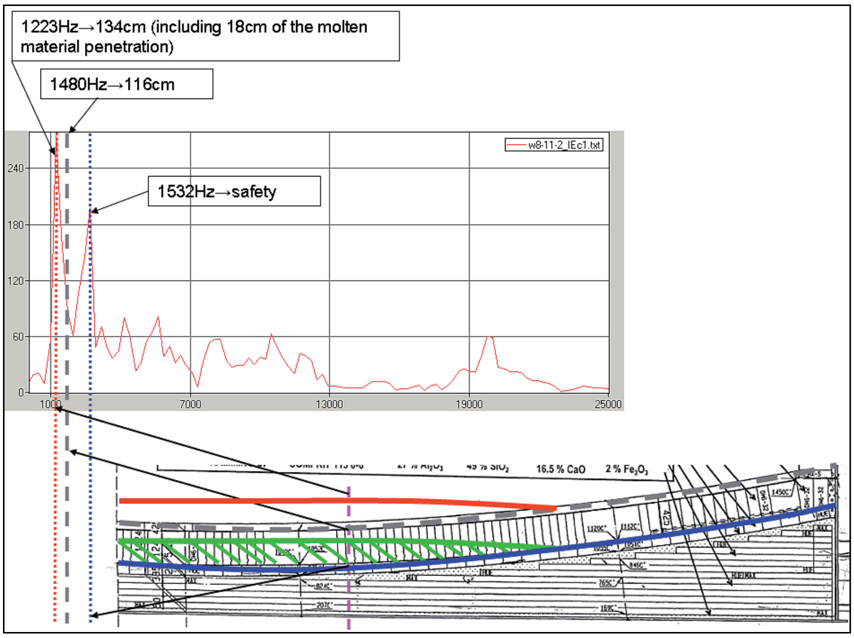

Figure 6: AU-E data analysis for the hearth lifting

Ultimately, based on structural modeling and the analysis of the furnace operations, it was concluded that the furnace hearth can be kept in stable condition if the operational parameters are maintained at specific levels, and if physical and NDT measurements are implemented on regular basis.

6 CONCLUSIONS

The Acousto Ultrasonic – Echo technique has proven to be a reliable and accurate method for furnace refractory condition monitoring. The following observations and conclusions must be emphasized based on the results of numerous electric and flash furnace inspections:

- AU-E provides accurate results for the refractory thickness/wear computation, based on the measurements taken on a dense grid of test points. Results from individual test locations can be used to generate the cross-sectional refractory profiles, and eventually, to build a 3-dimansional wear/thickness model.
- The thickness computations are based on physical measurements at multiple test locations as opposed to numerical modeling relying on temperature readings from a very limited number of thermocouples.
- Significant anomalies and discontinuities, such as cracks in bricks, are immediately identified, allowing for better maintenance scheduling and safer operations of the furnaces.

- Detection of build-up and estimation of its thickness provides means for furnace process optimization that can extend the campaign life.
- The AU-E results were validated through core drilling. They showed very good correlation with the physical measurements, typically with higher accuracy than provided by numerical modeling.

The regular inspections of the furnace refractory using the AU-E technique not only provide a “snapshot” of the current condition, but also show the deterioration rate and critical locations vulnerable to wear. Such results are frequently used for maintenance scheduling and process improvement.

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