NON-DESTRUCTIVE TESTING (NDT) TECHNIQUES FOR DETERMINATION OF REFRACTORY DETERIORATION IN SMELTING FURNACES

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ABSTRACT

Operation of pyrometallurgical and iron making furnaces is greatly affected by the integrity and thickness of their refractory lining. Hatch NDT Group uses three (3) innovative techniques to evaluate refractory lining integrity and thickness in operating furnaces: Acousto Ultrasonic-Echo (AU-E), Taphole Acoustic Monitoring (TAM), and Infrared (IR) thermography.

Acousto Ultrasonic-Echo (AU-E) was developed based on the stress wave reflection principles [1]. The system corrects for effect of temperature on the refractory wave speeds to compute accurate refractory thickness. The AU-E technique could also be applied to determine position of lining delamination, cracks and other anomalies within the refractory structure [2, 3].

The Taphole Acoustic Monitoring (TAM) system was developed based on the acoustic emission (AE) principles [4]. The receiving transducers are installed on the inlet and outlet cooling circuits of water cooled tapping blocks. Using the sound generated from flow of molten metal in the taphole, the system is capable of continuously determining refractory wear within the tapping channel. This 24/7 continuous monitoring system is also capable of assisting the operators for better lancing/tapping/drilling practice as it could illustrate the intensity of the hits on the inner refractory lining in the tapping block.

The infrared (IR) thermographic cameras are commonly used to determine "hot spots" on the vessels where the refractory wear could be worse than the surrounding areas. In our approach, the data from IR camera is used to accurately determine refractory thickness in one layer refractory lined cylindrical vessels such as converters and reactors [5].

In this paper, we introduce the principal concepts of the above three (3) NDT techniques and present case studies and examples to illustrate the accuracy and repeatability of the measurements.

ACOUSTO ULTRASONIC – ECHO (AU-E)

The Acousto Ultrasonic – Echo technique was developed in late 1990s. It is a patented technology that has been used for refractory thickness measurements and quality evaluation commercially for the last ten (10) years. The AU-E technique is based on multiparameter analysis of stress waves that are introduced to the tested element/structure through calibrated impactors. The waves propagate throughout the thickness of the refractory between the cold face and the hot face generating multiple reflections. These reflections are caused be local changes of material properties: cracks, voids, hydrated areas, metal impregnations or penetrations, and by interfaces between refractory layers. The stress wave reflected at the full thickness is also measured. The reflected waves are analyzed both in time and frequency domain. As a result the full thickness of the remaining material is computed and the flaws and anomalies are identified. Later these results are used to determine the overall condition of the tested sections of the furnace. The AU-E testing equipment including the workstation, sensors, impactors and other devices and tools, is shown in Figure 1.

Figure 1: The AU-E testing equipment

Equation 1 is the fundamental AU-E equation, where T is the thickness and f_p is the frequency of the P-wave reflecting between the two (2) solid interfaces. Velocity of the Primary stress wave, V_p, and temperature correction for refractory element, α, and the vessel shape factor, β, are fundamental parts of the AU-E thickness and quality calculations.

$$T = \frac{\alpha \beta V_P}{2 f_P} \tag{1}$$

To demonstrate the AU-E benefits for the maintenance and condition monitoring of furnaces, the accuracy and repeatability of the results should be examined. The following sections discuss various case studies that were substantiated by the clients at various pyrometallurgical vessels and plants.

AU-E Measurements of a Blast Furnace

In January of 2004 a blast furnace Argentina was evaluated using the AU-E technique [6]. The main objective was to detect the remaining sound carbon in the sidewalls refractory. This inspection was repeated approximately twenty (20) months later, in 2006 in order to monitor potential changes in the refractory lining. Since the AU-E technique is based on detecting stress waves reflection from the altered bricks and other material interfaces or cavities, it was critical to identify such reflections (peak frequencies) and later, based on the calibration data to convert them into remaining thicknesses. In Figure 2 an example of a core sample and the related AU-E signal spectrum is shown. Two significant frequency peaks were identified: the dominant low-frequency peak represents the full remaining thickness, while the higher frequency peak represents the interface between the sound and altered material. Numerous core samples were drilled after the AU-E survey was conducted. In general the AU-E results were validated and proved to be very accurate. As shown in Figure 2 the difference between the core sample and the AU-E result was only 10 mm. Typically, accuracy of 5% is achieved.

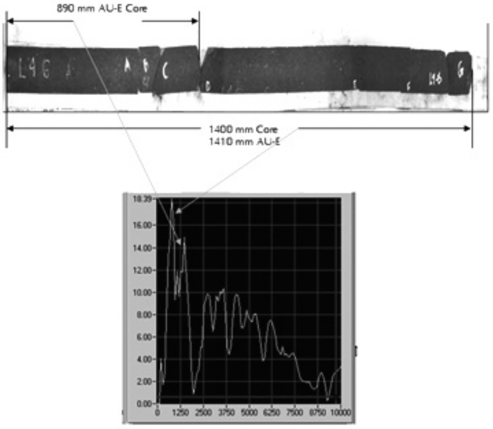


Figure 2: AU-E signal and the related core sample

The thickness values obtained from the numerous test locations were later used to generate the remaining refractory profiles of the individual furnace cross-sections. In Figure 3 one example is shown for both 2004 and 2006 surveys. They were compared to the core drilling results. The profiles matched very well both for the lower and the upper hearth, and were significantly more accurate the model generated based on the temperature measurements. In addition, the simultaneous analysis of the thicknesses measured by AU-E in both 2004 and 2006 showed the deterioration rate of the furnace refractory.

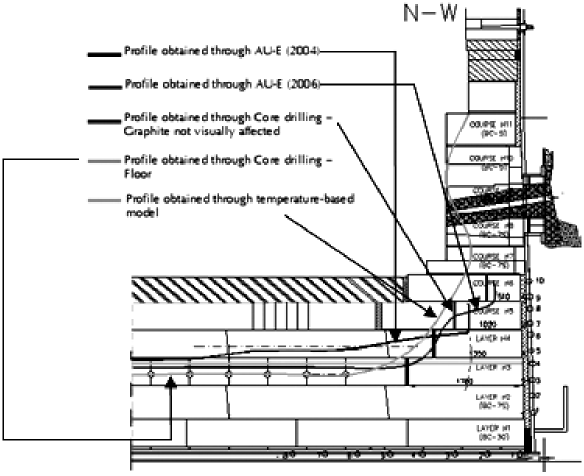


Figure 3: Remaining refractory profile for a Blast Furnace cross-section

AU-E Measurements of an Outokumpu Flash Furnace

Over a period of several years Hatch NDT Group experts have been conducting annual inspections of an Outokumpu Flash Furnace located in Australia [7]. As a result areas of extensive metal penetration into the hearth refractory lining were detected. These anomalies were monitored and reported during the consecutive surveys. Thanks to the improved data acquisition and analysis procedures the later reports showed voids and areas of metal infiltrated deep below the upper hearth into the safety lining. Over the years of operation this anomalies together with the extensive hearth expansion caused the two (2) upper brick layers to lift as high as ~700 mm. The cavity crated below was partially filled with metal. In Figure 4 (on the left) a photograph taken during the rebuild is presented, showing the hearth lifting.

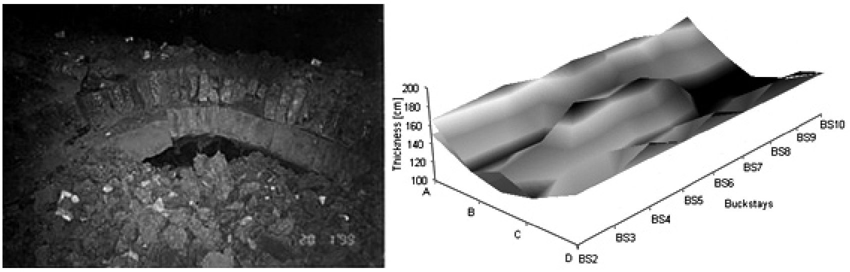
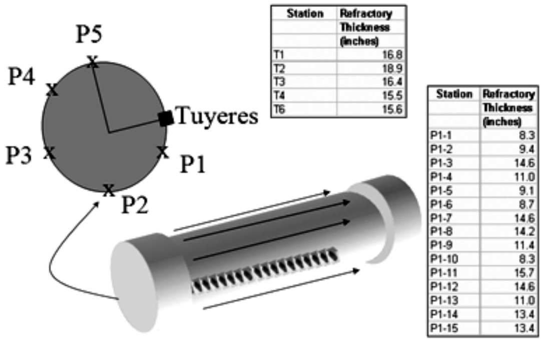


Figure 4: Upper hearth lift (left) and a 3D model based on the AU-E results (right)

Similar conditions were detected after the most recent AU-E survey. Significant amount of metal penetration into the refractory lining was detected by the Hatch NDT inspector. An effort was made to generate a 3-dimensional image of the current shape of the hearth based on the thickness measurements taken at individual locations from underneath the furnace. The model resulting from that interpolation is shown in Figure 4 (on the right). For clarity, any build-up detected on top of the refractory was neglected, and the 3D image only shows the thicknesses and shape up to the top of the working layer.

AU-E Measurements of a Cylindrical Reactor

The AU-E technique was used to measure the refractory thickness of a reactor in Chile [8]. The purpose of that survey was to provide data that would help to support or reject a decision regarding extending the campaign life of that reactor. The reactor was inspected along six (6) longitudinal lines. The inspection was carried out from the matte side to the slag side. Between eight (8) to fourteen (14) points along each line were tested. The locations of the testing stations together with the selected results obtained at individual points are shown in Figure 5.



Station	Refractory Thickness (inches)
T1	16.8
T2	18.9
T3	16.4
T4	15.5
T6	15.6

Station	Refractory Thickness (inches)
P1-1	8.3
P1-2	9.4
P1-3	14.6
P1-4	11.0
P1-5	9.1
P1-6	8.7
P1-7	14.6
P1-8	14.2
P1-9	11.4
P1-10	8.3
P1-11	15.7
P1-12	14.6
P1-13	11.0
P1-14	13.4
P1-15	13.4

Figure 5: The inspection lines on the reactor and the associated thickness measurements

Later, during the shut down, core drilling was conducted at some of the locations tested by AU-E. Core samples were taken at multiple locations and the refractory and build-up thicknesses data were extracted. These values were used to generate the refractory profiles for several cross-sections. Again, the physical measurements matched well with the results obtained through the application of the AU-E technique. Wherever the thickness was measured by non-destructive means it was confirmed through the core sample measurement. In Figure 6 cross-sections obtained using both methods are shown. They reveal the remaining refractory thicknesses within the range between 9 (22.9 mm) to 17 (43.2 mm) inches. Based on these results a pattern was also observed regarding the areas most vulnerable to brick wearing.

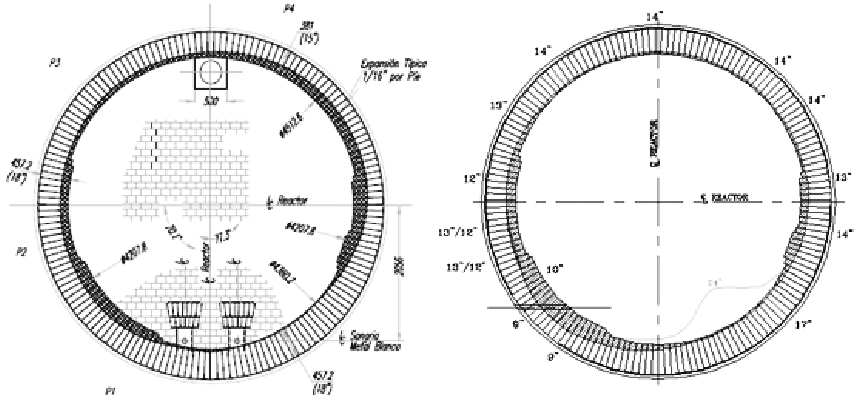


Figure 6: Remaining refractory profile (all the shaded areas) based on
AU-E results (left) and based on core drilling (right)

Summary of the AU-E Applications

The periodical application of the non-destructive techniques for the furnace condition monitoring leads to better safety, longer service of a vessel, controlled maintenance, and increased production. Accurate thickness measurements and flaw detection is possible using the Acousto Ultrasonic-Echo (AU-E) technique. Numerous furnaces of different designs (blast furnaces, flash furnaces, electric furnaces, converters and reactors) and dimensions were successfully tested at many different locations worldwide. Hearth integrity including thickness and delaminations, sidewall thickness, roof thickness and cracking, hydration detection, overall refractory thickness and quality assessment, and build-up thickness estimates where the main focus of AU-E measurement and inspection activities in the past 10 years. Years of experience and the continuous development and improvement of the monitoring and data analysis procedures make the Hatch NDT Group a one-of-a-kind provider of the furnace condition monitoring services.

TAPHOLE ACOUSTIC MONITORING (TAM) SYSTEM

The Need for a Continuous Monitoring System

A copper block, while maintained and operated properly, will not undergo severe deterioration. However, the refractory wears out due to lancing and tapping. If the lose is not detected then the copper block becomes exposed to lancing and to the molten metal. Eventually the molten metal could reach the cooling pipes and cause catastrophic explosions resulting in loss of operation time and cause serious injuries. In order to prevent such event two issues must be tackled: 1) a continuous monitoring system detecting deterioration in refractory inserts and in copper should be installed, and 2) best practices for tapping and lancing must be established, optimized and applied. The Taphole Acoustic Monitoring (TAM) system developed by the Hatch Non-Destructive Testing Group addresses both of these issues: it provides real-time monitoring of the taphole conditions, as well as proactively prevents damage by providing feedback instructions to the operating tappers [9, 10]

Basic Principles of Acoustic Emission

Acoustic Emission is a powerful technique for evaluating the conditions of materials and structures. AE may be defined as a transient elastic wave generated by the rapid release of energy within a material. This technique is used to safeguard against catastrophic failures, to assess structural integrity and to enhance safety in a wide range of structures. For the taphole monitoring, the AE system will be used to detect changes in refractory and copper thickness and to evaluate their integrity. The fundamental statement regarding Acoustic Emission says that *there is a physical source behind every acoustic signal. The part of the energy released by the source that is converted to high frequency vibrations is detected as Acoustic Emission*. Numerous sources of AE could be encountered while monitoring a complex industrial system or installation. In case of a tapblock the following sources of AE are expected: refractory deterioration, copper deterioration, molten metal flow, water flow in the cooling circuits, and ultimately water boiling in the pipes near the damaged area. The main goal for the TAM system is to detect and save the signals, and ultimately to identify the physical sources that they origin from.

Taphole Acoustic Monitoring (TAM) System – Conceptual Design

For the prototype TAM system the 4-channel (per taphole) commercial acoustic emission data acquisition computer was used. This system is equipped with high speed 16-bit A/D converters and allow for processing signals at a high sampling rate of 10 MSPS. These features, once supported be Hatch-developed data analysis software, make the system suitable for real-time processing of large amount of monitoring data.

In this particular application, the primary source of the signals is related to the flow of the molten metal. The signals are generated on the interface between the molten metal and the inner refractory lining, and the signal propagation is caused by the motion of the molten material and by the resulting thermal expansion of the refractory. The elastic wave propagates through the refractory and copper, and then approaches the cooling pipe. While both refractory and copper significantly attenuate the signals, the Monel pipe is a good medium for propagation. The signals propagate through the Monel pipe towards the sensors installed on the inlet and outlet. Given the known stress wave velocity within Monel, and the difference in time-of-arrival measured by the pair of sensors, the location of the signal source along the pipe is computed. This location is then related to the particular Zone/Section of the tapblock. In this way, the acoustically active area of the tapblock is detected. More detail on the source location and on its significance to the evaluation of the tapblock integrity will be discussed in further sections of this paper.

Since significant attenuation takes place while the signal propagates through the refractory and copper, the changes of the signal's parameters are related to the remaining thickness of the refractory lining and the copper. In general, the stronger the signal, the less attenuation, hence there is less material remaining. This concept is illustrated in Figure 7. In the long term, this observation will allow for the evaluation of the wear rate.

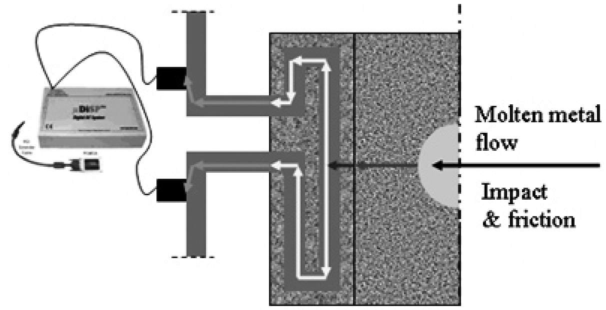


Figure 7: Signal propagation path within a tapblock

Out of the four (4) distinct attenuation components, see Equation 2 (Signal attenuation components), two (2) are variable, namely A_R and A_C. The values of these components change when the thickness of the refractory or copper changes. This relates back to the foundation of the Taphole Acoustic Monitoring (TAM) technique, which *reduced thickness results in less attenuation and stronger AE signals*.

$$A = A_R + A_C + A_{MC} + A_M \tag{2}$$

While stronger AE signals may occur due to reduced thickness (from refractory or copper wear), they may also result from *abnormal* acoustic events. It is then critical for this project that both those sources be detected.

AE Signals Source Location and Pattern Recognition

Since a pair AE sensors was mounted on a cooling pipe then the linear source location algorithm was used in order to compute the relative coordinates of the physical phenomenon producing each detected acoustic event. This procedure requires as input the distance between the two (2) sensors measured along the cooling pipe, and the stress wave velocity measured/calibrated for the waveguide – in our case the Monel pipe. As a result the distance X between the AE sensor #1 and the physical source of the AE signal is computed using Equation 3 (Linear source location formula), where L – the distance between the sensors measured along the pipe, v – wave velocity for the Monel pipe, ΔT – the difference in signal's time of arrival to both sensors.

$$X = \frac{1}{2}\left(L - v\Delta T\right) \tag{3}$$

Since the signals that pass through the filters are generated within the refractory or copper, the actual signal source is located within the area near the point that is indicated along the pipe. In this way, the tapblock volume can be divided into several sections or zones (see Figure 8). Every area marked in Figure 8 is represented by a corresponding section of the cooling pipe. Because the monitoring is focused on the tapping channel, only the signals from certain sections of the tapblock were analyzed. Zone 1 is located nearest to the hot face, while Zone 4 is located nearest to the cold face.

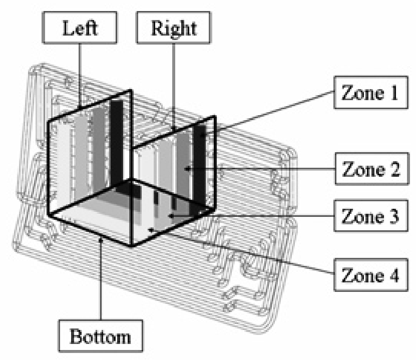


Figure 8: Zones and sections defined for the tapblock

In order to process the large number of AE signals (approximately 20 MB of data per tap) in an efficient way, the Hatch NDT Group developed Pattern Recognition (PR) software. The standard AE data acquisition and analysis software allows for extraction of multiple signal features from each waveform. The most commonly measured features include Peak Amplitude, Energy, Duration, Rise Time, and Average Frequency, among others. Since some of these parameters have little or no significance in terms of the signal source and its severity, a careful selection of useful signal features was required. With the use of a proper combination of the above features, it was possible to develop a successful signal classification tool for distinct AE sources that occur during furnace operation. The data collected during the trial monitoring was used to determine the number of distinct classes of AE signal. The Artificial Neural Network principles (including the concept of the Self-Organizing Maps) were used for this purpose.

Numerous data sets were iterated through the Pattern Recognition software until the number of classes of similar signals converged to a certain limit. Each class consisted of AE signals with similar features (i.e., similar values of the signal parameters used for analysis). This PR analysis, based on the Neural Network technique, was repeated on all data files gathered during the initial stages of the acoustic monitoring. In most cases, the computed number of signal classes was equal to four (4). A combination of these results with other features and with the source location results can in most cases lead to unique identification of signals that dominantly occur at different stages of the taphole operations, and that represent different levels of the material deterioration.

Correlation of the AE Signals with the Temperature Measurements

Since the TAM system was installed a few minor incidents have occurred that could potentially have impact on the monitored tapholes. The only incident that could have been classified as significant was related to an incorrect attempt to open the taphole. The hole was lanced out of the intended direction (see Figure 9) causing damage to the inner refractory inserts and the surround bricks.

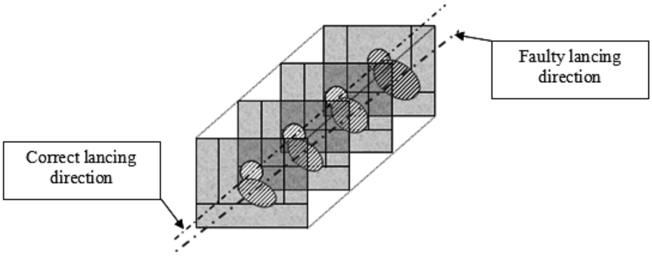


Figure 9: Faulty direction/orientation of the tapping channel

That situation was accompanied by a minor slag leak through the inner bricks. After the situation was brought under control the visual inspection showed that portions of the refractory inserts were significantly eroded and replaced with slag. No damage to the copper block occurred. Due to the slag infiltration the thermocouples readings triggered alarms.

These pieces of information were later correlated with the recorded and post-processed AE data. As part of the revised post-analysis process, the time series of the *acoustic asymmetry* (the difference between the Left and Right side of the taphole) was plotted and overlaid on the temperature data. The results are shown in Figure 10.

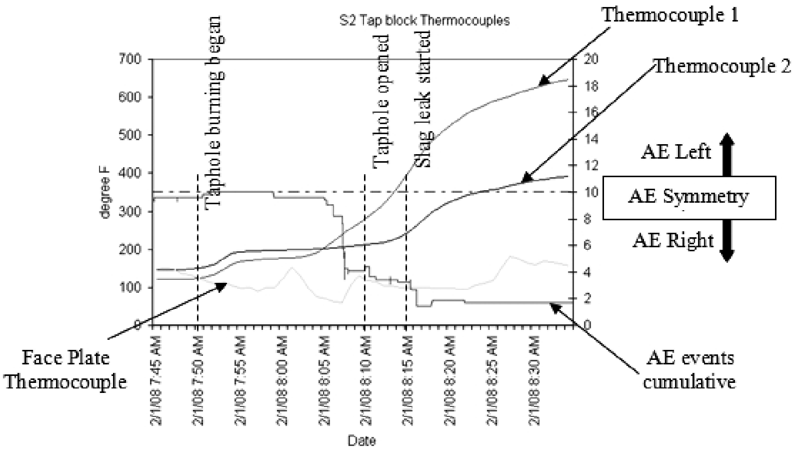


Figure 10: AE left-right asymmetry (total for zones 1 through 4), overlaid on the thermocouple data

Figure 10 shows the *acoustic asymmetry* (cumulative events for Zones 1 through 4) overlaid onto the thermocouple data. The AE symmetry line divides the taphole area into Left and Right sides (this refers to the AE data only, not to the temperature data). Between 7:50 am and 8:10 am, after the taphole burning began, and before it was opened, the dominant acoustic activity shows up on the Right side of the taphole (below the symmetry line in Figure 10). Clearly, the temperature increase on Thermocouple 1 matches the sharp AE shift towards the Right side (between 8:05 am and 8:07 am). Later, after the taphole is opened, dominant AE activity was detected on the Right side. At 8:15 am, after the slag leak started, another strong AE event was detected, shifting the *acoustic asymmetry* plot even more to the Right. Later, between 8:18 am and 8:34 am, the *acoustic asymmetry* stabilized.

Quasi -3D Image Generation of the Tapping Channel

While the above presented results in general showed very good correlation between the acoustic emission signals and other monitoring measures, they also emphasized the significant value added by the Taphole Acoustic Monitoring system. Based on the acoustic intensity and activity measured during the slag leak incident a quasi-3D image of the tapping channel was generated, see Figure 11. The red and yellow areas indicate the most active zones (where most AE signals were generated). A clear difference can be seen between the left and right images in Figure 11 corresponding to the slag leak and to normal operation, respectively. In Figure 11 the activity was shifted towards the right section of the hole where the damage was most severe. The highly active Zone 4 (darker colors) representing the cold face shows a large number of AE signals caused by the interaction with the face plate covering the taphole. In comparison, a rather symmetrical distribution of the acoustically active zones is typically observed during normal undisturbed tapping (Figure 11 right).

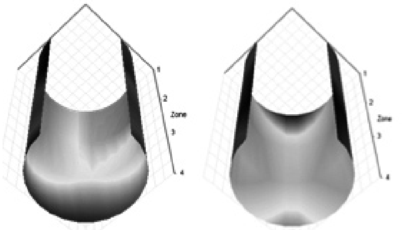


Figure 11: AE active zones during the taphole incident (left) AE active zones during the typical undisturbed tapping (right)

Summary of the TAM System's Features and Future Developments

Clearly, there is a direct strong correlation between the physical damage and the acoustic emission results: due to the faulty taphole operations the right and bottom refractory inserts were severely damaged and the high acoustic activity was recorded also from the right and bottom sections of the tapping channel. Based on the TAM output, the damage can be located (using the source location algorithm and the quasi-3D images), qualified (based on the pattern recognition software) and partially quantified (by the means of AE activity and intensity). Currently, a patent application is pending for the TAM system. The development work is focused on the following aspects:

- Software development for the actual 3D image generation of the tapping channel image
- Application of the pattern recognition software for detection of boiling water in the cooling pipes, which would be an indication of severe copper wearing.

INFRARED THERMOGRAPHY

Application of infrared thermography is a well established non-destructive testing method in evaluating the refractory wearing in cylindrical vessels. When an object is heated, its temperature will be increased due to energy absorption. This increased temperature will cause a dynamic heat transfer between the object and its surrounding media through convection, conduction and radiation.

From the NDT perspective, infrared thermography is based on the principle that heat transfer in any material is affected by the change in material thermal properties, specially those caused by a subsurface defect. Infrared radiation from the subsurface of an object is detected and registered using an infrared camera. Temperature differences on the surface, which may be related to the subsurface defects, can thus be localized based on the thermal images.

Based on this principle, this section proposes a method for refractory thickness determination in single layer refractory lined hollow cylindrical objects such as converters and reactors. The proposed method uses a thermal model of the converter and the thermographic image of the converter's outer surface to calculate the refractory thicknesses at the inspected spots.

The accuracy of the method depends on accurate measurements of refractory's surface temperature, shell's temperature and emissivity, ambient air's temperature and humidity, and refractory's conductivity. The method has been validated with experimental measurements performed on a slag cleaning converter.

Theoretical Basis

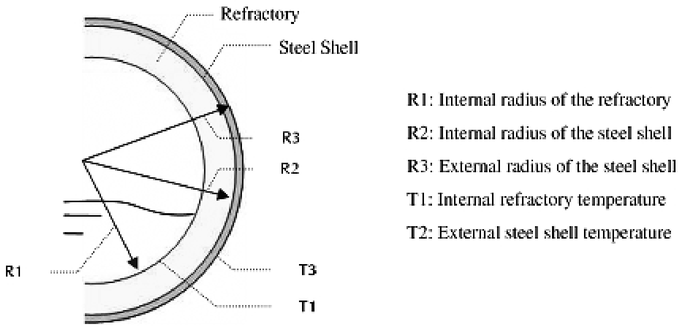


Figure 12: Schematic of a single layer vessel geometry

The schematic of a single layer vessel geometry is illustrated in Figure 12. Using the steady-state heat transfer formulation for the converter, the refractory thickness is calculated as:

$$t = R_2 - \frac{R_2}{exp\left\{ \frac{k_r\left(T_1 - T_3\right)}{R_3\left[h_s\left(T_3 - T_a\right) + \sigma\varepsilon\left(T_3^4 - T_a^4\right)\right]} - \frac{k_r}{k_s}\, ln\left(\frac{R_3}{R_2}\right)\right\}} \tag{4}$$

Where h_s is the convection coefficient of the shell and k_r and k_s are the conduction coefficients of the refractory and the shell respectively. In Equation 4 (Steady-state heat transfer formulation), T_a is the temperature of the surrounding air, σ is the Stephen-Boltzmann coefficient and ε is the emissivity of the steel shell.

In order to increase the accuracy of the model, the conductivity and convection coefficients are introduced to the model as functions of temperature. The emissivity of the steel shell at each inspection spot is obtained experimentally via using an infrared camera and a surface contact thermocouple. For each point, the emissivity setting of the infrared camera is changed until the camera temperature reading matches that of the contact thermocouple. Once the temperature match is achieved, the value of the emissivity setting in the infrared camera is recorded as the emissivity of the shell at that measurement point. This method has been successfully tested in refractory thickness measurement for a slag cleaning converter [11].

During the preliminary site testing the refractory thicknesses were measured at three different locations of a converter. The calculated thicknesses successfully matched the results obtained from the AU-E method at the same spots.

The thermographic pictures of the slag cleaning converter are illustrated in Figure 13 through Figure 15. A comparison between the AU-E and infrared methods is provided in Table 1.

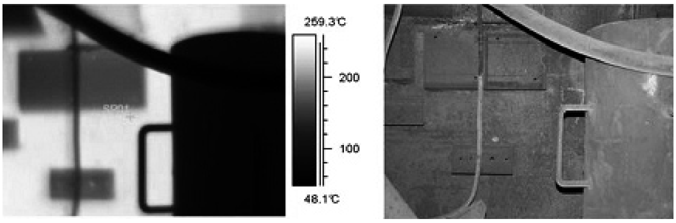


Figure 13: Thermographic image of the slag cleaning converter – Position 1

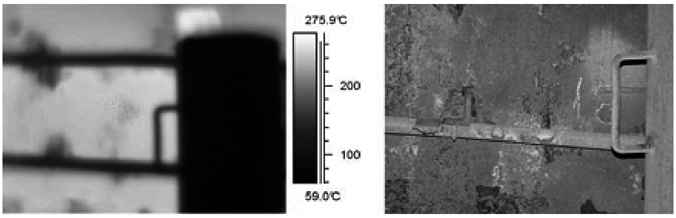


Figure 14: Thermographic image of the slag cleaning converter – Position 2

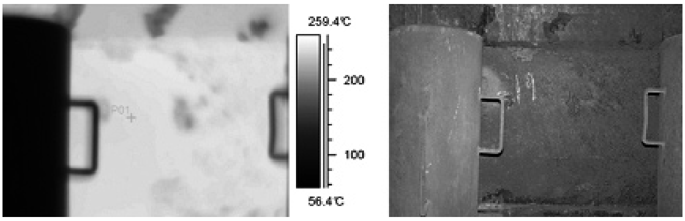


Figure 15: Thermographic image of the slag cleaning converter – Position 3

Table 1: Comparison between the AU-E and infrared results for the slag cleaning converter

Position #	AU-E Method	Infrared Method	Deviation from AU-E [%]
1	403 mm [15.88″]	374 mm [14.71″]	7%

2	367 mm [14.45″]	390 mm [15.36″]	-6%
3	357 mm [14.07″]	357 mm [14.07″]	0%

FINAL REMARKS

The Hatch NDT Group is experienced in conducting periodic furnace inspections and installing systems for continuous monitoring. Regular NDT evaluation, combined with the control system data, helps to extend both the campaign life of the furnace and the lifespan of its components. Over the years, thanks to cooperation with our clients and the Hatch Furnace Group, we have developed and patented several NDT techniques and monitoring systems that became standard components of the furnace maintenance operations [12].

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