An Insight on Non-Destructive Testing of Refractory Materials for Continuous Monitoring to prevent Unusual Breakdown

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ABSTRACT

Refractory materials constitute the foundational thermal and chemical barriers in high-temperature industrial reactors, including steelmaking furnaces, cement rotary kilns, glass tanks and petrochemical reformers. During operation, these linings are subjected to severe thermomechanical stresses, aggressive chemical slag corrosion and abrasive wear, making refractory degradation a leading cause of catastrophic equipment failure and unplanned plant shutdowns. The article provides a comprehensive review of modern Non-Destructive Testing (NDT) methodologies engineered for the continuous, real-time monitoring of refractory systems to prevent premature breakdowns and optimize in-service utilization. A systematic evaluation of several advanced diagnostic techniques like conventional Ultrasonic Testing (UT), the non-contact Laser Ultrasonic Pulse (LUP) method, Infrared Thermography (IRT), passive Acoustic Emission (AE) monitoring and endoscopic visual inspections is discussed. Industrial case studies demonstrate that LUP successfully tracks high-temperature microstructural degradation up to 1000 °C by calculating dynamic elastic properties in real time. Concurrently, IRT is analysed as a predictive tool in Fluid Catalytic Cracking Units (FCCU) and process heaters to map thermal flux trends, estimate residual lining thickness and eliminate emergency shell failures. Passive AE algorithms, utilizing localized piezo-electric sensors, are examined for their capacity to isolate micro-crack propagation under cyclic fatigue loading. Moreover, there is emerging paradigm of fusing multi-sensor NDT data streams with artificial intelligence (AI) and machine learning models to construct real-time "Digital Twins" of high-temperature vessels.

Keyword: NDT, Ultrasonic testing, LUP, Acoustic emission, Infra-red thermography

INTRODUCTION

Refractory linings are critical thermal and chemical barriers in high-temperature manufacturing processes. However, aggressive operational environments cause severe degradation such as thermal spalling, alkali infiltration and creep. If the insulating layer fails, the outer load-bearing carbon steel shells exceed their safe operating limit of 343 °C and experience rapid thermal softening above 540 °C, risking catastrophic rupture and dangerous loss of containment. To prevent breakdowns, modern industrial practices undergo transitions from reactive schedules to continuous, in-situ Non-Destructive Testing (NDT). While conventional Ultrasonic Testing (UT) is restricted to moderate temperatures due to its reliance on physical couplants, the Laser Ultrasonic Pulse (LUP) method offers a premier non-contact alternative capable of performing in-situ measurements up to 1000 °C. LUP tracks wave transit times to calculate dynamic elastic properties, such as Young's Modulus and Poisson's ratio, directly quantifying microstructural damage. [1-5]

Additionally, Infrared Thermography (IRT) provides macroscopic monitoring by mapping external surface temperatures to detect thermal anomalies or hot spots. This allows engineers to estimate residual lining thickness and proactively plan targeted maintenance. For real-time crack tracking, passive Acoustic Emission (AE) monitoring uses piezoelectric sensors to detect elastic stress waves without external energy inputs. Analysing signal indices like LOAD and CALM ratios helps distinguish minor microstructural adjustments from unstable, active crack propagation. For inaccessible areas, endoscopy provides high-resolution visual checks without requiring complete cool-down cycles. [6-7]

The ultimate realization of modern refractory diagnostic engineering lies in multi-source data fusion. Fusing streams from LUP, IRT, AE and endoscopy into machine learning models, such as Convolutional Neural Networks, constructs a high-fidelity "Digital Twin" of the vessel. This active digital twin provides a real-time health map of the furnace interior, enabling precise predictive maintenance, minimizing operational risks and maximizing real-life service utilization.

Non-Destructive Testing (NDT) in Modern Inspection Techniques for Refractory Materials:

The refractories need to be inspected properly to prevent any accidents and material losses. In modern days the refractories are inspected through different techniques like, **Non-Destructive Testing (NDT) Methods, Endoscopic Inspection Method, Digital Imaging & AI-Based Analysis and Radiographic Testing (X-ray or Gamma Ray).[1]**

Ultrasonic Testing (UT)

- *Principle:***Ultrasonic Testing (UT)** is a widely used non-destructive testing (NDT) technique for detecting internal defects and evaluating the integrity of materials, especially metals and welded structures, this method is also known as **Shadow Method.**In this method, high-frequency ultrasonic sound waves, typically ranging from **0.5 to 20 MHz,** are generated by a transducer and transmitted into the test material through a coupling medium such as water, oil or gel. As the ultrasonic waves propagate through the material, they interact with internal boundaries such as cracks, voids, inclusions or porosity (Fig. 1). When the waves encounter these discontinuities, part of the energy is reflected back to the transducer while the remaining portion continues to travel through the material. The reflected signals are received and converted into electrical signals, which are displayed on a screen as wave patterns. By analysing the time of flight and amplitude of these signals, inspectors can determine the location, size and nature of internal flaws. UT is highly sensitive, accurate and capable of detecting very small defects without damaging the material.[1][2][3]

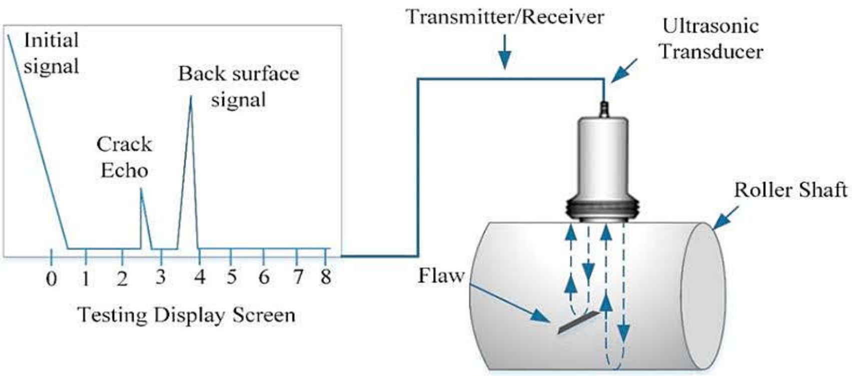

Fig.3. Ultrasonic Testing Basic Mechanism

- *Application:*Ultrasonic Testing (UT) is widely used in the inspection of refractory materials to detect internal defects and ensure their structural integrity. Refractories used in furnaces, kilns and reactors must withstand high temperatures and harsh operating conditions; therefore, detecting flaws before service is essential. UT helps identify internal discontinuities such as **unwanted porosity, cavities, cracks, inclusions and delamination** that may develop during manufacturing or service. High-frequency sound waves are transmitted through the refractory and any irregularities within the material reflect these waves back to the detector. By analysing the reflected signals, engineers can evaluate the internal quality, uniformity and density of refractory bricks or monolithic linings without damaging the component. This method improves reliability, safety and service life of refractory linings.[1][2][3]

There is a modified form of **Ultrasonic Testing (UT),** named **Laser Ultrasonic Pulse Method (LUP)** which is mentioned in so many research paper [5] and being widely used in several industries to monitor the internal defects (like, cracks, cavities and heterogenous structure or density) and the travelling time of the ultrasonic sound waves through the refractory material instead of using conventional **Ultrasonic Testing Method.** [5]

- ***Basic Difference between LUP and Conventional UT:*** The **Laser Ultrasonic Pulse (LUP)** method differs significantly from the **Conventional Ultrasonic Testing (UT)** method in terms of operation, contact requirement and application conditions. Conventional UT uses physical transducers that must be in direct contact with the material surface to transmit and receive ultrasonic waves. This contact-based approach requires "**Couplants"** and becomes difficult or unreliable at high temperatures, especially in harsh industrial environments.

  In contrast, the LUP method is a **Non-Contact Technique** that uses a high-energy laser to generate ultrasonic waves and a laser-based detector (LDV) to receive them. This allows testing without any physical interaction with the material.

  Another major difference is temperature capability. Conventional UT is typically limited to **room or moderate temperatures**, whereas LUP can perform **in-situ measurements up to 1000 °C**.

  Additionally, LUP provides more flexibility and can detect **microstructural damage (cracks, defects)** through changes in wave velocity and elastic properties, making it more advanced than conventional UT.[5]

- ***Effectiveness of LUP over Conventional UT:*** The Laser Ultrasonic Pulse (LUP) method is more effective than conventional UT because it enables non-contact, high-temperature testing, which is not feasible with traditional transducers. It can measure material properties in real-time up to 1000 °C, making it highly suitable for refractory materials in industrial conditions.

  LUP is also capable of detecting micro-level damage such as cracks and internal defects by analysing changes in ultrasonic wave velocity and elastic properties through the modified equation of Youngs' Modulus and Poisson's Ratio *Eqs. (1) & (2)*. Furthermore, it eliminates issues like couplant failure and sensor damage, ensuring higher reliability. Overall, LUP provides faster, safer and more accurate material evaluation in harsh environments.[5]

$$E = \frac{3v_L^2 v_T^2 - 4v_T^4}{v_L^2 - v_T^2}\rho \qquad (1)$$

$$\mu = 0.5\frac{v_L^2 - 2v_T^2}{v_L^2 - v_T^2} \qquad (2)$$

Where E is Young's modulus, μ is Poisson's ratio, v_L is the velocity of the longitudinal ultrasonic wave, $v_T$is the velocity of the transverse ultrasonic wave and ρ is the density of the sample.[5]

- ***Procedure of Laser Ultrasonic Pulse Method:*** In the Laser Ultrasonic Pulse (LUP) method, ultrasonic waves are generated and detected using lasers without physical contact. First, a high-energy pulsed **Nd:YAGLaser**(Fig. 2) is focused on the surface of the material. This laser energy is absorbed, causing a rapid local temperature rise and thermal expansion, which generates ultrasonic waves inside the material.These waves propagate through the sample in two forms:

  - Longitudinal waves (in ablation regime)
  - Transverse waves (in thermo-elastic regime)

On the opposite side, a **Laser Doppler Vibrometer (LDV)** detects these waves by measuring surface vibrations. The time taken by the waves to travel through the material is recorded. A small part of the laser beam with approx., 10^{-5} percentage of the energy was reflected by an anti-reflection coated glass onto a photodiode which triggered the LDV measurement (Fig. 4). A digital Oscilloscope showed the trigger signal of the photodiode and the measured ultrasonicwave signal of the LDV.

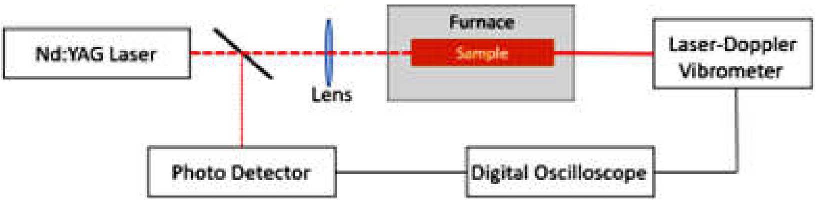

Fig. 4. Experimental setup. A single pulsed Nd:YAG laser was used to generate ultrasonic waves in the sample. These were detected by a Laser-Doppler-Vibrometer. The sample was heated to 1000 ◦C in a furnace. [5]

Using these travel times, the wave velocities are calculated. Then, with known material density, internal flaws and important mechanical properties such as Young's modulus and Poisson's ratio are determined using standard equations.

The experiment is often conducted in a high-temperature furnace, enabling real-time evaluation of material behaviour under extreme conditions. [5]

- ***Case Study of Laser Ultrasonic Pulse Method in Assessment of Intrinsic Damages in Refractory Materials at Harsh Industrial Environment:***
  In several researches [5] it has been demonstrated that the **Laser Ultrasonic Pulse (LUP)** method is highly effective for evaluating damage in refractory materials, supported by experimental data, graphs and statistical trends. In this particular research paper four different types of cylindrical ceramic samples with a length and a diameter of 50 mm were used.**Table 1**[5]contains the composition of the four ceramics alumina (KE99) andalusite (SA60), fused silica (SFQ) and high alumina composite (I_M0) produced by Steuler refractory linings.[5]

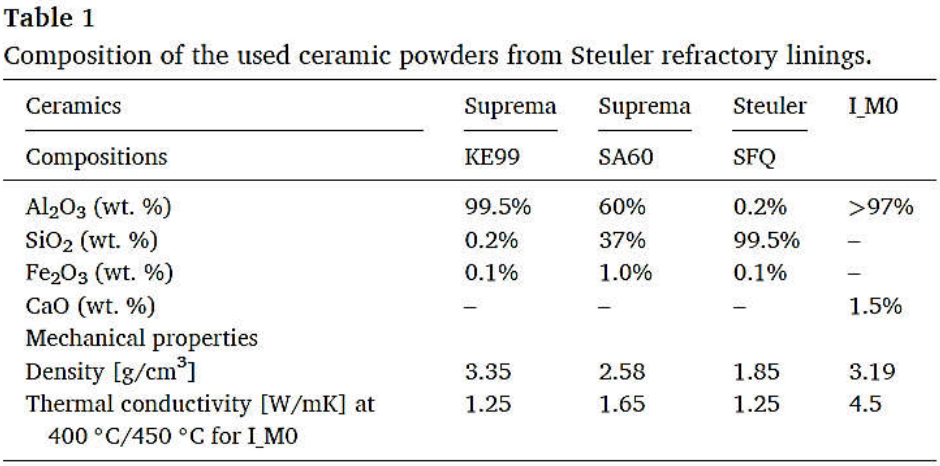

Table 1

Composition of the used ceramic powders from Steuler refractory linings.

Ceramics	Suprema	Suprema	Steuler	I_M0
Compositions	KE99	SA60	SFQ	
Al_2O_3 (wt. %)	99.5%	60%	0.2%	>97%
SiO_2 (wt. %)	0.2%	37%	99.5%	–
Fe_2O_3 (wt. %)	0.1%	1.0%	0.1%	–
CaO (wt. %)	–	–	–	1.5%
Mechanical properties				
Density [g/cm^3]	3.35	2.58	1.85	3.19
Thermal conductivity [W/mK] at 400 °C/450 °C for I_M0	1.25	1.65	1.25	4.5

Fig.5 illustrates how **Young's modulus** of four ceramic materials (KE99, SA60, SFQ and I_M0) varies with **temperature and applied pressure**. Initially, measurements were taken at three temperatures, followed by repeated testing after applying increasing loads (up to 57.5 N/mm²) until failure. For **unloaded samples**, Young's modulus increased with temperature for KE99 (+15 GPa, 12%), SA60 (+30 GPa, 86%) and SFQ (+5 GPa, 26%), but decreased for I_M0 (24 GPa, 17%). The increase is attributed to **closure of microcracks due to thermal expansion,** which improves wave propagation. However, I_M0 behaved differently due to its **cement-based matrix (CaO content)**, making it less responsive to thermal expansion. When pressure was applied, Young's modulus **decreased in all materials** due to crack formation and spalling. At maximum load, reductions were observed: KE99 (23 GPa), SA60 (12 GPa), SFQ (13 GPa) and I_M0 (45 GPa), indicating damage sensitivity.[5]

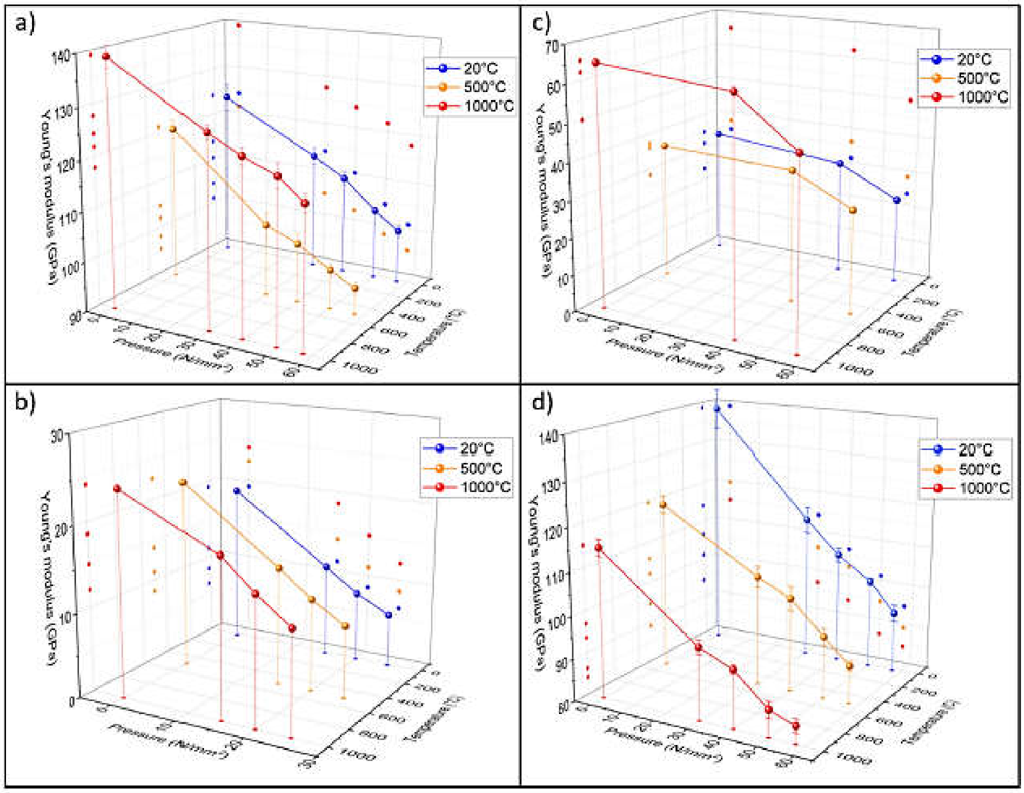

Fig. 5. Temperature and pressure dependence of Young's modulus measured using the LUP method for (a) KE99, (b) SA60, (c) SFQ and (d) I_M0.[5]

To evaluate thermal shock damage, samples were heated to **950 °C** and rapidly quenched to **10 °C**, repeating up to **20 cycles**. This caused significant degradation in mechanical properties. For **KE99,** Young's modulus dropped sharply from **116 GPa to 7 GPa after 10 cycles**, (Fig. 6) with the largest decrease occurring after the first cycle. It's **Poisson's ratio also reduced** from 0.31 to -0.05, indicating severe internal damage.[5]

Similarly, **SA60** showed a decline from **24 GPa to 3 GPa (20 cycles)** and Poisson's ratio from 0.17 to -0.21. **I_M0** exhibited rapid deterioration, decreasing from **254 GPa to 11 GPa within just 6 cycles**, with Poisson's ratio dropping from 0.39 to 0.21. These rapid reductions suggest **low thermal shock resistance**.

In contrast, **SFQ** showed a gradual and smaller decrease in Young's modulus **(18 GPa to 11 GPa)** while Poisson's ratio remained constant (0.25), indicating **better resistance to thermal shock.**[5]

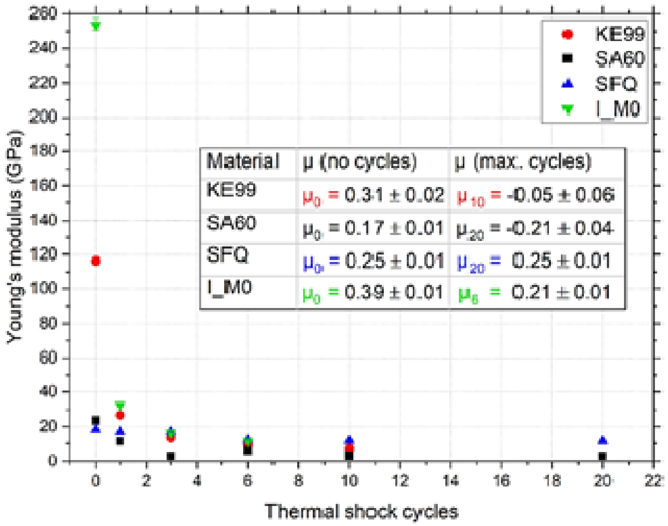

Fig. 6. Thermal shock cycle dependence of Young's modulus and Poisson's ratio for KE99 (red), SA60 (black), SFQ (blue) and I_M0 (green). [5]

Young's modulus and Poisson's ratio are key indicators of **crack formation and damage** in refractory materials, as confirmed by microscopic observations in Fig. 7. In initially undamaged samples, both properties show a **sharp decrease within the first two thermal shock cycles** if the material has low resistance to rapid temperature changes. This early drop highlights the initiation of **microstructural and macroscopic cracks**, clearly visible when comparing an undamaged sample (no cracks) with a thermally shocked one (visible crack network).[5]

Thermally damaged ceramics exhibit behaviour similar to **mechanically pressed samples**, as both show reductions in elastic properties due to internal damage. However, a key difference is that in thermal shock conditions, the **major degradation occurs very early (first few cycles)** rather than gradually.

Overall, material damage can be effectively evaluated through the **reduction of Young's modulus and Poisson's ratio**, along with direct observation of crack development, making these reliable indicators for assessing thermal shock resistance.[5]

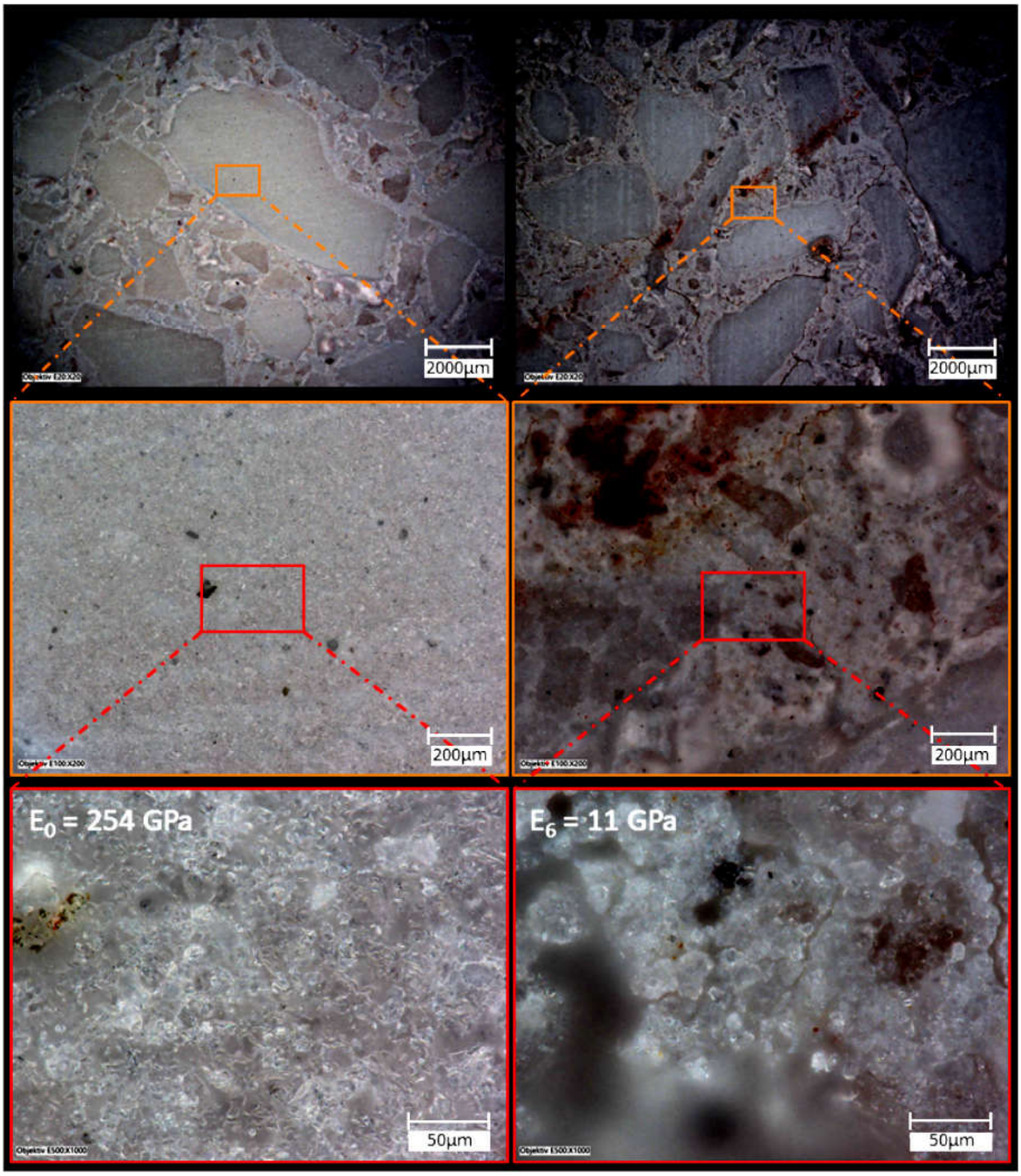

Fig. 7. Digital microscope images of the thermal shock influence on Young's modulus and crack formation of an I_M0 sample (right) compared to an unharmed sample (left).[5]

Overall, the results prove that LUP can accurately track damage evolution, thermal shock resistance and material degradation, making it a powerful tool for real-time monitoring of refractory materials.[5]

Infrared Thermography (IRT)

- *Principle:*Infrared Thermography is widely used in the petroleum, iron-steel and copper industry to monitor equipment and reduce costs. It is especially useful for inspecting refractory linings, heat-resistant materials used to protect vessels, piping, furnaces and flue gas ducts operating at high temperatures. These linings shield the outer structure from extreme heat and chemical exposure. If refractory linings fail, it can lead to serious damage and safety risks.[1][2][3]

  Thermography allows real-time, non-contact monitoring of linings while the plant is still operating. A five-year monitoring program on a **Fluid Catalytic Cracking Unit (FCCU)** in a UK refinery showed significant benefits. It helped engineers identify damaged areas early and plan maintenance before shutdowns. Earlier, repairs were only done after internal visual inspections during shutdowns.[6]

  With thermographic monitoring, unplanned refractory repairs were almost eliminated. The method is also effective for monitoring process furnaces and flue gas ducting, improving maintenance planning, safety and overall efficiency.[1][2][3]

Fig. 8. Infrared Camera

- ***Effect of Refractory Lining Failures:*** In a reactor of vessels, the materials move at high speed and it's highly erosive. Refractory linings are used to resist erosion and provide insulation, protecting the outer carbon steel shell from extreme heat. Carbon steel has a maximum safe temperature of **about 343°C** and **above 540°C**, it loses strength rapidly and cannot withstand the internal pressure.[6]

  If the refractory lining fails, the hot materials can quickly erode or weaken the steel shell, leading to equipment failure. This can cause leaks, posing serious safety risks, including fires and damage to the plant.

Although refractory technology has improved over the past **50 years**, failures are still a common cause of unplanned unit shutdowns. Since, furnace and reactors are the critical units in refineries, their failure affects overall operations and profitability. Unplanned shutdowns can be extremely costly, typically ranging from **$500,000** to **$1,000,000** per day depending on unit size and market conditions.[6]

- ***Refractory Condition Monitoring Using Temperature Trends:*** Temperature measurements in the FCCU were recorded every two weeks at 124 locations and organized into sections for trend analysis. These trends helped monitor refractory condition indirectly by tracking surface temperature changes. Since much of the refractory was new and recently inspected, a reliable baseline was established.

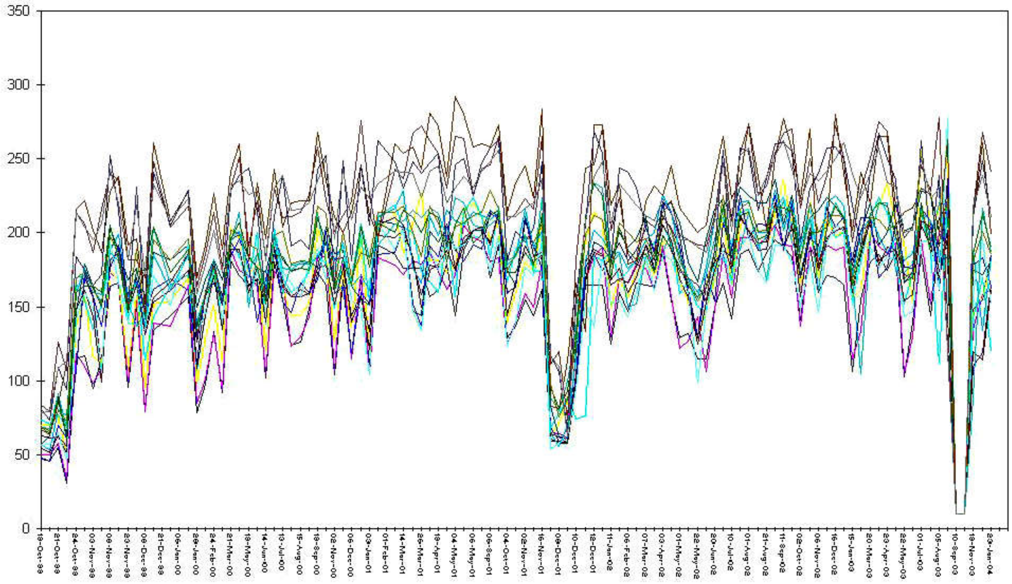

Fig. 9. Trend of Riser Surface Temperature Results Over Time. [6]

Because measuring emissivity and ambient conditions at every point was impractical, standard values for emissivity, reflected temperature, distance and humidity were used. Although this introduced some inaccuracy, consistent use of these values allowed reliable trend comparisons over time. Areas showing rising temperature trends were identified as potential problem zones and examined more closely.

Environmental factors like wind speed and direction could affect readings, but their impact was minimized due to repeated long-term measurements and high process temperatures. Wind conditions were still recorded for reference. Occasional sudden changes in temperature data were linked to plant shutdowns or process disturbances. After such events, full inspections were conducted since rapid thermal changes increase the risk of refractory damage.

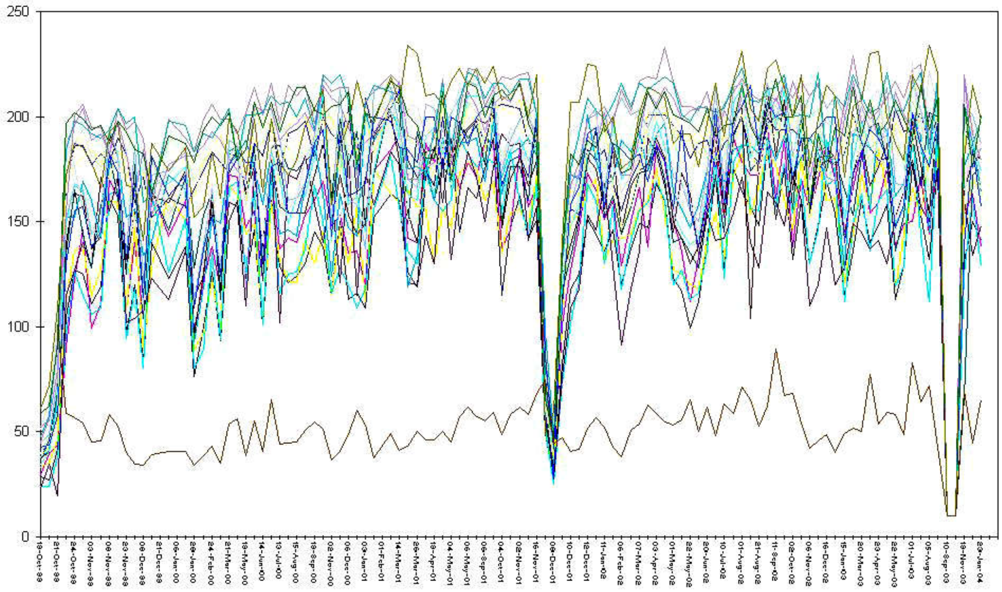

Fig. 10. Trend of Regenerator Shell Surface Temperature Results Over Time [6]

Fig. 9and Fig. 10 are the examples from the monitoring spreadsheet and show the surface temperature trend over the last five years for two different areas of the plant. In these five years, temperature trends generally increased, which is normal as catalyst erosion reduces refractory thickness, increasing heat transfer to the outer shell. Using known thermal conductivity data, engineers estimated remaining refractory thickness and predicted maintenance needs accurately.

This monitoring program significantly improved maintenance planning. During a planned shutdown in 2003, unplanned refractory repairs in monitored areas were completely eliminated, saving several hundred thousand dollars.[6]

- ***Case Study Over the Qualitative Survey Results****:* During the qualitative thermographic surveys, a crack-like defect was observed in the Feed Riser refractory (Fig. 11). This issue was first detected in April 2003, after which the monitoring frequency was increased from routine checks to once per week. Based on the highest recorded surface temperatures, a fitness-for-service assessment was carried out to evaluate the severity of the defect. At the same time, contingency plans were prepared to replace the affected section of the riser if a shutdown became necessary.

Continuous weekly monitoring allowed engineers to track the condition of the defect closely. Since no critical deterioration occurred immediately, the plant was safely kept in operation until the scheduled shutdown in September 2003. This approach helped the refinery avoid the high costs associated with an unplanned shutdown.

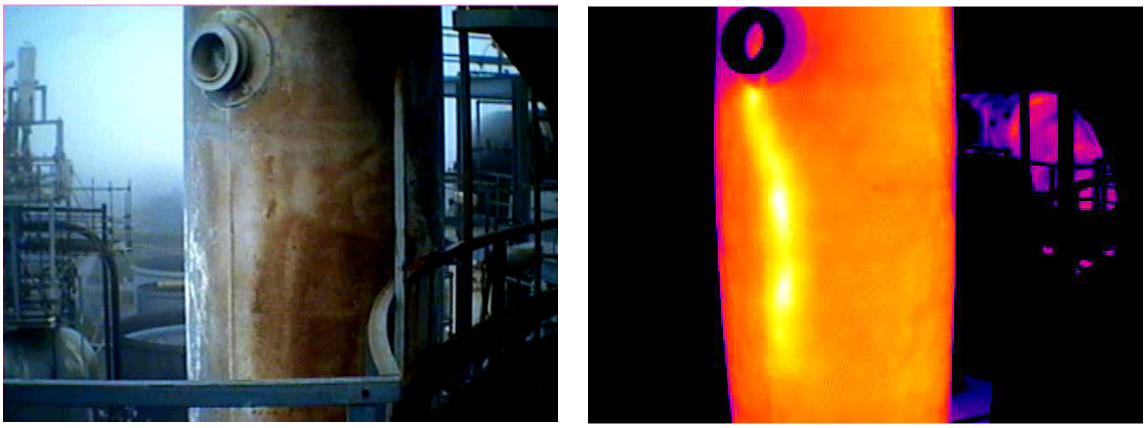

Fig. 11. Crack like defect in riser refractory lining. [6]

During the planned shutdown, internal inspection of the riser revealed that a section of the refractory lining had broken away, forming a V-shaped cross-section over a length of about 10 meters. The damaged portion was completely replaced during the same shutdown period.[6]

The air lines connecting the axial compressor to the regenerator pass through an air heater furnace, which is used in blast furnace. During this phase, the catalyst is heated to a temperature that allows combustion of torch oil injected into the catalyst bed. This process raises the temperature to the required operating level before introducing the oil feed into the system.

After the air heater, the airlines are lined with refractory material to protect them from high temperatures experienced during process. Routine qualitative thermographic surveys identified a hot spot in one of these air lines, indicating that some refractory lining had fallen away inside the pipe (Fig. 12).[6]

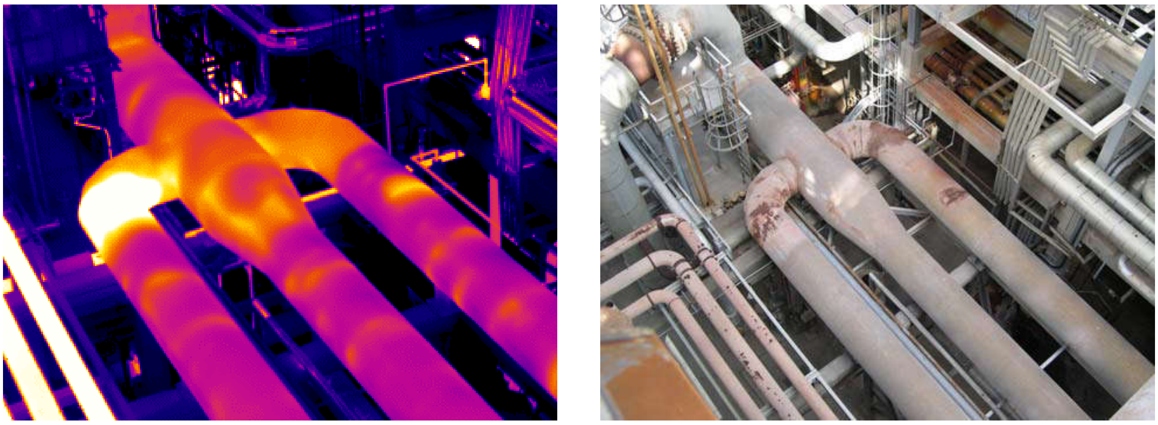

Fig.12. Thermal Image of Hotspot on Air Line. [6]

This failure was likely caused by rapid temperature rise during start-up, leading to different expansion rates between the refractory and the steel shell. As a result, the refractory detached from its support and fell off.[6]

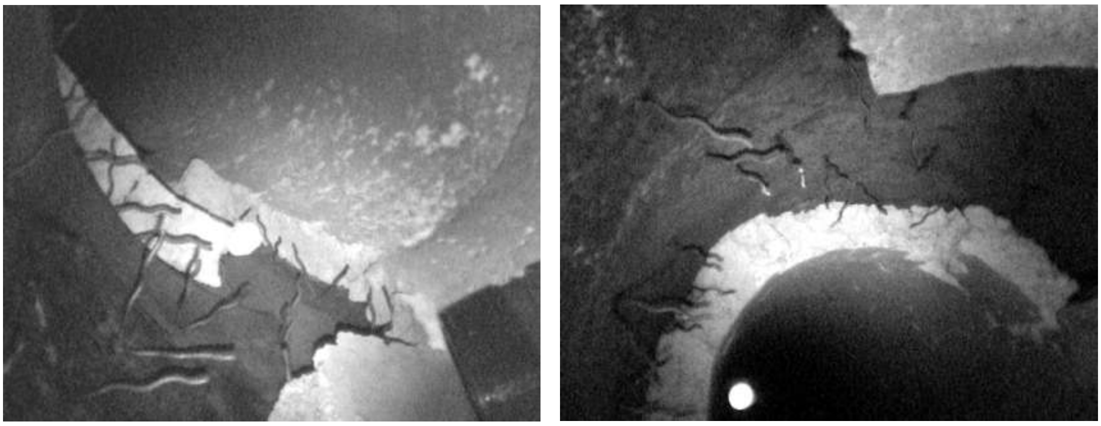

Fig. 13. Internal Refractory Damage. [6]

During the planned shutdown, internal inspection confirmed a missing section of refractory lining at the same location (Fig. 13). After repairs were completed, a follow-up thermographic image taken during start-up showed that the hot spot had disappeared, confirming successful restoration of the refractory lining (Fig. 14).[6]

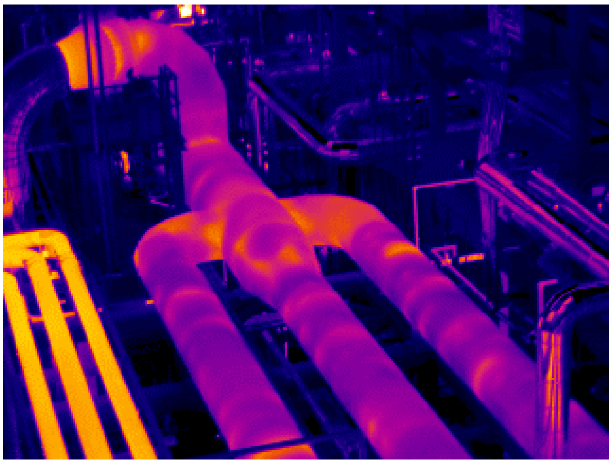

Fig. 14. Thermal Image of Air Line After Repairing the Lining. [6]

Acoustic Emission (AE)

- *Principle:* Acoustic Emission (AE) is a non-destructive testing (NDT) technique used for real-time, in-situ monitoring of damage evolution in materials and structures. The fundamental principle of AE is based on the generation of transient elastic waves when a material undergoes sudden internal changes such as crack initiation, crack propagation, plastic deformation or fibre breakage. These rapid energy releases stress waves (Acoustic Emission Waves) that travel through the material.[1][2][3]

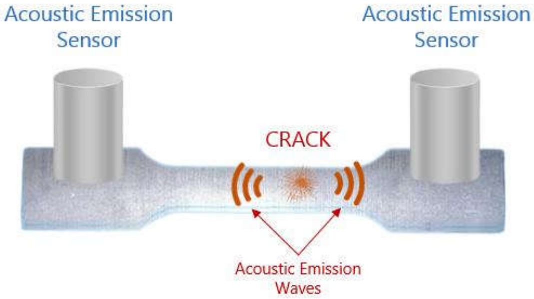

Fig. 15. Crack Propagation & Stress Waves.

Sensitive AE sensors, typically piezoelectric transducers, are attached to the surface of the structure to detect these waves. The detected signals are then amplified, processed and analysed to determine the source and severity of the damage. Unlike conventional NDT methods, AE does not require external energy input; instead, it listens to the energy released by the material itself.[1][2][3]

Fig. 16. AE Sensors are Attached at The Surface

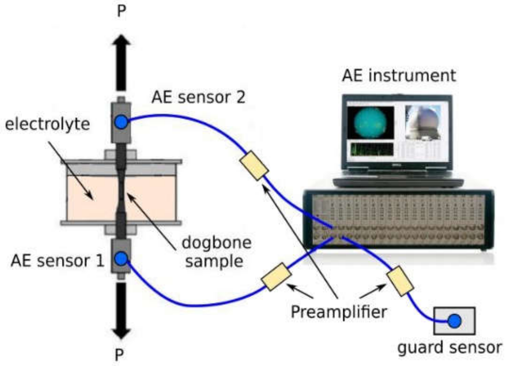

Fig. 17. Amplification and Analysis of Detected Signals

This technique is widely used to study fracture behaviour and assess structural integrity in pressure vessels, pipelines and industrial components. It enables early detection of defects, continuous monitoring under load and helps to prevent sudden failures by identifying active damage zones.[1][2][3]

- ***Study of Experimental Assessments****:* In a research paper of **KU LEUVEN**and**TATA STEEL,** it has been studied that, AE was used to determine the critical damage limits of refractory materials under cyclic loading. To support this, monotonic and cyclic three-point bending tests were performed, along with cyclic strain-controlled fatigue tests for validation.[7]

Two silica refractories with different brittleness were tested. Due to differences in their microstructure, especially existing micro-cracks, the materials showed different abilities to damp elastic waves. This created bias in AE results, making direct comparison difficult.

However, by using specific AE analysis methods like LOAD and CALM ratios along with controlled cyclic loading, this bias was reduced. These methods successfully identified critical strain levels that cause varying degrees of damage in refractories. The results matched well with fatigue resistance limits observed in the materials.[7]

Table 2. Materials Properties [7]

Sample	SB	MB
Chemical composition	SiO_2 97% Al_2O_3 1% CaO 2%	SiO_2 97% Al_2O_3 2% CaO 1%
Mineral composition	Cristabolite 23% Tridymite 77%	Cristabolite low 82% Anorthite/sodian 3% Amorphous 15%
Density	1880 kg/m^3	1870 kg/m^3
Porosity	19 %	19 %
Bending strength	8.8 MPa	2.5 MPa
Dynamic Young's modulus	8.5 GPa	4.2 GPa
Avg. sound velocity	2600 m/s	1810 m/s

- *Experimental Materials:*Two types of commercially available silica-based refractory bricks were studied. The first, **Silica Brick (SB)**, is made from quartz by pressing and sintering at **around 1500°C**. The second, **Modular Brick (MB)**, is produced by casting a mixture of fused silica grains and calcium aluminate cement. Before testing, MB was heat-treated at **about 1400°C** for **100 hours** to simulate the crystallization that normally occurs during early service. Both materials are commonly used in glass manufacturing units and coke ovens in the steel industry. Their chemical and physical properties are listed in **Table 2**.[7]

- *Experimental Procedure and Equipments:*The experiments were conducted at room temperature in two different labs. At KU Leuven, monotonic and cyclic three-point bending tests were performed with Acoustic Emission (AE) monitoring. The samples dimension is 40×40×150 mm^3, with a support span of 120 mm and were tested using a Shimadzu AG-X Plus machine (100 kN capacity). Load was applied under displacement control at 0.4 mm/min. Four AE sensors (two on top and two below) were placed 5 cm apart. AE data was recorded using a Vallen AMSY-5 system. Sensors operated between 250-700 kHz and signals were pre-amplified by 34 dB. A threshold of about 38.5-40 dB was set to filter noise.

AE hits are signals above the threshold and multiple hits from the same source are called events. Key AE analysis methods include the Kaiser effect (no AE until previous maximum load is exceeded, indicating low damage) and Felicity effect (AE occurs earlier, indicating damage). These are evaluated using the Load Ratio (LR): LR > 1 shows stable material, while LR < 1 indicates micro-cracking. The Calm Ratio (CR) measures AE during unloading; CR = 0 means intact material, while CR > 0.05 indicates severe damage. At Tata Steel, cyclic fatigue tests were conducted on smaller samples (25×25×150 mm^3) using a Zwick Roell machine. Loading was applied at 0.3 mm/min with up to 7000 cycles, simulating real service conditions.[7]

- *Experimental Observation & Evaluation:*Modular Brick (MB) shows lower ultrasonic velocity and dynamic Young's modulus compared to Silica Brick (SB) (Table 2). This difference is due to variations in mineral composition and heat treatment during production.

  From monotonic loading tests (Fig. 18), SB exhibits higher strength but lower strain before failure, indicating brittle behaviour without strain softening. In SB, Acoustic Emission (AE) activity begins at lower displacement and most AE energy is released suddenly at failure (Fig. 18a).

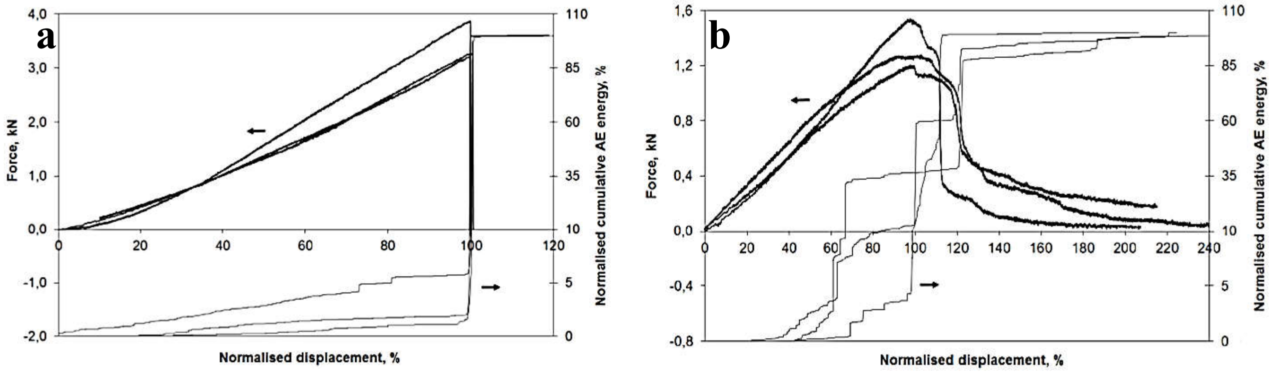

Fig. 18. Results of monotonic bending tests for three representative samples. The AE energy is normalised to the total for the experiment; the displacement is normalised to the displacement at the maximal force (a) SB (b) MB.[7]

In contrast, MB has lower strength and shows gradual strain softening. Its micro-cracks reduce strength but help create a more complex and branched crack path. AE energy graphs for MB show several bursts, indicating formation or growth of cracks (Fig. 18b). Unlike SB, large cracks in MB do not immediately cause failure, showing better crack resistance.

SB produces higher cumulative AE energy than MB. However, MB contains more micro-defects, which dampen AE signals and make direct comparison difficult. Also, for monotonic tests, there are no clear AE methods to determine critical damage based only on absolute AE data.[7]

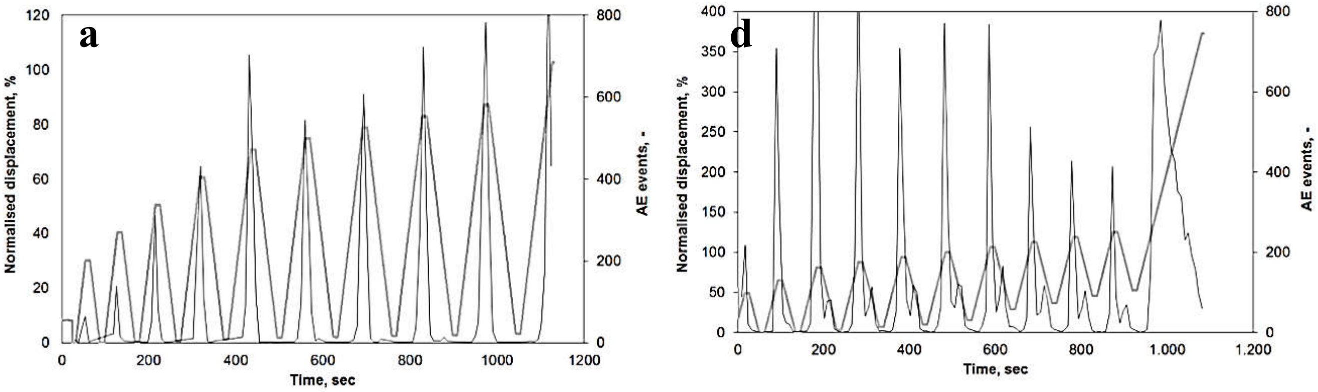

Fig. 19. Typical results of a cyclic test with AE monitoring on a sample of (a) SB (b) MB. The displacement is normalised to the displacement at max. force.[7]

Fig.19 shows key differences in Acoustic Emission (AE) activity during cyclic tests for both materials. In Silica Brick (SB) (Fig. 19a), AE activity mainly occurs during the loading phase, seen as peaks in the event graph. This indicates that most cracking happens when stress is applied.

In Modular Brick (MB) (Fig. 19b), significant AE activity is observed during both loading and unloading phases. This suggests more continuous crack movement and interaction inside the material.

During cyclic tests, MB shows a higher total number of AE events and greater energy than SB. This means more internal damage activity occurs in MB. It also indicates that the cyclic loading method helps overcome the effect of signal damping in MB, making AE detection more effective.[7]

Table 3. Avg. Normalised Displacement Limits.[7]

	SB	MB
LOAD ratio	46 ± 8 % (L1)	61 ± 9% (L2)
CALM ratio	68 ± 15 % (L2)	48 ± 7 % (L1)

The AE damage limits obtained from LOAD and CALM ratios were compared with cyclic fatigue results (Fig. 20). Two limits were identified:

L1 for intermediate damage and L2 for heavy damage, with values given in Table 3.

Most failed samples followed a power law trend and fell in the heavy damage zone (beyond L2 in Fig. 20). Samples that did not fail were found in the intermediate damage zone (between L1 and L2). No fatigue failure was observed for samples with loading amplitudes below L1.

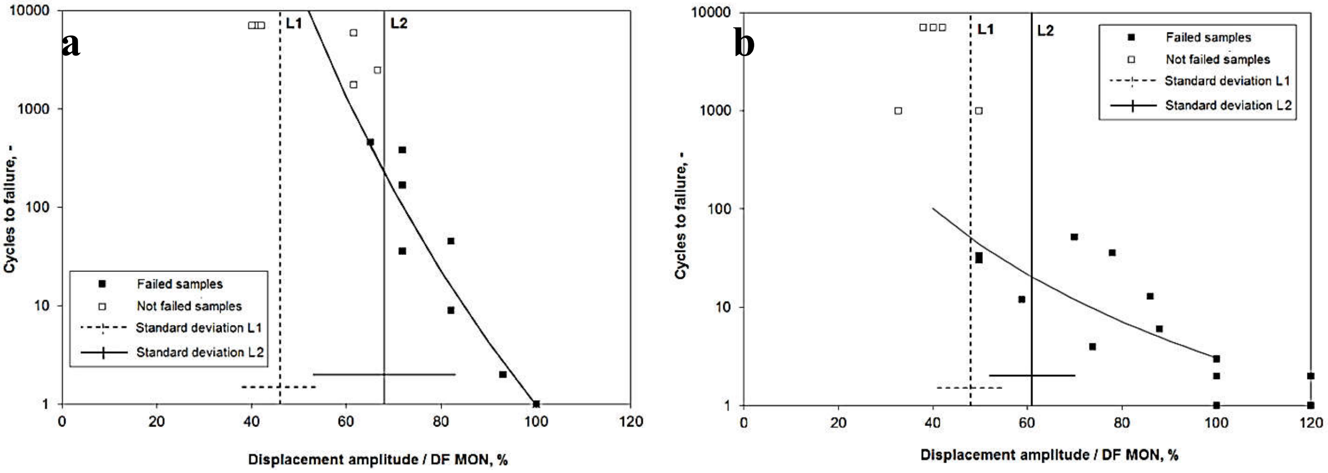

Fig. 20. Correlation of the displacement amplitude and cycles to failure for the fatigue tests on (a) SB and (b) MB.DF MON is the displacement at the max. force, avg. for the monotonic loading tests. The inclined line is the best power law fit for the failed samples.[7]

This shows a clear relationship between AE-based damage limits and fatigue behaviour. The correlation between fatigue resistance and damage levels is similar to patterns previously observed in concrete materials, as discussed by Hsu.

Endoscopic Inspection Method

- *Principle:* Endoscopic or visual inspection is a non-destructive testing (NDT) technique used to examine the internal condition of refractory linings in furnaces, kilns and reactors without dismantling the equipment. The principle is based on direct visual observation using optical devices such as borescopes or endoscopes. These instruments consist of a flexible or rigid probe equipped with a light source and a high-resolution camera, which is inserted through small openings or access ports.

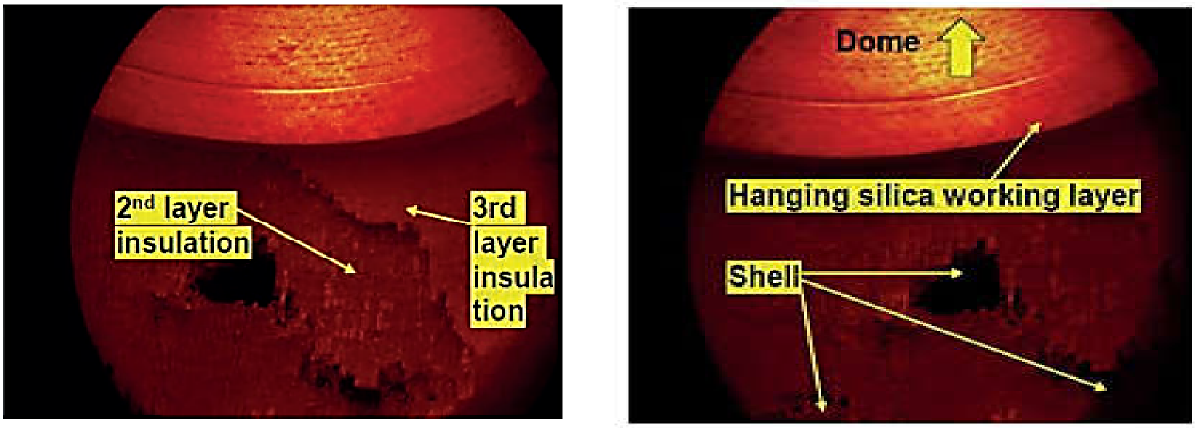

Fig. 21. Endoscopic Images of Hot Furnace (Before Lining)

The camera transmits real-time images or videos to an external monitor, allowing inspectors to closely observe the internal surfaces. This helps in identifying defects such as cracks, spalling, erosion, slag buildup and lining wear. Since it provides a direct view, it is highly effective for assessing localized damage and surface conditions.

Fig. 22. Endoscopic Images of Hot Furnace (After Lining)

Endoscopic inspection is widely used for routine maintenance and condition assessment, as it is quick, cost-effective and does not require shutdown or extensive disassembly of industrial systems.

- *Application:* Endoscopic or visual inspection is widely applied for examining the internal condition of refractory linings in furnaces, kilns and reactors without dismantling the equipment. It enables the detection of defects such as cracks, delamination, erosion and slag build-up by providing a clear, real-time view of internal surfaces even for confined or complex geometries where direct human access is difficult or unsafe.

Flexible or rigid borescopes can be inserted through small openings, allowing detailed inspection of hard-to-reach areas. It is particularly valuable during maintenance checks, shutdown inspections and troubleshooting. By identifying damage early, this technique helps in planning targeted repairs, reducing downtime and ensuring safe and efficient operation of industrial systems.

Fig. 23. Endoscopic Camera

- *Advantages:* Endoscopic or visual inspection offers several important advantages in industrial applications, particularly in monitoring refractory linings. One of the primary benefits is reduced downtime, as inspections can often be carried out without complete dismantling or prolonged shutdown of equipment. This leads to significant cost savings in both maintenance and production losses. The method also allows real-time assessment of internal conditions, enabling quick identification of defects such as cracks, erosion, or slag accumulation.

  Additionally, it supports effective maintenance planning by providing accurate information about the extent and location of damage. This helps engineers schedule timely repairs and avoid unexpected failures. By identifying only the affected areas, it also optimizes refractory material usage, reducing unnecessary replacements and improving overall operational efficiency. [2]

Digital Imaging & AI-Based Analysis

- *Principle:* Digital imaging combined with artificial intelligence (AI) has significantly advanced non-destructive testing (NDT) of refractory materials by enabling automated, accurate and real-time inspection. The principle involves capturing high-resolution visual and thermal images of refractory linings using cameras such as infrared thermography and optical imaging systems. These images contain detailed information about surface conditions and temperature distribution.
- Machine Learning algorithms, particularly in computer vision, process this data to detect patterns and anomalies. By training on large datasets of known defects, AI models can identify issues such as cracks, spalling, erosion and hot spots with high precision. The system continuously analyses incoming data, allowing early detection of damage and monitoring of its progression.

  This integration enables predictive maintenance by forecasting potential failures, reducing manual inspection efforts, improving reliability and ensuring safer, more efficient operation of high-temperature industrial systems.

- *Application:* To continuously monitor refractory condition using **Digital Imaging & AI-based analysis**, we combine multiple non-destructive testing (NDT) data sources into a single intelligent system and then use Machine Learning (ML) to detect damage patterns.

  First, each technique provides a different type of information. **Laser Ultrasonic Pulse (LUP)** gives internal properties like wave velocity and modulus, which indicate structural integrity. **Acoustic Emission (AE)** detects micro-cracking activity in real time. **Infrared Thermography (IRT)** provides thermal images that show hot spots and insulation loss. **Endoscopic inspection** supplies visual images of cracks, spalling and surface defects inside the furnace.

  Next, all this data is digitized and synchronized. Thermal images, AE signals, ultrasonic waveforms and visual images are processed to extract features such as temperature gradients, signal amplitude, frequency, crack size and defect location.Machine learning models (like, CNNs and LSTM) are then trained using historical labelled data. These models learn to recognize patterns linked to damage levelearly cracks, refractory thinning or severe failure zones.The system continuously compares real-time data with learned patterns. If abnormal trends appear the AI flags a potential failure.

  Finally, the output is visualized as a **digital dashboard or “Digital Twin”**, showing health maps of the furnace lining. This enables predictive maintenance, reduces unplanned shutdowns and improves safety by detecting damage long before failure occurs.

- *Advantages:* Advantages encompass enhanced accuracy, reduced downtime and the ability to predict failures before they occur, leading to optimized maintenance schedules and extended refractory life. This approach minimizes human error and ensures consistent quality control. [4]

CONCLUSIONS

1) This research establishes that integrating active, multi-sensor NDT diagnostics transitions refractory lifecycle management from a reactive, high-risk paradigm to a highly reliable predictive workflow. Laser Ultrasonic Pulse (LUP) testing serves as an invaluable tool for real-time high-temperature elastic characterization, with both Young's modulus (E) and Poisson's ratio (μ) accurately quantified to detect early-stage microstructural micro-cracking and spalling.

2) Macroscopically, Infrared Thermography (IRT) offers a continuous and reliable mechanism to track lining thinness and thermal anomalies via outer-shell temperature trends, preventing sudden steel shell ruptures and reducing maintenance expenditures by hundreds of thousands of dollars.

3) Furthermore, passive Acoustic Emission (AE) monitoring successfully resolves the internal damage accumulation under cyclic loading, identifying safe operational envelopes below the critical L_1 threshold and using LOAD/CALM ratios to evaluate fatigue limits. Incorporating visual endoscopic inspections for localized hot face assessments allows for comprehensive joint diagnostics. Ultimately, combining localized LUP microstructural tracking, continuous IRT thermal flux mapping, and AE stress-wave monitoring into an AI-driven digital twin framework provides a robust path toward optimizing in-service utilization, minimizing unexpected breakdowns, and ensuring sustainable operation in extreme high-temperature industrial environments.

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