



HPIL MANPOWER LEARNING AND DEVELOPMENT

REFRACTORY FUNDAMENTALS TRAINING MANUAL



Hi Prevue International Limited
Subsidiary of HPI Global, Canada

Module 1

Introduction to Refractories in Gas to Liquid Projects

Importance of Refractory Systems

Refractories are inorganic, nonmetallic, porous and heterogeneous materials composed of thermally stable mineral aggregates, a binder phase and additives. The principal raw materials used in the production of refractories are: the oxides of silicon, aluminum, magnesium, calcium and zirconium and some non-oxide refractories like carbides, nitrides, borides, silicates and graphite.

The main types include fire-clay bricks, castables, ceramic fiber and insulating bricks that are made in varying combinations and shapes for diverse applications. The value of refractories is judged not merely by the cost of material itself, but by the nature of the job and/or its performance in a particular situation. Atmosphere, temperature, and

the materials in contact are some of the operating factors that determine the composition of refractory materials.

What are Refractories used for?

Refractories are used by the metallurgy industry in the internal linings of furnaces, kilns, reactors and other vessels for holding and transporting metal and slag. In nonmetallurgical industries, the refractories are mostly installed on fired heaters, hydrogen reformers, ammonia primary and secondary reformers, cracking furnaces, incinerators, utility boilers, catalytic cracking units, coke calciner, sulfur furnaces, air heaters, ducting, stacks, etc. The majority of these listed equipment operate under high pressure, and operating temperature can vary from very low to very high (approximately 900°F to 2900°F). The refractory materials are therefore needed to withstand temperatures over and above these temperatures. Listed below are the sample melting temperatures of key metallurgical elements where refractory application is critical.

Due to the extremely high melting point of common metals like iron, nickel and copper, metallurgists have to raise furnace temperatures to over 2800°F. Furnaces are lined with refractory materials such as magnesia, which has a melting point of 5070 degrees.

Requirements of Right Refractory

The general requirements of a refractory material can be summed up as:

- Its ability to withstand high temperatures and trap heat within a limited area like a furnace;
- Its ability to withstand action of molten metal , hot gasses and slag erosion etc;
- Its ability to withstand load at service conditions;
- Its ability to resist contamination of the material with which it comes into contact;
- Its ability to maintain sufficient dimensional stability at high temperatures and after/during repeated thermal cycling;

- Its ability to conserve heat.

Introduction to Refractories in Gas to Liquids (GTL) Projects

The oil and gas industry operates under extreme conditions, including high temperatures, corrosive environments, and thermal cycling. Refractory materials, known for their exceptional heat resistance and durability, are crucial in protecting equipment and structures from the harsh conditions present in refining, petrochemical, and other oil and gas processes. They provide insulation, prevent heat loss, reduce energy consumption, and ensure the structural integrity of critical components.

One of the key applications of refractory materials in the oil and gas industry is in furnaces and kilns. These units are exposed to extreme temperatures during the refining and processing of hydrocarbons. Refractory linings help contain the heat within the furnaces, improving energy efficiency and preventing heat loss.

Additionally, they protect against thermal shocks and chemical reactions that can lead to premature equipment failure.

Another vital use of refractory materials is in the construction of chimneys and stacks. These structures are exposed to continuous high-temperature exhaust gasses, which can cause corrosion and degradation. By utilizing refractory materials, companies can ensure the longevity and reliability of chimneys and stacks, minimizing the risk of emissions, leaks, and downtime.

Refractory materials also play a crucial role in the protection of boilers, reactors, and other vessels used in the oil and gas industry. These components are subjected to intense heat and chemical reactions, making them susceptible to wear and tear. Refractory linings provide an effective barrier, extending the lifespan of these vessels and reducing maintenance costs. Refractories are imperative for manufacturing petrochemical products

Refractories are made up of natural as well as engineered materials. These typically incorporate the following

- Non-metallic or mixes of mixtures and minerals
- Dolomite
- Alumina
- Bauxite
- Zirconia

- Fireclays
- Chromite
- Silicon carbide, and
- Magnesite.

Furnace refractories are selected based on a large number of factors. Some of them include the following:

- Resistance to conductivity
- Physical wear
- Cost
- Maximum temperature exposure
- Resistance to chemical corrosion
- Thermal shock resistance, and
- Thermal conductivity, etc.

Overview of Gas to Liquids

Introduction

Gas-to-liquids (GTL) is a technology that enables the production of clean-burning diesel fuel, liquid petroleum gas, base oil and naphtha from natural gas. The GTL process transforms natural gas into very clean diesel fuel because products are colorless and odorless hydrocarbons with very low level of impurities.

Much of the world's natural gas is classified as "stranded," meaning it is located in a remote area, far from existing pipeline infrastructure. The volumes often are too small to make constructing a large-scale treatment gas plant cost-effective. As a result, the gas is typically re-injected into the reservoir, left in the ground, or flared, which is harmful to the environment. However, the availability of this low cost, stranded gas has incentivized companies to develop innovative technologies that can economically and efficiently utilize this gas converting it into a transportation fuel like diesel and jet fuel.

Refineries can also use GTL to convert some of their gaseous hydrocarbon waste products into valuable fuel oil which can be used to generate income.

Small-scale GTL plants are containerized units comprised of a reformer for synthesis gas production, a Fischer Tropsch (FT) reactor for syncrude production, and, in some cases, an upgrading package, which is used to further refine the FT products into the desired transportable fuel. Since these containerized units

already have about 70 percent of their construction complete before reaching the plant site, on-site construction costs are significantly reduced. In cases where capacity needs to be increased, additional units can be easily shipped via truck or ship and connected in parallel to the existing process. Depending on the technology, capacity can range anywhere from 100 barrels per day (bpd) to 15,000 bpd.

GTL Process Phases

Fischer-Tropsch is the process of chemical converting natural gas into liquids (GTL), coal to liquids (CTL), biomass to liquids (BTL) or bitumen from oil sands to liquids (OTL).

All four processes consist of three technological separate sections.

The production of synthesis gas (syngas).

The carbon and hydrogen are initially divided from the methane molecule and reconfigured by steam reforming and/or partial oxidation. The syngas produced, consists primarily of carbon monoxide and hydrogen.

Catalytic (F-T) synthesis.

The syngas is processed in Fischer-Tropsch (F-T) reactors of various designs depending on the technology creating a wide range of paraffinic hydrocarbons product (synthetic crude, or syncrude), particularly those with long chain molecules (e.g. those with as many as 100 carbons in the molecule).

Cracking – product workup.

The syncrude is refined using conventional refinery cracking processes to produce diesel, naphtha and lube oils for commercial markets. By starting with very long chain molecules the cracking processes can be adjusted to an extent in order to produce more of the products in demand by the market at any given time. In most applications it is the middle distillate diesel fuels and jet fuels that represent the highest-value bulk products with lubricants offering high-margin products for more limited volume markets. In modern plants, F-T GTL unit designs and operations tend to be modulated to achieve desired product distribution and a range of product slates.

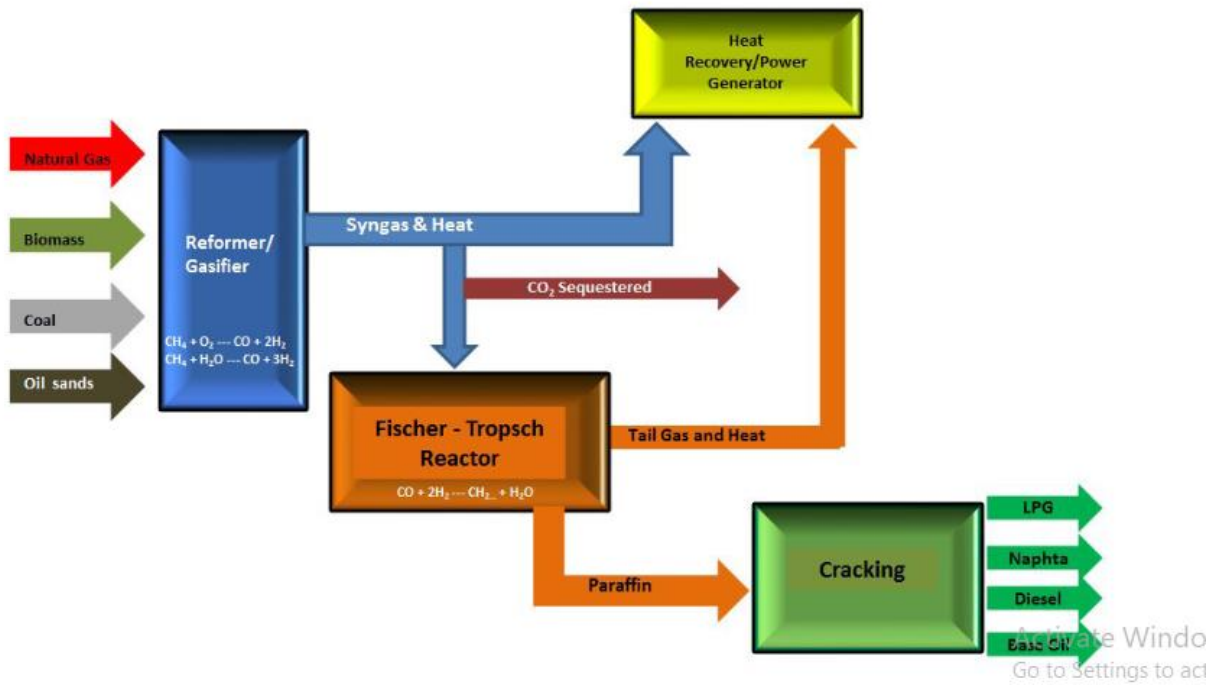


Fig. 1 – GTL technological process with Fischer-Tropsch synthesis reactor

Research and development in GTL process and plant involves several part of the plant: the production efficiency increment for each single unit used upstream and downstream the catalyst into the FT reactor in order to increase its selectivity and durability the design of the reactors to reduce the entire plant or module foot print

Start and Development

Synthetic fuel production technology, known as GTL, was invented in the 1920s. One of the best-known ways to create synthetic fuel is through Fischer-Tropsch (FT) synthesis. FT technology was initially developed in Germany to solve

petroleum shortages leading up to World War. By 1944, Germany was producing 124 Mbpd of synthetic fuels from coal at 25 FT plants.

Next-generation technology was developed in South Africa, which sought to support its economy without oil. In the 1970s, the technology evolved in Western Europe and the US with big plant and large scale production.

Starting from the last decades, advances in GTL technologies have enabled small-scale GTL, and even micro-scale GTL, to be operationally and potentially economically feasible.

Several factors are converging to drive the growth in the GTL industry:

- Desire to monetize existing stranded gas reserves;
- Energy companies keen to gain access to new gas resources;
- Market demand for cleaner fuels and new cheaper chemical feedstocks;
- Rapid technology development by existing and new players;
- Increased interest from gas rich host governments

As petroleum prices remain high, new discoveries make natural gas abundant and cheap by comparison, and more advanced energy companies are exploring ways to reduce the CAPEX of synthetic fuel production. As part of this goal, companies

are looking into building smaller-scale, modular plants that can operate in remote locations.

Several Gas-to-Liquids (GTL) technologies have emerged over the past three decades as a credible alternative for gas monetization for gas-producing countries to expand and diversify into the transportation fuel markets. The final GTL product may be syncrude, which can be injected into an oil pipeline, thereby avoiding the need to transport another product to market, or higher-value liquid fuels or chemical feedstocks such as gasoline, diesel (without sulphur and with a high cetane number), naphtha, jet fuel, methanol or di-methyl ether (DME).

Plants and Projects

World Commercial-Scale GTL Plants

At present, five commercial-scale GTL plants are in operation (Fig. 1). These five plants include:

- Bintulu GTL, Malaysia
- Escravos GTL, Nigeria
- Mossel Bay GTL, South Africa
- Oryx GTL, Qatar
- Pearl GTL, Qatar.

These five plants represent nearly 259 Mbpd of capacity. At 140 Mbpd, Shell's Pearl GTL complex represents more than 50% of the world's total commercial-scale GTL capacity.

The first GTL plant was developed by PetroSA in 1992. This 36- Mbpd plant is in Mossel Bay, South Africa. The plant utilizes FT technology to process methane-rich natural gas into high-quality, low-sulfur synthetic fuels. Products include unleaded petrol, kerosene, diesel, propane, distillates, process oil and alcohols.

Shell commissioned its first commercial GTL plant in Bintulu, Malaysia in 1993.

The plant's initial construction cost was \$ 850 M M . The 12.5 - Mbpd plant underwent a \$50 - MM debottlenecking that increased total capacity to 14.7 Mbpd.

Since 1993 has produced the following products: liquefied petroleum gas (up to 5%), naphtha (up to 30%), diesel fraction (up to 60%) and paraffin (up to 5-10%).

MODULE 2

API 936 Overview to GTL Projects

Refractory material is important to be made used of in oil and gas, petrochemical, power generation industries. As this equipment is exposed to high temperatures, chemical corrosion and mechanical stress they require the proper refractory materials. One way to make sure that refractory linings are installed and used according to the best strategies is through certification as set forth by the American Petroleum Institute (API) 936. This certification ensures that the installation, inspection and testing of all refractory linings are built to industry safety standards. What is API 936, what is the duty of an api 936 inspector and what are some examples to study for getting certified.

What Is API 936?

API 936 is a valuable certification that helps you prove your understanding of the API STD 936 Refractory Installation Quality Control Guidelines. There is a large degree of responsibility in making sure that the professionals who know how to handle and inspect refractory materials used at high temperatures are thoroughly

certified, this will be their certification. In other words, it is similar to having a module or degree in refractory material management and inspection. Finally, garnering this certification is great for an individual's career but also ensures that the industries like oil and gas, petrochemicals or energy commission their refractory installations correctly, timeously and safely which affects equipment integrity in a big way.

What is API 936 Refractory?

API 936 is the brand name given by API for refractory material quality control in an industrial area. Refractories are high-temperature resistant materials that can be used to line furnaces, kilns and reactors. It must also be noted that these materials are very important in industries such as petrochemical, oil refining and some parts of the power generation sector where they influence the structural wellbeing under extreme conditions. API 936 provides directions for the in-service installation quality control testing of refractory linings, to help ensure they are durable and high-performing under service conditions involving elevated temperatures.

The standard API 936 includes multiple topics like the selection of refractory material, installation procedures and some test methods to be used for evaluation of materials based on specific industrial conditions. The objective is to ensure refractory installations comply with the performance criteria requirements, which lowers downtime uncertainty and maintenance expenditure while also improving overall operational safety.

What Is API 936 Inspector?

API 936 inspectors are certified specialists who supervise the installation, quality control, and maintenance of fire-resistant coatings in industrial settings. These inspectors play a critical role in ensuring that fireproof installations meet API 936 criteria and can resist the rigours of high temperatures.

API 936 inspectors have the following primary responsibilities:

Ensure that the materials used in the fireproof installation match API specifications.

Monitoring the installation process to ensure that all necessary processes are performed.

Conducting tests on the installed fire-resistant layer to determine its integrity and functionality.

Identifying and documenting any flaws or areas of concern that could endanger the effectiveness of the fire-resistant coating.

To become an API 936 inspector, professionals must first pass a certification exam that assesses their knowledge of refractory materials, installation techniques, and quality control procedures. This qualification assures that inspectors have the competence required to keep industrial processes safe and efficient.

What Is API 936 Study Material?

API 936 inspectors are licensed specialists in charge of supervising the installation, quality control, and maintenance of fire-resistant coatings in industrial settings.

These inspectors are critical in verifying that fireproof systems meet API 936 criteria and can endure the rigors of high-temperature conditions.

The primary responsibilities of API 936 inspectors are:

- Ensure that the materials used in the fireproof installation meet API specifications.
- Monitoring the installation process to ensure that correct procedures are followed.
- Testing the installed fire-resistant layer to ensure its integrity and performance.
- Identifying and documenting any flaws or concerns that may affect the effectiveness of the fire-resistant coating.

To become an API 936 inspector, professionals must first pass a certification exam that assesses their knowledge of refractory materials, installation techniques, and quality control procedures. This qualification assures that inspectors have the competence required to keep industrial processes safe and efficient.

What Are The Key Aspects of API 936?

To better understand API 936, let's divide it down into its primary components:

1. Refractory Materials

API 936 digs into the world of refractory materials, offering engineers a thorough understanding of their properties, classifications, and uses.

2. Inspection and Testing

One of API 936's main objectives is to ensure the quality of refractory installations. This includes rigorous inspection and testing methods that meet the highest industry requirements.

3. Installation Guidelines

Learn about the best methods for installing refractory materials. API 936 describes the methods and strategies that engineers must use to ensure a successful installation.

4. Repairs and Maintenance

Learn how to analyze and manage potential difficulties that may develop during the refractory materials' lifecycle. API 936 provides guidelines on repair and maintenance to help installations last longer.

How Are The Implementation of API 936 in The Industry?

API 936 plays a significant role in the oil and gas industry by providing essential guidelines for working with extremely high-temperature materials. Think of it as a

set of well-defined rules that ensure safety and efficiency when constructing and maintaining equipment like furnaces and boilers.

The industry must follow API 936 norms and regulations to ensure the safe and efficient use of high-temperature materials. A true case study shows this:

Case Study: Refractory Lining in a Petrochemical Plant

In a petrochemical plant, there was a need to replace the refractory lining in a high-temperature furnace for safety and efficiency reasons. The company chose to apply API 936 standards to this project.

Implementation Steps:

Material Selection:

Following API 936 guidelines, the company carefully chose refractory materials that matched the furnace's specific temperature and chemical requirements.

Inspection and Testing:

Certified inspectors rigorously examined the selected materials to ensure they met API 936's strict quality standards.

Installation Practices:

A team of API 936-certified professionals followed the best practices outlined in the standard to accurately install the refractory materials.

Results:

Through the implementation of API 936, the company successfully upgraded the furnace's refractory lining with precision and safety. The advantages included:

Enhanced Safety:

The new lining complied with API safety standards, reducing the risk of accidents and ensuring the protection of workers and assets.

Improved Efficiency:

The chosen materials and installation techniques optimized the furnace's performance, enhancing operational efficiency.

Extended Lifespan:

Adherence to API 936 guidelines increased the refractory lining's lifespan, reducing the need for frequent replacements and leading to cost savings.

This case study demonstrates how implementing API 936 can result in safer, more efficient, and cost-effective operations within the oil and gas industry.

MODULE 3

Refractory Materials in Gas to Liquid Applications

Selection of Refractory Materials

Background

Refractories are material having high melting points, with properties that make them suitable to act as heat-resisting barriers between high and low temperature zones. Refractories are useful in constructing application-specific high temperature areas/surfaces, particularly in furnaces or boilers, as they minimize heat losses through structure. The value of refractories is judged not merely by the cost of the material itself, but by the nature of job and/ or its performance in a particular situation. Specifically, the performance of a refractory depends on its qualities and quantities in three phases-solid, glass/ liquid, and pores-which govern the ultimate property of a refractory material.

A 'green bond' is developed by mixing various sizes of similar refractory material having some strength and property, which are changed during firing/heat treatment in the course of service. The qualities of refractories are thus

dependent on their chemical, physical, mineralogical and thermal properties.

Refractory materials are generally tailor-made on the basis of:

- Process parameters like temperature profile, mode of operation, chemical environment, etc.
 - Expected quality characteristics
 - Best techniques for engineering and application, so that the final physical, chemical, mechanical, and thermal properties are compatible to the application
- Refractory materials are used in two different forms, namely, shaped and unshaped products.

Shaped refractories

The most familiar form of refractory materials is the rectangular brick shape.

However, refractories are presently available in a variety of shapes and sizes for convenience in construction.

Unshaped refractories

There is a class of refractory materials which can form joint-less lining. This class of refractory materials is called monolithic. All unshaped refractory materials have this ability to form jointless lining, and hence they are grouped as monolithic.

- Unshaped refractories are manufactured in powder form as granular material and known as castables, ramming masses, gunning mix, plastic masses, etc.
- Castables are mixed with water before casting .
- Ramming masses are first mixed with water or any other liquid to the required quality, and then rammed either manually or pneumatically with a heavy rammer.
- Gunning masses are passed through a machine in which the powder material is put under pressure and conveyed pneumatically through a hose. The material gets mixed up with water before it exits the hose nozzle, and sticks to the surface on which it is applied to form a lining.
- Plastic masses comprise ready-mix material that is applied manually in the furnace to form a lining.
- Gun Masses

Gunning mass spraying on worn out refractories of LD-Converter- The gunning machine is comprised of a telescopic gunning lance that is mounted on a Carcass frame with electric drive, a water pump, a material tank, water and material hosepipes and a regulation valve for the remote-controlled adjustment of MgO

base gunning mass and amount of water. A gunning repair is a time consuming operation and takes 10- 12 minutes.

Classification

The primary constituents of any refractory may be a single compound like alumina, silica or mullite, or a combination of these materials. Their melting points are as follows:

- Silica (SiO_2)- 1723°C
- Alumina (Al_2O_3) - 2050°C
- Mullite (71.8% Al_2O_3 , 28.2% SiO_2) - 1996°C

Relatively small amounts of oxides of sodium (Na_2O) and potassium (K_2O), and other minerals containing calcium (CaO), magnesium (MgO), titanium (TiO_2), and iron oxide, promote liquid-phase formation at low temperatures.

Hence, the presence of these oxides in refractories must be limited to trace amounts to avoid formation of low temperature liquid phase.

Refractories in which the predominant constituents are alumina, silica or a combination thereof may be placed in the following categories:

- Fireclay refractory

- High alumina refractory
- Silica refractory
- Mullite refractory

Alumina: Al_2O_3 , the oxide of aluminum; melting point 3720°F (2050°C); in combination with H_2O (water), alumina forms the minerals diaspore, bauxite, and gibbsite; in combination with SiO_2 and H_2O , alumina forms kaolinite and other clay minerals.

Alumina-silica refractories: Refractories consisting essentially of alumina and silica, such as high-alumina, fireclay, and kaolin refractories. (Mullite?) Alumina-zirconia-silica (AZS): Refractories containing alumina-zirconia-silica as a fusion cast body or as an aggregate used in erosion resistant castables and precast special shapes.

Amorphous: Lacking crystalline structure or definite molecular arrangement; without definite external form. anchor or tiebac: Metallic or refractory device that retains the refractory or insulation in place.

Mullites - Mullite or porcelainite is a rare silicate mineral of post-clay genesis. It can form two stoichiometric forms $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ or $2\text{Al}_2\text{O}_3 \cdot \text{SiO}_2$. Unusually, mullite has no charge balancing cations present. As a result, there are three

different Al sites: two distorted tetrahedral sites and one octahedral. Mullite was first described in 1924 for an occurrence on the Isle of Mull, Scotland. It occurs as argillaceous inclusions in volcanic rocks in the Isle of Mull, inclusions in sillimanite within a tonalite at Val Sissone, Italy and with emerylike rocks in Sithean Sluaigh, Scotland

Chemical Formula $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$

Background

Mullite is the mineralogical name given to the only chemically stable intermediate phase in the $\text{SiO}_2 - \text{Al}_2\text{O}_3$ system. The natural mineral is rare, occurring on the Isle of Mull off the west coast of Scotland.

Composition

Mullite is commonly denoted as $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ (i.e. 60 mol% Al_2O_3). However it is actually a solid solution with the equilibrium composition limits of 60~63 mol % Al_2O_3 below 1600°C .

Synthetic Mullite

Various starting materials and preparation methods are used to make synthetic mullite ceramics. For example, a mixture of solids, a mixture of sols, or a mixture of sol and salt can each be used as the starting materials.

Similarly, a variety of preparation methods exist, for example reaction sintering of mechanically mixed powders, hydrothermal treatment of mixtures of sols and chemical vapour deposition.

The starting materials and preparation method influence the properties of the mullite. Reaction sintered mullite made from mechanically mixed powders is usually characterized by low strength (<200 MPa) and low fracture toughness ($1 - 2 \text{ MPam}^{-1/2}$) due to amorphous grain boundary phases. In contrast gelation routes produce intimately mixed sub-micrometer particles that can be sintered or hot pressed to produce single phase materials with superior mechanical properties.

Mechanical properties can be improved further by producing composites.

Additions of Zr_2O and SiC have produced fracture toughness at room temperature close to $7 \text{ MPam}^{-1/2}$.

■ Refractories

The main use of high-mullite based products is in hot blast stove checker bricks. Many refractories in use in the steel industry have varying amounts of mullite based aggregates in them. Steel ladles, lances, reheat furnaces and slide gates are examples of mullite aggregate based products with various alumina contents (figure 1). The use of monolithic and precast shapes is increasing with the use of bricks declining.

The glass industry uses mullite based refractories in burner blocks, ports and in checker bricks as well as in the upper structure of the tanks where the glass is melted and in the drawing chambers.

Thermal shock resistance, chemical attack resistance, high hot strength and creep resistance are the primary properties valued by the industry.

Mullite based products are also resistant to particulate carryover into the glass melt. This is particularly important in flat glass production, where contamination by low levels of Al_2O_3 is undesirable.

The next largest user of mullite is the ceramic industry mostly in kiln furniture items such as kiln setter slabs and posts for supporting ceramic ware during firing.

The aluminium and petrochemical industries also use mullite-based aggregates for applications requiring chemical attack resistance, thermal shock resistance and hot-load strength.

Other Engineering Applications

New mullite materials that have more controlled mechanical and physical properties and are providing opportunities for a wider use of the material.

The good mechanical properties at high temperatures of high purity mullites have made them potential high temperature engineering ceramics, for example in turbine engine components.

Mullite is also a leading candidate material for high-strength infrared transmitting windows.

Other applications include electronic substrates and protective coatings.

Kaolinite is a clay mineral, part of the group of industrial minerals, with the chemical composition $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$. It is a layered silicate mineral, with one tetrahedral sheet linked through oxygen atoms to one octahedral sheet of

alumina octahedra. Rocks that are rich in kaolinite are known as kaolin or china clay.

Kaolinite has a low shrink–swell capacity and a low cation-exchange capacity (1–15 meq/100 g). It is a soft, earthy, usually white mineral (dioctahedral phyllosilicate clay), produced by the chemical weathering of aluminium silicate minerals like feldspar. In many parts of the world, it is colored pink- orange-red by iron oxide, giving it a distinct rust hue. Lighter concentrations yield white, yellow or light orange colors. Alternating layers are sometimes found, as at Providence Canyon State Park in Georgia, US. Commercial grades of kaolin are supplied and transported as dry powder, semi-dry noodle or as liquid slurry.

Fireclay refractory

Fireclays are hydrated aluminum silicates that occur naturally. They are sufficiently pure to serve as raw materials for refractories. The principal mineral in fireclays is kaolinite. While other clay minerals may be present, the formula $Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$ can usually represent the clay fraction. As kaolinite is heated to high temperatures when used to make refractories, it loses its water; theoretically, 45.9% alumina and 54.1% silica remain. Plastic and semi-plastic

fireclays, as their names indicate, develop varying degrees of plasticity when they are mixed with water. This is an important factor in the manufacture of fireclay bricks, because the plastic fireclays facilitate the forming process and act as a bonding phase for the raw and calcined flint clays, and they have greater variation in their impurity content.

Silica refractories

Silica bricks are made from raw materials that are essentially quartz. During the initial firing, alpha-quartz is first converted to beta-quartz, accompanied by an abrupt expansion at 573°C. Slow rates of heating are required through this temperature range to prevent cracking, as the volume change is about 0.9%.

Since the final firing temperature is somewhat over 1426°C, the brick as it is put into service consists of cristobalite particles (properties of cristobalite are not affected by temperature fluctuation, provided the temperature does not drop below 600°C), with possibly some having residual unconverted quartz cores.

High-alumina refractories

High-alumina bricks serve as a multi-purpose refractory material for severe environments. Most high-alumina refractories are classified according to their

alumina content, which could range from 50%-99%. They are designated as 50%, 60%, 70%, 80%, 85% and 90% alumina. Two classes of high-alumina refractories are distinguished by a microstructure that is essentially a single, crystalline phase.

These are:

- Mullite refractories and
- Corundum refractories.

High-alumina refractories- Mullite refractories

Mullite is about 72% alumina with 28% silica. The manufacturing procedures are designed to maximize the formation of the compound mullite ($3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$). A refractory with 71.8% alumina and 28.2% silica will be composed of only mullite ($3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$) if fired at equilibrium conditions.

However, the extent to which well-developed mullite crystalline form occurs in a refractory depends on the purity of the raw materials used and the manufacturing processes, particularly firing. Therefore, all high-alumina bricks with around 70% alumina may have a well-developed mullite phase.

Mullite refractories have excellent volume stability and strength at high temperatures. They are highly suitable material for electric furnace roofs, blast

furnaces and blast furnace stoves, hot metal cars, and the superstructure of glass tank furnaces.

High-alumina refractories- Corundum refractories

The 99% alumina class of refractories is called corundum. These refractories comprise single-phase, polycrystalline, alpha alumina.

Properties of refractory materials

The quality of a refractory and its suitability for a particular application primarily depends on its physical, chemical and mineralogical properties. It may be possible to assess the quality of a refractory on the basis of a single property or a group of properties. The most common properties that are considered in selecting the optimum refractory lining configuration are listed below.

- Apparent porosity
- Bulk density
- Modulus of rupture (MOR)
- Hot modulus of rupture (HMOR)
- s. Cold crushing strength
- Pyrometric cone equivalent (PCE)
- Thermal expansion

- Thermal expansion under load (TEUL) and creep
- Thermal conductivity

Both shaped and unshaped refractories are available in the market under different brand names with special features and for different applications. The analytical data on these products are generally provided in the company product brochures. However, purchasers are advised to get refractory samples analyzed once in a while to verify/cross check the supplier's claims as well as assess the quality of the procured refractory on their characteristics, consistency and variation in composition due to imperfect manufacturing.

Apparent porosity

The apparent porosity is a measure of the effective open pore space in a refractory into which molten metal, slag, fluxes, vapours, etc. can penetrate and thereby contribute to eventual degradation of the structure. The porosity of any product is expressed as the average percentage of open pore space in the overall refractory volume.

Bulk density

The bulk density is generally considered in conjunction with apparent porosity.

It is a measure of the weight of a given volume of refractory. For many refractories, the bulk density provides a general indication of the product quality. While evaluating a refractory brand or comparing several products of equivalent type (except insulating types), it is considered that the refractory with higher bulk density (generally concurrent with lower porosity) will be better in quality. The structure of a refractory having higher bulk density will be denser, resulting in better resistance to chemical attack, decreased metal penetration, better abrasion resistance and other related benefits.

Modulus of rupture (MOR)

The modulus of rupture (MOR) is the flexural breaking strength of a refractory. MOR is measured at room temperature and expressed in pounds per square inch or kilograms per square centimeter.

Hot modulus of rupture (HMOR)

The hot modulus of rupture (HMOR) is the flexural breaking strength of a refractory at a chosen elevated temperature or over a range of temperatures.

(1) The structural integrity and (2) general abrasion characteristics of a refractory can be estimated from HMOR, making it an essential property to determine the

suitability of a refractory in a certain temperature profile for a certain set of application conditions.

Cold crushing strength

The cold crushing strength is the capacity of a refractory to provide resistance to a compressive load at room temperature. It is the load, in pounds per square inch or kilograms per square centimeter, at which the refractory breaks.

Pyrometric cone equivalent (PCE)

The pyrometric cone equivalent (PCE) is a measure of the refractoriness and state of maturity of the material composition of a refractory product after firing.

It represents the state at which a refractory mixture/composition starts becoming soft and deforms within a particular temperature range, depending upon the heating pattern in the firing stage. Representative PCE values for selected refractories include:

- cones 36-37 for a 60% alumina product.
- cones 33-34 for super duty fireclay,
- cones 31-33 for high duty fireclay,
- cones 29-31 for medium duty fireclay

- cones 15-29 for low duty fireclay,

The cone values reported for refractories are based on a defined standard time-temperature relationship, so different heating rates will result in different

PCE values. PCE can be useful for quality control purposes to detect variations in batch chemistry that result from changes or errors in the raw material formulation.

Thermal expansion

Thermal expansion is the intrinsic characteristic of refractory products to expand on heating and contract on cooling. The dimensional changes of a refractory due to thermal expansion are commonly expressed in permanent linear change (%) and the coefficient of thermal expansion (Strength per unit length).

Thermal expansion under load (TEUL) and creep

Dimensional changes take place in a refractory under a compressive load at elevated temperature. The dimensional change could be linear on increasing the temperature range is known as thermal expansion under load (TEUL).

The dimensional changes due to extended period of holding/ soaking of a refractory at pre-selected temperature is nonlinear, and leads to plastic

deformation known as creep. More specifically, creep is the heat-activated plastic deformation of a body under stress as a function of time. TEUL and creep are typically determined in sequence in the same test, using the same sample.

Thermal conductivity

The thermal conductivity is defined as the quantity of heat that will flow through a unit area in a direction normal to the surface area in a defined time with a known temperature gradient under steady state conditions across the area. It indicates the general heat flow characteristics of refractories. The heat flow potential is higher with higher thermal conductivity value, and vice versa.

High thermal conductivity refractories are required for some applications where good heat transfer is essential, such as coke oven walls, regenerators, muffles, and water-cooled furnace walls. However, refractories with lower thermal conductivity are preferred in industrial applications, as they help in conserving heat energy.

The thermal conductivity of refractories is dependent on factors such as chemical and mineralogical composition, temperature, porosity, extent of sintering, and furnace environment. Porosity is a significant factor in heat flow through

refractories. The thermal conductivity of a refractory decreases on increasing its porosity.

Quality assessment of refractory materials

The critical properties of a refractory should be analysed for generic assessment of its quality, and to compare the analytical results with the quantitative values of the properties of the refractory that are supplied by the manufacturer.

Physical analysis

All refractory materials contain pores of varying quantity. The majority of the physical properties, that is, density, strength, expansion, and thermal conductivity of materials, are directly influenced by the quantity and quality of these pores.

Two types of pores-closed and open-are observed in a refractory.

Pores which do not have any connection with the atmosphere are known as closed pores, while those that have access to the atmosphere are known as open pores. These are normally expressed in terms of percentage of total volume and could be calculated from the mass and volume of any refractory material. The mass of a refractory could be measured either in solid state (W_{ss}) or in powder state (W_{ps}). Similarly, its volume too could be measured either in solid state (V_{ss}), which includes the volume of pores, or in powder state (V_{ps}), which does not

include the volume of pores. It is also possible to measure the volume of pores (V_{pore}) present in a solid state of refractory material.

By analysing porosity alone, it is possible to assess refractory quality.

Porosity is defined as the ratio of volume of vacant spaces/pores (V_{pore}) to the total volume of material (V_{ss}) expressed in percentage.

Therefore, porosity(%) = $V_{\text{pore}} / V_{\text{ss}}$

Specific or true density is defined as the ratio of the weight of the material in powder state (W_{ps}) to its volume (V_{ps}) in the same state. The material is powdered to some definite size so that there are no pores available in the material.

Therefore, true density (TD, in grams/cubic centimetre) = mass (W_{ps}) in grams/volume of solid (V_{ps}) in cm^3 .

Bulk density (BD) is determined for refractory material having open and closed pores. It is the ratio of mass in solid state (W_{ss}) to bulk volume (V_{ss}) of a refractory. Thereafter, the volume of open pores can be found out by some easy method (for instance, by filling the open pore areas with water or other liquid and measuring the volume of water/liquid, which gives the volume of open pores) to calculate the apparent density (AD) of the refractory. The apparent density (AD) is

defined as the ratio of mass in solid state (W_{ss}) to the resultant volume, which is obtained by adding the volume of solid (V_{ss}) with the volume of closed pores (V_{pore}). AD is expressed in grams/ cubic centimetre.

Therefore, $AD = W_{ss} / (V_{ss} + V_{pore})$ grams/ cm^3

The quantities of total pores, open pores and closed pores can be determined using three density data: i.e., true density, bulk density, and apparent density.

These values for any refractory could be easily obtained and are necessary for assessing its quality and expected performance.

MODULE 4

Components of Refractory System

Refractories are identified by their major chemical constituents, which govern their quality and properties. It is essential to carry out complete chemical analysis of refractory materials for its quality assessment. As a thumb rule, it is known that the higher the alumina content, the better is the property.

However, it is obvious that while the major chemical constituents of a refractory do play the most important role in determining its ability to perform, the minor constituents-mainly impurities also play a very important role in its performance.

Refractory materials are normally oxides having a tendency to react with one another at high temperature to form different compounds with different crystal structures. The mineralogical formation and crystal structures of the same chemical constituents will vary depending upon the extent of heat treatment/thermal exposure the material receives in manufacturing or in operating conditions. The crystal structure that forms will decide the performance of the refractory, as the resistance to corrosion/ erosion behaviour largely depends on it. Therefore, it is essential to know the microstructure of the

refractory along with its chemical constituents. Quality assessment could be carried out of the refractory material by analyzing randomly selected samples from the lot for complete chemical composition, apparent porosity, bulk density, apparent density, HMOR, and mullite content.

However, estimation of mullite percentage will require X-Ray analysis, for which facilities are not available everywhere. Hence, mullite percentage has to be estimated from other physical tests, and an occasional check of this parameter will suffice.

Refractory for pot furnace lining

Construction of a furnace would require the use of different types of refractories, each suiting the temperature profile of a particular area.

Red bricks, IS-6 bricks and IS-8 bricks are all fireclay refractory bricks whose standards are already outlined by the BIS (Bureau of Indian Standards) covering standard dimensions, physical and chemical properties.

Sillimanite block

The term 'Sillimanite' is in fact a misnomer. Sillimanite generally represents a high-alumina refractory with a higher percentage of mullite. High-alumina refractories are particularly suitable for high-temperature applications (such as in the open-pot furnace for glass melting), with typical process parameters like thermal stress and chemical environment. High-alumina refractories having the following characteristics are suitable for furnace floor construction:

- High temperature resistance (at least up to 1450 °C)
- High corrosion resistance (alkali resistant)
- Resistance to thermal fluctuation

- Apparent porosity
- Cold crushing strength
- Bulk density
- RUL
- HMOR (1400 °C)
- Mullite
- Value Parameter

Improving operating life of the furnace lining

The following practices may be observed while carrying out furnace lining, in order to ensure longer operating life of the furnace. The process begins with procurement of appropriate, good quality refractory material.

Consistent quality

The quality of the refractories used in pot furnace floor needs to be consistent and assured. Blocks are to be procured from reputed manufacturers, as the quality of such blocks can be expected to be uniform. Normally, reputed manufacturers have the requisite infrastructure and relevant manufacturing knowhow for developing the correct physical properties in the blocks such as strength at high temperature (HMOR), and correct mineralogy (mullite content). Once these desired properties are achieved during the manufacturing process, the performance of the refractory material will be predictable and better.

Using larger refractory blocks

The use of larger blocks reduces the number of joints while constructing a furnace lining. However, this does not always result in improvement of performance. The manufacturing of large blocks requires a high-capacity press for developing uniform property characteristics. Hence, it is necessary to consider the

dimensions of the block vis-a-vis its properties (from the suppliers' product brochure) to ensure its suitability for a particular application.

Further, random samples from the procured lots should be analysed to verify the manufacturer's claims with the results obtained from sample analyses.

Mortar quality

The qualities of mortar used in furnace lining should be similar to the refractory qualities / properties. Low shrinkage (less than 1%) high-alumina mortar should be used for joining the high alumina blocks.

Proper dimension

Dimensionally accurate and warpage-free blocks should be used in furnace lining.

Use of anticorrosive coating

The floor of the furnace is likely to be damaged due to the spillage of charge materials containing alkalis or due to contact with molten glass in case of pot failure. In general, it has been found that sparking and corrosion are the main causes of wear and tear of refractories in industrial processes. The glass industry is no exception. Bricks with resistance to sparking and corrosion are preferable for

using on the floor of the glass melting furnace. Anti-corrosive coating materials particularly suitable for alkali attack could be considered.

The coating should be uniform, and may be 5 mm thick.

Detailed Description

Dense Refractory Linings

Drying is the most critical process of the first heating cycle of monolithic dense refractories, as the reduced permeability of the resulting microstructure may lead to explosive spalling and mechanical damage associated with dewatering.

The first part of this review series pointed out

the various drying stages, the role of the binder components and the techniques that can be used to follow the water release in as-cast refractory materials, when they are exposed to heat.

Although defining a suitable heating schedule is a great challenge, some tools can be applied to minimize the spalling risks associated with steam pressurization. In this context, this second review article points out (i) the main drying agents and how they affect the resulting castables' microstructure (organic fibers, metallic

powders, permeability enhancing active compounds, silica-based additives and chelating agents), and (ii) the effects related to the procedures commonly applied during the designing of heating routine (i.e., the role of the heating rate, ramp versus holding time), as well as the influence of the castable's dimension on the overall drying behavior. Considering the recent advances regarding the design of refractory formulations and their processing, one may expect that incorporating suitable drying additives into the prepared composition should lead to a suitable and safer water release in such dense consolidated

Insulating Refractories

Insulating refractories are thermal barriers that keep heat and save energy. Furnaces used for melting, heat treatment, heat regeneration or for any other purpose demand maximum heat conservation so as to minimize heat losses for maximum heat efficiencies. As the cost of energy has increased, the role of insulating refractories has become more important. The use of considerable quantity of refractories is socially and economically justified. With today's energy costs at such higher levels has come the development of a wide range of new insulating refractory materials and technology of high-temperature insulation.

The function of insulating refractory is to reduce the rate of heat flow (heat loss).

Although it is not possible to totally prevent the flow of heat energy when there exists a temperature differential between two points, but it can be retarded.

There are three mechanisms of heat transfer that we must understand. These are conduction, convection, and radiation. We must consider all these three mechanisms when we study the overall conductivity of a given material.

Heat transfer by Conduction occurs via the transfer of energy from atom to atom (or molecule to molecule) in a material. Atoms vibrate faster in higher temperature as they possess more energy. This energy will be passed to the adjacent atoms having lower energy. Since atoms and solids are bonded to one another and are in close contact, conduction in solids is higher than in liquids.

Metals, especially, have high rates of conduction because both the atoms and their electrons conduct the electrons much more rapidly. Liquids generally have lower conduction rates than solids because of their lack of regular structure and strong bonding. Gases have much lower rates of conduction since their molecules exist at much lower concentrations and are in relatively infrequent contact. So, within metals, dense ceramics, and dense refractories Conductivity is the main mechanism of heat transfer.

Energy transfer by Convection relies on the mass movement of a fluid. The moving fluid may be either a liquid or a gas. Convection does occur horizontally; but it depends on the gravitational force of the earth. Again, in case of dense refractory bricks heat transfer through this process cannot happen since there is no fluid for convection

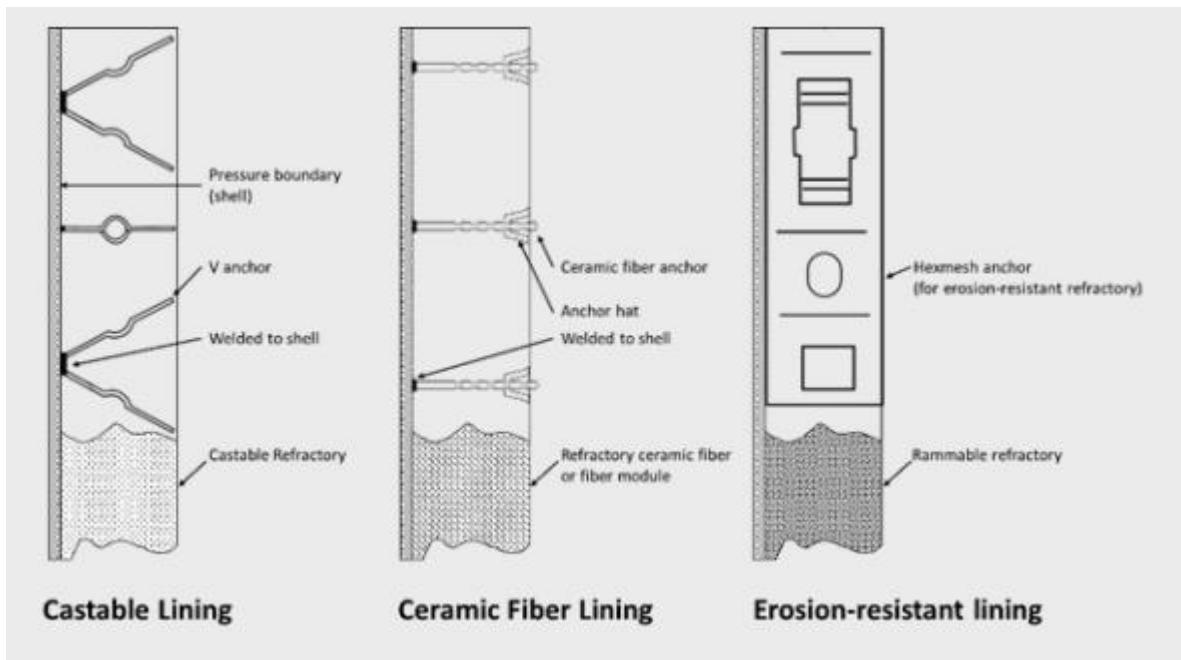
Radiation process of heat transfer does not require the presence of any material. Radiation occurs most readily through empty space.

The sun radiates energy through space to earth. Similarly all hot bodies radiate heat, and if they are hot enough they also radiate visible light which we call as glow

Metallic Anchors

For many refractory lining applications, reliable performance also depends on metal anchoring. Anchors come in a wide variety of shapes, but in general, secure the refractory lining to a steel component that provides structural support for the lining. Refractory ceramic fiber linings are typically installed onto studs and secured with a mechanically locking cap. Ceramic fiber cut or folded into modules rely on integral anchors that are installed by stud welding. Castable linings are anchored by wire anchors in a V or Y shape. Bricks are often self-supporting in

gravity walls or arches but can also be supported with metal anchors. When combined with bricks, metal anchors usually take the form of tiebacks, which hold the bricks in relative position while allowing for thermal expansion. Erosion-resistant linings, when used to protect steel internals from wear in linings, can be installed as thin as $\frac{3}{4}$ " into hexmesh anchoring. The design of the hexmesh accommodates for the differential thermal expansion between the refractory and the underlying steel. Several examples of linings with anchors are shown below (Figure).



A schematic showing generic refractory lining details for a castable, and ceramic fiber, and a thin-layer rammable lining with anchors

Refractory-lined equipment are essential to every refinery. It is the critical detail that enables construction of boilers, furnaces, and large vessels to be fabricated from carbon steel instead of expensive and demanding heat-resistant alloys. Quality lining design requires a combination of lining types and materials installed into a different anchor depending on the exact combination. The next post will discuss the properties that ensure the right refractory for the job as well as more detail about lining designs and combinations.

MODULE 5

Detailed Description and Analyses of the Instrumentation and Control System for a Refractory System

Pressure Transmitters and Gauges

Pressure gauges and transmitters are essential devices used to measure and monitor pressure levels in various systems. While pressure gauges provide visual indications of pressure, transmitters convert pressure readings into electronic signals for remote monitoring and control.

Both pressure transmitters and pressure gauges focus on pressure measurement and control. However, do you know the fundamental difference between the two?

Regarding this issue, firstly we need to figure out the definition of pressure transmitter and pressure gauge. Only by understanding their meaning, then we will naturally understand the difference between them.

What Is Pressure Transmitters?

Definition

A pressure transmitter outputs a standard signal. It is an instrument that contacts a pressure variable and converts it into a standard output signal in proportion. The pressure transmitter is mainly consists of three components: pressure sensing element (also known as pressure sensor), measurement circuit, and process connection. Just like a translator, its function is to the sensed pressure of a gas or liquid into a standard electrical signal (such as 4-20mADC, etc.).

Working Principle

The measuring diaphragm is slightly deformed by the direct pressure. Circuitry on the diaphragm converts the deformation into a voltage output. Voltage is

proportional to the magnitude of pressure. A dedicated circuit processing chip converts the voltage signal into 4-20mA current signal or 1-5V voltage signal, etc.

What Is a Pressure Gauge?

Definition

A pressure gauge is very common in people's daily life. It measures and indicates pressure above ambient pressure. Pressure gauges can be found in a variety of areas, whether in power plants, piping systems, medical devices, or in automotive repair shops and food and pharmaceuticals. Especially in industrial process control and technical measurements, mechanical pressure gauges are becoming more and more widely used due to their features such as durability and ease of manufacture.

Working Principle

A Bourdon tube pressure gauge, also known as a spring tube pressure gauge, is a common pressure measurement instrument. It uses a spring tube as a sensitive component. When pressure is applied to the spring tube, it deforms and one end of the spring tube is displaced. This displacement is proportional to the amount of pressure. With the attached pointer and dial, we can easily read the value of the

measured pressure. If there is atmospheric pressure inside the gauge casing, the pressure measured by the pressure gauge can be either positive or negative. However, if the gauge casing is sealed and evacuated, the pressure measured by the pressure gauge is absolute pressure. When fitted with an isolation device, a bourdon tube pressure gauge can also measure pressure in high-temperature, corrosive, viscous, crystallizing and particle-containing media. In high-accuracy elastic pressure measuring instruments, such as those with a precision level of 0.25 or better, the elastic elements are often made of constant elastic alloy, and in some cases, even quartz glass. The shaft hole of the transmission mechanism is inlaid with gem bearings or rolling bearings. Pressure gauges usually have long dials and some have digital displays.

Differences between Pressure Transmitter and Pressure Gauge

- Calibration of pressure transmitters requires the use of more accurate instruments, much more accurate than pressure gauges.
- The pressure gauge only needs to be checked for the relationship between inputs and outputs, whereas the pressure transmitter may need to be checked the relationship between input data and communication data.

- Calibrating pressure gauges necessitates specific measurement qualifications, typically reserved for manufacturers and new installations. Conversely, pressure transmitters often do not require calibration.
- The accuracy of the pressure gauge is poor, there is no output, and it cannot be operated by hand. Usually 5 points are tested to distinguish between pressurization and depressurization. Whereas smart pressure transmitters usually only need to be calibrated for zero and full scale.
- The output of the pressure gauge is a scale indication, easy to read. The pressure transmitter provides an analog output that needs to be connected to an ammeter with an appropriate level of accuracy for displaying the pressure readings.

From the above description, it is easy to know that the pressure value measured by the pressure transmitter under the same working conditions is more accurate, and the later function expandability is much higher than that of the pressure gauge.

Temperature Sensor

A temperature sensor measures the degree of hotness or coldness in an environment. It converts these measurements into readable units, facilitating

temperature control in various applications, from household appliances to industrial systems. This article will explain what is a temperature sensor, how it works, the different types available, and their various uses.

Key Points

- Temperature sensors measure temperature and convert it into electrical signals, playing a vital role in various applications, including industrial and household systems.
- They are classified into contact and non-contact types, with each serving specific purposes based on environmental needs and measurement accuracy.
- The integration of IoT technology into temperature sensors enables real-time monitoring and predictive failure detection, enhancing operational efficiency and safety across multiple industries.

Defining a Temperature Sensor

At its core, a temperature sensor is an instrument designed to measure the degree of hotness or coldness and convert this measurement into a readable unit.

Temperature sensors fall into two main categories based on their operational principles: contact and non-contact sensors. These devices play a crucial role in

temperature control across a range of applications, from household appliances to advanced industrial systems. Their primary role is to measure temperature accurately and relay this data for monitoring or control.

These sensors convert temperature measurements into easily interpretable electrical signals, including a temperature signal. They track temperature changes and consist of various components that facilitate precise measurement. This conversion facilitates effective temperature management, enabling adjustments and ensuring optimal performance in various environments.

How Temperature Sensors Work

Understanding the inner workings of temperature sensors involves delving into how they convert temperature variations into electrical signals. Most temperature sensors detect changes by measuring the resistance of a diode; as the temperature changes, so does the resistance. Specifically, as the temperature decreases, the resistance of the diode decreases, which is inversely proportional to the temperature change. Conversely, when the temperature increases, the voltage across the terminals of a diode increases, reflecting this change.

Vibrating wire temperature sensors operate differently. Changes in temperature modify the tension in a wire, altering its vibration frequency, which is then

converted into an electrical signal. The Encardio Rite vibrating wire temperature meter, for example, converts these temperature signals into an electrical frequency signal, allowing for precise temperature monitoring.

Types of Temperature Sensors

Temperature sensors are broadly categorized into two main types: contact and non-contact sensors. This classification aids in choosing the right sensor for specific applications, ensuring precise temperature measurement and control. Knowledge of these categories assists in making informed decisions about the best sensor type for any situation.

Contact temperature sensors measure temperature by being in direct contact with the object. Examples include thermocouples, thermistors, and Resistance Temperature Detectors (RTDs).

Non-contact sensors measure temperature without direct contact. They achieve this by detecting radiation emitted from a heat source. These include infrared sensors, thermal imagers, and radiation thermometers, suitable for measuring temperature from a distance or in hazardous environments.

Contact Temperature Sensors

Contact temperature sensors, such as thermocouple temperature sensors, work by coming into direct contact with the object or medium whose temperature is being measured. Thermocouple temperature sensors are widely used in industrial, automotive, and home applications due to their self-powered nature and rapid response times. They can operate over a broad temperature range, making them versatile for various applications. However, they have disadvantages like the small output voltage and requirements for precision references.

Resistance Temperature Detectors (RTDs) are known for their precision and stability, often made from high-purity metals like platinum. An rtd resistance temperature detector, another common type of contact sensor, exhibits significant changes in its physical characteristics in response to temperature variations. This makes them highly versatile and suitable for various applications where precise temperature monitoring is crucial.

Each of these sensors has its unique advantages, making them suitable for different environments and requirements.

Non-Contact Temperature Sensors

Non-contact temperature sensors measure temperature by detecting the thermal radiation emitted by an object or surface. Infrared sensors, for instance, can scan

different temperatures of the area or equipment being assessed without needing physical contact. This is especially useful for moving targets or extreme environments where direct contact is impractical or hazardous.

Non-contact temperature sensors come in various types. Common examples include:

- Infrared sensors
- Thermal imagers
- Radiation thermometers
- Optical pyrometers

These sensors are ideal for applications requiring minimal power and are efficient in monitoring temperature in hazardous or hard-to-reach areas. The capability to measure temperature from a distance makes them invaluable in many industrial and commercial settings, especially when using an accurate temperature sensor.

Common Temperature Sensors and Their Applications

An example of a temperature and humidity sensor

Temperature sensors come in various forms, each suited to specific applications.

In electronics, there are four main types of temperature sensors:

1. Negative Temperature Coefficient (NTC) thermistors
2. Resistance Temperature Detectors (RTDs)
3. Thermocouples
4. Semiconductor-based integrated sensors

These sensors are versatile, measuring temperatures in liquids, solids, or gases, such as temperature meters.

The choice of sensor often depends on the specific requirements of the application. From simple mercury-filled thermometers to advanced semiconductor-based sensors, each type offers unique benefits and suits specific environments and uses.

Thermocouples

Thermocouples are a type of temperature sensor that generates a voltage when two dissimilar metals are joined at one end. They function over a broad range, from -200 °C to 1750 °C, making them ideal for extreme temperature

measurements. This range permits their use in diverse environments, including industrial settings like water, mild chemicals, gases, and dry conditions.

Their durability and cost-effectiveness make them a popular choice for many industrial applications. Thermocouples offer reliable and accurate measurements, whether monitoring machinery temperatures in a factory or checking exhaust gases in an engine.

Resistance Temperature Detectors (RTDs)

RTDs are renowned for their high accuracy and stability, making them the most accurate temperature sensor among contact types. They work by changing resistance with temperature, providing precise readings essential for applications requiring high levels of accuracy. RTDs are often made from platinum for superior linearity and repeatability.

RTDs typically consist of a resistance element built into a probe or assembly.

Platinum, the most common material due to its high accuracy, comes at a higher cost compared to alternatives like nickel or copper. RTDs are extensively used in fields where precision is paramount, such as laboratory settings and industrial process control.

Thermistors

Thermistors, particularly Negative Temperature Coefficient (NTC) types, are highly sensitive to temperature changes. They exhibit high resistance at low temperatures, which decreases as the temperature rises. This trait makes thermistors highly responsive to temperature variations, offering accurate and rapid readings, especially in applications involving positive temperature coefficient materials.

NTC thermistors are celebrated for their superior accuracy and cost-effectiveness compared to other temperature sensors. With operating temperature ranges up to 250 °C for glass-encapsulated types, the temperature coefficient ntc thermistor suits various applications, from consumer electronics to automotive systems.

Semiconductor-Based Temperature Sensors

Semiconductor-based sensors typically feature a linear output, suitable for basic temperature monitoring. These sensors typically operate within the narrowest temperature range of -70°C to 150°C, which can limit their accuracy in certain applications. Though less accurate than other types, their straightforward interpretation of temperature changes makes them useful for general-purpose monitoring. A semiconductor based temperature sensor is a common choice for these applications.

These sensors are ideal for applications that do not require highly precise measurements but benefit from the ease of integration and cost-effectiveness. Common uses include basic environmental monitoring and simple electronic devices where high accuracy is not critical.

Choosing the Right Temperature Sensor

Selecting the appropriate sensor starts with understanding specific application requirements, which helps optimize performance and reduce costs. For example, thermocouples are preferred for applications with temperatures exceeding 1000 °C due to their high-temperature tolerance.

Sensor placement is crucial as it significantly impacts system efficiency and performance. Physical obstacles and design modifications can affect where a temperature sensor can be appropriately installed. These factors ensure the chosen sensor fits the application's operational limits, providing accurate and reliable measurements.

Benefits of Using Temperature Sensors

Temperature sensors offer benefits such as real-time data collection, enabling immediate responses to environmental changes. They improve energy efficiency by optimizing heating and cooling systems, leading to significant cost savings.

Additionally, temperature sensors contribute to safety by monitoring critical temperatures in various applications, from industrial processes to domestic appliances. They also help organizations comply with industry regulations and standards, ensuring operations run smoothly and safely.

Use Cases for Temperature Sensors

Temperature sensors are used in various fields, from household appliances to industrial applications. They are vital in hazardous environments like thermal and nuclear power plants, ensuring safety and efficiency.

Sensors for High Temperature Environment

For high temperatures, there are several types of temperature sensors available:

Thermocouples are mostly the ideal option for extreme temperatures.

Platinum RTDs provide high precision when there is a requirement for the greatest accuracy.

High temperature sensors are specialised for applications where processing temperatures regularly exceed 1000°C (1832°F). Industrial furnaces, combustion chambers, and metallurgical processing apparatuses are temperature-dependant

systems that require constant thermal monitoring to maintain optimal working conditions.

Flow Meters

What is a Flow Meter?

A flow meter (or a flow sensor) is type of flow instrument that is used to indicate the amount of liquid, gas, or vapor moving through a pipe or conduit by measuring linear, non-linear, mass, or volumetric flow rates. Since flow control is often essential, measuring the flow of liquids and gasses is a critical need for many industrial applications – and there are many different types of flow meters that can be utilized depending on the nature of the application.

When choosing a flow meter, one should consider such intangible factors as familiarity of plant personnel, their experience with calibration and maintenance, spare parts availability, and meant time between failure history, etc., at the particular plant site. It is also recommended that the cost of the installation be computed only after taking these steps. One of the most common flow measurement mistakes is the reversal of this sequence: instead of selecting a

sensor which will perform properly, an attempt is made to justify the use of a device because it is less expensive. Those “inexpensive” purchases can be the costliest installations.

How to Choose a Flow Meter

The basis of good flow meter selection is a clear understanding of the requirements of the particular application. Therefore, time should be invested in fully evaluating the nature of the process fluid and of the overall installation. The development of specifications that state the application requirements should be a systematic, step-by-step process.

Fluid and Flow Characteristics

The fluid and its pressure temperature, allowable pressure drop, density (or specific gravity), conductivity, viscosity (Newtonian or not?), and vapor pressure at maximum operating temperature are listed, together with an indication of how these properties might vary or interact. In addition, all safety or toxicity information should be provided, together with detailed data on the fluid’s composition, presence of bubbles, solids (abrasive or soft, size of particles, fibers),

tendency to coat, and light transmission qualities (opaque, translucent, or transparent?).

Pressure and Temperature Ranges

Expected minimum and maximum pressure and temperature values should be given in addition to the normal operating values. Whether flow can reverse, whether it does not always fill the pipe, whether slug flow can develop (air-solids-liquid), whether aeration or pulsation is likely, whether sudden temperature changes can occur, or whether special precautions are needed during cleaning and maintenance, these facts, too, should be stated.

Piping and Installation Area

Concerning the piping and the area where the flow meter is to be located, the following information should be specified: For the piping, its direction (avoid downward flow in liquid applications), size, material, schedule, flange-pressure rating, accessibility, up or downstream turns, valves, regulators, and available straight-pipe run lengths.

In connection with the area, the specifying engineer must know if vibration or magnetic fields are present or possible, if electric or pneumatic power is available,

if the area is classified for explosion hazards, or if there are other special requirements such as compliance with sanitary or clean-in-place (CIP) regulations.

Flow Rates and Accuracy

The next step is to determine the required meter range by identifying minimum and maximum flows (mass or volumetric) that will be measured. After that, the required flow measurement accuracy is determined. Typically, accuracy is specified in percentage of actual reading (AR), in percentage of calibrated span (CS), or in percentage of full scale (FS) units. The accuracy requirements should be separately stated at minimum, normal, and maximum flowrates. Unless you know these requirements, your meter's performance may not be acceptable over its full range.

Accuracy vs Repeatability

In applications where products are sold or purchased on the basis of a meter reading, absolute accuracy is critical. In other applications, repeatability may be more important than absolute accuracy. Therefore, it is advisable to establish separately the accuracy and repeatability requirements of each application and to state both in the specifications.

When a flow meter's accuracy is stated in % CS or % FS units, its absolute error will rise as the measured flow rate drops. If meter error is stated in % AR, the error in absolute terms stays the same at high or low flows. Because full scale (FS) is always a larger quantity than the calibrated span (CS), a sensor with a % FS performance will always have a larger error than one with the same % CS specification. Therefore, in order to compare all bids fairly, it is advisable to convert all quoted error statements into the same % AR units.

It is also recommended that the user compare installations on the basis of the total error of the loop. For example, the inaccuracy of an orifice plate is stated in % AR, while the error of the associated d/p cell is in % CS or % FS. Similarly, the inaccuracy of a Coriolis meter is the sum of two errors, one given in % AR, the other as a % FS value. Total inaccuracy is calculated by taking the root of the sum of the squares of the component inaccuracies at the desired flow rates.

In well-prepared flow meter specifications, all accuracy statements are converted into uniform % AR units and these % AR requirements are specified separately for minimum, normal, and maximum flows. All flow meter specifications and bids

should clearly state both the accuracy and the repeatability of the meter at minimum, normal, and maximum flows.

Table 1 provides data on the range of Reynolds numbers (Re or RD) within which the various flow meter designs can operate. In selecting the right flow meter, one of the first steps is to determine both the minimum and the maximum Reynolds numbers for the application. Maximum RD is obtained by making the calculation when flow and density are at their maximum and viscosity at its minimum.

Conversely, the minimum RD is obtained by using minimum flow and density and maximum viscosity.

If acceptable meeting performance can be obtained from two different flow meter categories and one has no moving parts, select the one without moving parts. Moving parts are a potential source of problems, not only for the obvious reasons of wear, lubrication, and sensitivity to coating, but also because moving parts require clearance spaces that sometimes introduce “slippage” into the flow being measured. Even with well-maintained and calibrated meters, this unmeasured flow varies with changes in fluid viscosity and temperature. Changes

in temperature also change the internal dimensions of the meter and require compensation.

Furthermore, if one can obtain the same performance from both a full flow meter and a point sensor, it is generally advisable to use the flow meter. Because the point sensors do not look at the full flow, they read accurately only if they are inserted to a depth where the flow velocity is the average of the velocity profile across the pipe. Even if this point is carefully determined at the time of calibration, it is not likely to remain unaltered, since velocity profiles change with flowrate, viscosity, temperature, and other factors.

If all other considerations are the same, but one design offers less pressure loss, it is advisable to select that design. Part of the reason is that the pressure loss will have to be paid for in higher pump or compressor operating costs over the life of the plant. Another reason is that a pressure drop is caused by any restriction in the flow path, and wherever a pipe is restricted becomes a potential site for material build-up, plugging, or cavitation.

Mass or Volumetric Units

Before specifying a flow meter, it is also advisable to determine whether the flow information will be more useful if presented in mass or volumetric units. When measuring the flow of compressible materials, volumetric flow is not very meaningful unless density (and sometimes also viscosity) is constant. When the velocity (volumetric flow) of incompressible liquids is measured, the presence of suspended bubbles will cause error, therefore, air and gas must be removed before the fluid reaches the meter. In other velocity sensors, pipe liners can cause problems (ultrasonic), or the meter may stop functioning if the Reynolds number is too low (in vortex shedding meters $RD > 20,000$ is required).

In view of these considerations, mass flow meters, which are insensitive to density, pressure, and viscosity variations and are not affected by changes in the Reynolds number, should be kept in mind. Also underutilized in the chemical industry are the various flumes that can measure flow in partially full pipes and can pass large floating or settleable solids.

Maintaining a Flow Meter

A number of factors influence maintenance requirements and the life expectancy of flow meters. The major factor, of course, is matching the right instrument to

the particular application. Poorly selected devices invariably will cause problems at an early date. Flow meters with no moving parts usually will require less attention than units with moving parts. But all flow meters eventually require some maintenance.

Primary elements in differential pressure flowmeters require extensive piping, valves, and fittings when they are connected to their secondary elements, so maintenance may be a recurring effort in such installations. Impulse lines can plug or corrode and must be cleaned or replaced. And improper location of the secondary element can result in measurement errors. Relocating the element can be expensive.

Flowmeters with moving parts require periodic internal inspection, especially if the liquid being metered is dirty or viscous. Installing filters ahead of such units will help minimize fouling and wear. Obstruction-less instruments, such as ultrasonic or electromagnetic meters, may develop problems with their secondary element's electronic components. Pressure sensors associated with secondary elements should be periodically removed and inspected.

Applications where coatings may occur are also potential problems for obstruction-less instruments such as magnetic or ultrasonic units. If the coating is insulating, the operation of magnetic flowmeters will ultimately be impaired if the electrodes are insulated from the liquid. This condition will be prevented by periodic cleaning. With ultrasonic flowmeters, refraction angles may change, and the sonic energy absorbed by the coating will cause the meter to become inoperative.

Gas Analyzer

Gas analyzers are critical instruments used in a wide range of industries to measure and analyze the concentration of various gases in a given sample. These devices play a crucial role in monitoring air quality, ensuring workplace safety, and maintaining optimal conditions in industrial processes. Understanding the different types of gas analyzers and their working principles is essential for selecting the right instrument for specific applications.

Gas analyzers are used in industries such as environmental monitoring, healthcare, manufacturing, and petrochemicals to accurately measure and

analyze the concentration of gases in a sample as they are vital for ensuring air quality, detecting potential hazards, and optimizing industrial processes.

There are various types of gas analyzers, each designed for specific applications.

Some common types include:

Infrared (IR) Gas Analyzers: These analyzers use infrared radiation to measure the absorption of specific gases. They are effective in determining concentrations of gases such as carbon dioxide, methane, and nitrous oxide.

Flame Ionization Detectors (FIDs): FIDs are commonly used for detecting hydrocarbons in the atmosphere. They work by ionizing hydrocarbon molecules in a flame and measuring the resulting electrical current.

Electrochemical Gas Analyzers: These analyzers utilize electrochemical cells to measure the concentration of gases such as carbon monoxide, sulfur dioxide, and oxygen. They are portable and commonly used for personal safety monitoring.

Photoionization Detectors (PIDs): PIDs use ultraviolet light to ionize gas molecules, allowing for the detection of volatile organic compounds (VOCs) and other gases. They are widely used in industrial hygiene and environmental monitoring.

Gas Chromatography (GC) Analyzers: GC analyzers separate gases in a sample using a column and then detect and quantify the separated components. They are highly versatile and can analyze a wide range of gases.

Understanding the working principles of gas analyzers is crucial for selecting the right instrument for a specific application. Common working principles include absorption of specific wavelengths of light, ionization of gas molecules, and separation of gas components based on their physical and chemical properties.

Types of Gas Analyzers

Gas analyzers can be categorized into several types based on their operation principle. The most common types include:

Electrochemical analyzers: These analyzers use electrochemical cells to measure the concentration of gas. They are commonly used for detecting and measuring toxic gases such as carbon monoxide or hydrogen sulfide.

Infrared analyzers: Infrared gas analyzers detect gas concentrations by measuring the absorption of infrared light by the gas molecules. They are especially useful for measuring gases such as methane, carbon dioxide, and nitrous oxide.

Flame ionization detectors: These analyzers use a flame to ionize carbon-containing compounds in the gas sample, and then measure the resulting ion current to determine the gas concentration. They are commonly used for measuring hydrocarbons in various applications.

Photoionization detectors: Photoionization detectors, or PID analyzers, use ultraviolet light to ionize gas molecules, and then measure the resulting ion current to determine gas concentration. They are often used for detecting volatile organic compounds (VOCs) and other hazardous substances.

Catalytic combustion sensors: These sensors rely on the principle of catalytic oxidation to measure gas concentration. They contain a catalytic element that reacts with the gas being measured, producing heat or a change in electrical conductivity that can be measured. These sensors are commonly used for detecting flammable gases.

Thermal conductivity analyzers: Thermal conductivity analyzers measure changes in the thermal conductivity of a gas mixture to determine gas concentration. They are often used for measuring the concentration of binary gas mixtures or the purity of gases such as nitrogen or helium.

Working Principles of Gas Analyzers

Gas analyzers work on different principles, depending on their type. Here's an overview of the working principles of the aforementioned gas analyzers:

1. **Electrochemical Gas Analyzers:** These analyzers use a sensor that contains electrodes immersed in an electrolyte. When a gas comes into contact with the electrodes, a chemical reaction occurs, resulting in the generation of an electric current. The magnitude of this current is proportional to the concentration of the gas being analyzed. Electrochemical gas analyzers are commonly used for detecting gases such as oxygen, carbon monoxide, and sulfur dioxide.

2 **Infrared Gas Analyzers:** These analyzers utilize the principle of infrared absorption by gases. They consist of a source of infrared radiation, an optical filter, a sample chamber, and a detector. The gas sample is passed through the sample chamber, where it interacts with the infrared radiation. Certain gases have characteristic absorption bands in the infrared spectrum, and the analyzer detects the decrease in the intensity of the transmitted radiation due to the

presence of these gases. Infrared gas analyzers are often used for measuring gases like carbon dioxide, methane, and nitrogen oxide.

3.Flame Ionization Detectors (FID): FID analyzers are specifically designed for measuring hydrocarbons. They work by combusting the gas sample in a hydrogen flame, resulting in the formation of ions. These ions are then detected by a collector electrode, producing an electric current proportional to the concentration of the hydrocarbons in the sample. FID analyzers are widely used in environmental monitoring and industrial applications.

4.Photoacoustic Spectroscopy (PAS): PAS analyzers utilize the phenomenon of photoacoustic effect. When a gas is exposed to modulated light of a specific wavelength, it absorbs the energy and generates a small acoustic wave. This acoustic wave is detected by a microphone, and its intensity is directly related to the concentration of the gas. PAS analyzers are employed for measuring trace gases, such as carbon monoxide, ammonia, and ethylene.

5.Mass Spectrometry: Mass spectrometers are advanced gas analyzers capable of detecting and analyzing a wide range of gases. They work by ionizing gas molecules, separating them based on their mass-to-charge ratio, and then detecting the ions using an electron multiplier. The resulting mass spectrum

provides detailed information about the composition and concentration of gases in the sample. Mass spectrometry is widely used in research laboratories and industrial settings for gas analysis and identification.

Conclusion

Gas analyzers are indispensable tools for measuring and analyzing gas concentrations in various applications. Understanding the different types of gas analyzers and their working principles is crucial for selecting the right instrument for specific needs. By accurately measuring gas concentrations, these instruments enable environmental monitoring, ensure workplace safety, maintain process control, and contribute to advancements in research and development. As technology continues to advance, gas analyzers are expected to become even more sophisticated, providing increasingly accurate and reliable gas analysis.

Control Valves

Control valves are critical components in various industrial systems, acting as the final control elements that modulate fluid flow, pressure, temperature, and level.

☒ These devices respond to signals from external controllers to adjust their position, thereby controlling the process parameters to desired levels.

This comprehensive guide explores the essential aspects of control valves, including their components, working principles, types, applications, selection criteria, and troubleshooting.

Understanding Control Valves

A control valve is a power-operated device used to regulate or manipulate the flow of fluids, including gasses, liquids, and steam.

It is a fundamental part of a control loop, serving as the final control element that implements the control strategy determined by the controller. The primary function of a control valve is to vary the size of the flow passage, as directed by a signal from a controller, to achieve the desired process variable. This enables the direct control of flow rate and the consequential control of other process quantities, such as pressure, temperature, and liquid level.

Key Components of a Control Valve

Control valves are complex devices consisting of multiple components, each playing a vital role in their operation:

Valve Body: The valve body is the housing that contains the internal trim parts, such as the plug, seat, and other components that allow the fluid to flow through the valve. The valve body is designed to withstand the static and differential pressures of the process fluid, as well as provide the necessary pipe-connecting ends and support for the seating surfaces and closure member..

Bonnet: An extension of the valve body that covers and protects the valve's internal moving parts. It also supports the actuator.

Trim: The internal components that come into direct contact with the process fluid. This includes the valve plug, seat, and stem, which are crucial for controlling the fluid flow.

Actuator: The actuator is the power source that provides the force to open and close the valve. Actuators can be pneumatic, hydraulic, or electric, and they are responsible for moving the valve's modulating element, such as a ball or butterfly.

Positioner: The positioner is a device that ensures the valve has reached the desired degree of opening. It helps overcome issues related to friction and wear, ensuring the valve accurately achieves the desired position. Positioners can be

pneumatic, electro-pneumatic, or digital, with the latter offering advanced functionality, including diagnostics and two-way digital communication.

Gland Packing: Seals the valve stem to prevent fluid leakage where the stem exits the bonnet.

Diaphragm: Used in some actuators, it converts the control signal into mechanical movement.

Yoke: A structural component that supports the actuator and connects it to the valve body.

How Control Valves Work

The primary function of a control valve is to modulate the flow of fluids through a system. This modulation is achieved by varying the position of a movable element (e.g., a plug or disc) within the valve, which adjusts the size of the flow passage

Actuators

An actuator is a component of a machine that produces force, torque, or displacement, when an electrical, pneumatic or hydraulic input is supplied to it

in a system (called an actuating system). The effect is usually produced in a controlled way. An actuator translates such an input signal into the required form of mechanical energy. It is a type of transducer. In simple terms, it is a "mover".

An actuator requires a control device (which provides control signal) and a source of energy. The control signal is relatively low in energy and may be voltage, electric current, pneumatic, or hydraulic fluid pressure, or even human power. In the electric, hydraulic, and pneumatic sense, it is a form of automation or automatic control.

The displacement achieved is commonly linear or rotational, as exemplified by linear motors and rotary motors, respectively. Rotary motion is more natural for small machines making large displacements. By means of a leadscrew, rotary motion can be adapted to function as a linear actuator (which produces a linear motion, but is not a linear motor).

Another broad classification of actuators separates them into two types: incremental-drive actuators and continuous-drive actuators. Stepper motors are one type of incremental-drive actuators. Examples of continuous-drive actuators include DC torque motors, induction motors, hydraulic and pneumatic motors, and piston-cylinder drives (rams).

Types of actuators

Mechanical

An actuator can be just a mechanism that is directly driven by the motions or forces of other parts of the system. An example is the camshafts that drive the intake and exhaust valves in internal combustion engines, driven by the engine itself. Another example is the mechanism that strikes the hours in a traditional grandfather clock or cuckoo clock.

Hydraulic

A hydraulic actuator typically uses the pressure of a liquid (usually oil) to cause a piston to slide inside a hollow cylindrical tube linear, rotatory or oscillatory motion. In a single acting actuator the fluid pressure is applied to just one side of the piston, so that it applies useful force in only one direction. The opposite motion may be effected by a spring, by gravity, or by other forces present in the system. In a double acting actuator, the return stroke is driven by fluid pressure applied to the opposite side of the piston.

Since liquids are nearly impossible to compress, a hydraulic actuator can exert a large force. The drawback of this approach is its limited acceleration. They

respond quickly to input changes, have little inertia, can operate continuously over a relatively large working range, and can hold their position without any significant energy input.

A hydraulic actuator can be used to displace the rack of a rack and pinion mechanism, causing the pinion to turn. This arrangement is used, for example, to operate valves in pipelines and other industrial fluid transport installations.

Pneumatic

Pneumatic actuator operating a valve through a rack-and-pinion mechanism.

A pneumatic actuator is similar to a hydraulic one but uses a gas (usually air) instead of a liquid. Compared to hydraulic actuators, pneumatic ones are less complicated because they do not need pipes for the return and recycling of the working fluid. On the other hand, they still need external infrastructure such as compressors, reservoirs, filters, and air treatment subsystems, which often makes them less convenient than electrical and electromechanical actuators.

In the first steam engines and in all steam locomotives, steam pressure is used to drive pneumatic actuators to produce a reciprocating motion, which is converted to rotary motion by some sort of crankshaft mechanism.

Electric

Electric valve actuator controlling a ½ needle valve.

Since 1960, several actuator technologies have been developed. Electric actuators can be classified in the following groups:

Electromechanical

An electromechanical actuator (EMA) uses mechanical means to convert the rotational force of an ordinary (rotary) electric motor into a linear movement. The mechanism may be a toothed belt or a screw (either a ball or a lead screw or planetary roller screw).

The main advantages of electromechanical actuators are their relatively good level of accuracy with respect to pneumatics, their possible long lifecycle and the little maintenance effort required (might require grease). It is possible to reach relatively high force, on the order of 100 kN.

The main limitation of these actuators are the reachable speed, the important dimensions and weight they require. The main application of such actuators is mainly seen in health care devices and factory automation.

Electrohydraulic

Another approach is an electrohydraulic actuator, where the electric motor remains the prime mover but provides torque to operate a hydraulic accumulator that is then used to transmit actuation force in much the same way that diesel engine/hydraulics are typically used in heavy equipment.

Electrical energy is used to actuate equipment such as multi-turn valves, or electric-powered construction and excavation equipment.

When used to control the flow of fluid through a valve, a brake is typically installed above the motor to prevent the fluid pressure from forcing open the valve. If no brake is installed, the actuator gets activated to reclose the valve, which is slowly forced open again. This sets up an oscillation (open, close, open ...) and the motor and actuator will eventually become damaged.

Rotary

Electric rotary actuators use a rotary motor to turn the target part over a certain angle. Rotary actuators can have up to a rotation of 360 degrees. This allows it to

differ from a linear motor as the linear is bound to a set distance compared to the rotary motor. Rotary motors have the ability to be set at any given degree in a field making the device easier to set up still with durability and a set torque.

Rotary motors can be powered by 3 different techniques such as Electric, Fluid, or Manual.[12] However, Fluid powered rotary actuators have 5 sub-sections of actuators such as Scotch Yoke, Vane, Rack-and-Pinion, Helical, and Electrohydraulic. All forms have their own specific design and use allowing the ability to choose multiple angles of degree.

Applications for the rotary actuators are just about endless but, will more than likely be found dealing with mostly hydraulic pressured devices and industries.

Rotary actuators are even used in the robotics field when seeing robotic arms in industry lines. Anything you see that deals with motion control systems to perform a task in technology is a good chance to be a rotary actuator.

Linear

A linear electric actuator uses a linear motor, which can be thought as a rotary electric motor which has been cut and unrolled. Thus, instead of producing a rotational movement, it produces a linear force along their length. Because it

generally has lower friction losses than the alternatives, a linear electric actuator can last over a hundred million cycles.

Linear motors are divided in 3 basic categories: flat linear motor (classic), U-Channel linear motors and Tubular linear motors.

Linear motor technology is the best solution in the context of a low load (up to 30Kgs) because it provides the highest level of speed, control and accuracy.

In fact, it represents the most desired and versatile technology. Due to the limitations of pneumatics, the current electric actuator technology is a viable solution for specific industry applications and it has been successfully introduced in market segments such as the watchmaking, semiconductor and pharmaceutical industries (as high as 60% of the applications). The growing interest for this technology, can be explained by the following characteristics:

- High precision (equal or less than 0,1 mm);
- High cycling rate (greater than 100 cycles/min);
- Possible usage in clean and highly-regulated environments (no leakages of air, humidity or lubricants allowed);
- Need for programmable motion in the situation of complex operations

The main disadvantages of linear motors are:

- They are expensive respect to pneumatics and other electric technologies.
- They are not easy to integrate in standard machineries due to their important size and high weight.
- They have a low force density respect to pneumatic and electromechanical actuators.

Thermal

- An actuator may be driven by heat through the expansion that most solid material exhibit when the temperaure increases. This principle is commonly used, for example, to operate electric switches in thermostats. Typically, a (non-electronic) thermostat contains a strip with two layers of different metals, that will bend when heated.

Thermal actuators may also exploit the properties of shape-memory alloys.

Magnetic

Some actuators are driven by externally applied magnetic fields. They typically contain parts made of ferromagnetic materials that are strongly attracted to each other when they are magnetized by the external field. An example are the reed switches that may be used as door opening sensors in a building security system.

Alternatively, magnetic actuators can use magnetic shape-memory alloys.

Soft actuators

A soft actuator is made of a flexible material that changes its shape in response to stimuli including mechanical, thermal, magnetic, and electrical. Soft actuators mainly deal with the robotics of humans rather than industry which is what most of the actuators are used for. For most actuators they are mechanically durable yet do not have an ability to adapt compared to soft actuators. The soft actuators apply to mainly safety and healthcare for humans which is why they are able to adapt to environments by disassembling their parts. This is why the driven energy behind soft actuators deal with flexible materials like certain polymers and liquids that are harmless

The majority of the existing soft actuators are fabricated using multistep low yield processes such as micro-moulding, solid freeform fabrication, and mask lithography. However, these methods require manual fabrication of devices, post processing/assembly, and lengthy iterations until maturity in the fabrication is achieved. To avoid the tedious and time-consuming aspects of the current fabrication processes, researchers are exploring an appropriate manufacturing approach for effective fabrication of soft actuators. Therefore, special soft

systems that can be fabricated in a single step by rapid prototyping methods, such as 3D printing, are utilized to narrow the gap between the design and implementation of soft actuators, making the process faster, less expensive, and simpler. They also enable incorporation of all actuator components into a single structure eliminating the need to use external joints, adhesives, and fasteners.

Shape memory polymer (SMP) actuators are the most similar to our muscles, providing a response to a range of stimuli such as light, electrical, magnetic, heat, pH, and moisture changes. They have some deficiencies including fatigue and high response time that have been improved through the introduction of smart materials and combination of different materials by means of advanced fabrication technology. The advent of 3D printers has made a new pathway for fabricating low-cost and fast response SMP actuators. The process of receiving external stimuli like heat, moisture, electrical input, light or magnetic field by SMP is referred to as shape memory effect (SME). SMP exhibits some rewarding features such a low density, high strain recovery, biocompatibility, and biodegradability.

Photopolymers or light activated polymers (LAP) are another type of SMP that are activated by light stimuli. The LAP actuators can be controlled remotely with

instant response and, without any physical contact, only with the variation of light frequency or intensity.

A need for soft, lightweight and biocompatible soft actuators in soft robotics has influenced researchers for devising pneumatic soft actuators because of their intrinsic compliance nature and ability to produce muscle tension.

Polymers such as dielectric elastomers (DE), ionic polymer–metal composites (IPMC), ionic electroactive polymers, polyelectrolyte gels, and gel-metal composites are common materials to form 3D layered structures that can be tailored to work as soft actuators. EAP actuators are categorized as 3D printed soft actuators that respond to electrical excitation as deformation in their shape.

Programmable Logic Controller

A programmable logic controller (PLC) is an industrial computer control system that continuously monitors the state of input devices and makes decisions based upon a custom program to control the state of output devices.

Almost any production line, machine function, or process can be greatly enhanced using this type of control system. However, the biggest benefit in using a PLC is the ability to change and replicate the operation or process while collecting and communicating vital information.

Another advantage of a PLC system is that it is modular. That is, you can mix and match the types of Input and Output devices to best suit your application.

History of PLCs

The first Programmable Logic Controllers were designed and developed by Modicon as a relay re-placer for GM and Landis.

☐ These controllers eliminated the need for rewiring and adding additional hardware for each new configuration of logic.

The new system drastically increased the functionality of the controls while reducing the cabinet space that housed the logic.

The first PLC, model 084, was invented by Dick Morley in 1969

The first commercial successful PLC, the 184, was introduced in 1973 and was designed by Michael Greenberg.

What Is Inside A PLC?

The Central Processing Unit, the CPU, contains an internal program that tells the PLC how to perform the following functions:

- Execute the Control Instructions contained in the User's Programs. This program is stored in "nonvolatile" memory, meaning that the program will not be lost if power is removed
- Communicate with other devices, which can include I/O Devices, Programming Devices, Networks, and even other PLCs.
- Perform Housekeeping activities such as Communications, Internal Diagnostics, etc.

How Does A PLC Operate?

There are four basic steps in the operation of all PLCs; Input Scan, Program Scan, Output Scan, and Housekeeping. These steps continually take place in a repeating loop.

Four Steps In The PLC Operations

- Input Scan

Detects the state of all input devices that are connected to the PLC

- Program Scan

Executes the user created program logic

- Output Scan

Energizes or de-energize all output devices that are connected to the PLC.

- Housekeeping

This step includes communications with programming terminals, internal diagnostics, etc...

These steps are continually processed in a loop.

What Programming Language Is Used To Program A PLC?

While Ladder Logic is the most commonly used PLC programming language, it is not the only one. The following table lists of some of languages that are used to program a PLC.

Ladder Diagram (LD) Traditional ladder logic is graphical programming language.

Initially programmed with simple contacts that simulated the opening and closing of relays, Ladder Logic programming has been expanded to include such functions as counters, timers, shift registers, and math operations.

Function Block Diagram (FBD) - A graphical language for depicting signal and data flows through re-usable function blocks. FBD is very useful for expressing the interconnection of control system algorithms and logic.

Structured Text (ST) – A high level text language that encourages structured programming. It has a language structure (syntax) that strongly resembles PASCAL and supports a wide range of standard functions and operators. For example;

```
If Speed1 > 100.0 then
```

```
    Flow_Rate: = 50.0 + Offset_A1;
```

```
Else
```

```
    Flow_Rate: = 100.0; Steam: = ON
```

```
End_If;
```

Instruction List (IL): A low level “assembler like” language that is based on similar instructions list languages found in a wide range of today’s PLCs.

Sequential Function Chart (SFC) A method of programming complex control systems at a more highly structured level. A SFC program is an overview of the control system, in which the basic building blocks are entire program files. Each program file is created using one of the other types of programming languages.

The SFC approach coordinates large, complicated programming tasks into smaller, more manageable tasks.

What Are Input/output Devices?

- Switches and Pushbuttons
- Sensing Devices
- Limit Switches

- Photoelectric Sensors

- Proximity Sensors

- Valves

- Motor Starters

- Solenoids

- Actuators

- Condition Sensors

Encoders Pressure Switches

- Level Switches

- Temperature Switches

- Vacuum Switches
- Float Switches
- Horns and Alarms
- Stack lights
- Control Relays
- Counter/Totalizer
- Pumps
- Printers
- Fans

What Do I Need To Consider When Choosing A PLC?

There are many PLC systems on the market today. Other than cost, you must consider the following when deciding which one will best suit the needs of your application.

- Will the system be powered by AC or DC voltage
- Does the PLC have enough memory to run my user program?
- Does the system run fast enough to meet my application's requirements?
- What type of software is used to program the PLC?
- Will the PLC be able to manage the number of inputs and outputs that my application requires?
- If required by your application, can the PLC handle analog inputs and outputs, or maybe a combination of both analog and discrete inputs and outputs?
- How am I going to communicate with my PLC?
- Do I need network connectivity and can it be added to my PLC?
- Will the system be located in one place or spread out over a large area?

Distributed Control System (DCS)

A distributed control system (DCS) is a control system for a process or plant, where control elements are distributed throughout the system. Unlike a centralized control system, where all control elements are located in a single

location, a DCS uses a distributed architecture, where control functions are distributed among multiple controllers.

Why Use a DCS?

The primary reasons for using a DCS include improved reliability, flexibility, and scalability. DCS systems allow for real-time monitoring, which is crucial for maintaining process efficiency and safety. By distributing control across various nodes, the system minimizes the risk of a single point of failure, thus enhancing operational reliability.

Confluent Cloud's capabilities enhance DCS systems by enabling seamless integration and real-time data streaming. This means that data from various nodes in the DCS can be ingested, processed, and analyzed in real time, improving decision-making and operational efficiency.

Components and Architecture

A DCS typically consists of several key components:

- **Control Nodes:** These are the devices that execute control functions.
- **Human-Machine Interface (HMI):** This allows operators to interact with the system and visualize data.

- **Data Communication Network:** Facilitates data transfer between control nodes and the HMI.
- **Field Instruments:** These sensors and actuators collect data from the physical environment and execute control actions.

DCS vs. SCADA and PLC Systems

While DCS, SCADA (Supervisory Control and Data Acquisition), and PLC (Programmable Logic Controller) systems all serve the purpose of controlling industrial processes, they have distinct differences:

DCS

Primarily used for complex processes where continuous control and monitoring are required.

SCADA

Generally used for monitoring and controlling large-scale systems, such as water treatment facilities and power grids. It focuses more on supervisory control.

PLC

Best for discrete control processes, such as assembly lines, where simple on/off control is sufficient.

Confluent Cloud can bridge the gaps between these systems, providing a unified data architecture that streamlines operations. By integrating data from DCS, SCADA, and PLC systems, businesses can gain a comprehensive view of their processes.

Core Functions and Benefits of a DCS

The core functions of a DCS include:

- Real-Time Monitoring
- Constant observation of processes to ensure optimal performance.
- Data Logging
- Recording historical data for compliance and analysis.
- Automated Control
- Enabling automatic adjustments based on real-time data inputs.

Benefits of a DCS: Unlocking Operational Excellence

A Distributed Control System (DCS) offers a range of benefits that significantly enhance operational efficiency in industrial environments.

Improved Real-Time Monitoring

By continuously collecting and analyzing data from various processes, a DCS enables organizations to maintain optimal performance levels and quickly identify potential issues. This proactive approach minimizes downtime, reduces maintenance costs, and enhances overall productivity. Streamlined processes lead to reduced downtime and increased productivity, making a DCS an invaluable asset for any industrial operation.

Automated Control

Through advanced algorithms and data analytics, a DCS can automatically adjust processes based on real-time inputs, improving consistency and quality in production. Continuous monitoring helps in the early detection of potential hazards, thereby enhancing safety across operations. By leveraging Confluent Cloud, organizations can further enhance this automated control by integrating real-time data streams, enabling even more sophisticated adjustments and decision-making capabilities.

Better Data-Driven Decision Making

By centralizing and analyzing operational data, organizations gain insights that were previously difficult to access. This capability allows for more informed

strategic planning and resource allocation. With access to real-time data, businesses can make proactive adjustments based on historical and current information. Confluent Cloud enhances these benefits by providing advanced analytics and machine learning capabilities, transforming DCS data into actionable intelligence. Ultimately, the benefits of a DCS, combined with advanced cloud solutions, empower organizations to achieve operational excellence and maintain a competitive edge in a rapidly evolving market.

DCS and Data Integration

Data integration is essential for Distributed Control Systems (DCS), as it enables the seamless flow of information from diverse sources, enhancing operational efficiency. In industrial settings, a DCS collects vast amounts of data from sensors, controllers, and field instruments. However, without effective integration with critical business systems such as ERP (Enterprise Resource Planning), CRM (Customer Relationship Management), and supply chain management, this valuable data can become siloed. This limits its potential for actionable insights and informed decision-making. By leveraging Confluent Cloud, organizations can effortlessly connect their DCS data with these external systems, providing a

comprehensive view of operations and facilitating data-driven strategies that enhance productivity and profitability.

Confluent Cloud offers robust real-time data streaming capabilities that significantly enhance the integration of DCS with other applications. This powerful platform allows organizations to process and analyze data as it flows from various DCS components, enabling instant insights and timely responses. For instance, by integrating production data with inventory management systems, businesses can optimize their supply chains, reduce waste, and improve overall operational efficiency.

Moreover, the scalability and flexibility of Confluent Cloud make it an ideal solution for modernizing DCS data integration efforts. As industrial environments evolve and expand, the demand for seamless data flow becomes critical.

Confluent's capabilities allow organizations to adapt their integration strategies effortlessly, accommodating new data sources and evolving business requirements without significant disruption. By integrating DCS with Confluent Cloud, organizations position themselves for future success and operational excellence.

Advanced Applications of DCS in Industry

- DCS systems are increasingly being used in advanced applications such as:
 - Predictive Maintenance
 - DCS enables organizations to continuously monitor equipment performance and analyze data trends to identify potential failures before they occur. This proactive approach allows for timely maintenance scheduling, reducing unexpected downtime and optimizing maintenance costs.
- Process Optimization
- In industries such as pharmaceuticals and food processing, DCS automates complex processes by dynamically adjusting parameters based on real-time data from sensors. This leads to improved product quality, reduced waste, and lower energy consumption.
- Real-Time Supply Chain Management
- DCS facilitates the monitoring of inventory levels and production schedules, allowing organizations to respond quickly to changes in demand. By integrating supply chain data with DCS, businesses can achieve a more agile and efficient operation.
- Energy Management

- DCS can monitor energy consumption across processes and identify inefficiencies in real time. By optimizing energy use, organizations can significantly reduce costs and enhance sustainability efforts.
- Quality Control
- Continuous data monitoring allows DCS to ensure that production processes consistently meet quality standards. This capability enables immediate corrective actions to be taken, minimizing the risk of defective products reaching the market.
- Enhanced Safety Monitoring
- DCS can integrate safety systems to continuously monitor critical parameters, helping to detect hazardous conditions early. This real-time monitoring supports rapid response actions, significantly improving workplace safety.
- Batch Process Management
- In industries like chemicals and food, DCS manages batch processes by controlling the timing and order of operations. This precision ensures consistent product quality and compliance with regulatory standards.
- Remote Monitoring and Control

- DCS enables operators to monitor and control processes from remote locations, enhancing flexibility and responsiveness. This capability is especially valuable in geographically dispersed operations, allowing for centralized management.
- Data Visualization and Reporting
- Advanced DCS systems provide intuitive dashboards and reporting tools that visualize key performance indicators (KPIs). These insights empower decision-makers to quickly assess operations and make informed strategic decisions.
- Integration with IoT Devices
- By connecting DCS with Industrial Internet of Things (IoT) devices, organizations can gather and analyze data from a wide range of sources. This integration enhances operational visibility and facilitates smarter decision-making across the organization.

DCS in the Era of Industry 4.0: Driving Smart Manufacturing

The advent of Industry 4.0 represents a significant transformation in industrial operations, emphasizing automation, data exchange, and the Internet of Things (IoT). In this new landscape, Distributed Control Systems (DCS) play a pivotal role

by serving as the backbone for smart manufacturing processes. A DCS enables real-time monitoring and control of production systems, allowing organizations to optimize operations while swiftly responding to changing market demands. By integrating advanced technologies, a DCS supports the seamless flow of data across all levels of an organization, enhancing collaboration and informed decision-making.

One of the key advantages of DCS within the context of Industry 4.0 is its capability to leverage big data analytics. As manufacturing environments become increasingly connected, the volume of data generated grows exponentially. A DCS can capture this data from various sources, enabling organizations to analyze trends, predict equipment failures, and identify areas for process improvement. By integrating with Confluent Cloud, companies can utilize powerful data streaming capabilities to ensure that insights are derived in real time. This real-time analysis enables informed decisions that enhance operational efficiency and productivity, essential for maintaining a competitive edge in the modern marketplace.

DCS Security and Compliance

In today's industrial landscape, the security of Distributed Control Systems (DCS) is paramount, especially as cyber threats become increasingly sophisticated. DCS environments often manage critical infrastructure and sensitive data, making them attractive targets for malicious actors. Implementing robust security measures is essential to protect these systems from potential breaches. This is where Confluent Cloud comes into play, offering advanced security features that enhance the protection of DCS environments, including data encryption, access controls, and real-time monitoring of data streams.

Compliance with industry regulations is another crucial aspect of DCS security. Many sectors, such as pharmaceuticals and energy, are subject to stringent regulatory requirements that mandate secure data handling and reporting practices. A DCS must not only safeguard operational data but also ensure that it meets these compliance standards. By leveraging Confluent Cloud, organizations can streamline their compliance efforts through automated data governance and comprehensive audit trails. This capability simplifies the process of tracking data access and modifications, making it easier to demonstrate compliance during audits.

Furthermore, the integration of DCS with Confluent Cloud enables organizations to enhance their security posture through real-time analytics and threat detection. By continuously monitoring data flows and user activity, organizations can identify anomalies that may indicate a security breach. This proactive approach allows for immediate response actions to mitigate potential risks before they escalate. With the ability to correlate DCS data with broader enterprise security measures, businesses can create a holistic security framework that not only protects their systems but also fosters confidence among stakeholders regarding the integrity and reliability of their operations. In an era where security and compliance are critical, the synergy between DCS and Confluent Cloud empowers organizations to operate securely and efficiently.

DCS Modernization

Modernizing a DCS is essential for leveraging new technologies and ensuring continued operational efficiency. This may involve upgrading hardware, incorporating advanced software, or migrating to cloud-based systems.

Confluent facilitates DCS modernization by providing a scalable platform that can integrate legacy systems with modern cloud solutions. This enables organizations to evolve their DCS capabilities without losing valuable historical data.

Benefits of DCS with Confluent's Real-Time Data Streaming

- Integrating DCS with Confluent's real-time data streaming capabilities offers several benefits:
- Enhanced Operational Efficiency
- Integrating DCS with Confluent enables real-time monitoring and control of complex processes.
- Instant insights into system performance allow for quick responses to anomalies and trends.
- Reduces downtime and improves overall decision-making across operations.
- Improved Data Accessibility
- Confluent Cloud centralizes data from multiple sources, including sensors and external applications.
- Provides comprehensive visibility into operations, facilitating effective performance analysis.
- Enables informed decision-making based on up-to-date information, driving productivity.

Advanced Analytics and Predictive Maintenance

- Real-time data streaming allows for the implementation of predictive analytics.
- Identifies potential failures before they occur, promoting proactive maintenance strategies.
- Unlocks actionable insights from operational data, leading to enhanced process efficiencies and reduced costs.
- Streamlined Resource Allocation
- Access to real-time insights enables better strategic planning and resource management.
- Organizations can optimize workflows and allocate resources effectively based on current data.

Competitive Edge

- Combining DCS with Confluent positions organizations to innovate and adapt in a data-driven landscape.
- Facilitates faster decision-making, ensuring organizations remain agile and responsive to market changes.

Conclusion

Distributed Control Systems are vital for managing complex industrial processes. Their integration with Confluent Cloud brings significant advantages, including real-time data streaming, advanced analytics, and enhanced security. As industries move towards automation and Industry 4.0, the synergy between DCS and Confluent will become increasingly essential for driving operational excellence and innovation.

By leveraging the capabilities of Confluent, organizations can maximize the benefits of their DCS investments, ensuring they remain competitive in a rapidly evolving industrial landscape.

Human-Machine Interface (HMI)

Human-Machine Interface (HMI) is a technology that provides a means for humans to interact with machines, devices, and systems. HMIs enable operators to control, monitor, and manage industrial processes, allowing for efficient and effective decision-making.

What is a Human Machine Interface (HMI)?

A Human-Machine Interface (HMI) is a user interface that allows a human operator to interact with a machine or process. HMI is typically used in industrial

settings to allow operators to monitor and control processes, such as those in a factory or power plant.

HMI can take a variety of forms, including graphical user interfaces (GUIs) on a computer, touchscreens, or physical control panels with buttons and displays.

They are used to present process data to the operator, allow the operator to input commands and setpoints, and present alarms and other information.

HMI is typically connected to a programmable logic controller (PLC), which is responsible for controlling the process based on input from the HMI and sensors in the field. The HMI simply presents information to the operator and allows them to input commands, which are then sent to the PLC to be implemented.

Types of HMI

There are several different types of Human-Machine Interfaces (HMI), which can take a variety of forms depending on the needs of the application.

Some common types of HMI include:

Graphical User Interfaces (GUIs): These are computer-based HMI that use a graphical interface to present process data and allow the operator to input commands. GUIs can be created using software such as Microsoft Windows or a specialized HMI software package.

Touchscreens: These are HMI that use a touchscreen display to present process data and allow the operator to input commands. They are often used in applications where a physical control panel is not practical, such as in environments where space is limited.

Physical Control Panels: These are physical HMI that use buttons, switches, and displays to present process data and allow the operator to input commands. They are often used in industrial settings where a GUI or touchscreen may not be practical, such as in environments with high levels of vibration or dust.

Web-based HMI: These are HMI that use a web browser to present process data and allow the operator to input commands. They can be accessed from any device with a web browser, allowing operators to monitor and control processes remotely.

How to Choose an HMI?

When choosing a Human Machine Interface (HMI) for an industrial process or system, there are several factors to consider to ensure that the HMI is the best fit for the specific application.

- **Compatibility:** It is important to choose an HMI that is compatible with the equipment and systems that it will be controlling. This includes

compatibility with the control system, communication protocols, and data formats used by the equipment.

- **Hardware:** The HMI should be designed to be rugged and durable, suitable for the environment where it will be installed. It should be able to withstand the temperature, humidity, and vibration that it will be exposed to.
- **Display:** The HMI should have a display that is clear, easy to read, and easy to navigate. The screen should be of a good resolution, with a high-quality display and backlight.
- **Usability:** The HMI should be easy to operate and understand, with intuitive navigation and clear, concise displays. It should be easy to use and understand by operators with different levels of expertise.
- **Data visualization:** The HMI should be able to display data in a clear and meaningful way, using graphics, charts, and other types of visual representations to help operators understand the process and make informed decisions.
- **Customizability:** The HMI should be customizable, with the ability to adapt to the specific needs of the process or equipment, as well as to the preferences of the operator.

- Remote access: The HMI should be designed to allow remote access so that operators can monitor and control the process from a remote location.
- Scalability: The HMI should be designed to be scalable, with the ability to handle more complexity and data as the process or equipment becomes more advanced.
- Support: The HMI vendor should provide good technical support and documentation, as well as software updates and upgrades.
- Cost: The HMI should be cost-effective and provide a good return on investment.

Advantages of Human-Machine Interface

Human-Machine Interfaces (HMI) have several advantages that make them useful for controlling and monitoring industrial processes:

Improved Efficiency: HMI allows operators to easily access process data and input commands, which can improve the efficiency of the process being controlled. By presenting data in a clear and concise manner, operators can make more informed decisions and take timely action when necessary.

Increased Safety: HMI can improve safety by presenting alarms and other important information to the operator. This allows operators to take timely action to address potential problems before they become serious.

Remote Monitoring and Control: Many HMI can be accessed remotely, allowing operators to monitor and control processes from a distance. This can be particularly useful in applications where the process is located in a remote or hazardous location.

Easy to Use: HMI is designed to be easy to use, even for operators who may not have technical expertise. This makes them an accessible tool for controlling and monitoring industrial processes.

Disadvantages of Human-Machine Interface

Human-Machine Interfaces (HMI) have some potential disadvantages that should be considered when determining whether to use one:

Dependency on the HMI: If the HMI fails or becomes unavailable, the operator may not be able to access process data or input commands, which can hinder the operation of the process being controlled.

Potential for Human Error: Operators can make mistakes when using HMI, such as inputting incorrect commands or failing to notice an alarm. This can lead to problems with the process being controlled.

Additional Cost: Implementing an HMI can be an additional cost, as it requires the purchase and installation of the HMI itself as well as any associated hardware and software. Complexity: Some HMI can be complex, which can make them difficult to use or require additional training for operators. This can be a disadvantage in applications where the operator needs to be able to quickly and easily access process data and input commands.

Applications of HMI

Human-Machine Interfaces (HMI) are used in a variety of industrial applications where they can help improve the efficiency, safety, and accessibility of the process being controlled.

Some common applications of HMI include:

Manufacturing: HMI is commonly used in manufacturing settings to control and monitor production processes, such as those on a factory floor. They can be used to present process data to operators, allow them to input commands and setpoints, and present alarms and other important information.

Power Generation: HMI is also used in power generation plants, such as those that use fossil fuels or renewable energy sources, to monitor and control processes such as boiler operation, turbine control, and electrical generation and distribution.

Water and Wastewater Treatment: HMI is used in water and wastewater treatment plants to control and monitor processes such as pumping, treatment, and distribution.

Oil and Gas: HMI are used in oil and gas production and refining to control and monitor processes such as drilling, pumping, and refining.

Chemical Processing: HMI is used in chemical processing plants to control and monitor processes such as mixing, reaction, and distillation

Module 6

Description and Analysis of typical operating parameters for a Refractory System

Current Industry Operations and Refractory Use

The chemical industries have processing equipment that spans a broad range of types, with associated processing temperatures ranging from as low as 370–425°C (700–800°F) to as high as 1870°C (3400°F). The refractory-lined units in a typical full-spectrum refinery can include fluidized catalyst cracking units (FCCUs), catalytic reformers, fired heaters, boilers, hydrogen reformers, ethylene furnaces, incinerators, and carbon furnaces. Some of these units are designed to have substantial insulating capability in their linings, while others are low-temperature-process units, like FCCUs that contain only a single layer of refractory designed to withstand the extremely severe abrasion caused by the catalyst.

The estimated cost of refractory lining installation and maintenance work for the chemical and petroleum industries is relatively low (as low as 1% of the total operating cost) compared to other equipment construction and maintenance costs; yet, refractory lining degradation and failure are leading factors for

frequency and duration of shutdowns. Due to lower operating temperature, as compared to other industries, refractory is not normally affected by high temperatures, yet refractory degradation may be caused by erosion, corrosion, and mechanical stresses caused by thermal cycling, depending on location of the refractory within the unit. Another problem that can affect refractory reliability is the manner in which the refractory is installed (i.e., pneumatically gunned, shotcreted, vibration cast, pump cast, and/or hand packed). Additionally, with operating time, minor imperfections can become locations of exacerbated lining degradation. Lining design (i.e., anchoring, lining thicknesses, and design of construction/expansion joints) can also add to lining degradation.

Also, the total tonnage of refractories in an average-sized full-spectrum refinery can be as high as 1000 tons of refractory for a single lining that is intended to last for at least a decade: a typical refinery requires approximately 2500 tons of refractory. Some of the more critical units are put on maintenance, with annual turnaround, and the replacement and repair of refractories for a single unit can amount to 250 tons, or a fourth of the lining.

Virtually all of the refractories used by chemical plants are monolithics. These include castables, cast vibration mixes, gunning mixes, low- and no-cement castables, plastics, and a variety of insulating refractories. Because many of the temperatures of refinery processes are too low to promote a ceramic bond to replace the hydraulic bond of calcium aluminate–bonded castables, the refractory practice has been based largely on phosphate-bonded plastics, which develop the needed properties at or below the process temperatures. Refractory practice varies widely from one company to another. Some companies have incorporated castables, especially vibratables, into their practice, and today companies are evaluating shotcretable refractories in locations where a ceramic bond can be developed at the process temperature.

However, the place where advances in refractories may have the greatest impact on efficiency in the chemical industry is in the boilers used to produce steam for power generation. Improvements in the thermal efficiency of boilers themselves, through improved insulation, and in the insulation used on transfer pipework could lead to reduction in heat loss and lower fuel consumption.

In the petrochemical and synthesized gas industries in particular, new designs in the catalyst support media and the installation of refractory insulation have

increased operation life and efficiencies of reactors of various types. New refractory designs for support media have allowed increased flow rate and longer productive life for expensive catalyst materials. More attention being paid to the use of sprayable refractory ceramic fiber lining materials as well as new microporous silica backup materials. More attention is also being paid to the use of precast parts for component of the various unit processes, and wider use of precast technology is anticipated.

Because it is so important to maintain shell temperatures of vessels and reactors above a threshold temperature to avoid condensation onto the shell, designers are trying to refine the models for predicting temperature gradients and cold face temperatures. Lack of data on the thermal conductivity of many commercial monolithic refractories is holding back progress in this area.

Barriers

Refractories and insulation materials play key roles in most of the varied unit operations involved in the production of chemical and petrochemical products; it is estimated that about 50% of the industries' direct energy consumption is in processes affected by refractories. Based on subsequent analyses of typical furnaces and unit processes, improvement of refractory systems for the chemical

and petrochemical industries could lead to energy savings opportunities of up to 266.4 TBtu/year. The specific barriers are shown below.

- Lack of understanding of high-temperature properties such as creep rupture, short-time strength, thermal conductivity, thermal expansion, ductility, and stability for the monolithic refractories used in this industry.
- Lack of understanding of the corrosion properties of refractories used in the chemical and petrochemical industries, which subject materials to conditions ranging from hot-oxidizing environments to environments that contain hot halogen gases or gases with entrained particles.

Chemical and Petrochemical

- Lack of understanding regarding turnaround times and maintenance costs, which have become increasingly more important cost elements. Lack of understanding regarding the reduction of energy consumption and air pollution.
- Lack of understanding regarding high-temperature and corrosive environments which limit refractory life and increase maintenance costs in numerous chemical and petrochemical reactors.

R&D Pathways

- Develop improved refractories for minimizing mechanical damage to refractory-lined refining vessels through reduction of the amount of mechanical stresses on the lining.
- Perform work to optimize the physical properties of refractories (i.e., thermal insulation, erosion resistance, corrosion resistance, thermal shock resistance, strength, porosity, and permeability) under known required operating conditions for specific unit types. Develop realistic and reproducible product development and quality control testing that can be used to relate step improvements in needed physical properties of the current refractory lining materials in service.
- Develop improved methods of analysis for high-temperature equipment through techniques for online refractory inspection.
- Develop longer-life refractories that are field-repairable, less brittle, and more shock-resistant.
- Acquire thermophysical, kinetic and mechanical data on refractories.
- Develop ceramic-metal-matrix composites with improved stability and explore surface modification and/or coatings for use in corrosive environments.

- Develop materials to withstand high temperatures while retaining superior strength, ductility, corrosion and wear resistance to resist damage due to corrosion and high temperatures present in the chemical process industry.
- Develop materials with enhanced resistance to organic acid environments and improved materials for chlorine-based processes, to improve plant operations and maintenance requirements and reduce costs.
- Develop refractories and refractory coatings for high-temperature furnaces to reduce energy and maintenance costs. Develop high-temperature nonstick surfaces that do not degrade or become volatile at high temperatures to help reduce needed maintenance of chemical process equipment.

Refractory materials, by definition, are supposed to be resistant to heat and are exposed to different degrees of mechanical stress and strain, thermal stress and strain, corrosion /erosion from solids, liquids and gases, gas diffusion, and mechanical abrasion at various temperatures. Different refractories are designed and manufactured so that the properties of the refractories will be appropriate for their applications. In most cases, refractory properties can be predicted from the results of appropriate tests; for others, knowledge and experience predict the refractory properties where direct tests correlating the properties are not

available. The testing of refractory properties can, in most cases, indicate the performance of a refractory in actual application. Hence, appropriate testing of refractories for predicting properties, closely simulative to their applications, is of great importance. In this chapter, the importance of the refractory properties is covered so that performance in actual application will closely resemble their characteristic properties.

Refractories are mostly used (70%) in basic metal industries. In iron and steel making in integrated plants, iron is made in the blast furnace. Here iron is formed from the reduction of iron ore by carbon in the presence of limestone, which helps in forming the slag. Inside the blast furnace, the refractories experience abrasion in the upper part and intense heat and molten slag and metal contacts in the lower region. After the metal and slag are formed, they come out through a tap hole, which is opened and closed intermittently as the liquid iron is formed. The property requirement of the tap hole material should be such that the hole can be conveniently drilled for tapping molten iron and slag out and then the hole can be plugged for the process to be repeated when the iron will be ready to be tapped. After the molten iron and slag comes out of the tap hole, it flows through the trough in the cast house, where the iron and slag are separated. Iron goes through the iron runner into the receiving ladles, and slag goes through the slag

runner in the slag ladle or slag pit. Thus, the properties of the trough should be that it resists the impact and splashing of the molten iron and slag. It also should have sufficient resistance to the molten iron and slag interface where the refractory is affected most. The property requirements in the cast house refractories are thus well defined.

In the steel-making process by the basic oxygen furnace (BOF), the molten iron from the blast furnace combined with some scrap iron is purified from the impurities such as C, S, P, Mn, etc. by blowing oxygen through the molten iron either by lances from the top or by blowing oxygen through pipes at the bottom. In the process, the molten metal experiences vigorous stirring along with intense heat. The refractory properties in the BOF should be such that it resists the molten slag (basic) and the high temperature generated in the process. Basic refractories (MgO-based) containing carbon are used, which provides the required properties of high temperature and resistance to basic slag.

Properties of refractories required in the electric arc furnace (EAF) are slightly different than those of BOF. In the electric arc furnace, steel is primarily made from scrap iron. Here the refractory properties should be that it can tolerate the mechanical impingement of the scrap iron and the arcing created from the

electric current. Arcing in the lining sometimes experiences intense heat in localized areas, called “hot spots.” The refractory property requirement is to have good mechanical strength, high refractoriness, and basic slag resistance.

In recent years, most of the metallurgical operations have usually been done in ladle metallurgical furnaces (LMF). The property requirements of these refractories are thus more stringent than classical ladle refractories. The refractory properties should be such that it will be able to resist the alloying operations along with reheating the molten metal when needed. The stringent property requirements of the ladle and tundish tubes (shrouds), slide gates, and nozzles should allow the operator to continue the process at the desired level. There are specific refractory property needs for the refractories used in the tundish backup and working lining. The working lining should be able to resist the steel and slag contacts and have enough shrinkage so that the lining should be able to deskill conveniently and completely.

In hydrocarbon industries, the property requirements of the refractories are different than those of metal industries. Although the temperature in petrochemical refining is much lower than in metal industries, the refractories

suffer a high rate of abrasion due to the flow of high-velocity particles at a continuous rate.

Hence, the major characteristic requirement of these refractories is abrasion resistance. Also, the refractories need to be able to conserve heat. Hence, there are defined ranges of thermal conductivity for different regions of the process so that the processes conserve energy during the conversion processes.

In the glass-making process, the refractories in the glass tank are in constant contact with the molten glass, and this poses different kinds of requirements for the refractory. Since glass in the molten state is quite fluid and tends to go through the refractory pores, the most needed characteristic should be nonporous refractories, and hence fused refractories are used in molten glass contact areas.

It is obvious that the property requirements of refractories vary significantly according to the application and use in different processes. Hence, individual refractories need to be designed with characteristic properties for specific systems since the requirements vary with different high-temperature processes.

Refractories are broadly divided into two categories—shaped (bricks and cast shapes) and unshaped (monolithic) refractories. There are two kinds of shaped

refractories—the primary kind is like brick or similar shapes and the kind is the shapes made from monolithic refractories, where they are dictated by the properties of the monolithic refractories. For shaped refractories (like brick making), attaining maximum density after the shapes are formed is the goal of the process.

There are different kinds of monolithic refractories, namely plastics, ramming mixes, mortars, coatings, castables/pumpables, and gunning mixes. The physical characteristics of plastics and ramming mixes are their ease of ramming to consolidate to proper density. For mortars and coatings, they should have appropriate consistency to be used as desired for the specific applications. For gunning mixes, the material should have good adhesion to the gunned surface, low rebound, and appropriate properties as designed. For castable/pumpable refractories, the primary characteristics are particle size distribution, which in effect controls the flowability along with proper addition of minor ingredients and controls the workability; setting and strength development upon curing and heating; and the bonding system, which dictates the high-temperature properties. Since the development of vibratable and pumpable castables, methods have been standardized for measuring the flowability of a castable, which can predict the

flow characteristics. The test consists of filling up a cone with the castable refractory and then letting it flow under vibration for a specified time. The predetermined flowability characteristics define the castable's use in actual applications.

Refractory properties can be classified as follows:

- Physical
- Density
- Porosity
- Strength
- Abrasion
- Thermal
- Thermal shock
- Thermal conductivity
- Thermal diffusivity
- Chemical
- Corrosion/erosion

PHYSICAL PROPERTIES

Physical property requirements for shaped and unshaped refractories are different. For shaped refractories, the main requirements are their density and porosity and dimensional tolerance. Monolithic (unshaped) refractories, on the other hand, have to be characterized with different parameters. For plastic refractories, the workability and aging characteristics are the prime requirements, whereas, for ramming mixes, the rammability with proper compaction is the main requirement. For castable/pumpable refractories, the prime requirement is the flowability at a specific water addition with or without vibration. In recent years, castable/pumpable refractories have been the most predominant monolithic refractories for most applications. Significant work has been done with castable/pumpable refractories since the development of low and ultralow cement castables. The development of sol-gel bonded refractories introduced the pumpable characteristics of Castables. Since then, the low and ultralow cement Castables have been designed to have self-flow and pumpable characteristics. This is achieved by careful selection of grain sizing of the castable components. Specific grain size distribution parameters are required in flowability for a castable to make it self-flowable and pumpable. The setting parameters are supposed to

be associated with the flowability since adverse effects may take place if the castable/pumpable does not satisfy the setting parameters.

Refractory materials are characterized by their physical properties, which often indicate the use and performance of refractory materials. The physical appearance of a refractory material sample, submitted for testing, is quite important since the results of testing of a refractory will be as good as the sample submitted for testing. The predictability of refractory uses in specific applications is, in most cases, dictated by past experience. In general, the basic physical properties can often indicate whether a refractory material can be used for intended applications. The following basic physical properties are often used to predict, select, and prescribe refractories for specific applications:

- Density and porosity
- Strengths—cold and hot, their importance
- Abrasion

The above properties are determined by standard ASTM (1) tests, and hence the materials are classified and characterized according to their physical test results.

The significance and characterization of the above tests can be summarized as follows:

Density and Porosity (ASTM D-20). The values of density and porosity determined by standard methods are used to recommend or predict the use of refractories for specific uses. In general, the higher the density, the lower the porosity. Also, other physical properties, such as strength, abrasion, and gas permeability, are often related to the density and porosity of the refractory.

Strengths. Cold and hot, their importance—The physical strengths, in both cold and hot conditions, are often characterized as measures of the use of refractory. Cold strengths indicate the handling and installation of the refractory, whereas hot strengths indicate how the refractory will perform when used at elevated temperatures. Initial strength develops in refractory materials during the forming process. For shaped refractories, the strengths often develop during the physical processing of the products and sometimes followed by higher temperatures where the refractory goes through a firing process. For monolithic refractories, the initial strength develops during the installation or forming process (for precast shapes), and the final strength develops while in application.

In recent years, more importance has been given to high-temperature strengths of refractories rather than cold strengths since refractories are used at elevated temperatures and not at room temperatures.

Strengths of refractories are measured as cold compressive strength, cold modulus of rupture, or hot modulus of rupture. Hot modulus of rupture provides best indication of the performance of a refractory material in use.

Cold Compressive Strength (ASTM C-133). The cold compressive strength of a refractory material is an indication of its suitability for use of refractories in construction. It is a combined measure of the refractory for the strength of the grains and also of the bonding system.

Cold Modulus of Rupture (ASTM C-133). The cold modulus of rupture of a refractory material indicates the flexural strength and its suitability for use in construction. It is indicative of the strength of the bonding system of the refractory product. Since the test is done at room temperature, it can only show its suitability and its use in construction. It provides no indication of how the refractory will behave at elevated temperatures.

Hot Modulus of Rupture (ASTM C-583). The hot modulus of rupture provides the indication of a refractory material about its flexural strength at elevated temperatures. Since refractories are used at elevated temperatures, the hot modulus of rupture is the true indicator of the suitability and performance of a refractory at high temperatures. Hence, in recent years, the hot modulus of

rupture has been prescribed and required by users as the most important test criterion for selection and use of refractories.

Abrasion Resistance (ASTM C-704). This is a measure of the resistance of a refractory material when high-velocity particles abrade the surface of the refractory. It measures the strength of the bond and the refractory particles and its resistance to the flow of high-velocity particles across its surface. The need for good abrasion resistance of refractory materials is most evident in petrochemical industries where fine particles impinge the refractory surface at high velocities at moderately elevated temperatures. A direct correlation between abrasion resistance and cold crushing strength has recently been established.

Thus, the cold crushing strengths can provide, and have a direct indication about, the predictability of a refractory material regarding its resistance to abrasion.

Thermal Properties

Thermal Expansion

This is a measure of the refractory about its linear stability when it is exposed to different ranges of high temperatures and then cooled to room temperatures. It is defined as a permanent linear change (ASTM C-113) and is measured by the

changes in the longest linear dimensions. Most refractory materials expand when heated. Hence, when refractories are installed at room temperatures, the whole structure tightens up when heated. But if the temperature reaches higher than the softening temperature of the bonding system, the structure may distort or collapse. Hence, refractory systems should always be designed in such a way that the maximum temperature attainable in the system is lower than the softening or melting temperature of the refractory ingredients (grains and bonding system). Often cracks are observed in monolithic refractory systems when cooled, but, in most cases, the apparent cracks visible on cooling close up after the system is heated up.

Thermal Shock

This is measure of the refractory property when the refractory is exposed to alternate heating and cooling. It is an important property for a refractory material.

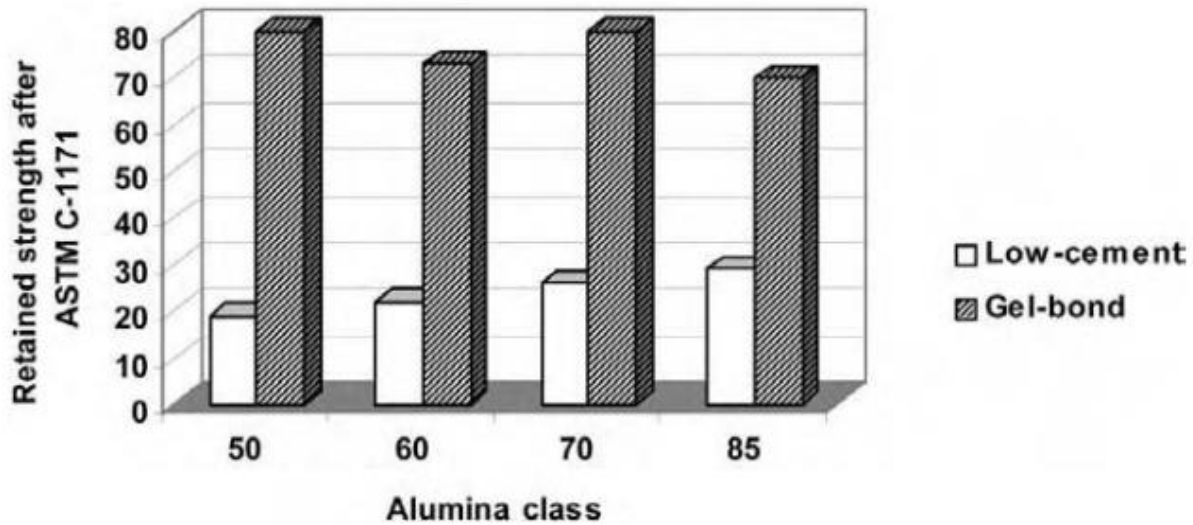
Most high-temperature processes experience heating and cooling. Both refractory grains and the bonding system expand while being heated and contract during cooling. Having similar grains in the structure, the thermal shock resistance

depends on the matrix bonding the grains. Thus, refractories having structures with built-in microcracks or defects show better thermal shock resistance than with rigid systems. In some refractories, the bonding system, by nature, possesses microstructural defects or cracks that provide better thermal shock resistance.

There are two standard methods for determining the thermal shock resistance of refractory materials. For brick shapes, thermal shock resistance is measured by “Ribbon Thermal Shock Testing” (ASTM C-1100), and for monolithic refractories the standard method is ASTM C-1171. These tests clearly differentiate among refractory materials about their resistance to thermal shocks. A clear difference is exhibited in castables where the different bonding systems are a low-cement castable and sol – gel bonding with similar alumina contents

Thermal Conductivity

Thermal conductivity is a measure of the refractory regarding its ability to conduct heat from the hot to the cold face when it is exposed to high temperatures. There are three different methods of determining thermal conductivity of refractory materials. ASTM C-210 is the standard method for determining



Retained strength of low-cement and gel-bond castables with similar alumina contents (grains) as per ASTM C-1171.

thermal conductivity of refractories; ASTM C-202 is the standard method for determining thermal conductivity of refractory brick; and ASTM C-1113 is the standard method for determining thermal conductivity of refractories by hot wire.

The thermal conductivity tests are particularly important for insulating refractories where the thermal gradients from the hot face to the cold face dictate the use of a refractory material for the specific uses.

Thermal Diffusivity

The thermal diffusivity property is particularly useful for carbon-containing materials. ASTM C-714 is the standard method for determining thermal diffusivity of carbon and graphite by the thermal pulse method.

Chemical Properties

The chemical properties of a refractory are defined by the chemical analysis of the refractory grains, by the nature of the bonding, and also by the ability of the refractory to resist the action of liquids when exposed to high temperatures.

The chemical properties of a refractory material are primarily dictated by the chemical composition of the refractory. The bonding system of the refractory plays a vital role in dictating its properties. When refractories are exposed to corrosive liquids at high temperatures, the extent of corrosion/erosion depends on the refractory grains and the chemical bonding system of the refractory.

Refractory corrosion may be caused by mechanisms such as dissolution in contact with liquid, a vapor –liquid or solid-phase reactions (3). It may also occur due to penetration of the vapor or liquid in the pores, resulting in an alternate zone. In most cases, corrosion is the result of some combination of these factors.

The nature and rate of dissolution of a refractory in a liquid can be calculated from a phase equilibrium diagram. A concentration gradient occurs in the refractory composition at the boundary region when the refractory comes in contact with the molten slag. The refractory components diffuse through the interfacial film and dissolve in the liquid. The interfacial film influences the rate of dissolution. The larger the concentration gradient, the faster the dissolution rate and thus the refractory dissolves more readily.

Corrosion/erosion resistance is one of the most important characteristics of refractories, which are exposed to molten metal and slag. Hence, the design of the tests closely simulating the conditions that the refractories experience during use is of great importance.

During the formulation of a refractory, close attention is given to a refractory composition in choosing the refractory grains and the bonding system. Thus, refractories used in an iron-making process will differ from that of a steel-making process since the nature of the metal and slag is different in these cases. In iron making, the metal and liquid slag is primarily neutral or slightly acidic in nature, whereas the slag is distinctively basic in the steel-making process. Refractories

chosen for iron making are based on alumina and silica, whereas magnesia base refractories are the choice for steel making.

.The specimens are then pulled out and cooled, the relative wears are visually compared, and then the areas around the maximum wear are measured. This gives the comparative corrosion/erosion behavior of the specimens tested. This test has been found to be the best simulative behavior of blast furnace cast house refractories.

Ceramic Properties

Ceramic properties of a refractory material are defined by its nature or reaction when exposed to heat. Refractories behave differently when exposed to heat, depending on the type of the refractory and how it has been formed. For fired bricks, the ceramic reactions and bonds have already been instituted by high temperature firing. Hence, when they are exposed to high temperature, they do not exhibit any further change. However, for unfired refractories, the formulations are designed so that the ceramic reactions are supposed to take place at those temperatures. Thus, for fired bricks like fireclay, high-alumina, magnesia-chrome-type bricks, which are already fired at high temperatures, do not exhibit any further ceramic reaction when exposed to high temperatures. But

for unfired refractories, like magnesia-carbon bricks and alumina-carbon bricks, the formulations are designed so that the ceramic properties will be developed at use temperatures.

For monolithic refractories, the formulations are made so that the ceramic properties develop when they are exposed to high temperatures. Monolithic refractories, like plastics, ramming mixes, dry vibratables, mortars, and coatings, are already prepared and are to be applied as received. By contrast, castables and gunning mixes are supposed to be mixed with water or the liquid bond for application. Thus, for monolithic refractories, in particular, it is of interest to find the ceramic reactions that take place at or before service temperatures.

Depending on the bonding system, the ceramic reactions for gunning mixes take place at high temperatures for specific applications. Thus, the organic bonding in gunning mixes acts only to help in adherence of the material on the gunned surface. With heat the organic bonding will burn out, leaving the ceramic bonding to take over at higher temperatures.

For castables and gunning mixes containing high-alumina hydraulic cements (calcium aluminates), the initial strength development occurs by the hydraulic process, while the ceramic bondings take place at higher temperatures).

Recent developments in low- and ultralow-cement castables/pumpables, the effects of the ultrafine particles are of great significance. The water requirements are low since the ultrafine silica fume particles (mostly used in these compositions) occupy part of the space of water. The effects are somewhat minimized in ultralow cement castables due to the use of lesser quantity of calcium aluminate cement.

Due to the recent development of sol – gel bonded refractories (2), the high-temperature properties of castable/pumpable refractories have improved significantly since the high-temperature phases are no longer low-melting. It forms mullite only at higher temperatures (since there is no CaO or MgO) and thus provides better properties at elevated temperatures.

MODULE 8

Refractory Lining Design and Installation

Introduction

Refractory lining design and installation are addressed here with respect to the thermal and mechanical behavior of the lining system. The chemical aspects of selecting refractory materials with respect to lining design and installation are not addressed here. Fundamentally, acid and basic processes dictate the type of refractory material (silica/acid and magnesia/basic) to be used. The primary purposes of refractory linings are to insulate the process temperature from the surrounding ambient temperature, to contain the product material, and to restrict the support structure (typically a steel structure) temperature to reasonable temperatures such that the steel maintains reasonable strength.

Typically, carbon steel begins to lose strength and stiffness (yield stress and elastic modulus, respectively) at temperatures that exceed about 800°F

Based on the process temperature, the basic geometry of the refractory lining system, and the type of support structure, the second concern is the expansion

forces developed in the lining and reacted by the steel support structure. This module describes the classical brick shapes, the primary classes of refractory lining geometries, the fundamental expansion behavior of each of the refractory lining geometries, the fundamentals of the need for lining containment, and the fundamentals in the use of expansion allowance material in the refractory lining system. Without appropriate lining containment, no expansion forces are developed and expansion allowance materials are of no use. Understanding the basic expansion behavior of each of the classical refractory linings configurations also greatly assists in knowing where to place expansion allowance material and the amount of expansion allowance material. Compressible blanket and board materials and plastics sheets are often used as expansion allowance in refractory linings. Guidance is provided in the amount of compressive displacement that can be anticipated in these materials. Most refractories tend to soften, or go plastic, at elevated temperatures.

This behavior must be accounted for in the installation of expansion allowance. It should also be kept in mind that when the brick lining is installed, special care is given to making sure that the brick mortar joints are completely aligned.

However, upon heatup of the brick, as expected, expansion occurs more on the hot face than on the cold face. As a result, misalignment occurs in the lining in the

heated operating condition. The resulting compressive bearing loads do not occur over the complete brick bearing surfaces in the heated condition. Because of this behavior, “hinges” are developed in the lining in which a small portion of the brick bears the compressive load. These hinges occur at usually predicted locations based on the lining geometry. The locations of these hinges will be discussed, which will assist in the location of expansion allowance and also assist in zoning methods in the lining installation.

That is, more crack-resistant brick should be placed in the hinge regions where higher operating stresses exist.

Castable lining systems are also addressed here in limited detail.

Basically, monolithic castable linings will behave in the same fundamental thermomechanical manner that brick linings behave. Brick linings have predetermined cracks (brick joints), where as castable linings do not.

Refractory Brick Shapes

Refractory brick shapes are provided in several geometric shape definitions(2 – 4). Figure 2 describes these basic shapes. The shape name is defined below each shape. There are the straight, split, soap, wedge, arch, key, skew, circle, jamb, and semi-universal. Brick size is specified by the three orthogonal dimensions starting

with the largest dimension proceeding to the smallest dimension. The straight is a rectangular shape. Splits and soap use the same procedure for specifying the shape size. The split is basically a horizontal slice of the straight, parallel to the largest face. The soap is essentially a slice of the straight, perpendicular to the largest face. The wedge and arch shapes are specified, for example, with the taper on the intermediate dimension. Note the A B C procedure in each case in which A is the largest dimension and proceeding to the smallest dimension C. There are several different skew shapes defined as end skew, edge skew, and side skew.

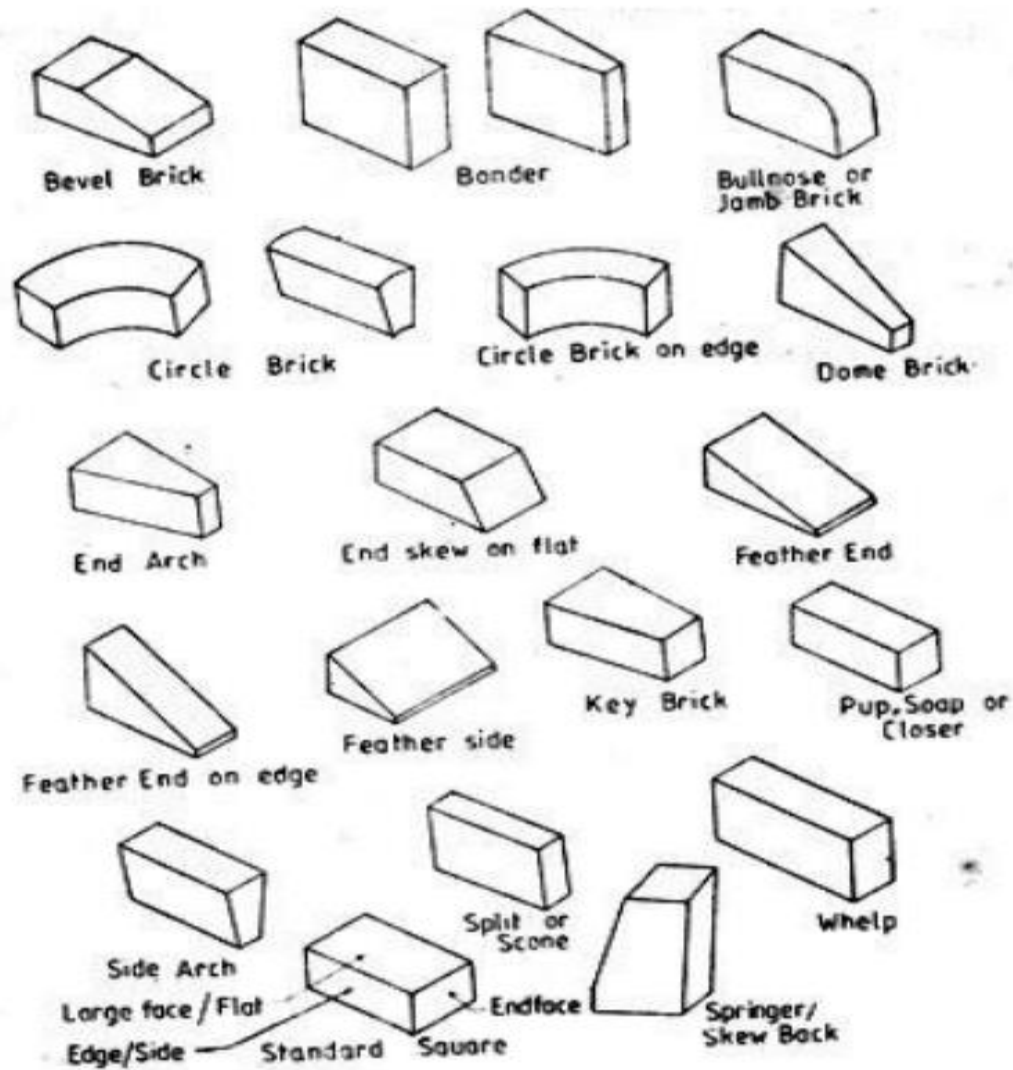


Figure 2 Primary shapes of refractory brick.

Predetermined schemes using combinations of the arch or key brick are usually worked out by the supplier of the refractory shapes or the designer of the refractory lining to accommodate the desired radius of the cylindrical shaped lining or the arch roof or of any lining in question.

These shapes are laid in various combinations to make up the desired dome radius. These shapes can be provided in various thicknesses such as 9 or 1 in. These shapes are also specified by a shape designation number that departs from the scheme defined above. As in cylindrical linings, combinations of the arch-key and wedge-key bricks are predetermined to make a desired dome radius.

EAF refractory dome designs are being replaced by more efficient water-cooled steel domes. Fluid bed reactors also have interior process domes made of special refractory shapes. In these shapes, through-thickness holes are incorporated into the shape that allow hot gas flow in which the hot gas flows upward through the process dome and fluidizes the material resting on top of the dome. Fluid bed reactors and blast furnace stoves are examples of roof domes. Steel-making ladles frequently use a two-layer brick lining (work lining and safety or permanent lining) in the ladle side wall. The brick lining against the steel shell side wall (safety) is typically a 3- to 6-in. refractory brick, and an insulation layer is sometimes used to help maintain the ladle's shell below critical temperatures. Sometimes a heat setting granular refractory material is used to create a monolithic layer in the ladle wall as well. The semi-universal shape has become a popular brick shape

used for the work lining (lining wetted by the molten steel). This shape has rounded ends that allow an easier and faster installation to the cylindrical contour of the cylindrical steel shell.

The semi-universal can typically vary from 3 to 9 in. in thickness. The semi-universal bricks are installed in a continuous spiral starting at the base of the wall and ending at the top of the wall. The installation is started at the base of the wall using special combinations of specially shaped bricks to the slope of the spiral. The semi-universal bricks are selected by a designation system defined by the manufacturer that defines the range of diameters that can be accommodated according to the diameter of the ladle wall. Semi-universal bricks are a variation in the shape of brick that can be installed in a range of shell diameters and still maintain tight joint integrity and tight contact with the backup lining or vessel shell. Ladle side walls are usually tapered in which the side wall radius increases from the base of the wall.

1 in. per vertical ft of height, causing the brick lining to be installed on a radius that increases with each course. The ladle steel shell wall radius can vary from about 45 in. (small ladles) to over 140 in. (large ladles) and in height from 8 to 15 ft. Some ladles are not round but are either elliptical or obround in shape, still

tapering from top to bottom. Semi universal shaped brick can be installed in the straight sections of the wall by as well as the curved sections by inverting the brick.

Steel-making ladle bottom linings are made in a variety of brick and types of refractory materials. Ladle steel shell bottom designs range from flat plate to elliptical dished plate. The flat bottoms are typically sloped to allow drainage of the molten steel to the discharge nozzle. Dished bottoms are also sloped. The molten metal discharges through a special slide gate design at the low side of the sloped bottom that is activated by an external mechanism located at the ladle bottom near the slide gate for discharging molten metal into the continuous caster.

In dish bottoms a castable, plastic refractory, or heat setting fill refractory is used to establish a sloping flat surface for the brick shapes. The bottom brick can be straights of various dimensions, but other shapes are sometimes used. Full precast or cast-in-place castable bottoms are also used. The impact region of the molten metal on the bottom is often made up of either thicker refractory or of a more impact-resistant quality of refractory. The region between the bottom brick and the sidewall brick is filled with a plastic refractory or castable refractory.

Special nozzle blocks are used at the discharge nozzle and around special porous plugs used for gas stirring. A plastic or castable refractory is used between the bottom straights and nozzle block or porous plug blocks.

Rotary kiln bricks or block shapes are typically arch, wedge, or circle shapes. The kiln lining includes a proper combination of one-half, two-thirds, and three-quarter splits. Manufactures have predetermined the combination of kiln shapes for a desired kiln shell inside diameter.

It should be kept in mind that the vessel shell dimensions, such as the shell radius of a cylindrical vessel, may vary from those specified on the design drawings.

Therefore, it may be prudent to provide actual vessel dimensions to the organization responsible for determining the combination of shapes in the lining.

Arch refractory linings are used in a variety of furnaces and tunnel kilns. Coke ovens are probably one of the most complicated refractory structures. For those not familiar with the steel-making industry, coke ovens are used to make coke (from coal) for processing raw iron from iron ore in a blast furnace. The coke ovens are made up of primarily silica block shapes. The shape design of the various silica block shapes make up the walls in the coke ovens.

Hot gases flow internally through chambers in the walls. The walls are heated, which in turn heat the pulverized coal, converting the coal to coke. Silica bricks are used because of the very low expansion of the brick at higher temperatures, giving a very stable structure in the operating temperature range of a coke oven.

Special retaining mechanisms restrain the structure during initial heating when the refractory undergoes a large expansion.

Typical Lining Geometries

Lining designs can be classified into five major geometries. They are arches, spherical domes, cylinders, cones, and flat walls. Each of these lining designs behaves in a unique way when heated to operating temperatures. That is, when the lining is heated and thermal expansion takes place, the lining will displace and brick joints at certain locations will open..

When the refractory bricks or blocks are heated, the bricks or blocks are distorted by the thermal expansion behavior and no longer fit the geometry of the lining. Therefore, brick or block joints will open. The portions of the lining brick joints that are in compression require quality mortar.

The arch lining design can be used as an example to demonstrate this point.

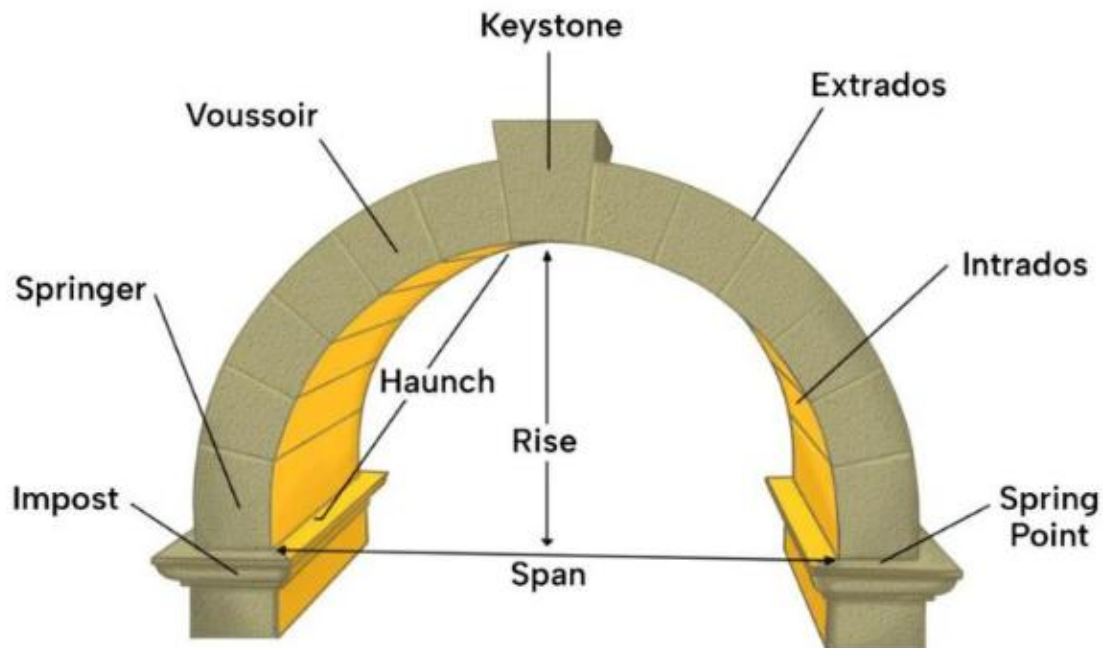


Figure 1: illustrates the unheated arch as installed with no loading and no hinges are formed.

Because of the hinge formations at these regions, higher-quality brick should be used in these regions of the arch. In addition, the brick mortar joints are not in full use at these three regions. Even with a well-insulated arch with an insignificant through-thickness temperature gradient, these hinges will still occur based on the amount or lack of expansion allowance.

Refractory spherical domes form hinges at the base region of the dome, one at the skewback and one a short distance up from the skew as illustrated in

Other refractory dome investigations have shown that the upper hot face hinge will migrate up and down in the brick joints above the skew due to cyclic heatup and cooldowns. The result is cyclic stresses in this lower portion of the dome. This helps to explain why the lower portion of the dome block tends to deteriorate faster than the rest of the dome. This lower region of the dome demands a higher-quality brick than the rest of the dome because of the cyclic stressing in this region. The mortar joints in the upper portion of the dome lining are in full bearing.

Cylindrical refractory lining systems are typical throughout industry. These types of linings consist of either a single or multiple lining systems inside a steel cylindrical shell. The steel shell provides the restraint as the lining inside expands due to the thermal heatup. Typically, the joints compress on the hot face end region of the joint. At the cold face end the joints open. Therefore, the critical portion of the lining with regard to quality mortar joints is in the hot face region of the radial brick joints. The cold face ends of the mortar joints are considerably less important than the hot face end. The circumferential compressive stress results in a radial compressive load of the lining against the steel shell.

In some instances such as in steel-making ladles, the steel cylindrical sidewall shell has a taper in which the shell radius increases from the bottom to the top of the wall. The shell wall can be classified as a truncated cone section. The refractory lining, when exposed to a cyclic heating and cooling of the lining hot face, will cause the lining to progressively ratchet upward in the tapered shell.

Other examples of cylindrical lined vessels include blast furnaces, blast furnace stoves, basic oxygen furnaces, torpedo ladles, shaft kilns, multiple hearth furnaces, and rotary kilns. Some refractory lined vessels have refractory lined conical bottoms. When heated, the conical lining will want to displace upward.

Therefore, the top mortar joint of the conical lining is critical. The cylindrical lining will be critical in restraining the upward expansion of the conical lining. At the ends of rotary kilns, restraint must be provided to contain and keep the kiln lining within the kiln shell.

Flat wall linings are not the most desirable type of lining but are necessary for rectangular shaped vessels. The hot face side of the lining brick joints (joints perpendicular to the hot face) will compress while the cold face end will open.

Basically, the flat lining will tend to curl inward, away from the flat shell. Typically, the vessel steel walls consist of flat plate and are laced with stiffener members

(Channel, I Beam, and WF Beam) on the exterior of the flat plate. Generally, anchoring of the refractory in a flat wall is required to keep resisting the inward force developed in the wall from heating. Specially designed anchors are used to anchor the refractory to the wall and may be made from metallic or ceramic materials, depending on the temperature and environmental conditions of the furnace..

Expansion Allowance

Expansion allowance is often used to reduce the expansion stress in the refractory lining. Expansion allowance is often used in lining systems made of magnesia and silica brick because of their high coefficient of thermal expansion. Approximate methods are used in which a percent of the full expansion displacement is taken for the amount of expansion allowance. Materials such as cardboard and plastic inserts are placed in brick joints that burn out at low temperatures. Compressible blanket of board materials are also used. Typically, low-density (10 to 25 pcf) blankets will compress to about 10 to 20% of their original unloaded thickness. Higher-density (50 to 60 pcf) board materials will only compress to about 80 to 90% of their original unloaded thickness.

Mortar joints can be taken into account as contributing to expansion allowance.

The thickness of the mortar joints considered here are in the range of 1/32 to 5/32 in. (1 to 4 mm). Mortar joints approaching 4 in. (6 mm) are used in some refractory lining systems such as coke oven walls.

In cylindrical refractory linings, expansion allowance can be used in the radial brick joints or in the circumferential joints. The relationship between the expansion allowance used in the radial joints for circumferential expansion allowance (DC) and expansion allowance used in the circumferential joints for radial expansion allowance (DR) is defined by the equation

$$DC = \frac{1}{4} \cdot 2pDR = \frac{1}{2} pDR$$

That is, the expansion allowance used in the radial joints is an expansion allowance that affects the circumferential growth of the lining, whereas the expansion allowance used in the circumferential joint affects the radial growth of the lining.

Therefore, the use of 3/8-in.-thick radial expansion allowance material on the lining cold face is equivalent to using 1/16-in.-thick expansion allowance material in 38 radial brick joints. The use of expansion allowance at the cold face of the

lining would allow the radial joints to remain in a more stable closed condition and minimize flow of process fluids or gases through the radial joints.

The use of plastic materials that burn out at a low temperature is perhaps better than a refractory blanket expansion allowance material. The blanket material may be easily compressed to a lesser thickness during installation, resulting in a loss of expansion allowance.

Expansion allowance in silica brick dome-type refractory linings is typically used only in the lower portion of the dome. The estimated portion of the dome above the skewback is in the lower quarter of the dome. Expansion plastic allowance material is placed in the vertical meridional joints. Domes made of alumina brick typically do not require expansion allowance.

Lining Containment

It is important to remember that the refractory lining must be maintained in compression during service. This is especially important when liquid metal is to be contained. Consideration of the expected thermal gradient in the refractory wall and expansion behavior of those materials and the steel shell at the temperatures must be considered. If the steel shell expands too much at service temperatures, compression of the lining is lost, allowing failure of the lining. If allowances for

expansion are not sufficient, the shell can be overstressed, causing shell damage and failure. Insufficient expansion allowance can also cause cracking and spalling of the lining refractory, leading to reduced lining life and failure of the lining.

Linings that are fully contained (or restrained) in all directions will result in a more successful lining. It has been shown that a fully contained lining is a stronger lining. An example of a well-contained lining is a cylindrical refractory lining on the interior of a steel shell with end restraints at both ends of the cylindrical lining or a spherical refractory lining on the interior of a steel shell and end restraint from the skew. It is important that the installed lining have full containment since a well-contained lining is not only a stronger lining but also a more stable lining.

Abrupt changes in lining thickness should be avoided since the hot face end of the thicker lining will not be contained. A transition in lining thickness can be accomplished by using corbelling, which allows a transition in the lining thickness and a transition of the expansion stresses from two extreme lining thicknesses.

Any type of abrupt change in lining thickness in any type of lining geometry is not desired.

Changes in the lining refractory quality can also affect the structure much as dimensional changes. The differences in the properties of various refractories can

change the heat flux and stress patterns in a lining. This is a normal practice where linings are zoned with different qualities of refractory, such as the slagline of a steel-making ladle. For example, a slagline using a 7-in. carbon bonded graphite bearing brick in the working lining, and a 3-in.-high alumina brick in the safety lining, has a calculated shell temperature of 8458F. With a 7-in.-high alumina lining as the working lining, it is calculated to have a 6028F shell temperature. This difference in shell temperatures can pose a problem because of stress imposed at the change boundaries because of differing expansion and strengths of areas of the steel shell. High-strength insulation materials allow reduction of shell temperatures without compression in service, enabling the lining to maintain compression and the shell to be kept at lower temperatures.

Hydraulic jacking is sometimes used in cylindrical linings as each layer of lining is installed. The jacking assures a tight lining and provides containment of each row. It is necessary to properly design for expansion in a lining installed in this way to ensure a proper stress distribution in the lining. Improper allowances will lead to spalling of the lining, damage to the shell, and loss of containment. If compressible blanket material is used as expansion allowance, then a portion of the expansion allowance is depleted because jacking compresses these blanket materials.

Staggered Joints

Most refractory brick linings are installed with staggered joints. From the thermomechanical viewpoint, this is good practice since a torturous path is created for process gases and fluids. The compressive loading on the hot face of a properly restrained refractory lining also creates a mechanical seal to assist in preventing flow of the process gases and fluids to the back side of the lining.

Typically, the backsides of the lining radial brick joints tend to open during the fully expanded condition of the lining. Therefore, the staggered joints are a valuable addition of mechanical seals. That is, the staggered joints allow the circumferential joints to act as mechanical seals. For example, staggered joints in a double-layered cylindrical lining can apply to the radial joints or the circumferential joints. That is, a staggered thickness of the double-layer lining can be employed. However, with the staggered thickness of the double-layer lining, the radial joints cannot be staggered. The staggered radial joint of a double-lining system is the more popular lining system. Figure 3 shows that the bonded roof design of a sprung arch can be classified as an arch roof with staggered joints. Note also that the flat tunnel kiln walls have staggered joints along the length, height, and thickness of the wall.

Selecting the Best Refractory

In selecting the best refractory for the applications, it is important to know the environment the refractory will be exposed to. The refractory engineer dealing with the chemistry aspects must make the appropriate decisions with regard to chemical compatibility with the process. Mechanical aspects should also be examined such as those listed in the ASTM Standards, Volume 15.01, Refractories; Carbon and Graphite Products; Activated Carbon.

All of the refractory testing standards are too numerous to list here. The major groups for testing standards for refractories include General; Basic Refractories; Carbon –Carbon Ceramic Brick; Fireclay Refractories; Insulating Firebrick; Mortars, Plastics and Castables; and Silicon Carbide Refractories. The next major category is Manufactured Carbon and Graphite Products. The third category is Activated Carbon, and lastly Advanced ceramics. The refractory standard tests are established for bulk density and porosity, cold crushing and modulus of rupture at room and elevated temperature, thermal conductivity, thermal expansion, creep and modulus of elasticity (MOE), or Young's modulus by sonic method.

The sonic method used to determine the refractory MOE usually results in a conservative estimate (too high) of the refractory MOE when compared to the static compressive stress–strain (SCSS) data. The sonic tests also do not provide a complete stress–strain relationship over the full stress and strain range. That is, the sonic test provides the slope (MOE) of the stress–strain curve at a very low stress due to the nature of the sonic test. Often the three-point bending test is used to establish a stress–strain data curve. However, due to the very limited tensile strength, the data curve is very limited. According to available information, the tensile MOE and compressive MOE are not similar. Therefore, the stress–strain data curve from the three-point bending test leads a mix of tensile and compressive stress–strain behavior. The SCSS test provides the best stress–strain data curves for room and elevated temperature. The outstanding problem is that there is no ASTM standard for the SCSS test. A limited number of labs can conduct SCSS tests. The SCSS data curves provide the most accurate data to predict the compressive stress–strain behavior of a lining system. SCSS data on candidate bricks also provide valuable information.

These data can be used to choose the brick that has the greatest combined ultimate compressive stress and ultimate compressive strain.

Refractory materials generally have values reported for expansion as reheat expansion on supplier literature. It is important to understand that reheat expansion (contraction) is a simple test that gives values for the first heating of a refractory but does not report thermal expansion. Reheat expansion is sometimes called permanent expansion and occurs on first use of the refractory. The refractory can undergo changes to chemical, crystal, and mechanical properties during the initial heating. Thermal expansion, sometimes called reversible thermal expansion, is the change of size as the material is heated and the contraction when cooled.

Both values are important to the performance of the refractory. Changes in material properties at temperature are especially important with castables, carbon –carbon refractories, and composite materials. Changes in these properties are usually not linear along the thermal gradient through the lining. Other properties important to the structure and performance of the lining are not linear as well, including strength and thermal conductivity.

Castables

With respect to the thermal expansion behavior of castable linings, they can be defined as a brick lining without joint. Tensile fracture will be initiated in the same

regions of hinge formation in a brick lining. The manner in which a castable is installed has a significant influence on the stiffness and strength of a castable.

Vibrated castable is significantly stiffer than gunned castable. Both vibrated and gunned castable with steel fibers are less stiff than that without steel fibers. Since steel fibers have a greater coefficient of thermal expansion than most refractory types of castables, the thermal growth of the fibers is greater than that of the castable. As a result, tensile fracture cracks are developed in the castable in the vicinity of the fiber. Large vibrated monolithic sections of castable are not always better than the simply poured castable monolithic sections without vibration.

The through-thickness temperature gradient can cause the large monolithic sections to thermally curl. With the higher stiffness and strength of vibrated sections, significant distortions and displacements will occur. Installing castable with steel fibers will not necessarily provide a stronger castable, but it will keep fractured pieces attached to the remainder of the lining. This is desirable to prevent clogging of various discharge openings in the vessel.

When using castables, it is important to consider the initial heating of the material. Castable undergoes considerable chemical changes during the initial heating, causing liberation of water from the refractory structure. Mechanical

water that forms steam at 100°C (212°F) can place minor stress on the structure but is usually generated slowly and able to migrate through the porosity of the refractory body without damage. Chemical water liberated from changes to the chemistry of the castable as the structure is subjected to heat is generally liberated at elevated temperatures. This causes rapid formation of high-energy steam at 400°C to 600°C.

This steam can be explosive to the structure and cause considerable damage. In some cases, explosions, destructive to the structure and dangerous to surrounding personnel and equipment, are possible. The initial heating schedule should allow for very slow heating through the critical temperature range. The use of organic fiber in the castable has enabled castable refractory to be heated at faster rates by improving the ability of steam to migrate out of the structure without damage.

MODULE 9

NDT Techniques for Furnace Refractory Lining Assessment

Globally, thousands of metallurgical furnaces and process vessels are lined by several types of refractories. The harsh smelting conditions result in continuous refractory wear and deterioration which ultimately causes furnace relines. For many vessels, the asset management workflow and refractory maintenance is predominantly proactive, and time based. Non-Destructive testing (NDT) methods can be utilized to change the traditional maintenance practices to a predictive and data-based decision-making function. In addition to reducing furnace refractory lining failures and molten metal leaks and run outs, this could potentially reduce the amount of toxically contaminated refractory waste disposal by extending the refractory lining campaign life. In this paper, we review the NDT techniques that are utilized to determine refractory lining thicknesses and conditions in furnaces and process vessels.

Introduction

In metallurgical and process vessels, refractory deterioration is the main reason for major overhauls and relines.

For this reason, the condition of refractory lining in process vessels and furnaces must be known. Gaps between the bricks could result in metal or chemical leaks and a large leak could result in a run-out, where uncontrollable volume of molten materials or unwanted chemicals discharge into the surrounding, causing expensive repairs and replacement, and most importantly, long vessel downtimes. Annually tons of refractory materials are disposed in landfills. A recent effort is trying to recycle the refractory materials and reuse in various applications. However, a large volume of the refractories is impregnated with aggressive and harmful chemicals that were migrated from the process host into the refractory pores and cannot be removed. Hence, the landfills containing refractory waste materials require rigorous and expensive monitoring systems to assure the toxic unstable chemicals will not enter into the ground water systems. For this reason, it would be best to minimize contaminated refractory wastes at the source, by prolonging the refractory lining campaigns. In the following section, we briefly review the NDT techniques that have been used to inspect and monitor metallurgical furnaces and process vessels. These include discrete measurements such as refractory sounding, radioactive tracer, infrared-thermography, thermal analysis based on traditional thermocouple or fibre optic data, electromagnetic radar systems, magnetic based systems, low frequency

pulse ultrasonic and Acou-sto Ultrasonic-Echo. Furthermore, acoustic emission technique can also be implemented as a long-term continuous refractory monitoring method.

Refractory sounding

Refractory sounding the oldest and most common way of recognizing if there is a delamination between the hot-face refractory and the backup lining or the lining/shell behind it. Usually, it is performed when the vessel is off-line, which reduces productivity due to the stoppage.

Radioactive tracers

Radioactive tracers were used to determine refractory thickness in furnaces during 1960s and 1970s. There are numerous published pieces of literature on the use of tracers in blast furnaces. This method uses radioactive isotope tracers with short half-lives. In earlier research, the radioactive tracers were introduced to the top of the blast furnace. As the tracers move downward with the burden, the receiver or tracer counter or Geiger counter counted the radiation that passes through the build-up, refractory and the shell. Theoretically, the quality of the refractory is the same throughout the furnace and shell thickness is uniform and so increases in radiation counts indicate a thinner and more worn refractory

lining. In reality, blast furnace linings are far from uniform and several types of refractories with different densities and material properties are utilized in the lining. In addition, the presence of staves and plates for cooling purposes added to the complexity of the lining.

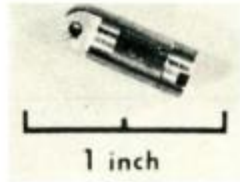
The thickness of accretion, impregnation of molten iron/slag in the refractory and variation of refractory quality influence the radiation counts. Therefore, the fluctuations in radiation counts do not necessarily indicate changes in refractory thickness.

In a more practical approach, the radioactive tracers are placed inside a pod and inserted at fix position in the known selected refractory bricks at different thicknesses and at different elevations.

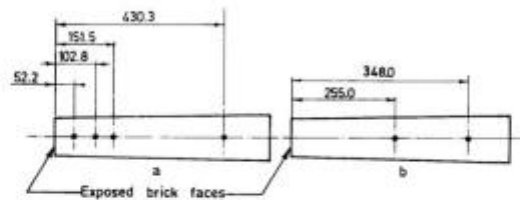
Radioactive tracer pod

Placement of pods in carbon refractory blocks at different thicknesses

Placement of the pods in different refractories at various locations in the blast furnace Fig. 1. Radioactive tracers for refractory thickness measurements in blast furnaces



Radioactive tracer pod



Placement of pods in carbon refractory blocks at different thicknesses

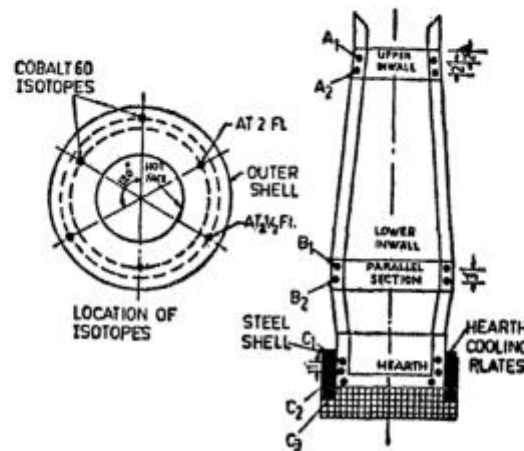


Fig 1 Radioactive tracers for refractory thickness measurements in blast furnaces

A scintillometer or Geiger counter from outside the blast furnace shell is used to locate the position of the tracer and the amount of particle emissions by each tracer insert pod. At the top levels, as the burden (coke and iron pellet/sinter) is moving downward and wearing the refractory, eventually the pod holding the tracer is broken and is carried downward by the burden. The inspectors with

Geiger counters detect the missing emissions which indicates the refractory wear and loss of the pod containing tracers. At the lower levels, molten metal causes refractory wear and reduction in number of tracers and pods. The presence of staves and plates for cooling purposes added complexity and difficulties in measuring the tracers.

Literature reviews on the use of radioactive tracers describe the use of ^{40}La , ^{192}Ir and ^{60}Co isotopes for lining thickness measurements. The major problem with this method lies in radiation exposure and its toxicity which poses health hazards to the operators. Hence, the use of this technique was completely stopped by mid-late 1970s.

Infrared (IR) thermography

In a process vessel or a furnace, if the refractory and shell are well bonded, Infrared (IR) thermography is the most common NDT technique used for determining hotspots and areas of potential concern in a process vessel. IR cameras provide a thermal image showing the temperature of the object on a colour scale where the darker colours are cooler, and the lighter areas are hot spots. Temperature differences on the surface may be related to differences in refractory thickness or may be a result of subsurface defects. The main advantage

of IR cameras is their relatively low price, fast inspection capability and interpretation, no contact, can be used at a distance so increases the safety for the inspectors. In recent years, a large variety of systems have been commercially available with a broad range of image resolutions and prices. See Table 1 for the range of thermal instruments and their range of temperatures. For metallurgical furnaces, only the top three techniques are applicable due to their required high temperature ranges.

Table 1 - Different temperature monitoring techniques and their temperature ranges

Techniques	Typical Temperature Range (°C)								
	-500	0	500	1000	1500	2000	2500	3000	3500
Optical Pyrometer									
Thermocouples									
IR Thermography									
Indicating Paints									
Liquid Expansion in Metal Bulbs									
Resistance Thermometer									
Bimetallic Strip									
Fusible Plug									
Thermistors									
Thermometer									

For furnaces with water cooling elements such as staves and plates, infrared cameras can only be used to identify relative hot spots and high temperature areas, which may indicate gaps between the coolers and surrounding refractories.

However, many furnaces have film cooling where the water flows over the shell continuously for cooling and heat transfer purposes. Infrared cameras are ineffective for these type of blast furnaces. Another problem related to IR thermography is that process vessels and furnaces have a steel shell which oxidizes over time. The rusting of the steel shell affects the surface emissivity of the vessel which may result in inaccuracies in the IR thermography measurements if the exact temperature data is required. In addition, gaps, cracks, and looseness of the refractory bonding will affect the results. Nearby heat sources and thermal reflections from nearby objects also affect the IR thermography data. There are thickness limitations for effective readings; for two- or three-layered refractory lining converters and reactors, thermal cameras are more effective than the thick refractory lined furnaces.

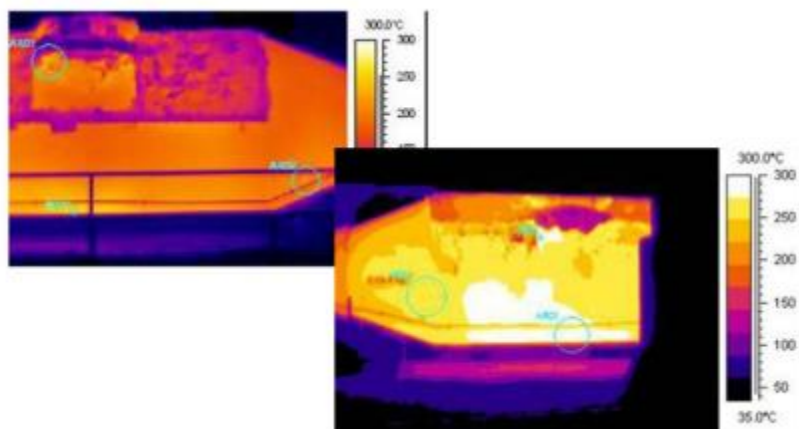


Fig 2: IR camera image of a torpedo car, showing refractory wear at the bottom by high temperature bright colour image.

For the above-mentioned reasons IR thermography is mainly used for rough estimates and the thermal images must be carefully collected under the same conditions for comparison purposes. In 2008, Hatch developed a methodology to use IR thermography to measure the refractory thickness in single layered hollow cylindrical vessels such as converters and reactors. This 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.

Thermocouple or RTD

Refractory thickness measurements based on the thermal analysis extrapolate thermocouple or resistance temperature detector (RTD) data to predict the refractory and/or skull thickness in operating furnaces and process vessels. In this method, thermocouples or RTD temperatures at known locations within the refractory and water temperatures from the staves are used to perform a one-dimensional steady-state heat transfer calculation to calculate the heat flux out of the furnace. In these simplified thermal calculations, it is assumed that the

refractory behaves as a homogenous heat conductor between the hot inner face and furnace shell. Thus, it is assumed that the heat flux is constant throughout the refractory. Thermocouples or RTD and water temperature in cooling blocks are used to gather the data for thermal calculations and thickness measurements.

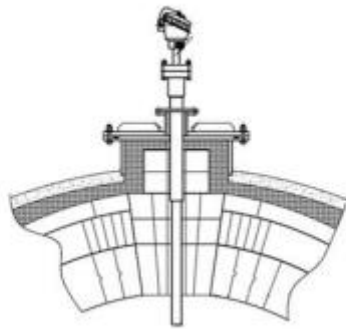


Fig. 3 demonstrates a typical thermocouple.

An inverse-geometry heat transfer calculation is used to estimate the heat flux, based on known temperature differences between the thermocouples (in locations where the thermocouples are duplex pairs installed at different radial depths in the wall), and/or between the thermocouples and the furnace shell or staves (where only a single thermocouple is installed on a given radial line). The remaining refractory thickness is then estimated based on the estimated constant heat flux and the hot face temperature of the refractory.

To accurately estimate the remaining refractory thickness, the temperatures used in the thermal analysis are taken from a time when there is little to no accretion/built-up on the hot face of the refractory – i.e., at the time when wear of the refractory is occurring. Therefore, the temperatures used for thermal analysis are the maximum temperatures recorded by each thermocouple. For duplex thermocouples, the temperatures used are the maximum temperature recorded by the “A” thermocouple (located closer to the hot face) and the corresponding temperature recorded at that time by the “B” thermocouple (located closer to the cold face). See Fig. 4 for an example of the highest temperature at “A” in blue and the corresponding temperature at “B” in orange.

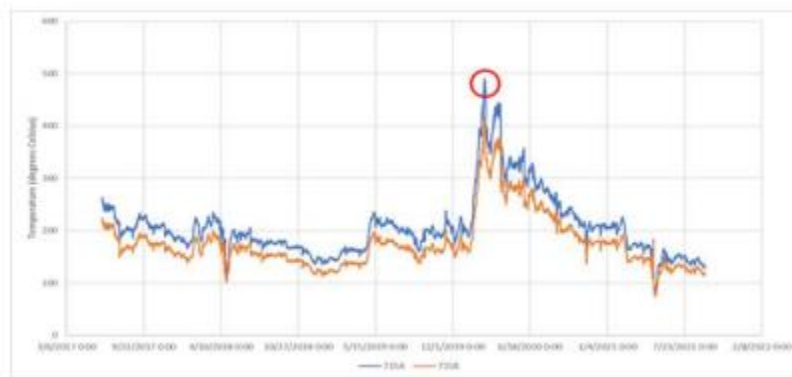


Fig 4: Example of paired thermocouple data with analysis temperatures (degrees Celsius) highlighted in red.

This method has the advantage of being easy to implement since most blast furnaces have thermocouples or RTDs built-in to the design, and the stove temperatures can easily be obtained. Additionally, since thermocouples or RTDs are continuously collecting data, they allow for continuous monitoring of the refractory condition.

However, this method also has several challenges that affects accuracy.

Discontinuities in the lining can result in miscalculations because air is a poor conductor of heat, whereas carbon and graphite bricks are excellent conductors.

Therefore, the thermal calculations for large block refractory lined blast furnaces are more accurate than those of small-sized refractory lined blast furnaces. The thermal modelling method of measuring refractory thickness relies on various sources of information. Unaccounted changes to any property in these models, such as refractory alteration or uneven water cooling, can result in inaccurate thickness predictions. Changing thermal properties due to material degradation can negatively affect the measurements. This makes the thermal modelling thickness calculation inaccurate if there are chemical attacks or metal impregnation, or metal infiltration that change the refractory bricks' chemical and physical properties.

Additionally, measurements can only be taken in locations where thermocouples already exist. This does not allow for additional measurements to be taken in areas of greater concern later in a campaign's life. Finally, multiple interpretations exist for the same thermocouple or RTD measurement due to build-up preventing a consistent heat transfer through the refractory brick. For instance, decreases in thermocouple temperature can be interpreted as forming a build-up layer or a chemical attack in the bricks. Metal impregnation and infiltration cause an increase in refractory thermal conductivity and may be interpreted as refractory wear and thickness losses. Over the furnace's campaign life, the number of permutations and combinations or various possible thermal interpretations becomes increasingly complex and decreasingly reliable. Fig. 5 below shows how multiple interpretations exist for the same thermocouple reading.

Regardless of all the complexities and uncertainties, refractory thickness calculation based on thermal analyses and modelling is essential and is the most common method to monitor furnace refractory lining. Certain improvements in modelling approaches, increasing the number of thermocouples, and use of data from the daily operation can improve this technique's accuracy and reliability. However, we believe that "blind spots" or the areas that cannot be identified by even the most complex thermal calculations and can only be detected by the

Acousto Ultrasonic-Echo (AU-E) techniques, which is described in this paper as well.

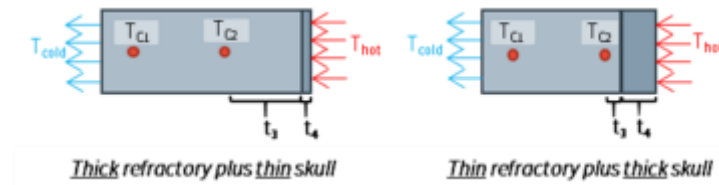


Fig. 5. Multiple interpretations of refractory thickness based on thermal modelling.

One problem with thermocouples and RTD sensor is the difficulty to implement them in large number, because of cabling, power, and connection requirements. For each measuring point, power and cabling must be provided and the cables must be protected from electromagnetic interference (EMI) by shielding and data needs to be converted from analogue to digital format. These problems limit the number of installed thermocouples, which consequently reduces the reliability and accuracy of the results. In recent years wireless systems are introduced but they have to function in high EMI fluctuated environment and the receiver need to be nearby.

Fibre optics

Optical fibres transmit light with low losses in central fibre core with slightly higher refractive index than the surrounding materials. There are two types of fibres, there are single and multiple-mode fibre optic cables. The fibre optics cables are typically between 100-250 microns in diameter and are immune to EMI, can collect multiple measuring points within the same cable with a single collecting and distributing data interrogation.

There are different fibre optics interrogation methods, and they are used to do temperature, distance, strain, and chemistry analysis. The selection of the fibres and interrogators depends on the type of information needs to be collected.

The same fibres can be used to collect either temperature or strain, depending on the interrogator. For temperature measurements, one of the methods is that a grating pattern on the core of a fibre optic strand will reflect light at a specific wavelength and frequency. The grating pattern changes with temperature such that the wavelength of the reflected light is proportional to the temperature change. Like any temperature sensor, the response to changes in temperature is calibrated to provide absolute temperature measurements. Another method uses Rayleigh scattering along a length of optical fibre where every point along the

fibre acts as a sensor. This method allows quasi- continuous measurement of temperature and strain profiles over distances of up to 70 m.

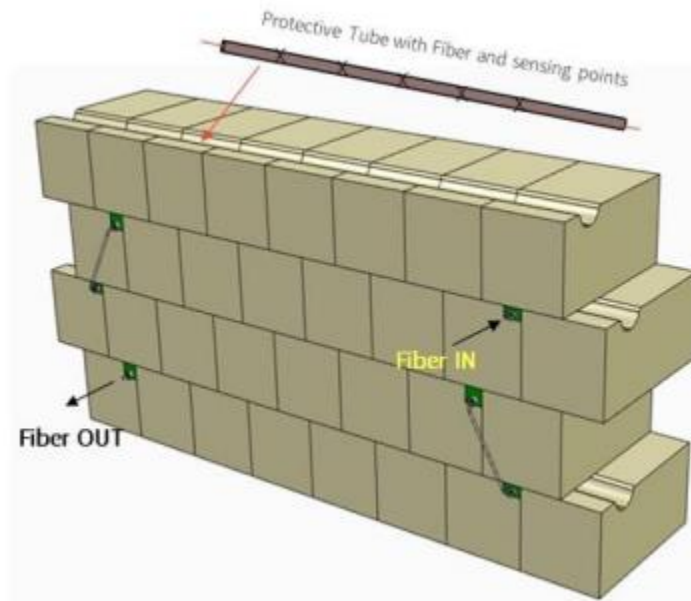


Fig. 6: Monitoring temperatures by fibre optics on refractory lined furnace walls, for thickness measurements

As early as 2009, fibre optics were used in tap blocks in non-ferrous furnaces to monitor taphole refractory wear. Hatch has developed refractory lining monitoring system based on measuring temperatures by fibre optics, embedded into conductive tubes in the electric furnace refractory walls (see Fig. 6). Similarly, fibre optics have been used for temperature monitoring in induction furnaces, porous plugs and RH degassers in steel making refractory linings. As the role of sensors increase in monitoring integrity and performance of the assets such as

furnaces and process vessels and their components, the role of fibre optics to collect crucial information such as temperatures, thickness (distance), chemistry and strain values. Recent solution through research at University of Oxford resulted in producing industrial growing sapphire fibre optics which could tolerate temperatures above 2000oC. This makes fibre optic sensors most desirable to be deployed in smelter applications and the authors believe that in the future we are going to see an increase in use of fibre optic sensors in monitoring of furnaces and process vessels.

Electromagnetic (Radar)

Radar systems have been used on the roof of blast and electric furnaces for the last several decades to determine the height of the burden (blast furnaces) and feed (electric furnaces). The short pulse electromagnetic (EM) signals are generated from the radar system and the reflections from the feed or burden is detected by the same instrument.

The difference in dielectric constant of materials, a quantity measuring the ability of a substance to store electrical energy in an electric field, cause the EM signals to reflect. The change in dielectric constant between air (dielectric = 1) and the surface of the feed or burden (dielectric = 7-8) is the reason for the EM signal to

echo back to the instrument. Frequencies of the radar systems are carefully selected to avoid dust and physical disturbances on the signal pathway. Based on the same principles, EM transceivers or radars can be placed against refractory to measure their thickness. The dielectric constant of ceramic based refractories is low (dielectric= 6-8) and for carbon-based refractories is high (dielectric = 10-15).

One of the advantages of the radar system is that it does not require to be in contact with the refractory and can be held a few millimetres above the surface and EM wavelengths are small, hence the precision in thickness measurements is high. The main disadvantage of radar system in metallurgical furnaces is their inability to go emit their signals through furnace or process vessel steel shells. All metallurgical furnaces have steel shells; hence, radar systems cannot be used to measure refractory condition from their cold face. For glass furnaces, that do not require steel shells, commercial units have been developed for refractory thickness assessments.

The glass furnace radars are designed to identify flaws, measure the erosion profile, and thickness of refractory materials. A data acquisition system is used to measure reflected EM waves, transform data to distance or thickness domain profile.

The transmitter impedance is matched with the material under investigation, and the thicknesses are computed based on time of flight and impedance correlations.

The radar frequency ranges are between 25 MHz – 30 GHz and can measure refractory thicknesses between 12.7 – 300 mm. The system is portable and can be used for inspection and periodic measurements. A fixed monitoring system also exists for continuous monitoring of sensitive areas in the furnace.

Still there are technical challenges with radar systems, for example, the conductivity and resistance of the refractories increase with increase of temperatures, so as the dielectric constants that could be challenge measurement accuracies. In addition, material properties, cracks and delamination are not visible to the EM signals, unless they are wide open (half of wavelength).

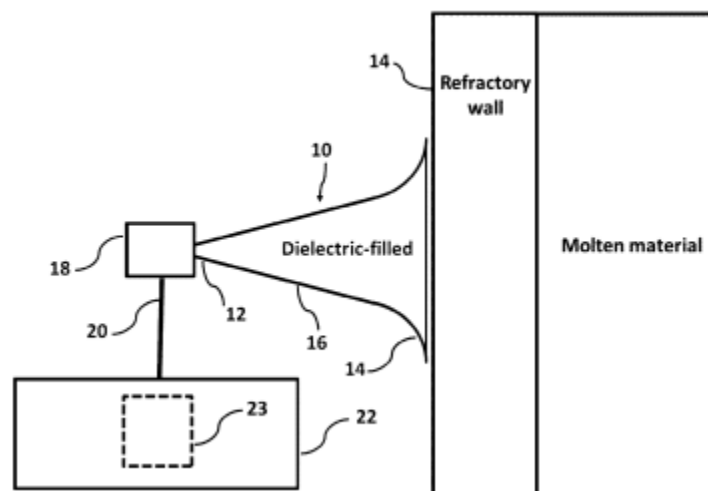


Fig. 7: Schematic of a radar system for refractory thickness measurement in glass furnaces.

Magnetic

Magnetic systems are used to determine the thickness of remaining refractory in single or multiple lined process vessels such as kilns, reactors, and converters. An electromagnetic based device called Covermeter, which is originally used for detecting position of rebars in concrete elements, can be used to determine the refractory thickness. A pair of coils are periodically charged by an electric current, also called pulse-induction, generating a magnetic field that creates an eddy current. If there is a ferromagnetic body nearby or rather, within the range, a secondary and opposite field direction eddy current field generated in the ferromagnetic body. The resulting secondary eddy current field strength can be used to determine the distance of the ferromagnetic body to the coils.

Once the inspectors are inside a kiln or converter, they can place the Covermeter probe on the surface of the refractory and measure the distance to the vessel's shell. Measurements are accurate, particularly in brick lined vessels and many points can be measured within a short time and avoid drilling or removing of the lining. In castable lined vessels, refractory anchors may cause difficulties by being

detected instead of the shell, hence, their position should be identified, and readings should happen in between the position of anchors (see Fig. 8).

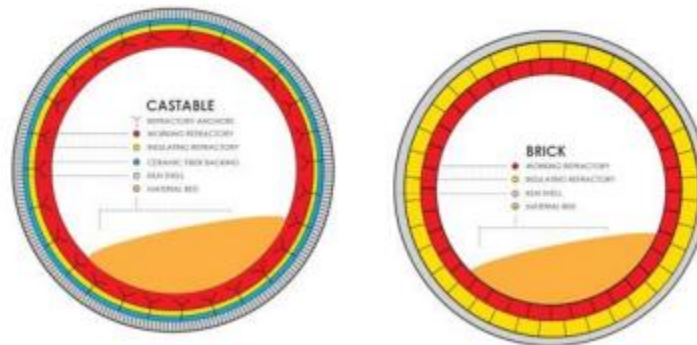


Fig. 8: Castable and refractory lined kilns

Ultrasonic

Low frequency “Ultrasonic Pulse Velocity” (UPV) systems such as PUNDIT and V-Meter have been used to determine refractory quality since Mid-80s. Using the UPV systems, a refractory with known thickness is placed between a transmitting and receiving transducer which are at opposite ends of the refractory sample. A low frequency “Ultrasonic through Transmission” (UTT) system with frequencies between 20 to 200 kHz is used to determine time of flight between the transmitter and receiver.

Generally, high ultrasonic wave speed indicates low porosity, high density, and high modulus of elasticity. “Ultrasonic Pulse-Echo” (UPE) systems are required to measure refractory thickness on an operating furnace. In UPE systems the transmitting and receiving transducers are placed on the same surface. The distance between the transmitting and receiving transducers should be minimal. Parker et al. demonstrated that the refractory/molten metal interface creates a distinguished reflection surface because the acoustic impedance in liquid is typically 13-15% less than for a solid refractory or accretion which means that at least 10% of the waves are reflecting from the wall. In their paper they demonstrated that a large amount of ultrasonic energy attenuates within the solid refractory because of temperature and porosity.

A decrease in the amplitude of reflected ultrasonic signals was noted as the sample was heated to higher temperatures. Temperature also affects the travel path of an ultrasonic waveform in solid. As the temperature increases the longitudinal or P-wave path widens which results in higher attenuation and a change in the reflection angle.

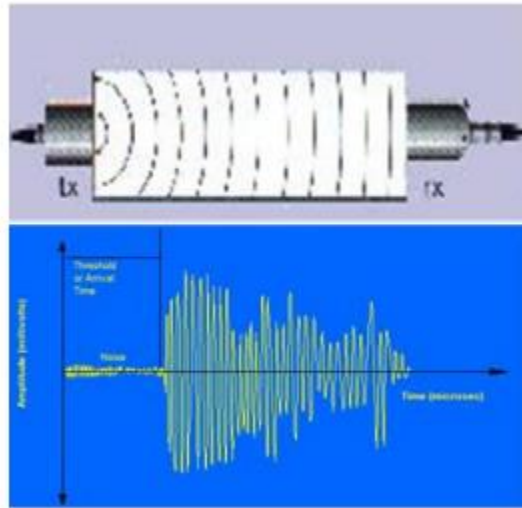


Fig. 9: Ultrasonic through transmission method to determine wave speed in refractories and evaluate their QA based on longitudinal (P-wave) speed, dynamic modulus of elasticity and Poisson's ratio.

For measuring refractory thickness wear in furnaces conventional ultrasound is not an option. A conventional ultrasonic system uses single frequency transducers with fixed and narrow bandwidths. An ultrasonic system with a “sweep frequency” pulse generator and broad band transducers was developed by Hatch NDT Group to determine stove thicknesses in blast furnaces. This Low Frequency Pulse Ultrasonic (LFPU) is a pulse-echo system that is capable of measuring stove thicknesses with a 2 mm precision. The multi-frequency ultrasonic pulses can travel into different layers of blast furnace wall and measure accretion and refractory at the tip of the stove. Even though the LFPU was proven to be

accurate for blast furnace stove thickness measurements, the system has not been used on thicker furnace refractories. The authors believe that the LFPU could be successfully implemented for refractory wall thickness measurements of less than 300 mm thick. In the near future LFPU will be tried on furnace sidewalls and the results will be published by Hatch NDT Group.

In mid-1990s a group of researchers from Magnitogorsk State Technical University in Russia made attempts to utilize the “ultrasonic tomography” technique to identify blast furnace hearth lining layers. Ultrasonic tomography is widely used in medical profession and refers to imaging by sections or sectioning, through the use of penetrating ultrasonic wave. In their approach Magnitogorsk which formed a Techno-Consulting in Mid-2000s, is using “Ultrasonic Mirror-Shadow Method”, to transmit and receive ultrasonic waves across sections of a blast furnace.

In these measurements ultrasonic sensors above 20 kHz are used to transmit and receive the signals. The receiving transducers are placed at 0, 20, 40, 60 degrees angles from the transmitting sensor across the blast furnace. The measurements are repeated in three to four different locations around the hearth. Based on wave speed differences due to material changes for each layer, the captured waves are used to create an “image-shadow”. The so called “image shadow” is

developed based on mathematical modelling and correlations between the arriving ultrasonic waves with blast furnace layers.

Based on the published literature, the ultrasonic signals are going through the shell, ramming, thick refractory lining, molten metal, hot and porous “Deadman” in the centre of the hearth, again the molten metal, thick refractory lining, ramming and finally shell then are detected and collected on the opposite side.

The high frequency of ultrasonic wave (above 20 kHz), high rate of signal attenuation because of temperature and material porosity, complex signal pathway from high to low and low to high acoustic impedances are part of the challenges and concerns in conducting ultrasonic tomography on an operating furnace.

Acousto Ultrasonic-Echo (AU-E)

The AU-E technique was developed in the late 1990s for the purpose of refractory thickness measurements in operating metallurgical process vessels, such as furnaces. It has been patented worldwide, and there have been over 80 publications to date describing the theory and practical benefit of this non-destructive testing method. The original idea was adopted from geophysical hammer seismic, concrete NDT impact-echo, and Miniature

Seismic Reflection (MSR) methods and was evolved for metallurgical furnaces and process vessels. A short transient impact pulse by a spherical tip ball-peen hammer or a mechanical impactor generates elastic waves into a process vessel such as a furnace or an individual refractory, and a receiving transducer or a sensor detects the direct and reflected elastic waves on the same surface at a short distance from the impactor. This impact produces the energy needed for generating elastic waves with sufficient amplitude to travel into the furnace lining or/and a single refractory and echo back. The reflected stress wave is collected by a sensor in the time domain by using a data acquisition system, which stores data for further analysis. The time-domain data can then be converted to the frequency-domain using the Fast Fourier Transform (FFT). The thermal correction coefficient for each refractory lining and shape correction factor for the vessel dimensions must be applied for each furnace type. The interpretation of the frequency responses leads to accurate remaining thickness measurements and cracks and flaw detection. Alternatively, a model frequency/layer thickness can be pre-calculated for each section of the vessel, such as sidewalls and hearth, and the resulting AU-E frequency spectra can be compared with the model calculation for identification of flaws, delamination, cracks, or thickness reductions. A calibration on refractory sample to identify apparent wave speeds for each

refractory types for the furnace is an essential step for creating a correct model and providing accurate thickness and distance calculations. The results of the AU-E signals can be used to detect material quality changes and chemical attacks within the refractory lining in blast furnaces at various isotherms. AU-E has also been used to identify the drilling position in salamander tapping projects, where correct identification of the line of convergence between the walls and the bottom slab.

AU-E system can be used to qualify individual refractories, based on their mechanical properties, particularly, the apparent compressive wave speed, dynamic modulus of elasticity and Poisson ration. In case that there are cracks in the brick, AU-E can determine their presence and location. Since the AU-E waves are low frequency and the wave speed is determined based on the multiple reflections within the brick, an individual measurement on a brick covers the entire brick volume and can qualify it within a minute.

Regarding accuracy, based on numerous verifications, the AU-E measurements are between 4-7% of actual thicknesses or anomaly positions. Accretion or build-up thickness measurements are within 15% of physical measurements due to the greater uncertainty in the wave speed in accretion.

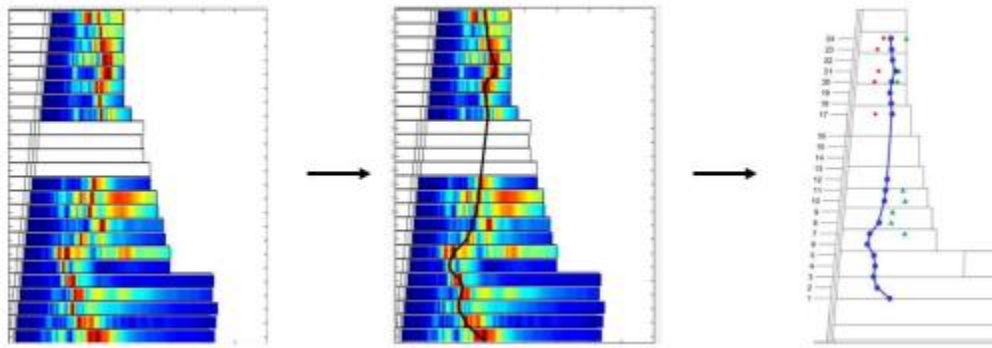


Fig. 10: A typical AU-E thickness spectra accumulation for a blast furnace wall and its 2D interpretation on a furnace sidewall drawing

There are numerous papers on the various aspects and applications of AU-E, namely principals, case studies for blast furnaces, non-ferrous furnaces and vessels, preventing and predicting maintenance.

Acoustic Emission (AE)

Acoustic emissions (AE) are small amplitude elastic (stress) waves generated due to a deformation within a structure. The formation of a crack or failure of a structural component will trigger the release of acoustic emission waves which collectively are known as “acoustic events”. AE transducers are attached to the furnace or process vessel shell with specific patterns to detect acoustic events. An

AE system uses the data from the acoustic events to provide the location and intensity of the deformation. AE is a passive system, and a failure or deformation is first required to have the system triggered and provide information. In 1990, a study was conducted by the European Commission about the application of AE in detecting tuyere leakage, furnace shell cracking and the application of “audiometry” or noise measurement of material flow over the blast furnace charging system chute.

The commission concluded that even though the signal conditioning and recognition is difficult, the AE technique is a powerful technique to solve specific monitoring problems. In 2008, the Hatch NDT Group developed and patented a Furnace Integrity Monitoring System (FIMS) based on application of acoustic emission. FIMS has been utilized in operating furnaces to monitor furnace shell cracking and refractory wear. The FIMS technique involves filtering the surrounding noise from the signal in real-time and relating the transient stress wave emissions to cracking or refractory movements and deterioration. The primary objective of FIMS is to prevent furnace leaks and run outs and secondary objective of FIMS is to monitor refractory wear in operating furnaces. In both applications, an array of AE sensors is required to be installed on the furnace

shell. For cost optimization purpose, the AE sensors can be localized at problematic regions such as taphole regions.

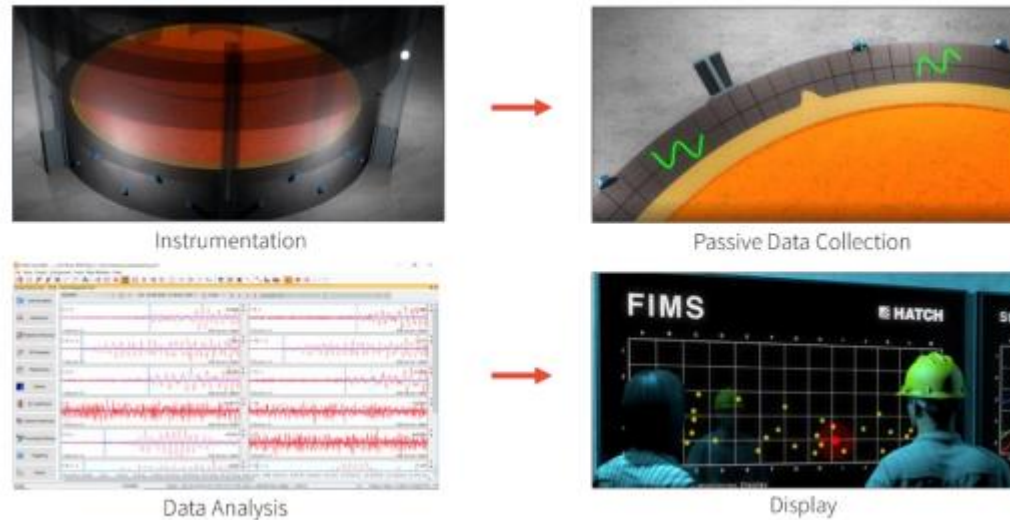


Fig. 11: FIMS – Application of AE in monitoring on-line structural damage and refractory health based on the stress wave propagation principals

AE systems can also be used for short-term monitoring and locating issues in process vessels. To locate leaks and cracks in operating acid precipitation, an array of AE sensors needs to be mounted on the shell of the vessels temporarily. The monitoring of each studied section may last for an hour, during which the vessel will be pressurized or operated like normal operations. All the AE activities during the study period is located in a pseudo- real-time on a display with their relative magnitude or energy level. Areas that are populated with significant AE events are interpreted as leak locations or cracking locations.

Conclusions

Process vessels and smelting furnaces are crucial equipment in the metallurgical process flow chart. Because of harsh thermo-mechanical and thermochemical environment, all these vessels are lined with refractory castables and bricks. Loss of refractory causes severe health and safety and commercial consequences, hence understanding the thickness and condition of the refractory lining in the operating process vessels and furnaces is crucial. In this paper, we reviewed, the existing refractory lining inspection and monitoring techniques. We are concluding that the AU-E and thermal monitoring techniques are the two most reliable methods for inspection and monitoring of metallurgical vessels and process vessels. For best results, the continuous thermal data should, either by thermocouples, RTDs or fibre optics and the results should be correlated with periodic AU-E inspection results.

The use of two techniques with different principals (thermal and stress waves) allows to evaluate the equipment more comprehensively. Trends and “end of campaign” predictions are only possible by collecting data continuously. Also, it is important to collect large amount of data by having numerous thermal collecting sensors and large number of AU-E collecting points, so allows a good coverage of

the vessel. Other instruments, such as AE and high temperature fibre optics are very promising and will be used more broadly in the coming future.

MODULE 10

Refractory Failure Mechanism

Corrosion/erosion resistance is one of the most important characteristics of refractories, which are exposed to molten metal and slag. Hence, the design of the tests closely simulating the conditions that the refractories experience during use is of great importance.

During the formulation of a refractory, close attention is given to a refractory composition in choosing the refractory grains and the bonding system. Thus, refractories used in an iron-making process will differ from that of a steel-making process since the nature of the metal and slag is different in these cases. In iron making, the metal and liquid slag is primarily neutral or slightly acidic in nature, whereas the slag is distinctively basic in the steel-making process. Refractories chosen for iron making are based on alumina and silica, whereas magnesia base refractories are the choice for steel making.

.The specimens are then pulled out and cooled, the relative wears are visually compared, and then the areas around the maximum wear are measured. This gives the comparative corrosion/erosion behavior of the specimens tested. This test has been found to be the best simulative behavior of blast furnace cast house refractories.

Refractories are used at elevated temperatures for structural purposes and they are used in many cases to contain a high temperature corrosive environment. This corrosive environment usually contains liquid (melted) phases that participate in chemical reactions with the refractory at the elevated temperatures resulting in refractory consumption or wear. It is usually not immediately obvious, but the oxidation and reduction state of the environment (as redox” conditions or oxygen “activity”) can participate in and influence the chemical reactions that take place. Along with chemical reactions during corrosion, physical changes occur that may be accelerated by the corrosion process.

Corrosion of refractories can be defined for the purposes of this discussion as follows:

Corrosion of Refractories – refractory wear by loss of thickness and mass from the exposed face of the refractory as a consequence of chemical attack by a

corroding fluid in a process in which the refractory and the corroding fluid react approaching chemical equilibrium in the zone of contact between the refractory and the fluid.

It is an essential point that corrosion reactions proceed in a direction toward localized chemical equilibrium. This means that phase equilibrium diagrams can be used to analyze corrosion situations and to predict chemical strategies to minimize corrosion and wear rates. This gives persons interested in refractory corrosion two options. The first is to view corrosion as a chemical and physical process without a detailed application of phase equilibrium diagrams – called the “phenomenological approach”. The second is to use the information in the phenomenological approach and to use phase equilibrium diagrams. This latter option is required for a full understanding of refractory corrosion.

There are many types of refractory systems – fusion cast and/or bonded brick in a “working” lining placed in front of a backup or “safety” lining (or simply placed against a “shell”), thick-wall applications of concretes (and other monolithics) where the lining thickness is usually on the order of 75 mm or greater, and thin-wall applications of monolithics where the lining thickness is typically less than about 25 mm. It is beyond the scope of this chapter to cover every type and

application possible. There are fortunately a few fundamental principles that the investigator can apply to any corrosion situation, and it is a purpose of this chapter to provide those fundamental principles.

First Fundamental Principal on Refractory and Slag Compatibility

The first fundamental principles is that “acid” refractories tend to resist “acid” slags better than “basic” slags and, conversely, “basic” refractories tend to resist “basic” slags better than “acid” slags. The definitions of acidity and basicity in room temperature solution chemistry and of refractory chemistry at elevated temperature have a key difference:

Definition of Acidity and Basicity in Solution Chemistry at Room Temperature –an acid contains an excess of hydrogen ions (H^+) over hydroxyl ions (OH^-) considering a “baseline” defined as neutrality (a “pH” of 7.0). An acidic substance contributes hydrogen ions to a chemical solution to make it more acidic whereas a basic substance contributes hydroxyl ions to make it more basic.

Definition of Acidity and Basicity in Corrosion Chemistry at Elevated Temperature – an acidic material contains an excess of silica content (SiO_2) over basic materials (usually CaO) considering a “baseline” defined as neutrality (a CaO/SiO_2 ratio of

1.0). An acidic material contributes SiO_2 in a corrosion reaction whereas a basic material contributes CaO or MgO in a corrosion reaction.

This leads to the observation that acid refractories are more “compatible” with acid slags, i.e. acid materials experience less corrosion loss against acid slags as compared to basic slags. In a like manner, basic refractories are more compatible with basic slags than with acid slags.

In a strict definition of compatibility, mineral phases will not react at elevated temperature if they are compatible. This means on a microscopic basis, they will “stand beside” one another or coexist at equilibrium without reacting to form new substances. In general usage, the term “more compatible” just means “less reactive”.

There are more complex definitions of acidity and basicity for high temperature chemistry than those given above. For example, in steel refining the term “V” ratio is used where a ratio exceeding 1.0 implies a basic chemistry (usually a basic slag chemistry) and a ratio below 1.0 implies an acid chemistry.

Corrosion reactions should be viewed as attempts by the system to achieve compatibility by progressing toward equilibrium. Refractories are rarely at chemical equilibrium on a microscopic scale since they are typically made from

mixtures of different minerals. However, at the immediate corrosion interface between the refractory and the slag, the localized volume elements may be at or close to chemical equilibrium.

Second Fundamental Principle on Porosity and Corrosion Rates

Most refractories contain void space or porosity. This porosity may be open pores that can be penetrated by a fluid media (i.e. “apparent” porosity) and/or it may be closed porosity that is not easily penetrated by fluid media. If a refractory contained no porosity (or brick joints, expansion joints, or construction joints), the corrosion reaction is limited only to the face exposed to the corrosive media (called the hot face). When porosity is present, particularly when open porosity is present, the corrosive media can penetrate the refractory causing destructive reactions behind the hot face.

Most investigators have found that slag corrosion rates increase linearly with the percentage of apparent porosity within the refractory. This is usually true within a limited range of apparent porosity – for example in the range 12-16% apparent porosity – but it is not necessarily true at high apparent porosities (>20%).

It is for this reason that attention is directed toward achieving higher densities in refractories, i.e. obtaining the lowest possible apparent porosities.

Higher density refractories usually exhibit lower wear rates. Understandably, very low-density refractories may exhibit less spalling resistance leading to higher wear rates by another process such as thermal shock. This points to the fact that corrosion loss is one part of many possible contributors to an overall wear rate for a furnace lining. Usually one wear process, such as corrosion, is the dominant wear process.

Because corrosive fluids can penetrate the refractory, such penetration usually results in disruption and even destruction of the “matrix” of the refractory.

The matrix is the area of “sintered fines” that hold together “bonded” bricks and monolithic refractories. Usually, the matrix contains more impurities and more porosity than aggregate particles. Therefore, corrosion affects the “weakest” component of the refractory at a higher rate than denser or higher purity particles. In extreme cases of matrix attack, rapid erosion of coarse refractory aggregate can occur.

Phenomenological Description of Corrosion

The phenomena that occur during refractory corrosion are well known to anyone that has been around a furnace containing reactive process components such as slags or glasses. It is obvious that the reactive component, hereafter called the

“slag”, must contact the refractory’s exposed surface or hot face at elevated temperature. It is at this interface that corrosion begins and continues throughout the life of the lining.

In conventional refractory designs, the lining is at least one brick thickness (>225 mm), and the lining typically features a safety lining for a total thickness of at least 450 mm. The slag freeze plane may be located in a zone of 40-75 mm behind the hot face. In some cases, slag may penetrate up to 150 mm behind the hot face.

Thin Wall (Steep Temperature Gradient)

Here the refractory corrosion reactions occur primarily at the immediate hot face and there is little or no slag penetration. Microscopic examinations usually show that penetration is confined to a depth of less than 100 microns (0.1 mm) behind the exposed hot face. This situation may be called “Stage I” of slag attack where reactions occur at the immediate hot face.

It is found that the hot face temperature primarily affects the rate of corrosion reactions. If the hot face temperature is held just below the point that the products of corrosion become liquid (melt), corrosion will be very slow or nonexistent. Most authorities believe that if the hot face is maintained at no more

than 200C above this melting temperature (called a lowest eutectic temperature), reasonable corrosion rates will be observed. However, when the hot face temperature is more than 200C above the eutectic, corrosion is rapid.

In time, extensive corrosion of the refractory takes place so that the refractory is at "Stage II" of corrosion). Stage II is characterized by two phenomena: (1) full penetration of the refractory and (2) extensive disruption by corrosion of the hot face region. Stage II follows Stage I only if there is a sufficiently broad temperature gradient to allow penetration.

In Stage II, the coarse aggregate in a bonded refractory exhibits penetration – particularly along grain boundaries (boundaries between crystals making up polycrystalline aggregate particles). The direct bonding between the matrix and the aggregate particles is disrupted, but this bonding still exists.

Slag penetration in Stage II can result in densification spalling. This type of spalling occurs because the thermal expansion coefficient in the slag penetrated zone is different than that in the unpenetrated cold face region. On continued thermal excursions (cooling and heating), spalling can occur at the line of demarcation between penetrated and unpenetrated areas. The residual lining, after spalling, then begins the corrosion process anew progressing from Stage I to Stage II again.

Toward the end of the life of the refractory lining or in cases of relatively slow corrosion rates and where densification spalling has not taken place, the refractory hot face zone may progress to a final stage of corrosion that may be called “Stage III”.

In this case, bonding in the hot face region and up to 2-4 mm behind the hot face is minimal. The slag itself “appears” to be the only phase holding the residual aggregate particles in place. This is probably a result of the higher viscosity of the slag in the hot face region created as a consequence of dissolution of the refractory in the slag.

Because of the influence of slag viscosity maintaining some coherence in the hot face zone in Stages II and III with thick wall designs, a key process variable affecting corrosion rate is hot face temperature. Many investigators recommend a hot face temperature not more than 20oC above the solidus temperature between the slag and the refractory. Such temperature restrictions are impractical in many thick wall refractory designs.

Finding the Root Cause of a Refractory Failure

Step 1: Discovery Process

It is necessary to collect and document some basic information. In many cases, the discovery process requires interviews with plant and installation personnel. These professionals know first-hand about the refractory process. The following information should be identified and documented:

Material samples and data sheets of the existing brick or refractory lining—this information may be supplied by the purchasing agent or by the plant engineer;

Material samples of the ash clinkers and slag—samples may be supplied by maintenance or engineering personnel from the plant;

Chemical analysis of the fuel being burned (coal, startup oil, refuse, wood, steel, aluminum, etc.)—this information may be supplied by the plant engineer;

Storage location and duration of the storage prior to installation—this may be supplied by the plant or the installation contractor;

Manufacture date of the refractory material—this information may be supplied by the refractory manufacturer;

Ambient condition at the time of the installation—this should be supplied/verified by both the plant personnel and the installation contractor;

How much material was installed—this information may be supplied by plant personnel and/or the installation contractor;

How it was installed or applied (pneumatically, troweled, poured, shotcrete, etc.)—this may be supplied by the plant or the installation contractor; and

How the material was cured and/or dried and what procedures were followed—this information may be supplied by the plant and/or the installation contractor.

Step 2: Examine the Existing Material and Testing

The existing material (or the lack thereof) should be examined for signs that may indicate the root cause of the failure. When looking at an existing refractory lining or photos of the existing lining, keep in mind the following questions:

Did the material fail due to thermal shock (large sections of the top surface area sheared away)?

Is there any evidence that the materials had been exposed to excessive temperatures (excessive shrinkage, glazing, etc.)

Is there any evidence of mechanical abuse (broken and jagged edges or holes)

Did the material fail due to the operation of the equipment, furnace, or boiler?

Was the refractory material installed improperly (i.e., porous or popcorn-like texture)?

Collecting Samples for Testing: Samples of the existing refractory material should be gathered and sent out for a cold crush test, which will verify the strength of the installed material. The results can be compared to the manufacturer's material data sheets. If the strength of the existing installed material is low, it is probable that the mix was too wet when installed.

Samples of the existing slag and ash clinkers should be gathered and sent out for chemical analysis. The slag samples should also have a pyrometric cone equivalent (PCE) test performed to verify the minimum temperature that the refractory may have been exposed to.

Step 3: Calculate the Base-to-Acid Ratio

The next step is to document the environment to which the refractory material was exposed. One way to do this is by calculating the base-to-acid ratio (b/a),

using values taken from the information received from the chemical analysis test mentioned in Step 2. This b/a value will give a starting point as to what type of refractory material should have been chosen.

Here is one way to calculate the base-to-acid ratio:

When the base-to-acid ratio is less than or equal to .25, it indicates an acid condition. An acid condition would indicate that a SiO₂ type refractory should be considered.

When the base-to-acid ratio is greater than .25 but less than .75, it indicates a neutral condition. A neutral condition would indicate that an Al₂O₃, SiC, or chrome type refractory material should be considered.

When the base-to-acid ratio is greater than or equal to .75, it indicates a basic condition. A basic condition would indicate that an MgO or Dolomite type refractory material would be considered.

Step 4: The Review Process

Now it is time to analyze all the information gathered in Steps 1 and 2. All of the service conditions must be reviewed and analyzed thoroughly in order to see how

they could affect the installed/failed material. This includes the fuel or raw materials being burned, startup fuel used, ash and slag content, gas temperatures, and plant operations and procedures. For example:

Moisture content in the fuel can affect the refractory material. High moisture content or combined moisture content in the fuel with a reducing atmosphere can cause a separation of silicon carbide base materials (grain). This separation can occur when the total percentage of the moisture content found in the fuel is greater than fifteen percent, or when the combined total percentage of the moisture content in the coal and the reducing atmosphere percentage are greater than fifteen percent.

Certain amounts of chemicals (iron oxide, potassium, or sulfur) found in the fuel, slag, or ash could react with cements (calcium-aluminate) that are present in a cement-bonded type refractory, especially if a reducing atmosphere is present.

Certain startup fuel (i.e., #6 oil) may contain vanadium, which could react with the silica and lime in the cement found in a cement-bonded-type refractory. When vanadium is present, it can cause a chemical attack and surface failure, or cause a complete refractory failure (no refractory present).

Step 5: Review of Installation Procedures

The final analysis also must take into account proper installation procedures. All of the items listed below could prevent a refractory material from reaching its proper strength. A refractory material that is not able to reach its designed strength has the highest potential for failure.

Properly Manufacture Date and Storage: Refractory material should be manufactured in the proper time period based on the installation date and manufacture date. One year is recommended for a cement-bonded material used for conventional seals inside boilers, and three months or less for materials used in high temperature and abrasion areas such as those found inside fluidized bed boilers, cyclone fire boilers, or wet bottom ash hoppers. Refractory material always should be stored in dry, well-ventilated conditions. Use fresh refractory materials and follow proper storage procedures to ensure that the refractory will not lose strength.

Proper Water for Mixing: Many common industrial compounds can easily contaminate a refractory mix and seriously affect its strength. Certain salts can react with the refractory cement to make the material almost useless. It is recommended by most refractory manufactures that potable water (suitable for

drinking) should be used for mixing. The use of the wrong type of water (e.g., river water) will hinder the ability of the refractory material to reach its proper strength.

Equipment and Pot Life: Using the right type of mixer, following proper mixing procedures, and being aware of the materials' pot life also must be considered. Using the wrong mixer or pneumatic gun also could impact the strength of the refractory material. For example:

Many pneumatically applied refractory materials require the material to be pre-wetted prior to the actual mixing and installation. If the installing contractor had used a continuous feed mixer (i.e., one that adds dry material into a hopper and the water is added only at the nozzle), the material could not be pre-wetted due to the nature or characteristics of using a continuous feed mixer. This could reduce the strength of the installed material.

Every refractory material has a pot life, which designates how long a mixed refractory material can be used after mixing. Failure to follow recommended pot life times could result in a refractory material not reaching its proper strength. If the pneumatic installation of the refractory is interrupted for a period of time

longer than the recommended “pot life” time period, the material found in the mixer and hoses should be discarded and not re-used.

Ambient Conditions: Cold or hot weather could adversely affect the strength of a refractory material. It is recommended by most refractory manufacturers that the final mix temperature should be in a specific range. Though they all differ slightly, it is recommended that the final mix temperature should be in a range of 40° to 90° F. It is also very important to protect the installed materials from freezing for a minimum of forty-eight hours or until thoroughly dried. Failure to take into consideration the ambient conditions at the time of installation could impact the ability of the refractory material to reach its proper strength.

The following formula is one way to estimate/adjust the variables relative to mixing a refractory material (e.g., water temperature, air temperature, storage temperature):

$$X = [(W * T) + .22 (Wc * Ts)] / (W + .22Wc)$$

W = weight of water (a quart of water weighs 2.08 pounds)

Wc = weight of dry refractory

T = temperature of water (degrees F)

Ts = temperature of solids (degrees F)

X = temperature of mixed refractory (degrees F)

Using the above formula and knowing the ambient conditions at the time of installation can help determine if the installed material was adversely affected by the ambient conditions.

Curing Procedures: Only after the refractory material has been cured and/or dried will it be at its proper strength. Almost all refractory materials (except those that are phosphate-bonded) must be cured prior to the drying process. Failure to properly cure a cement-bonded refractory material is the number one contributor to refractory failure and lack of longevity. Curing allows the chemical action to take place inside the refractory and helps ensure that the refractory can reach its maximum strength when properly dried. It is recommended that the surface of the refractory be kept moist (curing compound, wet canvas bags, or spraying water) or the surrounding atmosphere humid for a period of at least twenty-four hours.

Drying Procedures: The dry-out or bake-out of the refractory will take place after the curing period and removes all mechanical and chemical water left in the installed material. It allows the refractory material to reach its proper strength. Unlike the curing of refractory, which is done right after the installation (usually by the installing contractor), the dry-out can be completed any time. This does not apply to phosphate-bonded refractory materials, however, as a phosphate-bonded material must be cured and dried at the same time. A phosphate-bonded material must be dried within the first two to three weeks after installation because such a material will begin to absorb moisture from the surrounding atmosphere. Eventually, over a period of two or three weeks, the material will begin to slump and fall off.

New lining should be heated gradually to let the moisture escape and reduce internal stresses. The rule of thumb is to base the hold time on the thickness of the thickest area of refractory lining found on the entire work project. For example, if the thickest area is four inches thick, the hold time is four hours.

The following heating schedule is of a general nature for ideal conditions for a one-inch-thick refractory lining on fluidized bed furnace walls:

Raise temperature at 75°F per hour to 250° to 400°F range. Hold for two hours at 250° to 400°F

Raise temperature at 75°F per hour to 600° to 800°F. Hold for two hours

Raise temperature at 75°F per hour to 1,050° to 1,200°F. Hold for two hours

Raise temperature at 75°F per hour to operating temperature

In many applications, conservative heating rates can be followed without great penalty; but in some cases, such rates are uneconomical from a production standpoint. Each material has its own allowable deviation for conservative heating schedules. Check with the refractory manufacturer or refractory expert for a compromise between safe heating rates and operating costs. Following improper dry-out procedures can have the following adverse effects upon the refractory: It will never reach its maximum strength, and it will contribute to a spall at the refractory surface.

Know Your Quantities: Finally, to help ensure that the refractory material is not installed too thickly or too sparsely, it is important to know the quantity of material required for proper installation. This quantity then can be compared to the amount that was installed. For example:

Insufficient material installed on the lower furnace walls inside a fluidized bed boiler could contribute to excessive stud and tube wall failure.

Excessive material installed on the lower furnace walls inside a fluidized bed boiler in conjunction with not following proper curing and/or drying procedures could contribute to a complete refractory material failure.

Final Analysis

Finding the root cause of a refractory material failure must take into account many different factors, such as material selection and manufacture date, plant operations, material storage, mixing, installation, curing, and drying. Only by understanding all aspects pertaining to the design and installation of the refractory material can one find the root cause of the failure and help eliminate future failures. A refractory failure is the number one cause of boiler inefficiency and a major contributor to boiler shut-downs. Refractory that is properly selected

and installed will always last longer, help minimize the amount of shutdowns required, and lead to savings in annual fuel cost. Experts agree that refractory designed and installed to save energy also saves money at a rate that is essential for efficient plant operation

Module 11

API 936: Essential Training for Refractory Quality

Refractory material is important to be made used of in oil and gas, petrochemical, power generation industries. As this equipment is exposed to high temperatures, chemical corrosion and mechanical stress they require the proper refractory materials. One way to make sure that refractory linings are installed and used according to the best strategies is through certification as set forth by the American Petroleum Institute (API) 936. This certification ensures that the installation, inspection and testing of all refractory linings are built to industry safety standards. What is API 936, what is the duty of an api 936 inspector and what are some examples to study for getting certified.

What Is API 936?

API 936 is a valuable certification that helps you prove your understanding of the API STD 936 Refractory Installation Quality Control Guidelines. There is a large

degree of responsibility in making sure that the professionals who know how to handle and inspect refractory materials used at high temperatures are thoroughly certified, this will be their certification. In other words, it is similar to having a module or degree in refractory material management and inspection. Finally, garnering this certification is great for an individual's career but also ensures that the industries like oil and gas, petrochemicals or energy commission their refractory installations correctly, timeously and safely which affects equipment integrity in a big way.

What is API 936 Refractory?

API 936 is the brand name given by API for refractory material quality control in an industrial area. Refractories are high-temperature resistant materials that can be used to line furnaces, kilns and reactors. It must also be noted that these materials are very important in industries such as petrochemical, oil refining and some parts of the power generation sector where they influence the structural wellbeing under extreme conditions. API 936 provides directions for the in-service installation quality control testing of refractory linings, to help ensure they are durable and high-performing under service conditions involving elevated temperatures.

The standard API 936 includes multiple topics like the selection of refractory material, installation procedures and some test methods to be used for evaluation of materials based on specific industrial conditions. The objective is to ensure refractory installations comply with the performance criteria requirements, which lowers downtime uncertainty and maintenance expenditure while also improving overall operational safety.

What Is API 936 Inspector?

API 936 inspectors are certified specialists who supervise the installation, quality control, and maintenance of fire-resistant coatings in industrial settings. These inspectors play a critical role in ensuring that fireproof installations meet API 936 criteria and can resist the rigours of high temperatures.

API 936 inspectors have the following primary responsibilities:

Ensure that the materials used in the fireproof installation match API specifications.

Monitoring the installation process to ensure that all necessary processes are performed.

Conducting tests on the installed fire-resistant layer to determine its integrity and

functionality.

Identifying and documenting any flaws or areas of concern that could endanger the effectiveness of the fire-resistant coating.

To become an API 936 inspector, professionals must first pass a certification exam that assesses their knowledge of refractory materials, installation techniques, and quality control procedures. This qualification assures that inspectors have the competence required to keep industrial processes safe and efficient.

What Is API 936 Study Material?

API 936 inspectors are licensed specialists in charge of supervising the installation, quality control, and maintenance of fire-resistant coatings in industrial settings.

These inspectors are critical in verifying that fireproof systems meet API 936 criteria and can endure the rigors of high-temperature conditions.

The primary responsibilities of API 936 inspectors are:

Ensure that the materials used in the fireproof installation meet API specifications.

Monitoring the installation process to ensure that correct procedures are followed.

Testing the installed fire-resistant layer to ensure its integrity and performance.

Identifying and documenting any flaws or concerns that may affect the

effectiveness of the fire-resistant coating.

To become an API 936 inspector, professionals must first pass a certification exam

that assesses their knowledge of refractory materials, installation techniques, and

quality control procedures. This qualification assures that inspectors have the

competence required to keep industrial processes safe and efficient.

What Are The Key Aspects of API 936?

To better understand API 936, let's divide it down into its primary components:

Refractory Materials

API 936 digs into the world of refractory materials, offering engineers a thorough understanding of their properties, classifications, and uses.

Inspection and Testing

One of API 936's main objectives is to ensure the quality of refractory installations. This includes rigorous inspection and testing methods that meet the highest industry requirements.

Installation Guidelines

Learn about the best methods for installing refractory materials. API 936 describes the methods and strategies that engineers must use to ensure a successful installation.

Repairs and Maintenance

Learn how to analyze and manage potential difficulties that may develop during the refractory materials' lifecycle. API 936 provides guidelines on repair and maintenance to help installations last longer.

How Are The Implementation of API 936 in The Industry?

API 936 plays a significant role in the oil and gas industry by providing essential guidelines for working with extremely high-temperature materials. Think of it as a set of well-defined rules that ensure safety and efficiency when constructing and maintaining equipment like furnaces and boilers.

The industry must follow API 936 norms and regulations to ensure the safe and efficient use of high-temperature materials. A true case study shows this:

Case Study: Refractory Lining in a Petrochemical Plant

In a petrochemical plant, there was a need to replace the refractory lining in a high-temperature furnace for safety and efficiency reasons. The company chose to apply API 936 standards to this project.

Implementation Steps:

Material Selection:

Following API 936 guidelines, the company carefully chose refractory materials that matched the furnace's specific temperature and chemical requirements.

Inspection and Testing:

Certified inspectors rigorously examined the selected materials to ensure they met API 936's strict quality standards.

Installation Practices:

A team of API 936-certified professionals followed the best practices outlined in the standard to accurately install the refractory materials.

Results:

Through the implementation of API 936, the company successfully upgraded the furnace's refractory lining with precision and safety. The advantages included:

Enhanced Safety:

The new lining complied with API safety standards, reducing the risk of accidents and ensuring the protection of workers and assets.

Improved Efficiency:

The chosen materials and installation techniques optimized the furnace's performance, enhancing operational efficiency.

Extended Lifespan:

Adherence to API 936 guidelines increased the refractory lining's lifespan, reducing the need for frequent replacements and leading to cost savings.

This case study demonstrates how implementing API 936 can result in safer, more efficient, and cost-effective operations within the oil and gas industry.

Body of Knowledge for API 936 Refractory Personnel Certification Exam

Effective April 2024, August 2024, and December 2024 (Replaces Dec 2021)

API certified 936 refractory personnel must have knowledge of installation, inspection, testing and repair of refractory linings. The API 936 Refractory Personnel Certification Examination is designed to identify applicants possessing the required knowledge.

The exam consists of 75 scored questions and 10 pretest questions; and runs for 3 hours and 15 minutes; no references are available during the exam, and nothing may be brought into the test center.

The exam focuses on the content of API 936 and other referenced publications.

API Publications:

- API Standard 936, Refractory Installation Quality Control Guidelines – Inspection and Testing Monolithic Refractory Linings and Materials, 4th Edition, June 2014*
- API TR 978, Monolithic Refractories: Manufacture, Properties, and Selection, 1st Edition, March 2019
- API TR 979, Applications of Refractory Lining Materials, 1st Edition, October 2018
- API TR 980, Monolithic Refractories: Installation and Dryout, 1st Edition, April 2018

B. ASTM (American Society for Testing and Materials) Publications:

- C113-14 (2019) – Standard Test Method for Reheat Change of Refractory Brick
- C133-97 (2021) – Standard Test Methods for Cold Crushing Strength and Modulus of Rupture of Refractories
- C181-11 (2018) – Standard Test Method for Workability Index of Fireclay and High-Alumina Plastic Refractories

- C704-15 -Standard Test Method for Abrasion Resistance of Refractory Materials at Room Temperatures

Candidates are expected to demonstrate knowledge in the following categories:

1. Laboratory Testing Procedures

The test questions may be based on the following topics:

1. Terms and definitions
2. Test methods (e.g., C704, CCS, PLC, Density) and related calculations
3. Material Qualification
4. Testing equipment, sample preparation techniques, dimensional requirements for test specimens
5. Various materials utilized (for example, plastic, ceramic fiber, anchor, metal fiber, corrosion coatings, etc.)
6. Curing and firing procedures
7. Acceptance/rejection criteria

8. Responsibilities of personnel and documentation requirements.

2. Applicator and Material Qualification

The test questions may be based on the following topics:

1. Installation methods (e.g., gunning, casting, ramming, and hand packing)

2. Sampling and sample preparation procedures

3. Terms and definitions

4. Procedures for determining optimal water content and mixing

5. Applicable formulation and manufacturing information

6. Applicable knowledge of equipment and qualification process

7. Applicable test panel/mockup requirements

8. Applicable environmental controls

9. Surface preparation requirements

10. Responsibilities of personnel and documentation requirements

3. Installation

The test questions may be based on the following topics:

1. Terms and definitions
2. Responsibilities of personnel and documentation requirements
3. Knowledge of detailed execution plan including design details and quality standards
4. Packaging and storage requirements
5. Surface preparation and cleanliness requirements
6. Anchor: welding, layouts, patterns, materials
7. Frequency and methods of production sampling: gunning, casting, hand packing
8. Water addition: quantity and temperature, mixing procedures
9. Fiber addition: percentage, material, mixing
10. Installation environmental controls (minimum and maximum temperatures)

11. Guniting procedures and equipment, including variables that affect guniting quality (i.e., air pressure, humidity, temperature, aging, water pressure, water purity, additives)
12. Knowledge of flash set
13. Casting procedures and equipment (e.g., air vibrator, vibrator frequency, vibrator sizing, forming, setup)
14. Ramming / Hand packed procedures and equipment

4. Inspection

The test questions may be based on the following topics:

1. Terminology, job specifications, application standards
2. Inspection and data collection procedures
3. Lining design and installation requirements
4. Visual and nondestructive test methods and qualification testing methods

5. Application/limitation for various inspection techniques (for example, hammer testing, sonic testing, radiography, core sampling, portable abrasion testing)
6. Material verification and traceability
7. Acceptance and rejection criteria
8. Repair procedures
9. Curing and dry out procedures
10. Inspectors' and contractors' responsibilities
11. Record keeping systems and requirements

5. Post-Installation

The test questions may be based on the following topics:

1. Terms and definitions
2. Responsibilities of personnel and documentation requirements
3. Knowledge of dryout requirements
4. Sealing requirements (for example, water mist, covering, membrane, curing)

5. Application and time limits for applying membrane curing compounds
6. Environmental conditions required for curing
7. Heating equipment, methods and procedures (e.g., gas fired burner, stress relieving heating elements)
8. Placement of temperature sensing probes
9. Knowledge of manufacturer's recommended heatup and cooldown schedules
10. Applicable heating rates for various classes of refractories
11. Lining integrity inspection techniques

5 Common Causes of Refractory Failure and How to Fix Them

All process heaters operate at high temperatures and are constructed with process tubes inside a refractory-lined enclosure, which is heated by radiant heat from gas-firing or, less commonly, oil-firing.

Refractory linings are insulating and minimize heat loss, making them essential to retaining the high-temperature environment. However, when subjected to high temperatures, refractory can deteriorate and potentially lead to failure if remedial work is not carried out.

Types of refractory lining include refractory ceramic fiber, brick, and castable or concrete. If refractory failure results in an unplanned shutdown, it can cost plants more than \$1m/day in lost production.

In this article, we will discuss the most common causes of refractory failure, how to inspect fired heaters or furnaces for damage, and the methods of repairing refractories online without the need to disrupt normal operation.

MODULE 12

Refractory Failure and Maintenance

Deterioration Due to Length of Service

As refractory linings age, their physical properties change. The high-temperature environment causes microstructural changes to the binders within the materials, leading to a loss of surface or internal strength. If the refractory material carries a compressive load, such as bricks, or castable linings, this can lead to local, or widespread failure.

If the refractory is subject to flame impingement, which is common in many radiant wall applications, the useful life will be shorter.

In oil-fired heaters, refractory deterioration is accelerated by corrosive agents in the combustion products. Fortunately, there are few cases where oil-firing is used now.

Incompatible Refractory Materials

A combination of refractory materials is a common feature in fired heaters.

Openings such as doors often use fiber and brick material, and peep sights may use IFB, castable, or fiber modules.

A standardized design using different materials can be challenging as each material has varying properties at high temperatures. Therefore, refractory linings can become damaged, leaving the shell exposed to hot flue gases and causing hot spots.

To lower the risk of mismatched refractory materials, it is a good idea to work closely with the refractory supplier to ensure comparable materials are used around openings.

Loss of Support

All types of refractory linings are attached to and supported by the external steel shell of the fired heater. The conventional support is provided by an anchoring system, which is welded to the shell.

Frequently, the welded joint between the shell and the anchor is compromised by corrosion and support is lost. The corrosion is caused by hot flue gases penetrating through the refractory lining and condensing upon reaching the

cooler shell. The local environment is ideal for rapid oxidation, or corrosion of the weakest point; the weld.

Once support is lost, individual bricks, modules, etc. can fall away, leaving the metal shell exposed, which creates a domino effect and the failure of adjacent refractory lining.

At a plant in Europe, a hot spot was discovered on the transition shell ducting between the radiant and convection sections of a CCR Platformer. In this case, the failure of the ceramic fiber blanket in the roof left the shell exposed to hot flue gas. This caused the external shell temperature to exceed 560°C/ 1040°F.

To prevent overheating the shell until failure, the production rate on the CCR Platformer had to be decreased, resulting in a loss of production of more than \$400,000 per day.

Mechanical Stress

There are several factors that can cause mechanical stress to lead to refractory failure. This includes:

- **Vibrations**

Vibration or interference from other equipment can cause refractory to become displaced and break down over time.

- **Thermal expansion/ spalling**

This occurs when refractory linings expand and contract at different rates due to thermal conditions. This often leads to cracking and spalling which can cause failure if not repaired.

- **Impact**

Mechanical impact from falling objects or components can also damage refractory.

Poor Installation or Maintenance

Improper installation or maintenance is a common cause of refractory failure.

Factors such as installation techniques, curing time, inadequate support, or poor-quality materials can all weaken the refractory and contribute to its failure.

Refractory installation begins at the manufacturing stage. Good communication between the manufacturer and the plant is critical to ensure that the refractory is

fit for purpose. It should be resistant to thermal stresses and other processes caused by the operating environment. Parameters such as temperatures, start-ups and shutdowns, flue gas temperature and chemical components, and required heat loss should all be evaluated.

Once manufactured, the refractory should be stored in a dry, well-ventilated space and installed within three months for high-temperature or high-abrasion operating environments. If installed and maintained correctly, refractory linings should last 20 years or more.

However, several characteristics could suggest issues at the installation stage. For example, if you notice fiber modules have fallen from the roof or gaps have appeared, it could be due to an issue such as insufficient stud welding. It could also be a sign of shell corrosion, which is more common if a protective alloy cladding, such as IGS' High Velocity Thermal Spray (HVTS) has not been applied to the shell before installation.

Whilst there is a range of potential installation issues that can lead to refractory failure, regular and diligent inspections can help to identify damage early to allow remedial work to be carried out.

How to Inspect Furnaces for Damage

Often the first sign of refractory failure is a hot spot on the external steel shell since direct observation of the problem area is not possible. IGS has designed and developed Cetek's Lancescope™ fired heater inspection tool. It allows the undertaking of a high-temperature furnace inspection to determine the scope of the problem, often avoiding an expensive shutdown of the heater.

The hot inspection system uses a state-of-the-art digital camera system, which provides clear, detailed images of problem areas up to 3000°F (1650°C). The furnace inspection system can be inserted into openings as small as 2.75" (7cm) and reach up to 30ft (10m). In applications below 1000°F (540°C), the heater inspection system provides illumination via a high-temperature light source for optimum clarity.

The benefit of performing a hot inspection includes:

- Performed while the unit is in operation
- Provides insight into production availability
- Identifies damage in early stages
- Reduces maintenance costs

- Minimizes repair downtime
- Maximizes production

Methods to Repair Refractory

Once the damage has been identified, there are usually options to fix the issue.

Production can be interrupted to take the asset offline and carry out conventional repairs, or the furnace can continue to run at reduced performance until the next planned turnaround. However, this could exacerbate any existing damage.

Alternatively, an online refractory repair service is available where there is no need to bring the heater off-line and production will not be interrupted or capacity limited. This is a good option to temporarily fix damage until the next planned turnaround.

A team of refractory technicians can be mobilized at short notice and the repair involves creating minimal access point openings to insert specially designed components and repair material, delivering a semi-permanent repair lasting at least until the next turnaround.

Conclusion

There are numerous causes of refractory failure, but shutting down the furnace should always be a last resort as this has a huge impact on production and revenue. The operating environment is responsible for most refractory failures and a common oversight is to increase the furnace temperature without assessing the impact that this will have on the design parameters of the refractory. Planning for over-capacity can help to mitigate the risk of refractory failure if specifications change after installation.

Understanding and preventing refractory damage is key to the overall furnace performance. IGS recognizes the effects of asset failure and works in partnership with plants worldwide to optimize equipment reliability and performance.

Identifying refractory damage early and understanding the reasons behind it will help operators increase furnace up-time and maximize overall performance which could save millions in otherwise lost revenue.

If unexpected performance losses are impacting your operations, IGS can mobilize quickly to help you identify, fix, and prevent future damage.

MODULE 13

Installation of Refractories

Steps to Refractory Installation for Successful Refractory



How to Install Refractory?

The advanced development of engineering technology has made steps to refractory installation more effective.

Every plant manager must know about refractory lining before refractory installation procedure. It is the layer applied to kilns or furnaces to resist high heat, thermal shocks, and abrasion.

Hence, it is important to know how to apply refractory materials. This includes refractory bricks, monolithic refractory, and refractory castables.

So, you need a skilled refractory installation contractor for proper refractory installation.

Steps to Refractory Installation Procedure

As one of the top refractory contractors in the country, Sing Lian Ping has a reliable process for refractory installation. Below are the methods to install refractory:

Installation

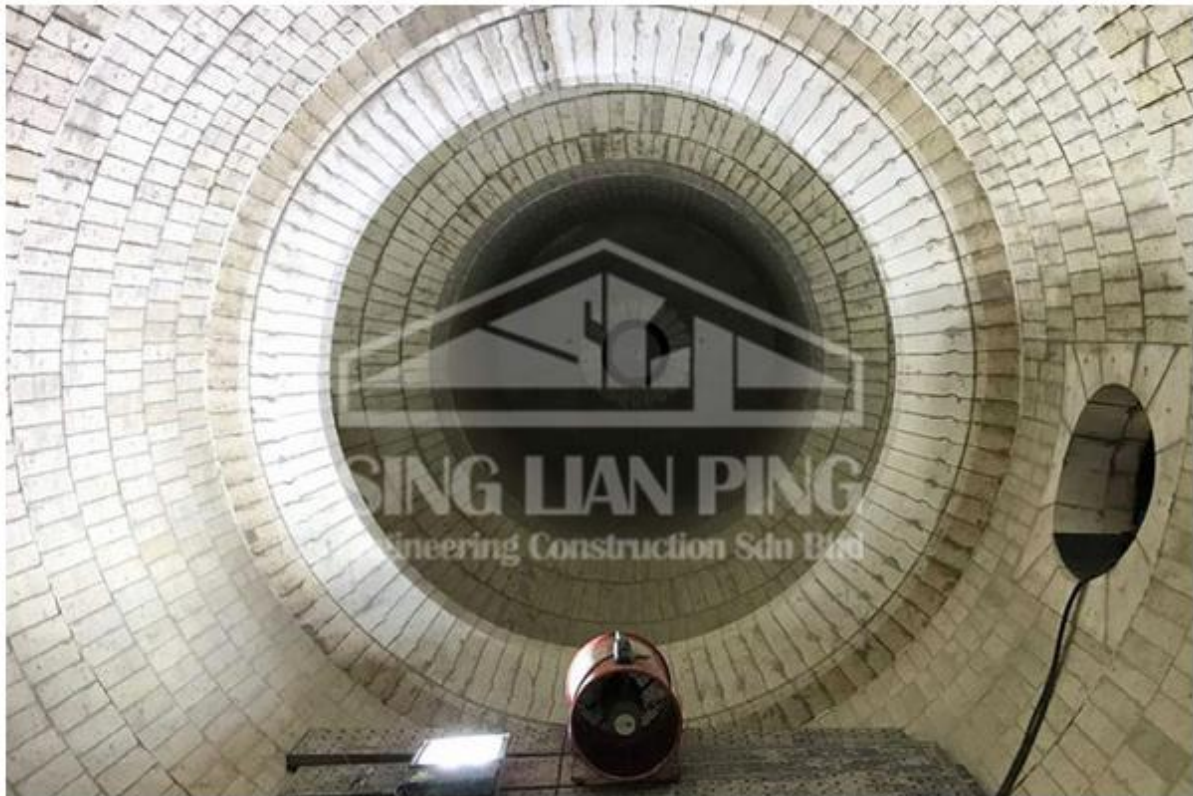
Curing

Temperature Control

Water Removal

Drying Out

Process of Refractory Lining Installation



Installing the Refractory Lining

After consulting with the hired refractory contractor, industrial refractory installation is conducted.

This process is the mixing of a certain amount of water with a fixed amount of refractory castable.

If not, the incorrect amount of water can spoil the refractory lining. Among these are lower strength, longer time to set, and more water to remove during the dry out process.

Hence, the contractor must use the right amount and type of water. Refer to the refractory material datasheet for the utmost accuracy

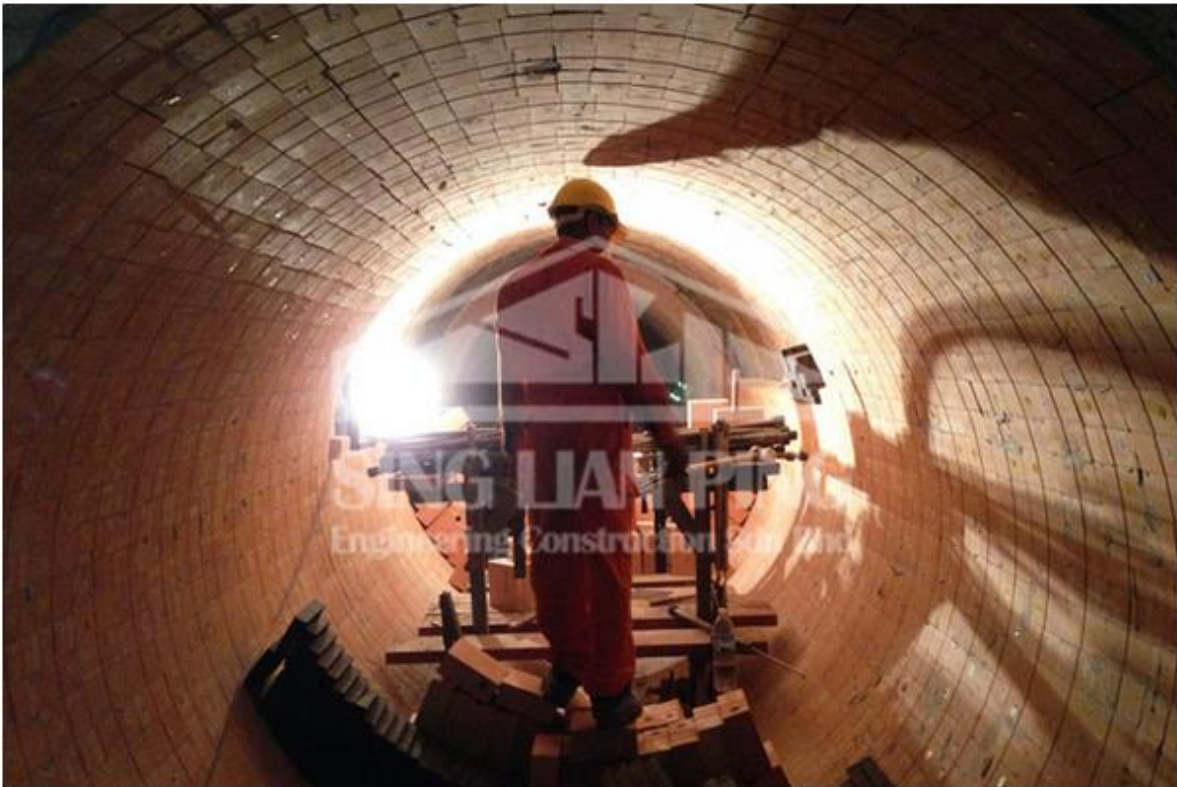
Curing the Refractory Lining

The castable refractory curing procedure is the process where the water reacts with the refractory cement. It is completed when the refractory material has hardened to its final form.

However, it is an intricate process. This is because the temperature of surroundings and castable can impact curing success.

Thus, curing needs a precise temperature range for it to work. Lower temperatures can weaken the curing. This will lead to lower permeability and longer curing time.

Comparably, higher temperatures will set the refractory product too quickly. Hence, it will affect the densification, making the refractory lining unfit for application.



Refractory Installation Temperature Control

Temperature is a major part when installing refractory. So store all refractory materials and equipment under a controlled setting.

If they are cold, you will lose precious time waiting for them to reach the desired temperature. Thus, refractory contractors put heaters surrounding the curing process depending on the ambiance.

Additionally, uncontrolled storage and mixing temperatures will disrupt further steps to refractory installation methods. Hence, causing severe spalling to the refractory lining.

Water Removal of Refractory Installation

After installing and setting the refractory monolithic, the next step is water removal. To do this, apply heat to remove both physical water and chemical water.

Then, the water will evaporate at certain temperatures. However, the steam will cause volume expansion which can increase the internal pressure.

By applying the correct methods, the refractory lining is stronger with no risk of spalls.

Drying Out Process

Lastly, conduct the drying out process for the refractory castable lining.

The dry-out process requires expertise from the right refractory engineering contractor. If done improperly, the refractory lining will crack and weaken quickly.

Also, the steam explosion might happen, risking the workers and the refractory project.

Therefore, discuss with your refractory contractor for a dry-out plan of your plant.



The Proper Steps to Refractory Installation

Attention to detail is crucial for refractory installation success.

Regardless of the above methods, do note that every refractory project is unique.

But recognizing the basics is also essential.

Certainly, this includes plant operations, refractory material selection, and refractory processes. Above all, they should be managed by a professional refractory engineering contractor.

How to Repair Refractory Installation Failures

Refractory installation failures can happen when you are least expecting it.

Although refractory is essential for heat-generating industries, refractory installation lacks the attention it deserves.

That is why you need a certified and experienced refractory contractor. Because they can properly design and install refractory engineering. Hence, you can save up to 5-7% of fuel costs.

But, it is difficult to detect why refractory materials fail. This is due to the complex process only refractory installers can figure out.

What causes Refractory Installation Failure?

Chosen refractory material does not fit the environment

The burned fuel damages the refractory monolithic

Improper handling of refractory materials (mix, install, dry out and store)

The selected refractory product does not fit the environment after the burning process

So, as one of the top engineering contractors for refractory in Malaysia, SLP has a tried and tested guide to fix refractory installation failures.

Module 14

How to Repair Refractory Installation Failures

1. Analyze the Refractory Materials

Before refractory rebuilds are in order, the refractory installation contractor will collect important details. This is done by conducting refractory failure analysis.

Refer: API 936 Refractory Quality Management Control

List of inspection data for refractory damage repairs:

Datasheets of current refractory brick or refractory lining

Samples of heated materials

Location of refractory materials storage

Refractory products date of manufacture

Conditions during previous refractory installation

Quantity of installed refractory insulation

Previous installation and dry out process



2. Check the Current Materials

Any experienced engineer will always find the main cause of refractory installation failure.

Once identified, the refractory contractor can find other options of refractory lining solution that last longer.

Questions when inspecting damaged refractory materials:

Was the material damaged due to thermal shock?

Did excessive shrinkage due to high temperature cause the rupture?

Was the refractory material installed improperly?

Did the equipment operation damage the material?

Are there any mechanical injuries?

After answering these questions, the refractory engineer will collect material samples to test.

First, it will go through a cold crush test. Then, the strength of the refractory material will be analyzed. Afterward, compare the results with the datasheets. Lastly, the results will show whether the refractory mix was too wet or too dry.

3. Ratio Calculation of Materials

Based on the analyses in steps 1 & 2, the refractory contractor will measure the moisture content of the heated material.

As a matter of fact, the level of moisture combined with atmospheric moisture will separate the silicon carbide-based materials.

This will happen if the moisture percentage of the heated material passes 15%.

Thus, it will react with the cement-based refractory such as high alumina refractory cement.

If the refractory breach repair procedure is the same, it will cause a chemical attack and surface failure of the refractory. Hence, more costs to take care of.



4. Review Refractory Installation Process

Finally, the refractory contractor will install the proper refractory repairs and conduce refractory inspection.

Equally important, the refractory installation contractor must handle the refractory material. As a result, it reaches its desired strength for a more durable refractory repair.

How to Handle Refractory Materials Properly

Use fresh materials and follow proper storage methods.

Refractory material manufacturers suggest using drinkable water for mixing.

Use the right type of mixer, follow the set mixing process, and take note of the material's pot life.

Ensure the final mix temperature is in a specific range.

A proper curing process allows proper chemical action to happen and helps the refractory reach its maximum strength when dried.

Remove all mechanical and chemical water to reach its desired strength by drying out the cured refractory.

Know the exact quantity of materials to ensure the refractory is not too thick or too sparse

The Right Refractory Installer for Proper Refractory Installation

All in all, various factors may cause the failure of a refractory installation.

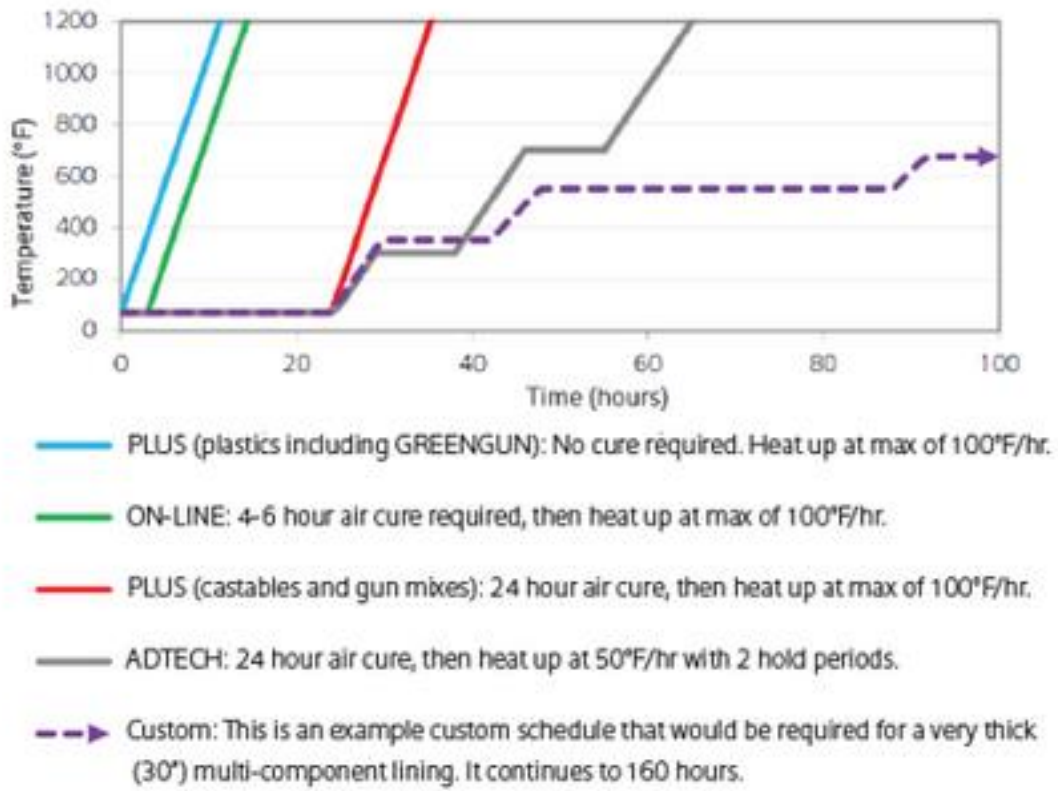
That is why it is important to take care of the basics as thoroughly as possible.

Factors such as refractory material selection, plant operations, mixing, installation, curing, and drying should be managed properly.

By following the correct procedures, you can effectively prevent any future refractory failures. Or at least still have time to fix the damage done.

All in all, refractory experts agree that properly designed and installed refractory not only saves money but is essential for productive plant operation.

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We find ourselves in the cold-weather-installations time of the year. The proper installation of refractory castables includes mixing, placing, curing, and drying.

Installation

Careful attention must be paid when adding water and mixing castable materials.

Excessive amounts of water can negatively impact the refractory – lower strength, longer set time, and more water that must be removed during dryout.

Lower strength and excessive water to remove can make for a higher-risk dryout.

Use the proper water target, which can be found on the product datasheet.

Curing

The curing process begins when the water is added to the castable and begins to react with the cement. The process ends when the material is hard and has achieved its final set. Curing behavior is directly impacted by both the ambient and castable temperature. The ideal curing temperature range is between 70°F and 90°F. Curing at temperatures below 70°F can produce negative effects: lower strength, lower permeability, and extended curing time.

Conversely, excessively hot conditions can cause the material to set too quickly, resulting in poor densification or even render the material unable to be put in place.

Temperature control

Store material and equipment in a controlled atmosphere. Cold refractory material can take several days to stabilize to the desired temperature. Use heaters in cold conditions to apply heat to the vessel or space around the curing refractory. Heaters should not be pointed directly at refractory surfaces.

Storage and mixing temperatures of refractories are paramount to achieving desired installation characteristics.



Failure to properly mix, place, and cure refractory materials along with using improper dryout schedules or practices can result in severe spalling (as shown in photo above).

Water Removal

After the castable has been installed and hardened, there are two types of water remaining: physical water and chemical water. Both must be removed before the refractory material can be used in service.

Physical Water: enables the castable to flow, and is also referred to as “free water” because it sits in the pores of the castable and is not bound by any hydrate phases.

Chemical Water: chemically combined water tied up in various cement hydrate phases.

Heat needs to be applied to remove both types of water. The physical and chemical water is released at certain critical temperatures during the dryout which are as follows:

- Removal of free water: 212°F (100°C)
- Dehydration of major cement phases: 440°F (227°C), 530°F (277°C), and 1020°F (549°C)

All water must be removed in a controlled manner and dryout schedules should pay attention to these critical temperatures.

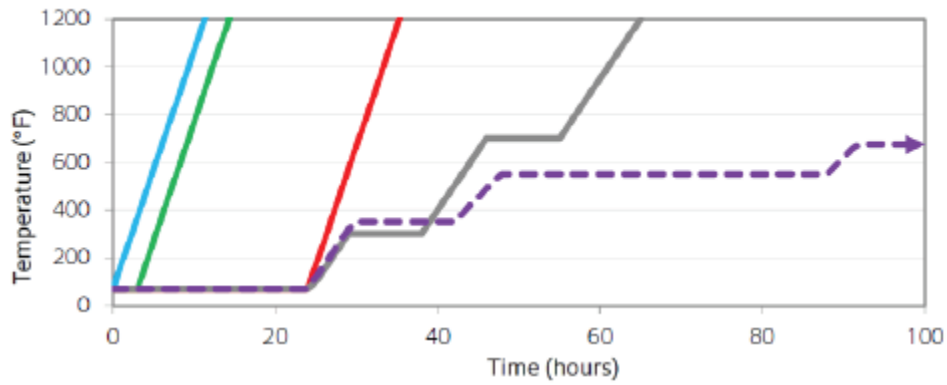
When water turns to steam there is a volume expansion of approximately 1,600 times. This increase in volume causes high pressures within the lining. At each critical temperature there is a high potential for developing internal pressures that could exceed the strength of the refractory castable and cause the material to spall.

Dryout Schedules

The dryout process is usually the last step before a refractory castable lining is put into service. The recommended practices of must be followed for each mixing, placing, curing, and dryout step in order to achieve the optimum lining. The dryout should not be compromised because improper procedure may lead to microcracks, shorter life, or a steam explosion.

Standard schedules dryout schedules to be applied in many circumstances used to guide the process. They are illustrated below.

The standard schedules can be used with single component linings that are 9 inches thick or less. Excessively thick and multi-component linings must be evaluated on a case-by-case basis. Non-refractory variables (such as weep holes and wicking practice) may be required.



- PLUS (plastics including GREENGUN): No cure required. Heat up at max of 100°F/hr.
- ON-LINE: 4-6 hour air cure required, then heat up at max of 100°F/hr.
- PLUS (castables and gun mixes): 24 hour air cure, then heat up at max of 100°F/hr.
- ADTECH: 24 hour air cure, then heat up at 50°F/hr with 2 hold periods.
- - - Custom: This is an example custom schedule that would be required for a very thick (30") multi-component lining. It continues to 160 hours.

