

Applications of Refractory Lining Materials

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Foreword

This report is the second in a series of three American Petroleum Institute (API) reports covering the use of refractory concrete (castables), plastics, and ramming mixes for applications for the hydrocarbon processing industry (HPI). Its content is complimented by the two other reports in this series:

- [API TR 978](#), Monolithic Refractories: Manufacture, Properties and Selection
- [API TR 980](#), Monolithic Refractories: Installation and Dryout

These API technical reports update and add to the original reports written by Committee 547 of the American Concrete Institute (ACI) in 1979 and 1989. The ACI reports are ACI 547.R-79, *State-of-the Art Report: Refractory Concrete*, and ACI 547.1R-89, *State-of-the Art Report: Refractory Plastics and Ramming Mixes*.

ACI Committee 547 was organized in 1969 to provide a reliable and comprehensive source of information on monolithic refractory technology. In subsequent years, participation in the ACI refractory technical community waned. At the same time, participation increased on the API committee that was drafting refractory content. The API committee currently runs a certification program for refractory practitioners based on [API Standard 936](#), *Refractory Installation Quality Control—Inspection and Testing Monolithic Refractory Linings and Materials*. To facilitate use of the updated content in the API certification program, ACI allowed API to use the material from the two above-mentioned ACI publications, no longer maintained by ACI. This enabled API to create new technical reports by updating and adding to the material from the ACI reports.

API formed the Vessel Refractory Task Group in the late 1980s with the objective of providing a standard for the inspection and application of quality controls for monolithic refractories used in refining applications. In response to demands for greater reliability and cycle life objectives, refiners had already developed their own company specifications for refractory installations for the highest-value applications, where unit availability is critical. A cottage industry of supporting quality control experts and inspectors evolved has helped owners reduce this gap in the last few decades. Up until that time, however, manufacturers and installers largely had little say in this development, and uniform industry standards were never developed or adopted.

To address this issue, a broad representation of all the stakeholders gathered as part of the API's spring and fall Refining Equipment Standards Meetings. Addressing the standards gap and noting the many similarities in owner- and equipment manufacturer-developed specifications, the API task force undertook the task of identifying useful industry practices and/or negotiating to agreement best fits for standards application. API's *Refractory Installation Quality Control Guidelines—Inspection and Testing Monolithic Linings and Material* was first issued in 1996 as a recommended practice. After a number of subsequent revisions, it was approved as [API Standard 936](#) in 2006, with a certification program that began in 2004.

In addition to maintaining [API 936](#) and overseeing the certification program, the task force reorganized in 2014 under the API Committee on Refinery Equipment (CRE) and became the Refractory Project Group. As a project group, work expanded to writing ceramic fiber and brick quality control standards and unit-specific applications, such as sulfur recovery units and hydrogen furnaces, as well as drafting technical reports (such as this report). In response to this broadening recognition of the need to advance this technology for HPI applications, the API CRE reclassified the group as a full subcommittee in 2016, and it now works under the title of Subcommittee on Refractory Materials (SCRM).

Contents

	Page
1 Scope	1
2 Referenced Documents	1
3 Terms and Definitions	1
4 Hydrocarbon Processing Applications	4
4.1 Fluid Catalytic Cracking Units	4
4.2 CO Furnaces	22
5 Applications Outside of Hydrocarbon Processing	26
5.1 Iron and Steel	26
5.2 Nonferrous Metal Production	38
5.3 The Ceramic Industry	39
5.4 Glass Production	42
5.5 Mineral Processing	42
5.6 Power Generation and Incineration	44
5.7 Aerospace Technology Applications	45
5.8 Nuclear Applications	46
5.9 Miscellaneous Applications	46
References	48
 Figures	
1 Example of a Fluid Catalytic Cracking Unit Showing Key Components	5
2 Cyclone Dipleg Trickle Valve with Hexmetal Retained Refractory Lining to Prevent Erosion Damage to Steel	6
3 Example of FCCU Showing Types of Refractory Lining Materials Used by Component Location	8
4 Standard Lance Grid Hexmetal Used in Cyclones Applications	9
5 A Typical Two Stage Cycles in Regenerator Showing Primary (Green) and Secondary (Yellow) Stages for Each of 9 Pairs in the Vessel	10
6 Typical Cold Wall Slide Valve	11
7 Cold Wall Refractory Lined Expansion Joint with Bellows Protected and With Erosion-resistant Refractory and Hexmetal on Steel Sleeves	11
8 A Typical Third Stage Separator	12
9 The Revised ASTM C704 Test Replaces the Old Style Aluminum Body Sand Blasting Nozzle Using a Taped Open Trigger with a Precisely Dimensioned Stainless Steel Nozzle Machined Specifically for Testing	13
10 A Typical Sulfur Recovery Unit	15
11 A Vendor System of Interlocking Shapes	17
12 Hexhead Ferrules Installed on a Thermal Reactor Tubesheet	18
13 Example of a Continuous, Infrared Temperature-measuring Device for Fired Heaters	19
14 A Typical Oil Refinery Fired Heater	20
15 A Typical Delayed Coker	23
16 A Typical Gas Fired Rotary Kiln Used for Calcining or Complete Combustion of Coke From Delayed Coker of Fluid Coker Operation	24
17 Typical Blast Furnace Showing Some of the Possible Application Areas for Refractory Concretes	28
18 Typical Basic Open Hearth Furnace for Producing Steel from Blast Furnace Iron and Scrap Steel	30
19 A Typical Electric Arc Melting Furnace	31

Contents

	Page
20 Cross Section of a Direct Arc Furnace	35
21 Channel Induction Furnace	36
22 Coreless Induction Furnace	37
23 A Typical Reverberatory Aluminum Melting Furnace	41
24 A Nose Ring of a Rotary Cement Kiln	43

Tables

1 Characteristics of Different Types of Gasification Processes	25
2 Typical Operating Temperatures for Iron and Steel Plant Furnaces	33

Application of Refractory Lining Materials

1 Scope

This technical report focuses specifically on the information on the applications of refractories contained in two American Concrete Institute (ACI) refractories documents:

- ACI 547.R-79, *State-of-the-Art Report: Refractory Concrete*;
- ACI 547.1R-89, *State-of-the-Art Report: Refractory Plastics and Ramming Mixes*.

The original content of these ACI reports was focused primarily on steel- and glass-making applications, which represent the largest refractory markets. API, in tailoring the revision of this content to the hydrocarbon processing industry (HPI), has greatly expanded the text pertaining to the specialized oil refining and petrochemical processing applications. At the same time, API has retained and updated the information covering applications outside of the HPI (see Section 5) because of the similarities and applicability that this information has for refractory professionals in these other industries.

2 Referenced Documents

[API Standard 560](#), *Fired Heaters for General Refinery Service*

[API Standard 936](#), *Refractory Installation Quality Control—Inspection and Testing Monolithic Refractory Linings and Materials*

[API Technical Report 978](#), *Monolithic Refractories: Manufacture, Properties, and Selection* ¹

[API Technical Report 980](#), *Monolithic Refractories: Installation and Dryout* ¹

ACI SP-34, *Handbook on Concrete Reinforcement and Detailing*

[ASTM C71](#), *Standard Terminology Relating to Refractories*

[ASTM C638](#), *Standard Descriptive Nomenclature of Constituents of Aggregates for Radiation-Shielding Concrete*

[ASTM C704](#), *Standard Test Method for Abrasion Resistance of Refractory Materials at Room Temperature*

3 Terms and Definitions

NOTE See [ASTM C71](#) and [API 936](#) for additional information on definitions.

3.1

abrasion resistance

The ability to withstand the effects of eroding particles for an extended period without significant loss of material or other damage.

NOTE 1 Often referred to as “erosion in fluid solids units,” such as FCC units, which is technically incorrect, but commonly understood in refining jargon.

NOTE 2 For refractory materials, abrasion resistance is measured in the form of eroded volume loss in accordance with [ASTM C704/C704M](#).

EXAMPLE A vapor stream containing solid particles.

3.2

casting

The application of wet mixed castable refractory by placing (possibly with the aid of vibration), pouring, or rodding.

3.3

catalyst

A substance that causes or accelerates a chemical change without being permanently affected by the reaction.

EXAMPLE Catalyst circulated between reactor and regenerator vessels in FCC process.

3.4

cyclones (of a FCCU or fluid coking unit)

Components, usually internal, used for inertial (momentum) separation of particulate solids from flue or product gas.

EXAMPLE See Figure 5.

3.5

erosion of refractories

Mechanical wearing away of the surfaces of refractory bodies in service by the washing action of moving liquids or gases, such as molten slags or high-velocity particles.

NOTE In the case of moving solid particles, this is more correctly termed “abrasion.”

3.6

erosion service

Refractory application in which erosion resistance is a determining feature of lining service life.

EXAMPLE Refractory lining applications, such as transfer lines, overhead lines, cyclone linings, and deflector shields of fluid solids units.

3.7

fluid catalytic cracking unit (FCCU)

A refining process consisting of reactor and regenerator vessels and interconnecting piping in which particulate catalyst is circulated at elevated temperatures to upgrade low-value feedstock to high-value products, such as heating oil, gasoline components, and chemical feedstocks.

NOTE Also known as a “cat cracker.”

EXAMPLE See Figure 1 and Figure 3.

3.8

fluid coking unit

A thermal cracking process where feed is injected directly into the reactor, forming hydrocarbon products that are generally heavier than those produced by catalyst cracking and particulate coke similar in size and flow characteristics to FCCU catalysts. The unit consists of two major vessels with transfer lines circulating fluidized coke particles between the reactor [operating at 900 °F (480 °C)] and the burner [operating at 1300 °F to 1350 °F (700 °C to 730 °C)].

3.9

heavy weight castable

Castable refractory with a density roughly greater than 150 lb/ft³ (2400 kg/m³).

3.10**hexmetal**

A metallic anchoring system constructed of metal strips joined together to form hexagonal enclosures where erosion-resistant refractory is packed after welding to the base plate steel.

NOTE Thickness is usually $\frac{3}{4}$ in. or 1 in. (19 mm or 25 mm).

3.11**insulating firebrick**

A refractory brick characterized by low thermal conductivity and low heat capacity.

NOTE Also known as "IFB."

3.12**lightweight castables**

Refractory concrete having a unit weight less than 100 lb/ft³ (1602 kg/m³).

3.13**material qualification testing**

Pre-installation testing of refractory materials in which production lots of refractories manufactured for a specific installation are sampled and tested to confirm that they meet specified physical property requirements.

3.14**medium-weight castables**

Castable refractories with densities roughly between 100 lb/ft³ and 150 lb/ft³ (1600 kg/m³ and 2400 kg/m³).

3.15**normal-weight castable**

Refractory concrete having a unit weight greater than 100 lb/ft³ (1600 kg/m³).

3.16**ramming**

The use of compressive force or impact to deform a stiff refractory mix, causing it to completely fill the intended volume (e.g. a hexmetal cell) and/or fully bond or join to previously placed refractory (e.g. thick plastic linings).

3.17**reactor (of a FCCU or fluid coking unit)**

The vessel in which cracking reactions occur or are completed and product gases are separated from coke and/or catalyst particulate. Usually operates at 900 °F to 1000 °F (480 °C to 540 °C).

3.18**regenerator (of a FCCU)**

Vessel in which coke and residual hydrocarbons are burned off of the catalyst and the flue gas is then separated from the catalyst. Usually operates at 1200 °F to 1400 °F (650 °C to 760 °C).

3.19**silicon carbide (SiC) grit**

Abrading medium used in the [ASTM C704](#) test.

NOTE Silicon carbide is sized and loaded into the testing apparatus at a controlled rate and quantity to meet the test requirements.

3.20

slide valve (of a FCCU or fluid coking unit)

A refractory lined valve used to control process flow of gases and particles through the valve. It is typically a gate design with refractory on the gate, orifice, and body portions exposed to the process flow, and may be either a hot or cold wall design.

3.21

transfer line (of a FCCU or fluid coking unit)

Refractory lined pipe used for the transport of hot particulate medium and gases between process vessels.

3.22

turnaround

A planned outage of a refining process unit in order to conduct inspections and repairs of internal components, typically lasting multiple weeks.

4 Hydrocarbon Processing Applications

4.1 Fluid Catalytic Cracking Units

4.1.1 Operating Conditions

Fluid catalytic cracking units (FCCUs) are designed to crack heavier feeds into light end products, such as gasoline and jet fuel, that have greater market value. The heavier feed is introduced into the oil riser transfer line, where it encounters hot regenerated catalyst that is circulated from the regenerator. The ceramic particles supporting the zeolite catalyst typically have a mean particle size of 60 μm . The catalyst circulates between a reactor that is operating at 900 °F to 1000 °F (480 °C to 540 °C) and a regenerator that is operating at 1300 °F to 1400 °F (705 °C to 760 °C). The overall operating pressure is ~15 psig to 30 psig (1.93 bar to 3.86 bar); see Figure 1. Once in the reactor, the hydrocarbon gases and catalysts are separated by the means of cyclones. The hydrocarbon product gases travel upward and through the overhead system in the reactor to a fractionator, which separates the hot gases into their various product streams. The spent catalyst is then transferred to the regenerator.

4.1.2 Reactor

The mixture of lighter hydrocarbon gases and catalysts enter the reactor through a riser line that leads to one or more cyclones. Cyclones are vertical steel-barreled structures that are typically internal to the vessel. The internal riser line and cyclones are typically lined with erosion-resistant refractory. The gases with suspended particles typically enter the cyclone tangentially through inlet ducts at the top of the barrels. The gases spin around in a vertical vortex within the barrel. Because of this spinning action, the denser particles are thrown to the outer wall by centrifugal force. Friction on the outer wall causes the particles to slow down and accumulate on the outer wall, where gravitational forces and momentum cause them to spiral down through the cyclone. The lighter particles, mainly gases, exit through an outlet tube that extends down from the ceiling in the center of the cyclone.

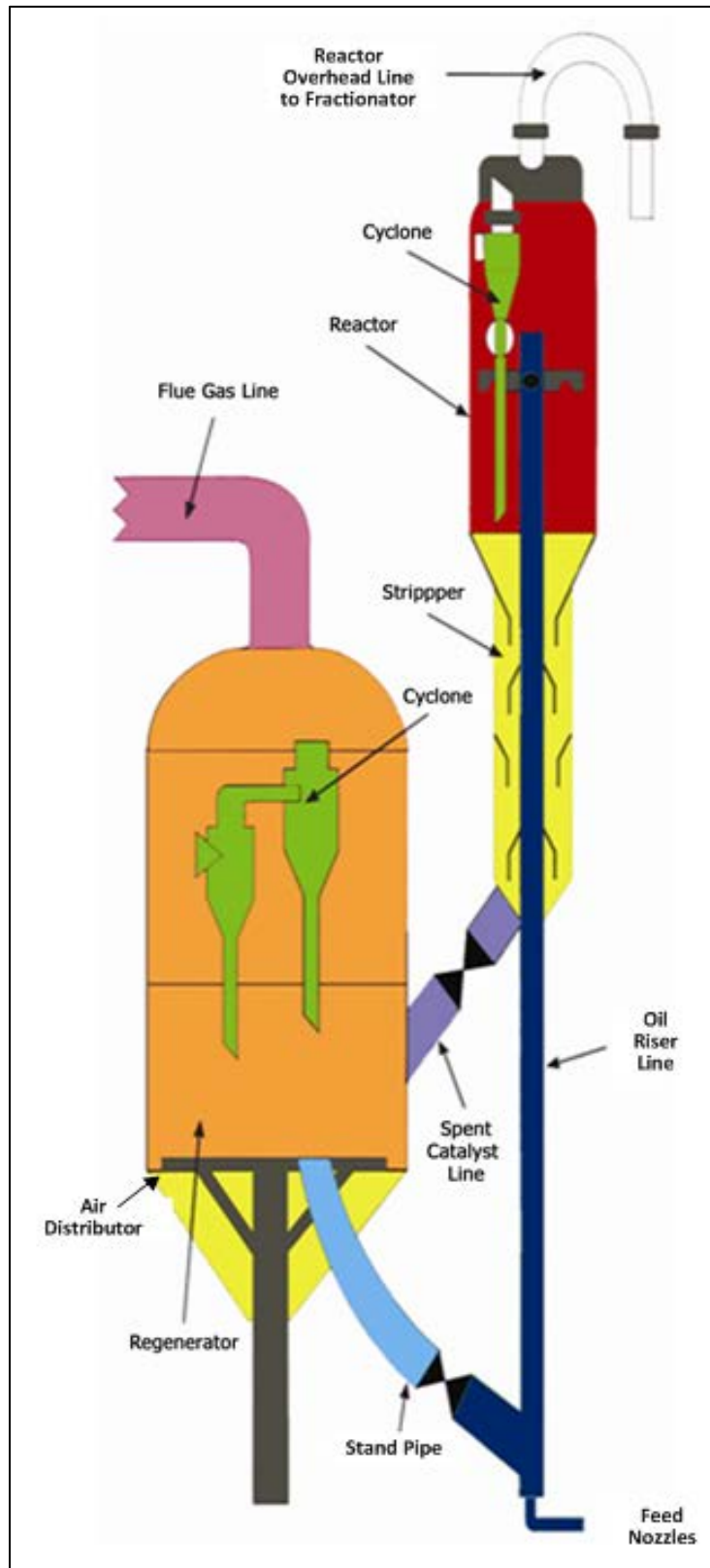


Figure 1—Example of a Fluid Catalytic Cracking Unit Showing Key Components

As the catalyst particles spiral downward, the cyclone effectively captures the catalyst, using a geometry of cone transitions and cylinders having a reduced diameter. By the time the particles enter the dipleg in the lower half of the cyclone, the cross-sectional area is greatly reduced, the catalyst particles are concentrated, and their particle velocity is reduced to a relatively tame, linear downward flow. Gas bypassing up the dipleg is prevented by sealing at the end of the dipleg provided by a trickle valve and/or submersion in a fluidized bed (see Figure 2) [1]. Trickle valves in the reactor are typically refractory lined for erosion resistance.

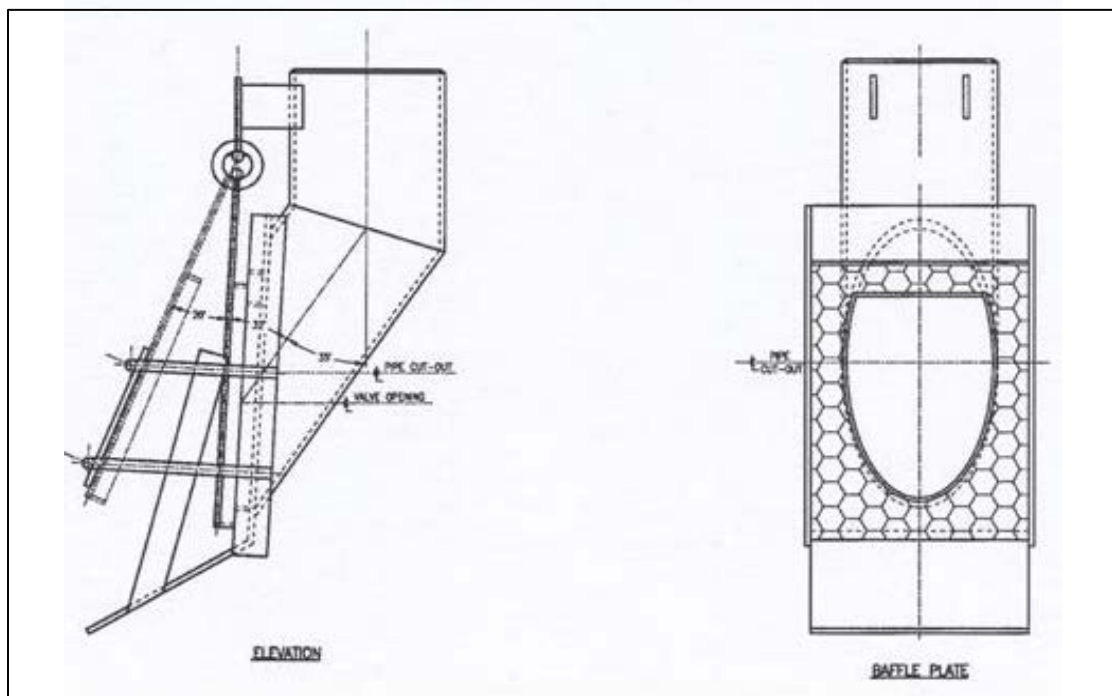


Figure 2—Cyclone Dipleg Trickle Valve with Hexmetal Retained Refractory Lining to Prevent Erosion Damage to Steel

Cyclones are typically staged in pairs with a crossover duct between the outlet of the primary cyclone and inlet to the secondary. Most of the catalyst is recovered in the primary cyclone [2]. Secondary cyclones are smaller in diameter than the primary cyclones. They are not designed to handle the same mass as the primaries, but the lining is exposed to higher gas velocities with less velocity gradient effects and more turns due to the lower loading of catalyst in the air stream. Erosion in secondary cyclones is typically more severe in the inlet scroll and at the top of the dipleg [3, 4].

Once separated from the catalyst, the gases exit through the outlet tube located at the top of the secondary cyclones, where they are collected in the plenum chamber and then pass through the overhead line. Meanwhile, the catalyst with residual hydrocarbon and coke adhered to its surface cascades through steel sheds and/or packing in the stripper section. In this section, steam is introduced to strip retained hydrocarbons from the catalyst, creating a counter flow of gases up through the stripper and reactor, which eventually exits through the reactor overhead. The spent catalyst makes its way to the bottom of the stripper, where it is transported through the spent catalyst transfer line and is circulated back into the regenerator.

4.1.3 Regenerator

In the regenerator, the spent catalyst is mixed with air and reacts with the remaining coke and hydrocarbons on the catalyst in a fluidized bed. This combustion reaction reheats and regenerates the catalyst. While the catalyst is cycled back through a transfer line to the oil riser to repeat the process, the flue gases are separated from the catalyst. There is at least one, but more commonly, two, stages of cyclones to perform this function within the regenerator. On the regenerator side, the gases produced have no marketable value other than the thermal and

pressure energy they contain. Once this energy is removed via boilers and/or expander systems, the flue gas is further treated to remove additional particulate and chemical emissions prior to releasing to the atmosphere.

There is a large array of components used to treat flue gas downstream of the regenerator. These include tertiary cyclone vessels, electrostatic separators, carbon monoxide (CO) furnaces, and/or wet gas scrubbers. In addition, there may be additive catalysts used in the unit to remove oxides of sulfur (SO_x) and/or oxides of nitrogen (NO_x), particularly in full burn units processing high levels of resid in the feed. Full burn units have been known to have afterburning problems that can overheat and accelerate the corrosion of steel components within the vessel and overhead line [5, 6, 7]. Consequently, they are typically equipped with staged regeneration features and/or catalyst coolers. The afterburning problem is caused by incomplete combustion of the CO in the bed and lower regenerator that makes its way into the cyclones and/or overhead before it finds oxygen to react with.

4.1.4 Lining System Design Practices

The large size and continuous nature of the process make startup and shutdown of the unit very time-consuming. Many of the other process units in the refinery have an operation that is integrated with the unit and, therefore, dependent on its operation. This, together with the high value of the products produced, makes downtime very costly for FCCUs. Moreover, temperatures and pressures limit the operator's ability to monitor internal components for wear, so shutdown can occur with little or no advanced warning. Consequently, performance of the internal wear components is essential and refractory linings play a key role in the overall reliability of the unit, not just to retain process heat, but to protect internal steel surfaces from wear due to the erosive effects of rapidly moving catalyst.

Linings in FCCUs are usually alumina-silica castable refractories with high-purity calcium aluminate cements, supported by metallic anchors attached to the steel that the refractory is designed to protect. Based on the color-coded locations shown in Figure 3, these refractories include:

- medium-weight castable refractories for the walls of the primary vessels (green);
- erosion-resistant, heat-insulating refractories for transfer and overhead lines (blue); and
- dense, extreme erosion-resistant refractories for lining cyclones, slide valves, and wear plates (red).

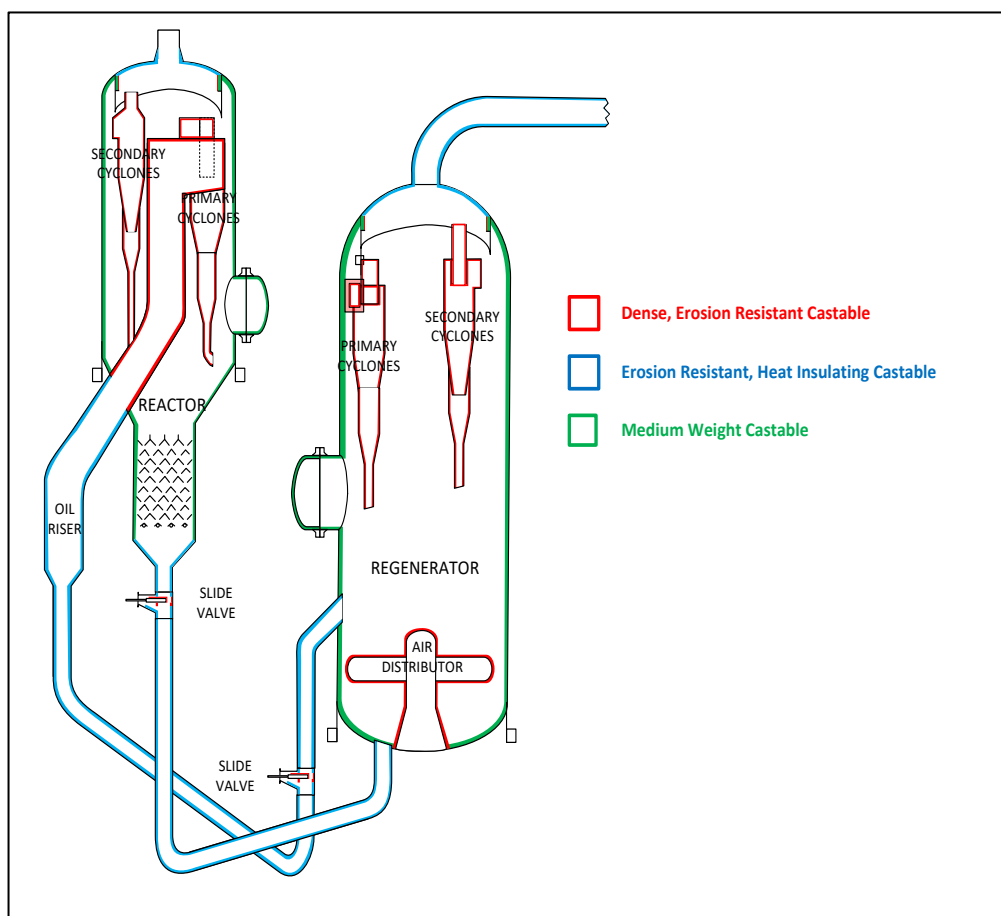


Figure 3—Example of FCCU Showing Types of Refractory Lining Materials Used by Component Location

Lining thickness typically ranges from $\frac{3}{4}$ in. to 1 in. (19 mm to 25 mm) for interior hot wall linings and 3 in. to 6 in. (76 mm to 150 mm) for lining of external surfaces with cold walls, such as the vessel shell or transfer line pipe [8]. These refractories are generally applied by gunning on the vessel sidewall, casting metal fiber-reinforced refractories in the transfer and overhead lines, and ramming or hand packing refractory for the lining of cyclones, slide valves, and wear plates. The consistency of castable refractories is the key to allowing the refractories to be installed with the complex geometries within the unit, and provides a smooth surface to minimize attrition of the catalyst, while also protecting the steel.

The consistency of the castable also means that installation quality is highly dependent not only upon the quality of materials, but upon the quality in which those materials are installed [8]. The convergence of the need for high reliability and the sensitivity of monolithic refractories to application quality drives the need for the best possible application quality control and assurance. This need fostered the development of [API Standard 936, Refractory Installation Quality Control—Inspection and Testing Monolithic Refractory Linings and Materials](#), which was first published as a best practice in 1996.

Metallic anchors for refractory linings in cold wall FCCU applications consist of v-studs attached to the steel at an approximate spacing of two times the lining thickness. Anchor tines are generally designed with a bend or wave along their length to prevent slippage during operation. Slippage between the anchor and refractory is undesirable because it can lead to a gap forming between the lining and the shell. These types of gaps allow hot gas to bypass and circulate behind the refractory, resulting in hotspots on the shell. On the other hand, anchors with long horns bent parallel to the hot face of the lining or hooks on the end of the tines can cause shear planes where the lining is subject to spalling. Plastic tips or pitch is often used on the ends of the tines to provide for thermal expansion of the tines.

For hot wall lining applications, hexmetal or hexmetal-like anchoring systems, referred to as “hexalt anchors,” are generally used to allow for the higher thermal expansion of the steel shell relative to the refractory. Notable hexalt anchors include K-bars, Hexcels, Half-hexes, Curl and Speedcel 3 anchors. Like hexmetal, these anchoring systems are designed to segment the lining into biscuit-like components at regular spacings with tabs to hold them in position at operating temperatures (see Figure 4). In this way, the refractory lining responds like an accordion when strained by the two-to-threefold-higher thermal expansion coefficient of the steel, relative to the refractory. Hexmetal is also used in plenum and grid skirt applications where the steel is designed to flex to accommodate the thermal growth of hot steel components attached to the cold wall shell.

Examples of key refractory lined components are depicted in Figure 5 through Figure 7. Figure 5 shows a typical arrangement of nine cyclone pairs inside a regenerator vessel, color coded in green (primary) and yellow (secondary). Each cyclone is internally lined with dense refractory that is selected and installed for optimum erosion resistance. Each pair is arranged with the bulk of the solids collected in the first or primary stage cyclone. The outlet from the primary cyclone then feeds directly into the secondary cyclone (see the right side of Figure 5), which is designed for higher efficiency to remove a significant amount of fines that escape from the primaries. A typical air distributor (light blue) and air ring (dark blue) are shown in the bottom of the regenerator. These components are typically lined with refractory on the outside. They provide the air used to regenerate the catalyst in a fluid bed that typically occupies the lower portion of the regenerator, known as the “dense phase.”

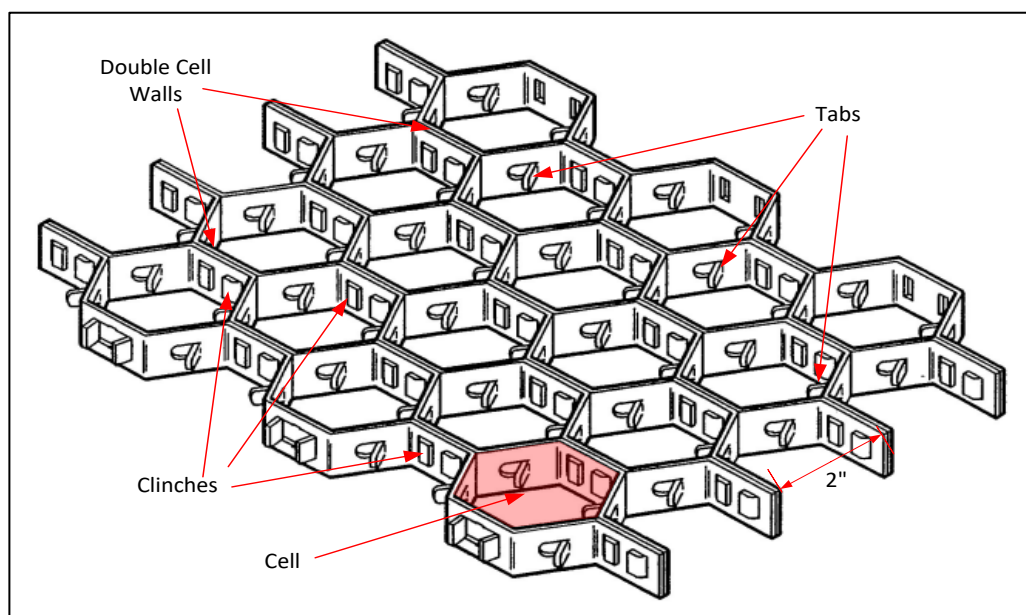


Figure 4—Standard Lance Grid Hexmetal Used in Cyclones Applications

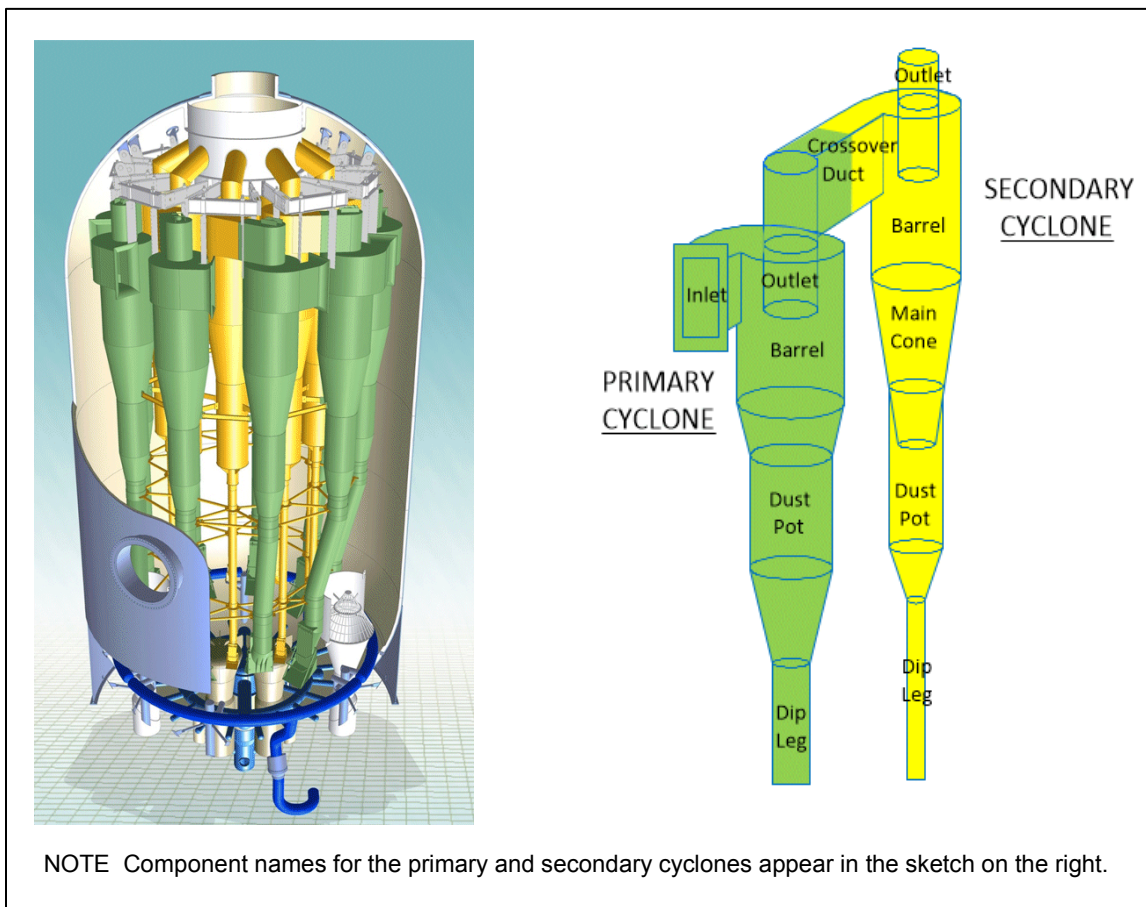


Figure 5—A Typical Two Stage Cycles in Regenerator Showing Primary (Green) and Secondary (Yellow) Stages for Each of 9 Pairs in the Vessel

Other refractory lining components found on the transfer lines are slide valves and expansion joints. Figure 6 depicts a typical cold wall slide valve used to control flow through the lines. The body wall is largely lined with erosion-resistant, heat-insulating refractory, while internal components, such as the gate and the orifice, are typically lined with denser refractories with optimum erosion resistance.

While many refractory lined systems are designed with hard pipe where both refractory and pipe flex with thermal expansion, many others use expansion joints. Figure 7 depicts a typical expansion joint with multiple bellows.

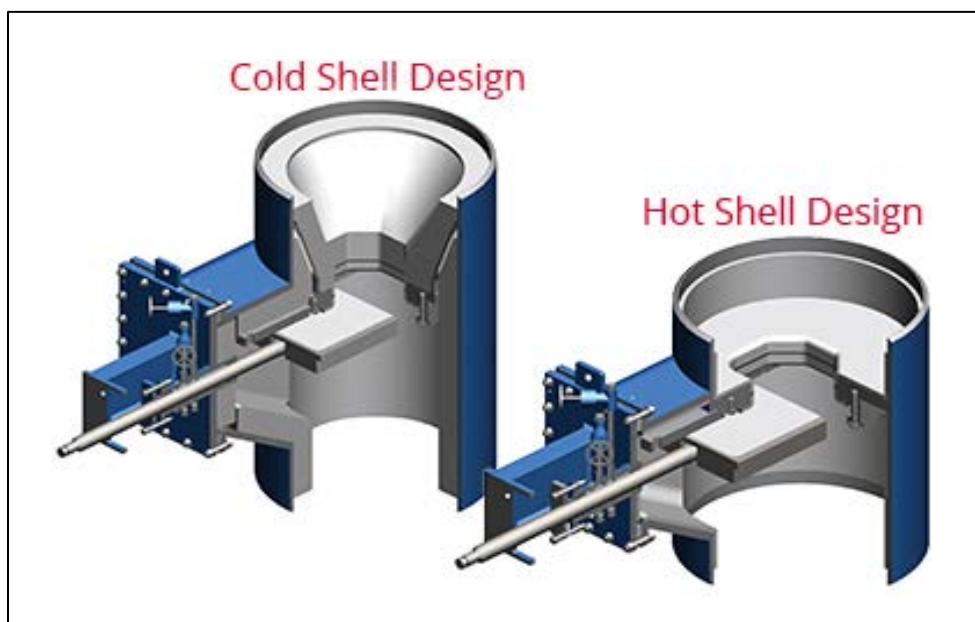


Figure 6—Typical Cold Wall Slide Valve



Figure 7—Cold Wall Refractory Lined Expansion Joint with Bellows Protected and With Erosion-resistant Refractory and Hexmetal on Steel Sleeves

Another important vessel in the flue gas line downstream of the regenerator is the third stage separator (see Figure 8). While the initial two cyclone stages typically recover over 99.99 % of the fines circulated in the process, a further reduction in particulate emissions is typically required. The tertiary cyclone vessel has not been previously discussed, but it has an important function to further reduce fines losses to those less than 5 μm in size, typical. To achieve this, the cyclones are typically smaller in size and operate at much higher velocities than the initial two-stage cyclones. Recovered quantities are relatively small in volume, allowing a periodic batch extraction of the collected catalyst from the bottom cone. While insulating refractories can be used on the external walls, the vessel is more commonly externally insulated. Cyclones within the vessel are lined internally with extreme erosion-resistant refractory.

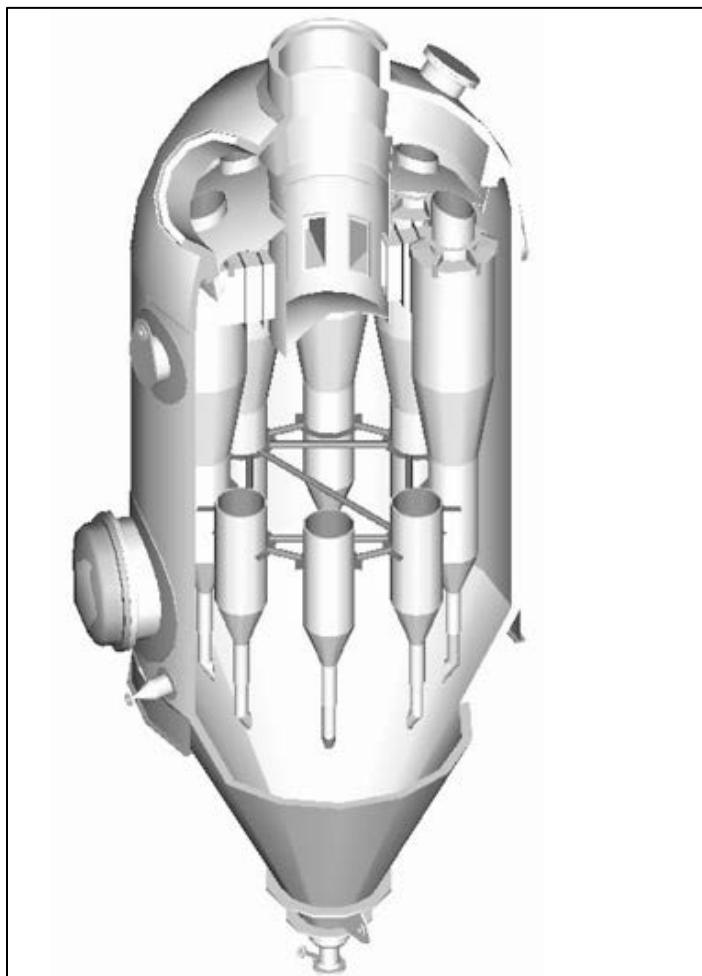


Figure 8—A Typical Third Stage Separator

4.1.5 Continuing Drive for More Erosion-resistant Cyclone Lining Materials

Cyclones are typically internal components of FCCU vessels, having internal wearing surfaces within the cyclones that are typically lined with extreme erosion-resistant refractories. While the availability of more erosion-resistant refractories has improved severalfold in recent decades, the demand for refractories with better erosion resistance continues. This demand is driven by economics to optimize the reliability of the refractory, while exposing the linings to higher throughput conditions and longer run lengths that will maximize the overall utilization of the unit. Failure to meet expected erosion levels can result in failures of the cyclones to effectively contain the catalyst within the unit, and the resulting catalyst losses will eventually force unplanned shutdowns.

[ASTM C704/C704M](#) is a standard that has played a key role in this development. Titled *Standard Test Method for Abrasion Resistance of Refractory Materials at Room Temperature*, the ASTM test is essentially a controlled grit blasting of a surface of pre-fired refractory samples. The relative erosion (abrasion) resistance is determined by the volume of refractory lost over the test duration. In addition to the obvious temperature difference between test and FCCU operating conditions, a single specimen is tested for only a short amount of time (between 435 and 465 seconds) and only uses 1000 grams of SiC grit, which is much coarser and more angular than FCCU catalyst, while using a highly accelerated velocity. In spite of these differences, the test continues to be a widely used tool for the selection and quality control of refractories in FCCU applications.

Because of the improvement being made in the erosion resistance of products, reproducibility issues of the standard are being increasingly amplified. The best erosion-resistant refractories produced in the 1970s gave a loss of $\sim 8 \text{ cm}^2$, while materials today are pushing losses of 2 cm^2 or less, with much-improved field performance.