SILICON

MITIGATING FAILURES OF ABRASION RESISTANT REFRACTORY LININGS

EXECUTIVE SUMMARY

End-users in the petrochemical industry consider failures of abrasion-resistant linings to be one of the most critical pain points in their operations, leading to process disruptions, premature repairs and early replacement of critical processing equipment – especially in FCC vessels. This results in a significant increase in operational costs and a decrease in product yield.

Notably, discussions about these failures often focus on their secondary symptoms rather than the root cause.

This whitepaper addresses a critical design flaw in abrasion-resistant refractory linings, which allows refractory lining bypass to occur. It explores the causes and consequences of bypass, examines the behavior of conventional closed and non-closed cell anchoring systems in both coking and non-coking environments and introduces an alternative anchoring solution.

Highlights:

- Refractory lining bypass is the primary cause for failure in abrasion-resistant linings due to the inherent flaws in the design of conventional closed cell and non-closed cell anchoring systems.
- Refractory lining bypass through gaps and cracks in the lining allows process gases and liquids to reach the processing equipment's shell, causing unwanted buildup and flow disruptions. This can lead to a variety of failures and an increase in operational costs.
- Bypass can cause coke jacking, refractory biscuiting, accelerated corrosion and complete lining separation.
- These failures result in process disruptions, catalyst loss and emergency shutdowns.
- An alternative semi-closed anchoring system is introduced that features the advantages, while mitigating the disadvantages, of conventional closed cell and non-closed cell systems.
- Through testing it was demonstrated that a semi-closed anchoring system can effectively mitigate lining bypass and preserve refractory material, thereby enhancing the efficiency, safety, and long-term sustainability of petrochemical processing equipment.

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Chapter 1 - Introduction

Pressurized petrochemical processing equipment, such as Fluidized Catalytic Crackers (FCCs), have been a staple in the downstream refining market for over 80 years. Since the introduction of the first commercial FCC unit in 1942, significant enhancements have been made to improve the mechanical reliability and to adapt the process to evolving market demands. Renowned for its flexibility in petroleum refining, the FCC process stands out as the most adaptable vessel, capable of efficiently processing various feedstocks[1] . FCCs play a pivotal role in producing valuable products from crude oil, promoting operational efficiency and economic viability in the refining industry. Their output not only significantly contributes to the overall production of refined products but also reflects advancements in catalytic cracking technology.

The longevity and efficiency of operations hinge on reliable equipment and processing innovations. One crucial aspect contributing to the resilience and durability of such equipment is the implementation of abrasion resistant refractory linings. Given the demanding nature of FCC operations, where catalyst particles are in constant motion and abrasive elements are present, the use of abrasion-resistant refractory linings becomes paramount. These linings act as a protective barrier, mitigating the wear and tear caused by abrasive forces and high-velocity particles within the processing unit.

Experiences shared during recent API 936 gatherings indicate that end users consider abrasion-resistant lining failures to be one of the most critical pain points in their operations. This situation results in substantial costs for end users as they cope with and repair these failures. While each FCC design may differ slightly in their approach to their end-products, the problems they face in areas where conventional abrasion-resistant linings are applied remain similar.

This article aims to draw attention to an inherent flaw of the design of abrasion-resistant linings leading to a variety of failure mechanisms significantly impacting the operational efficiency of FCCs and similar equipment. This article will delve into the causes and repercussions of this design flaw and explores alternative solutions to mitigate the issues.

Source: 1 - Sadeghbeigi, R. (2020), Fluid Catalytic Cracking Handbook

Chapter 2 - Refractory Lining Bypass

Processing equipment walls are lined with refractory materials specifically designed to shield the vessel from the harsh processing environment. These refractory linings utilize metallic anchoring systems for structural support. While a diverse range of refractory products and anchoring systems are available for various applications, a common goal is to establish a continuous monolithic lining for optimal protection of the processing equipment.

However, abrasion-resistant linings, typically ¾” (19mm) or 1” (25mm) thick, fail to achieve this goal of sustaining a continuous monolithic lining, due to the traditional anchoring systems specified, which leads to refractory segmentation and the creation of a **multi-lithic lining.**

These conventional metallic anchoring systems, which are usually flush with the lining, allow for the formation of gaps and cracks spanning from the processing side to the shell side of the lining. Process gases and liquids reaching behind the lining is therefore a common occurrence in abrasion-resistant linings. This presence of undesirable elements of the processing environment behind the lining is called **refractory lining bypass.**

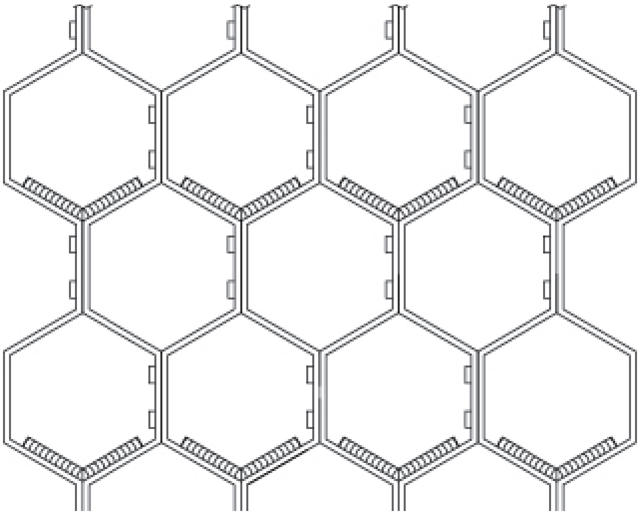
To understand how bypass occurs, it is important to understand the conventional types of anchoring systems for abrasion-resistant linings used within the petrochemical industry.

2.1 Metallic Anchoring Systems

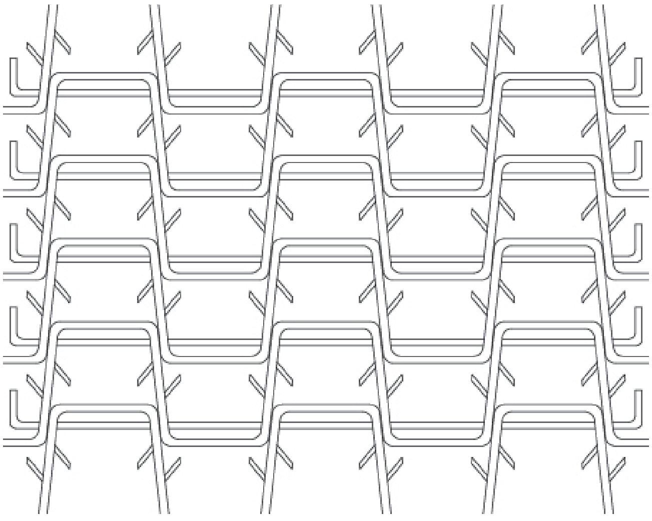
Closed Cell Anchoring Systems

A closed cell anchoring system comprises small, enclosed volumes in which refractory is compacted. The refractory contained within a closed cell is called a cookie. Other than through openings in the metal strips forming the mesh, the refractory is not continuous. Hexagonal mesh, or hex metal, is the most used anchoring system for abrasion-resistant linings. It is constructed from continuously connected metallic sheets that form hexagonal cells. The complete system mimics a honeycomb formation. The mesh is first welded to the vessel wall and the hexagonal enclosures are later packed with refractory. Flexible mesh, or flex mesh, is another example of a closed cell anchoring system.

These types of systems are characterized by a high metal-to-refractory ratio and a high number of welds per area.



Standard honeycomb hex metal/mesh.

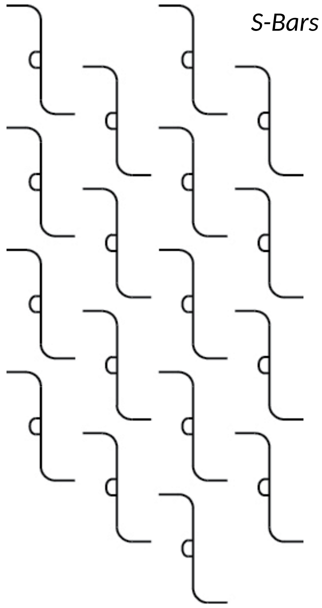


Flexible mesh, bound together with a prong.

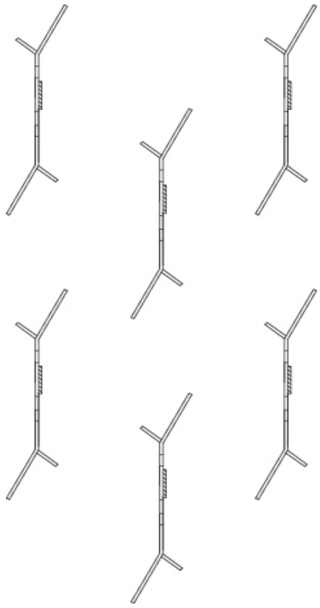
Non-Closed (Open) Cell Anchoring Systems

A non-closed cell anchoring system does not create a series of individual refractory cells (cookies). The refractory is a continuous system, and the individual metallic anchors are embedded in the refractory (except for exposed metallic parts flush to the lining). Examples are S-Bars and K-Bars, both considered so-called hexalt anchors. Some hexalt systems (e.g. individual hex cells) have characteristics of both closed and non-closed cell anchors.

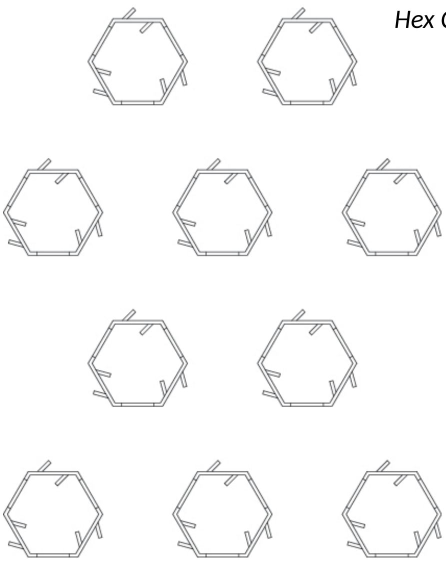
These types of systems are characterized by a low metal-to-refractory ratio and a low number of welds per area.



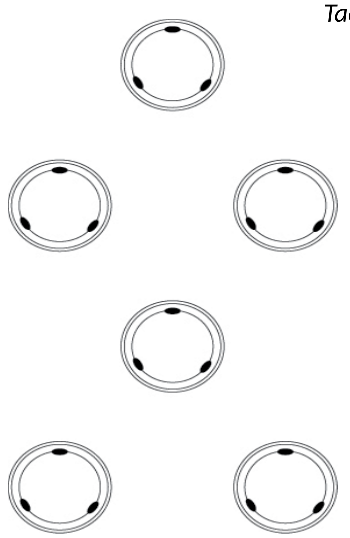
S-Bars



K-Bars



Hex Cells

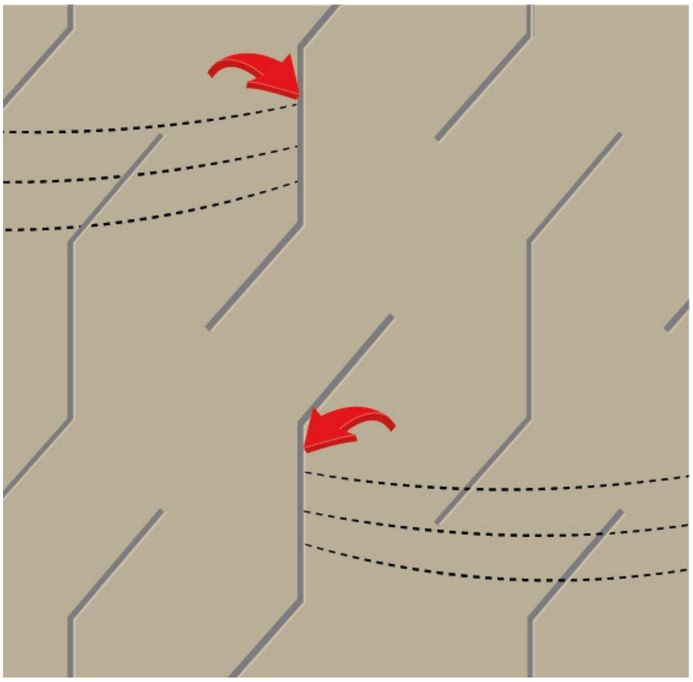


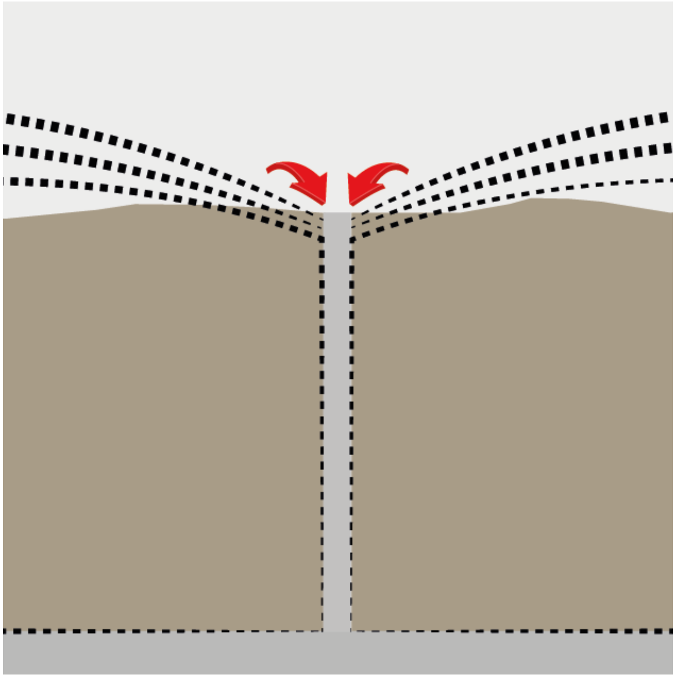
Tacko

2.2 Mechanisms of Lining Bypass

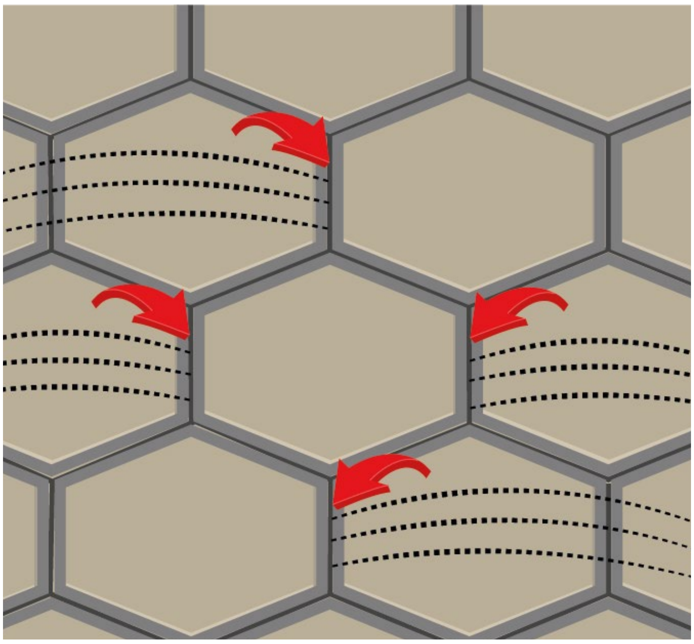
The ways lining bypass occurs with traditional anchoring systems in abrasion-resistant linings can be categorized as follows.

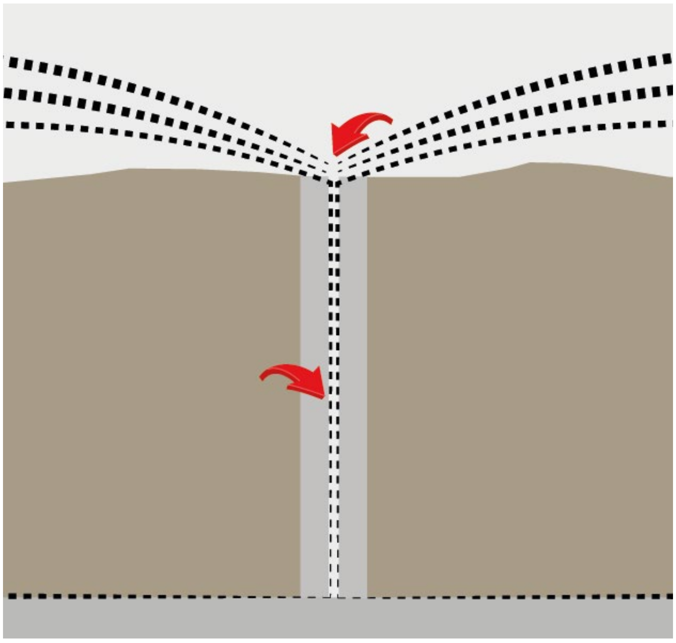
Bypass through gaps between refractory and metallic anchoring
At elevated temperatures, refractory materials contract while metals expand, both at varying rates. This difference in expansion rates naturally results in physical gaps forming at the interfaces between refractory and metal, a process exacerbated by repeated thermal cycling. In hex metal linings these gaps extend unimpeded from the lining surface to the vessel wall, establishing a direct pathway for process gases and liquids to seep behind the lining. Traditional hexalt anchors similarly feature areas where this can happen. Incorrect installation of refractory could also allow for small gaps to be formed where gases and liquids may pass through.





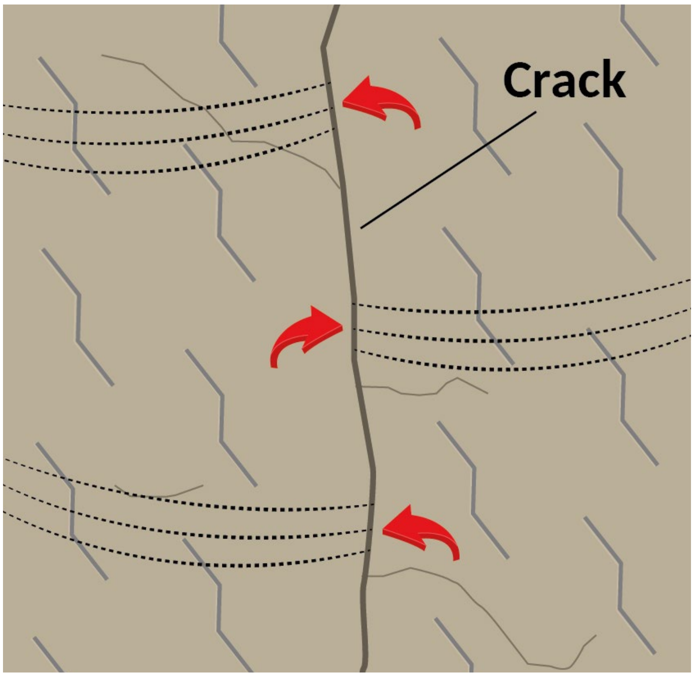
Bypass through gaps between plates of metallic anchoring
If the anchoring system is composed of interconnected metal sheets such as hex metal, at its inception and worsened over time, gaps may form between these sheets. In the case of hex metal, these gaps extend freely from the lining surface to the vessel wall, inherently creating conditions conducive to lining bypass.

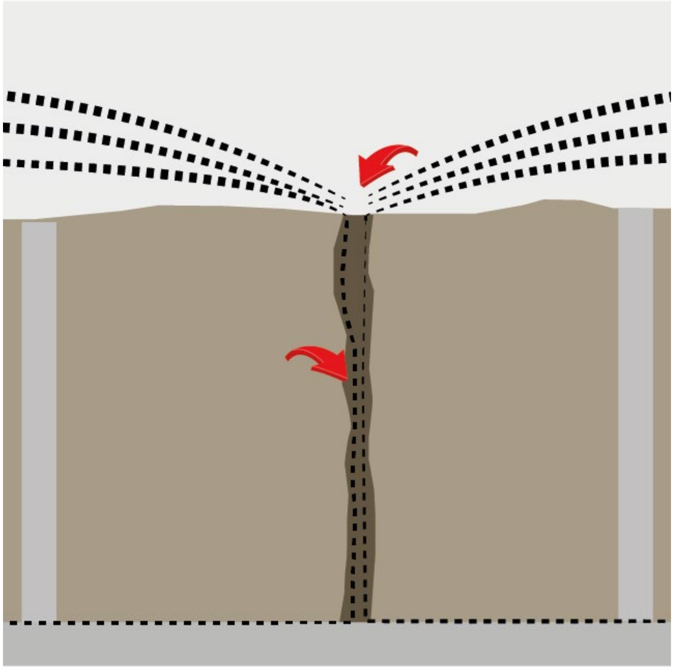




Bypass through gaps between refractories
Large areas of refractory may be installed in batches within an enclosed area. Installed refractory is given time to set, after which the set refractory becomes a physical barrier for the next area to be installed. Any newly installed refractory does not bond with set refractory and this inherently causes the lining to become segmented. Such interfaces, called cold joints, can lead to lining bypass. A certain amount of cold joints during refractory installation is unavoidable. However, the impact of failure mechanisms occurring here can be minimized by designing the cold joint in such a manner that the risk of lining bypass is reduced to a minimum.

Improperly mixed, installed, or insufficiently supported refractory may also experience some form of cracking or segmentation due to the inflexible behavior of most abrasion-resistant materials and thermal cycling. This can also lead to bypass.





Absorption through refractory porosity
It should be noted that refractory linings inherently have a certain level of porosity, which might absorb some of the elements of the processing environment. However, this absorption typically does not reach the vessel wall, and therefore, it does not cause significant detrimental effects. This phenomenon is therefore not considered lining bypass and is not further discussed.

2.3 Repercussions of Lining Bypass

This section will elaborate on the repercussions of refractory lining bypass and how this manifests differently in coking and non-coking environments, and closed cell and non-closed cell anchoring systems.

Coking and Non-Coking Environments

An FCC is commonly known for having two main processing environments, a coking side and a non-coking side. The coking side is closely linked to the part of the vessel called the "Reactor", where an intentional reaction takes place that causes the creation of cokes formation, a form of dehydrogenated carbon. The "Fluid" part in FCC refers to the liquid, fluidized bed that is present on the Reactor side. This liquid causes the coking environment's most prominent concern, so-called coke jacking, where bypassed liquid and solid coke push the lining away from the shell.

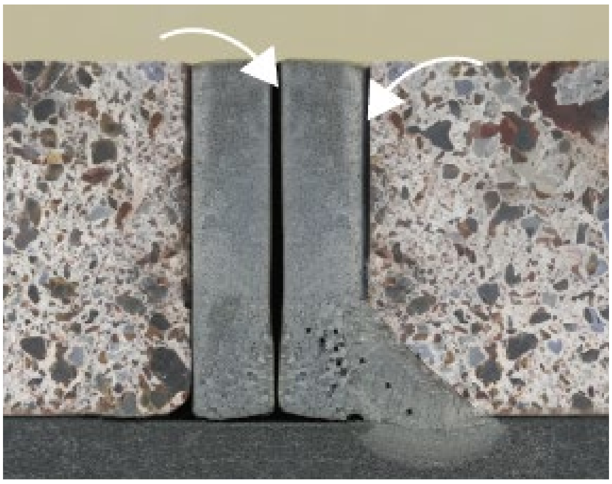
An example of built-up cokes formation.

The non-coking environment is typically found in the "Regenerator" part of the FCC, where spent catalyst is split from small clumps of coke and "regenerated" for reusability in the process. In the regenerator, most internal components are covered by light-colored residual catalyst dust. The small particles lead to a higher abrasiveness and velocity than on the reactor side. This, combined with a higher operating temperature and a low-oxygen environment, can lead to accelerated deterioration of linings and may pose challenges to the anchoring system, potentially resulting in operational issues.

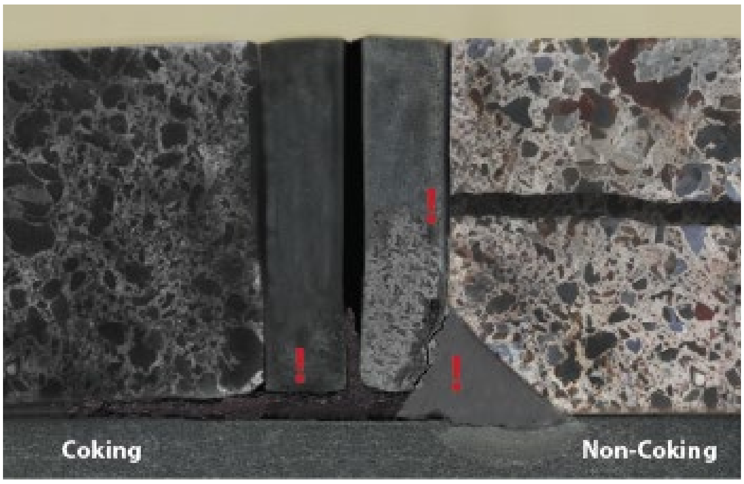
Thick layers of catalyst dust can be found in the regenerator, non-coking environments.

Closed Cell and Non-Closed Cell Anchoring Systems

Both closed cell and non-closed cell systems have shown to be susceptible to failure in coking and non-coking environments. Once bypass sets in, its phenomena will manifest differently as seen in the images below.

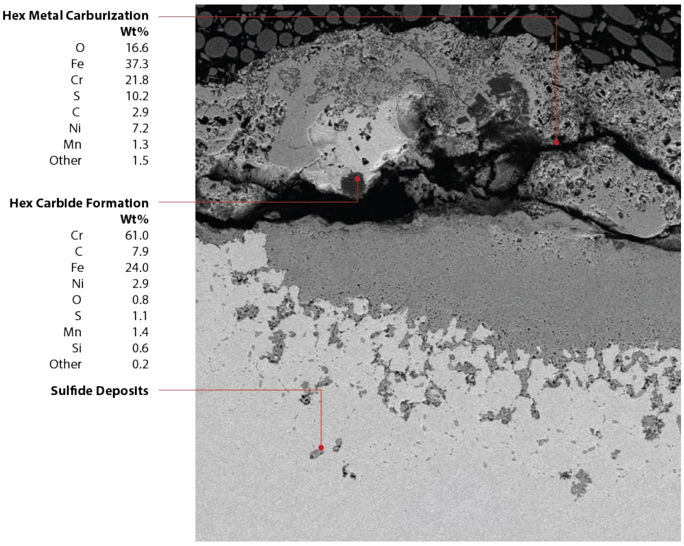


Hex metal after refractory installation into the enclosed cells. The anchoring design combined with possible installation gaps and shrinkage allow pathways to bypass the lining and remain behind the lining.

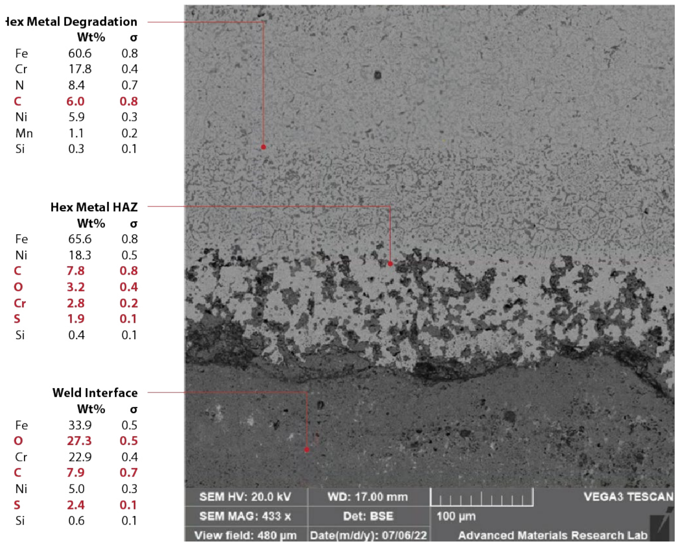


Installed refractory will be exposed to different processing environments in coking versus non-coking environments. A few notable highlights between the environments are a large absorption of dark particles into the refractory (so-called "coking over") in coking service and higher processing temperatures in regenerator processing environments.

In the images below, a sample of a failed anchoring system in each environment has been microscopically analyzed to clearly understand the true consequences of bypass. When undesirable process elements reach the weld interface between the anchor and the shell, the stainless steel becomes locally sensitized and the corrosion resistance is reduced. The test results clearly indicate that carburization and sulfidation represent the final stages of anchor failures, initiated by carbon and sulfur content as well as catalysts. These failures happen solely due to the allowance for bypass to occur.



Failed Hex Sample in Coking Environment



Failed Hex Sample in Non-Coking Environment

Despite the closed cell system being the most used and recognized anchoring system, its design allows for various pathways that bypass the protective lining within the cell. A key weakness of a closed cell system is the presence of gaps between clinches of connected metal sheets. Additionally, shrinkage of the refractory during dry-out may also create small gaps between the steel and the refractory. These gaps allow gases, catalysts, and various processing elements to flow behind the lining, settle and build up over time – directly affecting not only the anchor system but also the shell and the lining's overall effectiveness.

Inherent in its design, closed cell systems allow for pathways that reach behind the lining.

In non-closed cell anchoring systems, the distance between anchors is larger than in closed cell systems and thus increases the volume of refractory per unit area while reducing the anchoring support. This can lead to material sagging during installation in overhead and side-hand orientations, where the effect of gravity has a more significant impact than in a flat, downward-facing orientation. This effect is well-known by licensor specifications. It is mitigated in fabrication environments by restricting the orientation of abrasion-resistant refractory installation to be downwards only.

Refractory material sagging during installation in the side-hand orientation.

Regardless of the method of bypass occurring, failure is a matter of time in both anchoring systems. The following sections take an in-depth look at the failures occurring in coking and non-coking environments for each anchoring system.

Coking Environment Failures

In coking environments, a notable difference compared to non-coking environments is the black discoloration of refractory material. The porous nature of refractory exposes it to carbon-containing gases, liquids, and solids present, leading to product absorption. This absorption causes refractory cells to slightly expand, contributing to coke jacking – an added stress on welded metal due to a leveraging effect away from the shell. While expanding refractory cells are a factor, a more significant stress contributor in coke jacking results from coke buildup behind the lining, facilitated by bypass.

Refractory after coke absorption.

Case Study: FCC Reactor Cyclone - Closed Cell System

Liquid bypass has caused a coke build-up so significant that the continued formation and expansion of this build-up not only caused coke-jacking to separate the hex metal from its welded interface, but also caused numerous components to crack along

Left/Middle: A Reactor cyclone dipleg that required replacement within 3 years of operation due to bypassed refractory lining. Right: Carburized steel shell of at least 6mm after prolonged exposure to bypass.

From the observations, it is evident that bypass was at the root of the thick build-up behind the lining:

1) Bypass allowed continued coke formation behind the lining.
2) Due to exposure of the coke-forming elements, stress corrosion cracking occurred in sensitized hex metal. [2]
3) The shell was exposed to sulfidation and carburization, weakening its structural integrity.
4) Coke jacking caused a large portion of the anchoring system to be separated from the shell, while the shell itself ruptured.
5) The failure was sufficiently large that a complete blockage was observed. This warranted an emergency shutdown.

Source: 2 - Jerry Wilks (2010), Damage Occurring in FCC Hexmesh Systems

Case Study: FCC Transfer Line – Non-Closed System

Non-closed systems aim to achieve a monolithic lining, often at the expense of refractory retention in the event of cracking. Coking in these linings is concerning, as the absorbed coke exerts additional forces on the refractory. This process causes unpredictable crack formation, leading to more bypass. Due to the absence of an interconnected mesh, refractory material may completely dislodge, causing isolated hotspots and corrosion.

Also, in this case, bypass serves as the root cause of a component failure, albeit the failure only occurs after unpredictable cracks have formed.

From the observations, it is evident that bypass was at the root of the thick build-up behind the lining:

1) Uncontrolled cracking observed through thermal cycling, coke absorption and no crack propagation barriers. From this point, bypass mechanisms start to occur.
2) Bypass causes cokes to continue building up behind the lining. Coke jacking of refractory causes chunks of refractory to potentially separate from the shell and other refractory.
3) Fully exposed steel will experience hot spots and may require steam cooling.
4) Due to fully exposed steel, corrosion may occur faster leading to emergency leaks and patch repairs or shutdowns.

Refractory with missing chunks.

Non-Coking Environment Failures

Compared to coking environments, non-coking environments are typically characterized by a higher processing temperature, reducing atmospheres, and faster particle flow velocity. These factors typically cause more turbulence and lead to various other phenomena that are not commonly present in coking environments. Refractory here typically looks “toasted” and whiter throughout.

Due to the low-oxygen environment, stainless steel anchoring systems may have a lower corrosion resistance. This is especially prevalent behind the lining, where gases move fast and without obstruction.

Another notable observation which occurs mostly in non-coking environments, is the separation of hot-face facing portions of refractory cells, resembling laminated refractory. This phenomenon is called biscuiting due to its resemblance to biscuits.

Refractory spalling, called biscuiting.

Case Study: FCC Regenerator Cyclone – Closed Cell Systems

Gas bypass in a low-oxygen processing environment can cause rapid deterioration of hex metal and its weld interface to the shell, as seen in this case study. In addition, this regenerator cyclone suffered damage in various locations on the shell due to carburization, manifesting as small pitting marks. Heavy catalyst loss was also experienced. An emergency shutdown was necessary, requiring both shell repairs and full replacement of the lining.

Backside of Regen Cyclone Hex

Frontside of Regen Cyclone Hex

Biscuiting & Hex Spalling

It was notable that the backside of the lining was more affected than the front. This failure could not have occurred without bypass.

1) Carburizing and sulfidizing elements, as well as catalysts, build up behind the lining and deteriorate the anchoring system and shell.
2) Sensitization of steel occurs, leading to a domino effect of hex metal and its welded joints to the shell being deteriorated until the point of separation from the shell.
3) Refractory as well as partial hex metal starts spalling, peeling and biscuiting.
4) Hex metal sheets separate from the shell, leaving the shell exposed. At this point, an excess of 50 tons of catalyst loss was experienced daily.
5) The absence of vessel protection led to damage to both the vessel and its supports. A catastrophe was averted by initiating an emergency shutdown.

Case Study: FCC Riser – Non-Closed Cell Systems

Similar to non-closed cell systems in coking environments, monolithic linings in such open systems cannot adequately absorb the expanding and contracting behavior of the refractory.

In non-coking environments, this tends to manifest in smaller, but more frequent, unpredictable crack formations. Once these cracks form, gas bypass is inevitable and heavily affects the creation of isolated hot spots.

The image on the right displays a riser lining where most of the smaller cracks did not propagate further. However, with the large runaway cracks, warping of the steel shell was experienced. Fortunately, no catastrophic incident occurred, but the riser lining required almost 30% replacement of its refractory and anchoring. Once again, refractory bypass was the underlying cause of the repair needs.

Runaway cracking in refractory.

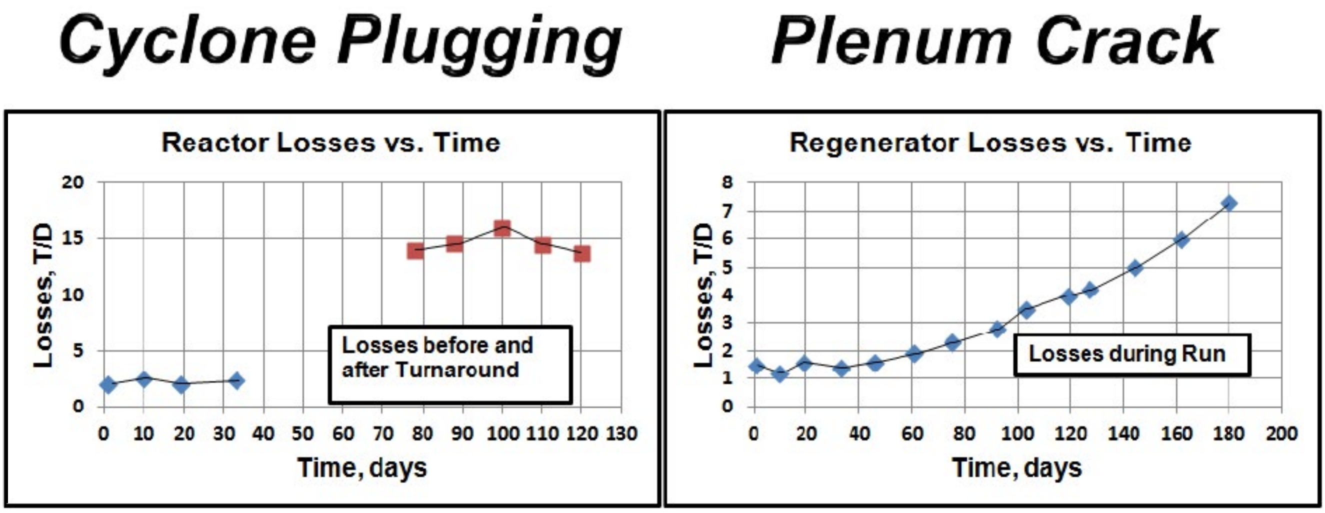
2.4 Operational Impact of Lining Bypass

Damages resulting from lining bypass have a significant impact on the operational costs, repair efforts, and maintenance due to the disruption it causes in the flow process of internal components and the overall process. Over the past two decades, there has been a growing emphasis among end-users on vessel reliability, leading to an increased recognition of the importance of long-term success strategies over cheap short-term repairs, that eventually cost more.

Vessels that are designed to run for 4-6 years before a shutdown, should be maintained to such a degree that this duration can be achieved without unexpected interruptions or loss of efficiency in its intended product yield. Any unforeseeable occurrences directly impact the vessel's strategic and economic value to the refinery and its customers.

For example, unwanted catalyst losses, which can cost up to 3,000 USD per ton of catalyst, directly impact the cost-to-profit ratio and product yield. These losses often occur due to inefficient and unintended processing behavior in cyclone environments, directly affecting the reliability of refining equipment. On an annual basis, these added costs can range between 1 million (1 ton of catalyst loss per day) and 25 million USD (25 ton of catalyst loss per day), depending on the size and the age of the vessel and its lining, and could necessitate early shutdowns. Considering the market value of the processed product and a vessel's daily barrel output, the lost profit resulting from an unplanned shutdown can amount to an additional 2-5 million USD per day.

Overall, it is evident that unpredictable behavior of hard-to-inspect abrasion-resistant linings can lead to costly operational inefficiencies and increased cost-per-barrel. These inefficiencies contribute to premature and more frequent repairs, and possibly failure of a component's structural integrity, potentially requiring replacement before its full intended run-cycle is completed. All of this leads to higher costs and lower profits.



A case study of the performance of cyclones in reactor and regenerator environments performed by BASF in 2019. [3]

The image on the left-hand side illustrates an example of catalyst loss within a reactor environment. During a planned turnaround, the abrasion-resistant hex metal lining could only be inspected from the hot-face side. The lining appeared to be in good condition and repair was not deemed necessary. However, thermal shock during the vessel's start-up sequence, coupled with unobserved weakened weld interfaces of the hex metal and unwanted build-up behind the lining caused by bypass, resulted in complete lining detachment and subsequent cyclone plugging. This flow obstruction caused significant operating inefficiencies.

The image on the right-hand side illustrates an example of catalyst loss within a regenerator environment. Gradual lining degradation led to localized areas of refractory being removed, exposing the plenum shell. This led to flow inefficiencies in the remaining lining and rapid deterioration of the shell, which was eventually breached. Both repercussions contributed to a gradual increase in catalyst loss. This significantly diminishes the process efficiency and raises the cost-per-barrel.

Source: 3 - Jason Goodson, Joe McLean (2019), Catalysts Losses and Troubleshooting

Chapter 3 - Mitigating Lining Bypass

The previous section described the repercussions of lining bypass and its relation to the conventional anchoring systems for abrasion-resistant linings. Despite numerous documented failures associated with these systems, they are still widely used and specified. This section revisits the advantages and disadvantages of the conventional anchoring systems and explores solutions that retain their benefits while eliminating the drawbacks.

3.1 Closed Cell Systems

Advantages:

- Runaway cracking is contained within the boundaries of the closed cell.
- Interlinked mesh can delay an early individual weld failure from causing the whole system to fail.
- Optimum cookie size for compacting during refractory installation and refractory retention during service.
- Ease of refractory installation.
- Widely available.
- Familiar to most refractory installers.

Disadvantages:

- Does not create a continuous monolithic protection by design, but rather a segmented multi-lithic set of isolated cells.
- High metal-to-refractory ratio. This leads to a less protective lining due to a lower presence of refractory material and a higher presence of metal-refractory interfaces.
- Prone to physical gaps, either between metallic strips or on interfaces between metal and refractory, that reach the vessel wall and lead to lining bypass.
- Laborious anchor installation.
- Complex to fit onto curved surfaces and into confined spaces.
- Challenging to inspect effectively.
- Continued weld failures can cause emergency shutdowns due to flow disruption.
- Turbulence in one area may affect another area negatively due to its interlinked nature.

3.2 Non-Closed Cell (Open) Systems

Advantages:

- Monolithic protection by design.
- Useful for quick patch repairs.
- Individual anchors do not require special modification or bending prior to installation.
- Individual anchor failures typically do not cause flow disruption.
- Easier anchor installation.
- Large selection of options on the market.

Disadvantages:

- Low metal-to-refractory ratio. This might offer insufficient anchoring support for the refractory lining.
- Prone to physical gaps on interfaces between metal and refractory that reach the vessel wall and lead to lining bypass.
- Runaway cracking leads to unpredictable bypass.
- Runaway cracking leads to the detachment of large refractory chunks. These detached chunks can create localized hotspots, which in turn can lead to shell warping and leaks.
- Monolithic protection gradually transforms into segmented multi-lithic protection over time due to the formation of cracks and gaps.
- Larger refractory areas between anchors lead to sagging during refractory installation and suboptimal refractory retention during service.
- Requires an additional physical barrier to terminate and compact refractory. This results in numerous cold joints, especially in large areas.
- May be proprietary products with little case history.
- May require new specifications and training on inspection criteria and installation methods.

3.3 Past Mitigation Efforts

The industry has made the following efforts to enhance closed cell systems.

a) Increasing refractory height above the anchoring system creating a top monolithic layer.

In this case, the refractory height was double the hexmetal height (1” hexmetal, 2” refractory). The 1” top layer experienced spalling due to lack of anchorage and soon abraded. This caused chunks of unanchored refractory to detach.

b) Altering design of hex metal to allow more refractory through to prevent pathways of bypass.

Several design alterations were introduced to the market with the aim of reducing the metal-to-refractory ratio. However, these concepts underestimated the ability of gases and liquids to penetrate the inevitable gaps created by an interlinked system, even though minimized.

Both efforts failed to achieve enough success for widespread adoption. However, a new type of system can be proposed that incorporates the beneficial features of both closed cell and non-closed cell systems.

3.4 Semi-Closed Cell Anchoring System

Conventional anchoring systems are generally over-anchored or under-anchored. A so-called semi-closed cell anchoring system should have an optimum balance between anchorage and refractory. In addition, a semi-closed cell anchoring system should mimic the shape and effectiveness of closed cell anchoring enclosures while allowing for continuous refractory flow similar to non-closed cell anchoring systems.

This system should feature the advantages while mitigating the disadvantages of both closed cell and non-closed cell systems:

- Optimum cookie size for compacting during refractory installation and refractory retention during service.
- Optimum metal-to-refractory ratio ensuring adequate anchoring for structural support and enough refractory material to maintain the monolithic integrity.
- Lasting monolithic protection throughout the lining.
- Not prone to the formation of gaps with a direct pathway from the lining surface to the vessel wall, thereby mitigating bypass.
- Not prone to runaway cracking, due to cracking being contained within the boundaries of the semi-closed cell.
- Potential localized deterioration of the lining does not affect surrounding areas due to the independent behavior of semi-closed anchoring.
- Individual anchor failures typically do not cause flow disruption.
- Provides predictable wear behavior.
- Ease of anchoring installation.
- The anchors can be welded at a single point or at multiple points.
- Individual anchors do not require special modification or bending prior to installation.
- Ease of refractory installation.
- Refractory flow and compaction are observable within each cell due to flow-through.
- During refractory installation there is little to no need for temporary molds or barriers to compress the refractory.
- Useful for both patch repairs, relines and new equipment.

3.5 Considerations

Any alternative anchoring system poses risks that need to be considered with the aim of achieving the optimum design for abrasion-resistant linings. Some key considerations are as follows.

- **Refractory Cohesion**

  How can bypass be mitigated in a cohesive monolithic lining compared to a segmented multi-lithic lining, especially in areas with unavoidable cold joints?

  Desired Performance: The refractory should show no signs of direct bypass of liquid or gas. Due to isolated pockets of compacted cold joints, it should not show significant travel of liquid or gas behind the lining.

- **Refractory Structural Integrity**

  How will the abrasion-resistant refractory behave as a reinforced section of monolithic compared to conventional segmented closed cell refractory under loads encountered during service?

  Desired Performance: The refractory should show a significantly increased resistance to separate from its anchoring system and from the shell when exposed to the same load.

- **Mechanical Anchoring Integrity & Design**

  Is the anchor strong enough after installation, while allowing sufficient continuity of refractory?

  Desired Performance: The strength of a welded semi-closed anchor should exceed that of an individual weld in an interconnected hex cell to mitigate a single weld failure.

In addition to the considerations mentioned above, numerous other factors might need to be addressed, exceeding the scope of this white paper. When evaluating any alternative solution, compatibility with the vessel's design, unique processing conditions, and other potential complexities of the application must be assessed.

In the next chapter, the considerations regarding refractory cohesion and structural integrity are further discussed because they are closely related to bypass and its repercussions.

Chapter 4 - Testing & Results

To address the considerations of the previous chapter and evaluate the effectiveness of semi-closed cell systems as opposed to closed cell systems in minimizing lining bypass and ensuring optimal substrate protection, penetration tests and pull tests were conducted. The objective of the penetration test was to evaluate lining bypass in both systems and to demonstrate that semi-closed cell systems are less conducive for bypass compared to closed cell systems. This evaluation took into account the impact on cold joints in both scenarios.

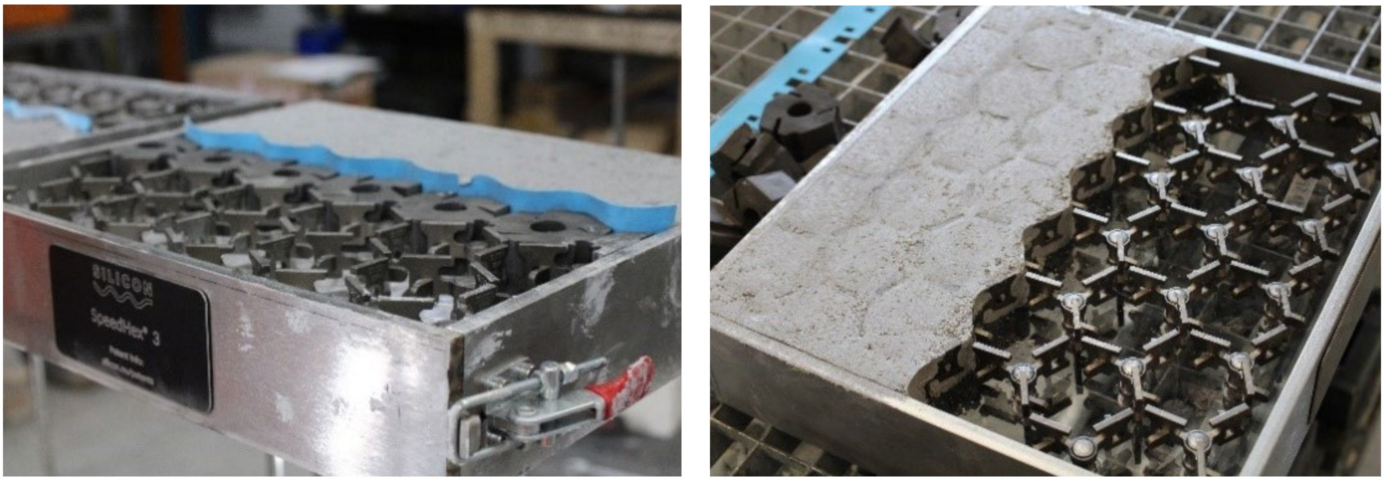
The pull tests were conducted to evaluate the strength of the lining in semi-closed cell systems and closed cell systems.

The following conditions were taken into consideration for the test setup:
- Anchors were installed with the same pattern as industry recognized hex metal (2” cookies).
- Refractory materials used are standardly recognized by petrochemical end-users and licensors.
- Refractory materials were installed by experienced refractory installers.
- Refractory materials were cured and fired according to manufacturers’ specifications.

4.1 Penetration Test

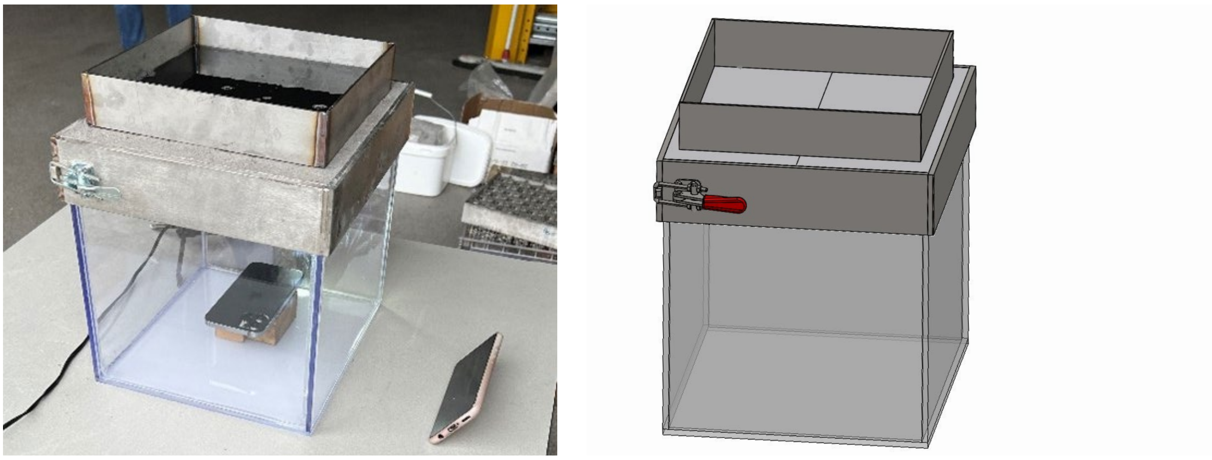
The test setup sought to simulate the impact of FCC process fluids on various abrasion-resistant refractory linings, showing a semi-closed cell anchoring system (SILICON SpeedHex® 3) and a closed cell anchoring system (traditional Hexmetal), with a focus on cold joints. Although duplicating exact FCC process conditions, with typical temperature and pressure values, proved impractical, the aim was to assess the potential occurrence of bypassing under normal ambient conditions. To achieve this, water colored with black ink was selected as the fluid to detect any signs of bypass behind the lining.

Sample panels with semi-closed and closed anchoring systems, incorporating various types of industry-standard refractories, were utilized. Panels with the semi-closed cell system had its refractory material installed in two phases—half of the panel received refractory installation, was terminated with refractory backing clips, underwent a complete dry-out cycle lasting approximately 24 hours, and then the remaining refractory was installed in the other half. This deliberate process was employed to purposely create a cold joint. Panels with the closed cell system were also installed in two phases, with the hex cell in this case forming a hard barrier for installation of the other half of refractory. After the dry-out cycles were completed, 1 liter of ink-colored water was poured over each sample panel, after which it was observed for 10 minutes.



Semi-closed cell system refractory installation with an intentional cold joint.

Click **here** for the 24 hour dry-out timelapse video.



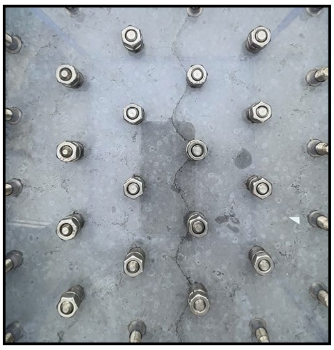
Penetration Test Setup, liquid placed on top of lining, captured in container below.
Apple iPhones used to capture videos of the process.

Result Summary

Sample Type: Semi-Closed Cell System

Before Test

After 90 Seconds



After 3 Minutes

After 10 Minutes

Observations

Minor absorption of the test fluid through and reaching behind the refractory lining was observed.
No penetration or lining bypass was observed within the cells or at the cold joint after 10 minutes.

Sample Type: Closed Cell System

Before Test

After 10 Seconds

After 20 Seconds

After 90 Seconds

Observations

Penetration or lining bypass was observed within seconds in the cells and at metal joints with all test fluid flowing through. This may be attributed to cold joints formed between the refractory material and the closed cell anchoring system as well as occasional gaps at the metal joints. The tests concluded within approximately 90 seconds, as the test fluid had fully penetrated the lining by that time.

The results of the penetration tests demonstrated two phenomena:

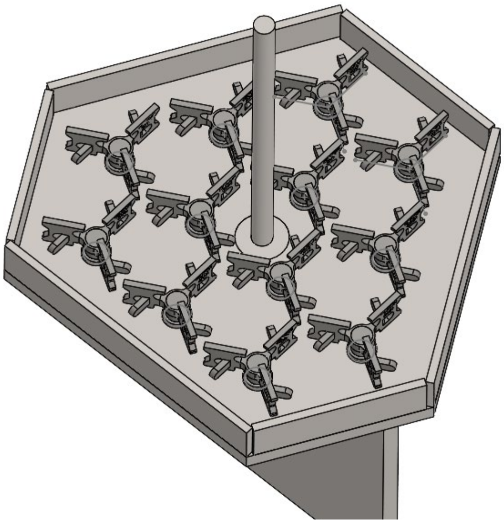
- Absorption of liquid in the refractory (observable by the light discoloration of refractory).
- Circumvention of the lining by the liquid via direct bypass to the shell (observable by the dark buildup behind the refractory and passing through the plastic backing).

It was evident that the semi-closed cell anchoring system provided superior protection against lining bypass by showing no signs of direct liquid bypass, as opposed to the closed cell anchoring system, where significant fluid bypass occurred within seconds.

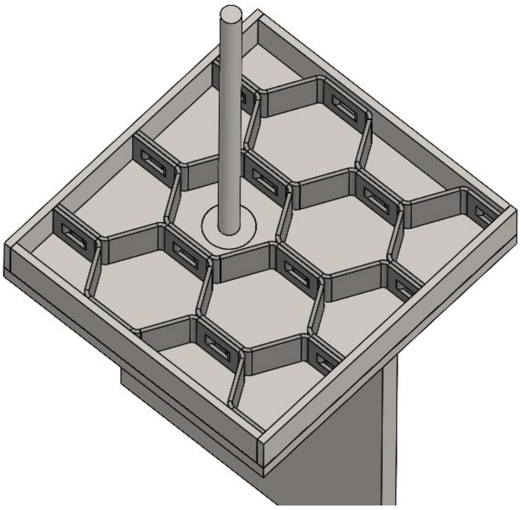
Although absorption occurred in the refractory materials for both systems – which is to be expected in typical processing environments – the time it took for the initial signs of absorption to manifest in the semi-closed system suggests that in actual processing environments this would not pose any concern. This is attributable to the absence of pathways that would allow fluids to bypass, as seen in closed-cell systems.

4.2 Pull Test

Various sets of semi-closed and closed cell anchoring systems, each featuring different industry-standard abrasion resistant refractories, were utilized. A pull pin was freely inserted into a cell to assess the force needed to extract a closed refractory cell (cookie) from the lining.



Semi-closed cell system before refractory installation.



Closed cell system before refractory installation.

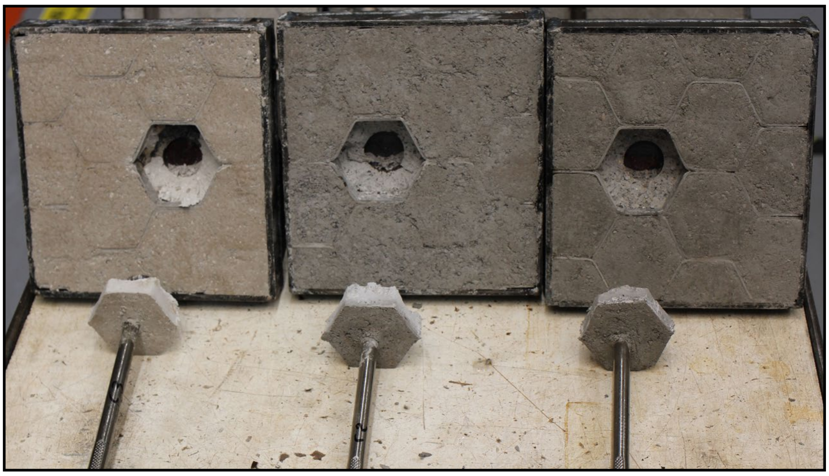
Result Summary

Sample Type: Semi-Closed Cell System, After Pull Test

Observations

On average, approximately 42.9 kN of force was required to pull out a cookie.

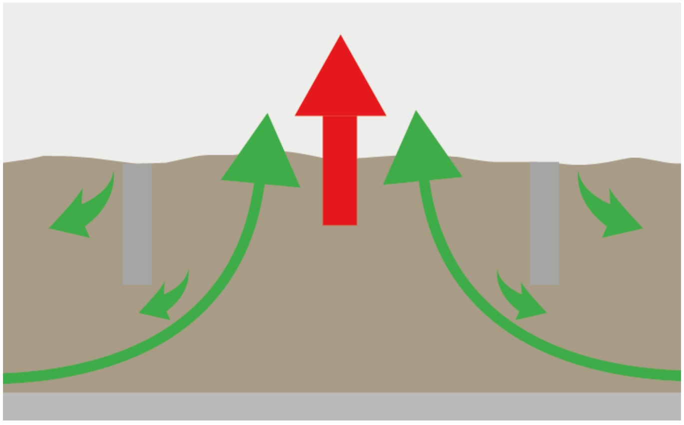
Sample Type: Closed Cell System, After Pull Test



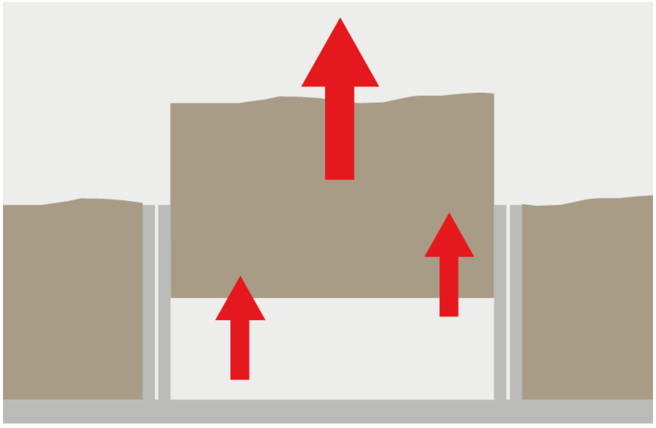
Observations

On average, approximately 7.6 kN of force was required to pull out a cookie.

The pull test results revealed that the semi-closed cell system showed a significant difference to the closed cell system in retaining abrasion-resistant refractory material. This is attributed to the design of the semi-closed cell system, with embedded anchors in a monolithic refractory lining providing robust support and resistance against forces that could cause refractory separation from the anchoring. Refer to the illustration below for a visual representation of these forces in both systems.



Representation of exerted forces during pull test in semi-closed cell system.



Representation of exerted forces during pull test in closed cell system.

Chapter 5 - Conclusion

Refractory lining bypass, particularly in abrasion-resistant linings for Fluid Catalytic Cracking (FCC), poses a significant and expensive challenge for the industry. The limitations of traditional closed cell and non-closed cell anchoring systems, for example, hex metal and its inability to create a continuous monolithic lining, highlight their vulnerability to lining bypass. Consequently, this creates a potential for costly operational disruptions and premature structural failures.

The transition to a semi-closed cell system, such as the demonstrated SpeedHex® system, emerges as a reliable and strategic solution. This alternative has been supported by conclusive testing affirming the effectiveness in mitigating lining bypass and preserving refractory material, thereby enhancing the efficiency, safety, and long-term sustainability of petrochemical processing equipment

Sources

1 - Sadeghbeigi, R. (2020), Fluid Catalytic Cracking Handbook – An Expert Guide to the Practical Operation, Design, and Optimization of FCC Units (Fourth Edition)
2 - Jerry Wilks (2010), Damage Occurring in FCC Hexmesh Systems – Refcomm Galveston 2016
3 - Jason Goodson, Joe McLean (2019), Catalysts Losses and Troubleshooting – Refcomm Galveston 2019

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