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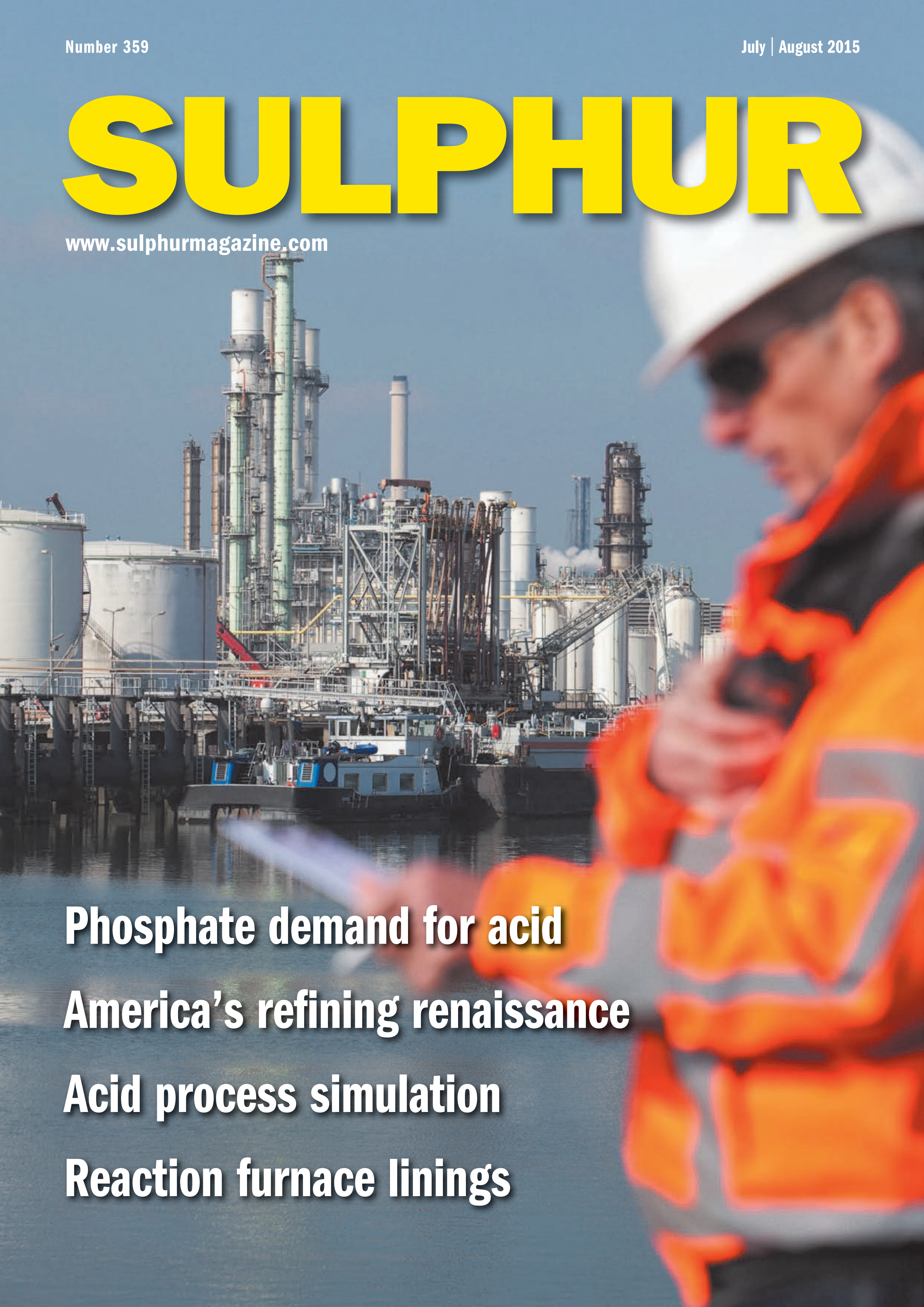


Phosphate demand for acid

America's refining renaissance

Acid process simulation

Reaction furnace linings

Limiting factors on reaction furnace linings

SRU operators are experiencing increasing demands for improved reliability due to significant changes in emission regulations and penalties, more severe operating conditions, high cost of repairs and the consequential impact a reaction furnace failure can have on other operating units in refineries. Management is finally paying more attention to these issues; however, before the SRU problems can be properly addressed they first must be fully understood.

Many companies have suffered from refractory issues in reaction furnaces. The same issues regarding premature refractory failure are repeated time and again all over the world. The impact to the plant may include the following:

- premature and/or frequent maintenance repairs or lining replacements required between or during planned outages
- longer downtimes due to extra refractory work requirements
- extended start-up times or even failures due to dryout issues
- shell breeches and the safety and environmental issues associated with this extreme failure
- loss of production capability of related units during unexpected or extended reaction furnace outages.

In other words, less run time, less reliability, higher costs and, worse, less profit. Many operating companies today are only too aware of these issues but are unaware of how to correct them.

There are reasons the same failures occur repeatedly and there are ways to significantly improve these situations. Refractories are often considered a commodity that anyone can design, supply and/or install; making refractories almost an afterthought.

In actuality, SRU linings are complex structures that require careful consideration. These units operate under some of the most severe service conditions in a refinery and the consequences of getting it wrong up front then brings in the added costs and frustrations of dealing with substandard design, materials of construction, or workmanship for the entire working life of the SRU or until lining improvements are implemented.

Fig 1: **Typical extreme refractory failures**

Under certain conditions, all reaction furnaces are capable of melting any refractory made today. Refractory specialist Thorpe Speciality Services Corporation bases its lining recommendations on an optimised lining approach. Linings must be designed for the real world operating conditions for reaction furnace service which encompasses start-ups and shutdowns, natural gas firing, O_2 enrichment, hydrocarbon slugs, operational errors, thermal excursions or complete unit overheating from poor burner mixing or damaged burner components. It is not a matter of "if" but "when" a thermal event stresses the lining. Every unit should be evaluated for its size, geometry, thermal profiles, etc. in an effort to optimise the lining to better endure these events.

Project considerations

Many of the problems with today's refractory lining systems actually begin in the project phase. With refractory, there are normally numerous contributory issues combining to eventually result in a failure or need for repair, sooner than is necessary.

Project structure

How a project is structured can have a significant impact on how decisions are made and therefore on the final end product and its performance. The refractory specifications are normally established by the licensor early in a project and are used to determine vessel and duct sizing, etc. Unfortunately, due to the extreme variations in size, geometry, and changing operating requirements for these units, such specifications may be inadequate. Getting refractory knowledgeable people involved early in the project is dependent on how the project is structured and is essential in mitigating problems that can further develop. If the project has divided the refractory components (design/supply/installation) between a licensor, mechanical erector(s), various equipment OEMs, vessel fabricators and local installers, the communication path and responsibility trails are often too long to effectively assure optimal lining designs and installations. Too often inappropriate companies are involved in the refractory process.

Problems are typically the result of the project team having limited knowledge of the complexity and importance of the refractory system as they focus primarily on a low cost and schedule. To assure the success and reliability of the lining, Thorpe believes the refractory design, supply and installation should not be fragmented, and the refractory company should be involved at the very beginning of the design phase.

Lack of refractory knowledge

Several factors contribute to the lack of an industry-wide, thorough understanding of the diverse and complex issues associated with sulphur reaction furnaces. It is important to recognise that owners, manufacturers, designers and installers have become more dependent upon improved monolithic (ie. castables, plastics, etc.) refractory lining systems in recent decades. The significant improvement over the last 25 years in monolithic product formulation, installation knowledge and equipment, has contributed to the replacement of many brick applications with monolithic linings throughout the industrial markets. There has been a corresponding loss of understanding of brick systems. This is particularly true in refineries where either monolithic materials or ceramic fibre based products are used in most other units outside the SRU. Since it is generally accepted that brick linings are the best choice for thermal reactors there has arisen a "disconnect", a preferred product form that has experienced a declining user base.

With the loss of brick design and installation skills, it is easy to understand why owners/EPC/licensor/OEMs, for which refractories are only a small component to the entire SRU process, are not aware of the details involved in this critical, specialised part of the unit. Most owners/EPCs/licensors/OEMs do not normally have a true refractory design engineer, familiar with SRU linings, on staff. The lack of proper refractory design knowledge combined with having to compete for projects on a price basis, results in the limited need to consider improved methods. Most refractory specifications focus primarily on the individual materials to be used without sufficient regard for how those materials must be integrated for the specific application to meet performance expectations. It is the systems' performance that is critical, not the individual materials.

Lack of customer feedback

In an attempt to defend the EPC/licensor/OEMs from some of these comments, it should be noted that many are very good, quality conscious companies and individuals operating on the firm belief they are providing the best linings possible. Part of the problem between belief and reality is that most times customers do not give proper feedback to the original project participants. Thorpe has seen numerous occasions where failures occurred well within the warranty period but the plant proceeded to perform repairs without contacting the original responsible parties. This makes for a more economical repair compared to getting the original parties notified, mobilised to inspect, time to evaluate the failure, etc. all before beginning the actual repairs. This results in a continuation of poor designs or processes from project to project by the original suppliers who are unaware they had a problem.

What needs to change?

Higher priority on the refractory process

To optimise lining life and performance it is strongly suggested to think about refractories sooner in the project rather than later. If reliability is important, the refractory linings should be considered as an integrated system requiring careful consideration through all phases of the entire project instead of passing this important function down the project food chain. Ideally the lining design, material supply and installation would be a single source supply and responsibility in order to prevent miscommunications and misunderstandings. As these functions are normally divided and each step bid out independently, it may require restructuring the project and owner education to allow for a single-source evaluation and award. Overall, since these linings should be brick construction, the evaluation process should focus on companies that emphasise and are active in industries and units involving complicated brick construction, but also including active participation in brick design and construction in SRU linings. The demanding nature of these units makes it imperative that awards be based on the knowledge and ability of the refractory company rather than the low dollar proposal or to a "good ol' boy" network system.

Better understanding of reality

The burner systems in reaction furnaces, whether for low temperature gas plant operations or for refinery related units with or without O_2 enrichment, can (and do) melt any refractory made today. Designing for only the theoretical operating range should not be acceptable. Optimising the system to better survive those upset conditions is the only way to get the best reliability and longest refractory life with the lowest life cycle cost.

Demand an engineered system

One of the biggest misconceptions in the marketplace is that if it is on a drawing, then the lining is engineered. If so, one can definitely argue the quality and depth of the engineering on some of the drawings utilized. Many of these should be labelled "bill of material" or "refractory placement" drawings which would be more accurate. Material science does apply to refractories just as it does to the steel components. There are physical material properties that when understood against the operational demands of these systems, can be applied to thermally and mechanically balance the system to optimise the lining performance. An engineered system will address and control many aspects of the system which goes through many changes on its way to a potential of say 1,650°C. Much of the true engineering of a self-supported brick system is performed behind the scene and is not obvious to the untrained person looking at the drawing. To illustrate the point, a few of the concerns that need to be addressed to optimise a lining system are discussed.

Thermal balance of the entire system

While the refractory lining system is designed to protect the steel shell from high temperature corrosion and metal failure, it is the exterior weather shroud (often inappropriately called a rain shield or shroud) that protects the shell from low temperature corrosion. Both systems, in unison, are designed to protect the vessel shell from high and low temperature

Fig 2: **Full thermal protection shroud**

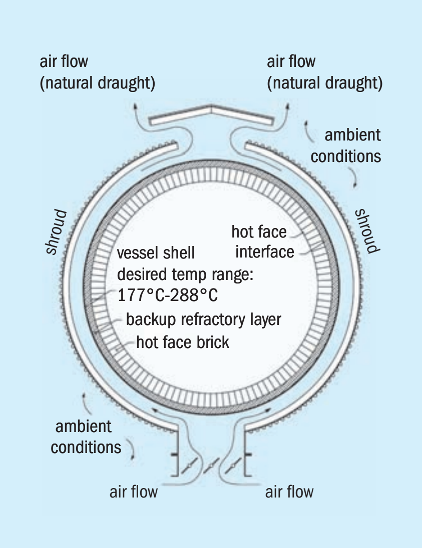
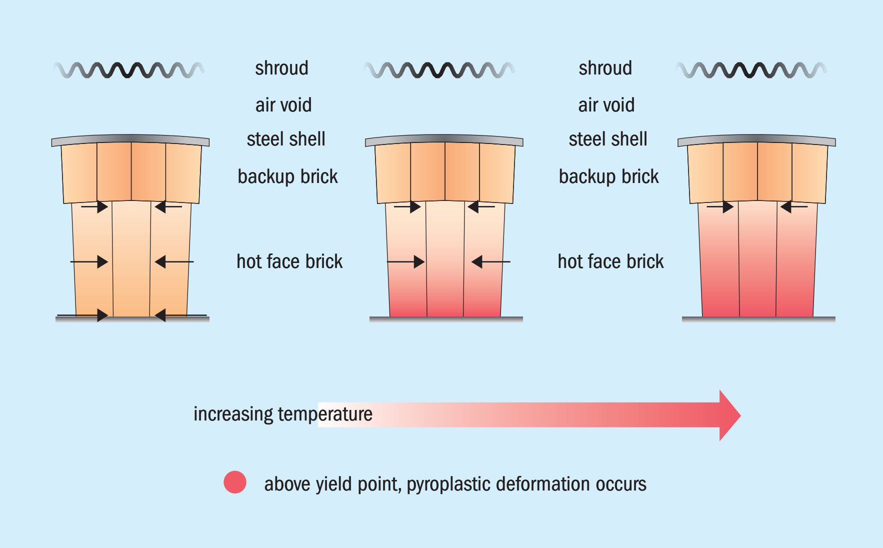


Fig 3: **Design issue for hot face brick**



corrosion. To those unaware, it seems natural to separate these two items (the refractory and the external shroud) in the initial construction. Often the two systems are designed by completely different companies (assuming an external shroud was even used). However, the external shroud can have a significant effect not only on the vessel shell temperature, but also on the thermal profile through the refractory lining. This thermal profile can have a significant effect on the ability of the refractory lining components to perform under the extreme stresses and temperatures to which they are exposed. These systems should be designed by the same engineer familiar with the dynamics of both systems and the interaction between these systems.

Proper lining thickness

Determining the ideal lining thickness to optimise performance is a complicated process. The importance of this step is often overlooked. Often, generalised rules of thumb or a similar sized unit is used from a past job that appears to have been successful and as long as a simple thermal calculation seems to show a proper shell temperature; this process stops. However, lining thickness is a function of many factors, some of which are; vessel diameter, thermal profile through the system, mortar quality and design, brick shape, physical properties of lining materials, etc. Determining proper lining thickness is usually an iterative process as the design engineer balances the effects of the complete thermal system to stresses in the refractory lining and how to control or moderate those effects within the properties of the materials utilised.

Hot load strengths

For unsupported (unanchored) brick linings, consideration of the hot load strength of the refractory products is critical and is the beginning point for designing these systems. Generally the unrestrained thermal expansion of the lining will be approximately three times as much as the vessel shell. When heat is applied, the lining goes into severe compression. If the thermal profile through the lining is excessive, it will plastically deform under the stress resulting in what is referred to as “hot load deformation”. So essentially, hot load deformation occurs when the temperature of the material exceeds the point at which it will be able to resist the compressive stress to which it is subjected. While there can be other contributory issues, the evidence of hot load deformation is seen when units are inspected after a service campaign in the form of open joints overhead, sagging brick, or complete collapse of rings overhead.

Minimising deformation is a critical component of an overall design. Most specifications do not even address these issues or are misdirected by attempting to make references to specific manufacturers’ brand names (or equals) or other physical properties that may have no bearing on the design. One example is specifications for alumina content. The error is assuming that higher alumina content automatically translates into higher hot load strengths. This is sometimes a result of looking at the melting temperature of the individual brick product and not understanding that materials weaken before they melt; i.e., these properties are not directly related to each other. A severe, high temperature, long duration testing regimen clearly shows there are significant differences in these supposedly competitive high alumina bricks and also show, for example, that the highest alumina (99%) bricks are not good for typical usage in reaction furnaces. Field experience has also proven this to be true. Direct testing for the needed properties should be required.

Brick keying action

Due to lining movement as a result of thermal expansion/contraction, it is essential that the individual brick shapes have the necessary “keying action” to keep them from slipping out of position. One must remember that gravity is pulling down on the overhead brick 24/7. If there is not enough keying action or taper on a brick, it will slip out. Should this happen, the entire ring will become unkeyed and the likely result is more brick falling down creating a larger hot spot and typically a shell breech.

Utilising standard brick ring tables will provide a design engineer many options to simply turn a circle, but will not tell them which combinations are best for the application. Choosing the correct brick shapes with the proper amount of keying action requires an experienced designer familiar with the brick shape options, their benefits and disadvantages combined with the need of the specific application.

Fig 4: **Classic examples of high temperature deformation**

Controlling brick movement

Unrestrained, brick will continue to move as the unit is thermally cycled with the end result being large open joints, hot spots or collapse or failure of the immediate area of the lining. On the other hand, an excessive amount of restraint will overstress the lining and the vessel shell resulting in possible damage to both. Controlling brick movement requires knowledge and experience to utilise the correct balance between restraining brick movement by use of the selective brick shapes in the correct places while relieving the expected stresses with properly placed and designed expansion relief.

Summary

Improved reliability and performance is possible for these units, even for full time oxygen enriched, high temperature operations. First one must realise the importance of the refractory linings and then raise and maintain the visibility (the coordination) of all aspects involving refractory. Once this is accomplished, detailed attention should be given at every step of the project, from start to finish, using the following three keys to reliability:

Engineered lining design

Qualifying a designer cannot be based on how old they are or how many drawings they have generated. Careful consideration must be given to:

- familiar with real world operating conditions of the unit
- full understanding of the thermomechanical issues of the lining
- skilled in complicated brick construction techniques
- able to model the complete external/internal thermal systems
- familiar with information critical to the installation crews
- clear understanding of the critical material properties needed for the specific lining design.

Proper material selection

Not only is proper material selection critical, but also long duration high temperature testing to confirm that specific material properties will meet design stress expectations, particularly for the hot face brick materials. Typical ambient QA/QC testing of the other lining materials is normally sufficient.

Experienced installation crews

Not all refractory installers are knowledgeable and skilled at complicated brick construction for SRU reaction furnaces. Careful attention should be paid to the skill level of the installers, the use of appropriate equipment and installation procedures to assure that only experienced crews are involved in the installation of these linings.

A case history

The Suncor Edmonton Refinery situated in the Strathcona County near Edmonton, Alberta, Canada, processes feedstock from the oil sands of northern Alberta. The refinery processes 142,000 bbl/d to produce products including gasoline, diesel and jet fuel.

The sulphur recovery unit (SRU), commissioned in 2008, consists of two identical two-stage air-based Claus trains (305 t/d) joined to a common selective oxidation SUPERCLAUS® stage (406 t/d).

The SRUs have been operated on average at 152 to 203 t/d inlet sulphur feed equivalent, with the reaction furnace normal

Fig 5: **Brick slippage due to insufficient keying action**

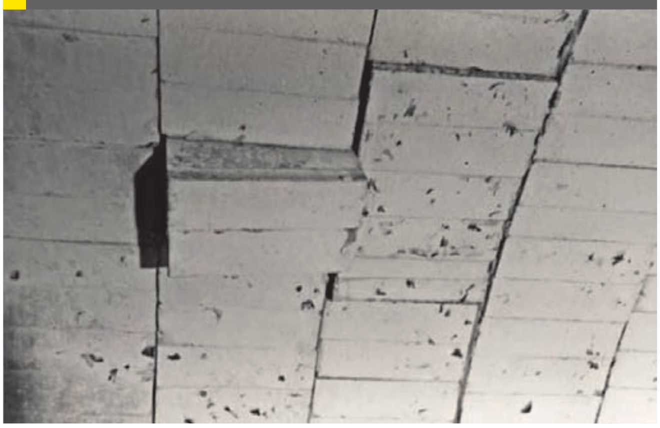
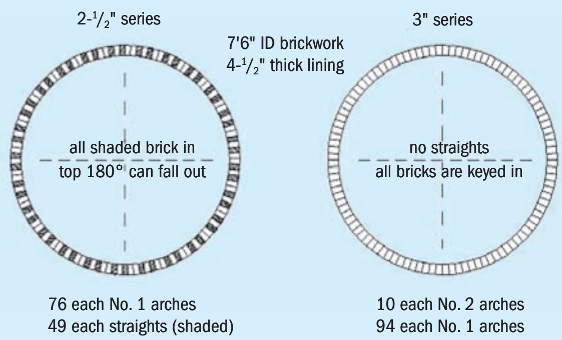


Fig 6: **Sample ring combinations from standard guides**



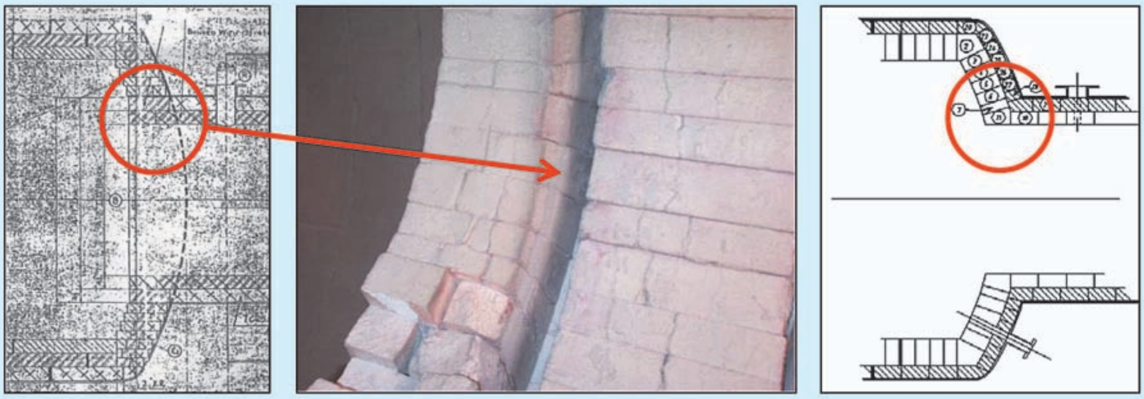


Fig 7: **Controlling brick movement**

Drawing on left illustrates improperly oriented brick on the dished head and the result of unrestrained brick movement on the bullnose ring (center picture). Drawing on right illustrates properly oriented head brick resulting in an anchored bullnose ring with expansion relief designed into the outlet throat.

operating temperature in the 1,288°C to 1,343°C range.

The original installation of the reaction furnace was lined with a hot face castable lining and a backup insulating castable lining. The anchor system for the SRU reaction furnace refractory includes metal clips and tiles. The clips were constructed of cast alloy (25 Cr -12 Ni) ASTM A447.

After a little more than two and a half years of operation the SRU units were shut down for a routine inspection during the 2011 spring turnaround. While not expecting to perform any refractory repairs, it was discovered both units had suffered severe degradation of the refractory linings and required extensive repairs before the plant could safely restart. Due to the extensive damage found in the choke ring, the top half section of the refractory in the furnace was removed, finding that the anchor clips were corroded due to high temperature sulphidation. This type of corrosion was also found on the shell with worse severity in the area around the manway, but without major impact on wall thickness at any location on the shell. The choke ring and top half of both furnaces were replaced in kind to allow time for a complete lining system redesign.

To improve the SRU reliability and safety by reducing the potential for a shell breach due to refractory lining failure, a project was initiated to re-design the reaction furnace linings and to improve the main burner turndown capability and control.

Thorpe was contracted to design, supply material and install the new refractory linings for both SRU 1 and 2 which occurred during the refinery 2013 spring turnaround. The new refractory installation consisted of a two brick layer design to replace the original full castable lining.

Refractory lining failure factors

- **Metallic anchors:** castable refractory linings need to be anchored to the shell for support and are problematic in SRU applications as their integrity is compromised by their exposure to high temperatures and acid gas.
- **Refractory impurities:** bonding systems in high alumina castables inherently have impurities, which at the high temperatures and reducing environment of sulphur plant reaction furnaces can be reduced to components with lower melting points compromising the strength of the lining.
- **Volumetric changes:** mineralogical transformations cause volumetric changes in unfired monolithic refractory forms that are disruptive to refractory integrity.
- **Installation deficiencies:** quality of a castable refractory lining is dependent on field mixing variations and quality of the dry-out process.
- **Rapid rate of temperature change:** operational history showed that rapid temperature changes were present during cold start-ups, hot start-ups, shutdowns and when switching between natural gas and acid gas firing exceeding the recommended maximum rate of 70°C/hour.

Jacobs perspective

Jacobs was awarded the supply of licensor technology and engineering design of the SRUs. They completed the design basis memorandum (DBM) and were then awarded the FEED and detailed engineering phases. Bid packages were developed based upon the Jacobs design which included a two layer brick system and weather shield, but the refinery refractory specifications were added later before bids were solicited. The refinery refractory specifications were general and not specific to SRUs, and were castable based standards; therefore the lining package was changed to castable. Although one bidder did offer a brick option, this was not considered as it was 10% higher in cost. None of the bidders, all considered experts in their field, expressed any concern with the castable design. The detail design of the refractory was performed by the selected vendor. As this was viewed as their specialty, Jacobs and the refinery had little to no input on the final refractory or weathershield details.

Thorpe inspection findings

Thorpe was not involved in the SRU units when originally installed but were called in to perform a refractory inspection in 2011. During and after this inspection, Thorpe found many issues associated with the lining design that is common in industry today. Some of the common errors found across the industry that also appear in the original linings for this project are highlighted below.

Operating design conditions

Believing theoretical operating conditions are appropriate for refractory design is a common error. Reaction furnaces have a long history of operating outside of design conditions for many reasons. Some of these include poor burner mixing (whether due to poor burner design, heat damage or corrosion to burner internals), abnormal feedstream composition, difficulties that arise with natural gas standby, loss of quench steam, startup/shutdown situations and operator error. The lining design should be robust enough to endure most of these upset events. This lining was not optimised for high temperature operation from many perspectives.

Fig 8: **Damaged versus new anchor clips at choke ring**

Anchor clip in service *New anchor clip*

Taking shortcuts

Compromising reliability to reduce cost or accommodate skill level of refractory installers is another common error. Due to the high cost of the refractory materials needed for these units and the labor intensive demands of their installations, these shortcuts knowingly or unknowingly, can lead to significantly lower costs but result in poor reliability. Some of these shortcuts may include decreasing lining thickness, use of inappropriate refractory product forms (monolithic, brick, etc.), use of supposedly "equal" material that is not actually "equal" for this service, differences in installation techniques, etc.

Also contributory to some of these issues is an overall change in the marketplace. For many less severe applications industry wide, older brick systems have been converted to the use of monolithics for their lining systems (plastic, castable, etc.). This is due to significant improvements in the last 25 years to the materials, installation techniques and equipment and attention by inspectors for those applications. The result for any unit requiring complicated brick systems for reliability (such as reaction furnaces) is that many engineers/contractors have lost the skill sets to properly design/install complicated brick linings such as these and revert to utilising what they know; monolithics.

Lining system

Reaction furnaces operate at high temperatures in a severely reducing atmosphere with other gases involved (hydrogen, sulphur, etc.) that can and do affect the refractory material properties and contribute to premature lining failures. While monolithic materials can perform adequately for a length of time in these units at lower temperatures, they suffer many disadvantages when compared to properly designed self-supported brick systems. Thus, regardless of the stated maximum service limit of the individual materials utilised, the lining system was highly compromised in this application. In this case, a properly optimised system would have allowed hundreds of degrees increase in operating temperature range.

External thermal protection system

Many in the industry today still consider this to be a simple "rain shroud", but it is so much more. The shroud effectively "moderates" ambient weather events that would otherwise affect vessel shell temperatures. Maintaining proper thermal control of the vessel shell can prove impossible without a full and properly designed shroud and an understanding of all of the factors involved in this system. This is especially true in colder climates such as Canada. Adding to the problem is the fact that the shroud is normally designed and supplied completely independent of the refractory system. In Suncor's case, corrosion was found on the vessel shell due to a combination of issues with the refractory lining and the external thermal protection system. This higher shell temperature can also affect the performance of the refractory lining by de-rating the effective service limit of the lining system.

Lessons learned

Specialised refractory knowledge and experience

The refractory lining must be treated as an engineered specialty item with a high level of attention.

A qualified refractory design engineer/company specializing in SRU linings should be selected. Normal in-plant refractory contractors typically do not have the skills to be considered for this function.

The refractory design engineer/company should be engaged no later than the FEED stage.

Main burner turndown and operability

Should be capable of achieving startup/shutdown ramp rates of 100°F/hour to avoid adversely affecting the refractory system yet not damaging the burner metallurgy in doing so.

Refractory standards and specifications

Currently there are no industry accepted design specifications for SRU refractory linings. A knowledgeable design engineer/company is critical to long term success.

Applying a general refractory standard not specific to SRUs can lead to a false sense of security and result in inadequate lining installations.

Operational experience feedback

It is important that the owner notify the original parties involved of problems during operation to so they can learn and improve their services to avoid repeating inadequate designs.

Project team comments

Bid packages containing design points (lining thicknesses, materials, etc.) limit the liability of those quoting those linings. Many bidders knowingly, or unknowingly, use these guidelines to provide a proposal matching what was asked for and to limit their own liability. This does not typically lead to notifications of concern by the bidder to the owner as this is also an acceptance of responsibility if corrected. Good or bad, the project team gets the lining they request.

It is crucial that a line of communication be established early in the project with the key stakeholders on the project team (including licensor) to enable review and then acceptance or rejection of any proposed furnace refractory design changes (mechanical, material, thickness, etc.) before proceeding further. ■

Acknowledgement

This article is a condensed version of the Brimstone Sulfur Symposium papers "Understanding today's limiting factors on reaction furnace linings by A. Piper and J. Proctor of Thorpe Specialty Services Corporation, presented in Vienna in May 2013; and "Limiting factors on reaction furnace linings part 2 – A case history", by D. Koscielnuk and M. van Son of Jacobs Comprimo, M. Young and S. Maldonado of Suncor Energy Inc. and A. Piper and J. Proctor of Thorpe Specialty Services Corporation, presented at Vail in September 2014.