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CRU Nitrogen + Syngas 2016

29th International Conference & Exhibition

Improving Down-fired Steam Methane Reforming Flue Gas Flow Uniformity Using the New StaBlox™ Reformer Tunnel System

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For decades, down-fired steam methane reformer furnaces have utilized flue gas tunnels (aka “coffins”) along the radiant section floor to collect and improve flue gas flow uniformity. These tunnels range from 4 to 10 feet high, 2 to 3 feet wide, and 40 to 100 feet long, depending on the unit design capacity. However, the conventional refractory firebrick or tongue-and-groove firebrick construction has always constrained the flue gas to non-uniform flow which has been correlated to non-uniform catalyst-tube temperatures and accelerated tube aging. Due to tunnel size and refractory volume, traditional brick design uses only basic shapes. Typical brick and mortar installations require several physical features which severely limit tunnel effectiveness, making uniform flue gas flow unachievable. The ability to design and construct tunnels using new highly-engineered refractory shapes is new to this industry and could be the answer to improving flue gas tunnel effectiveness and improving catalyst tube reliability and longevity.

BD Energy Systems and Blasch Precision Ceramics have co-developed an improved reformer tunnel system to achieve near-perfect flue gas flow uniformity among and along the tunnels. This system combines BD Energy's vast steam methane reforming experience and Blasch's customized-precision-refractory-shapes design and manufacturing expertise. The result is unparalleled flue gas flow control using the Blasch StaBlox™ reformer tunnel system.

Because of this new ability to fine-tune flue gas flow, these tunnels can be adapted to other applications and can open the door to previously unexplored SMR process possibilities. This paper compares conventional tunnel construction and design to the BD Energy Systems/Blasch Precision Ceramics construction and design, focusing on the benefits of improved flue gas flow uniformity and potential catalyst tube reliability improvements.

INTRODUCTION

Catalyst Tube Failure

Top-fired reformer arch burners heat catalyst-filled tubes for steam methane reforming. The catalyst tubes are heated by both radiation and convection from the flue gas (exhaust), which flows downward through the radiant box. Catalyst tubes typically are designed for a service life of 100,000 hours. In reality, however, tube longevity varies. Some tubes remain in service for 20 years, while others age much more rapidly, failing far ahead of schedule. Typically, reformers develop regions where tubes degrade more quickly, seemingly without cause.

Catalyst tube inspection reports indicate that excessively high catalyst tube temperatures are correlated positively to accelerated catalyst tube aging and premature tube failure. Even when the average tube temperature is within design limits, non-uniform flue gas velocities cause some tubes to be heated more than others. Higher than average tube temperatures have been correlated to radiant box regions with greater than average flue gas velocities.

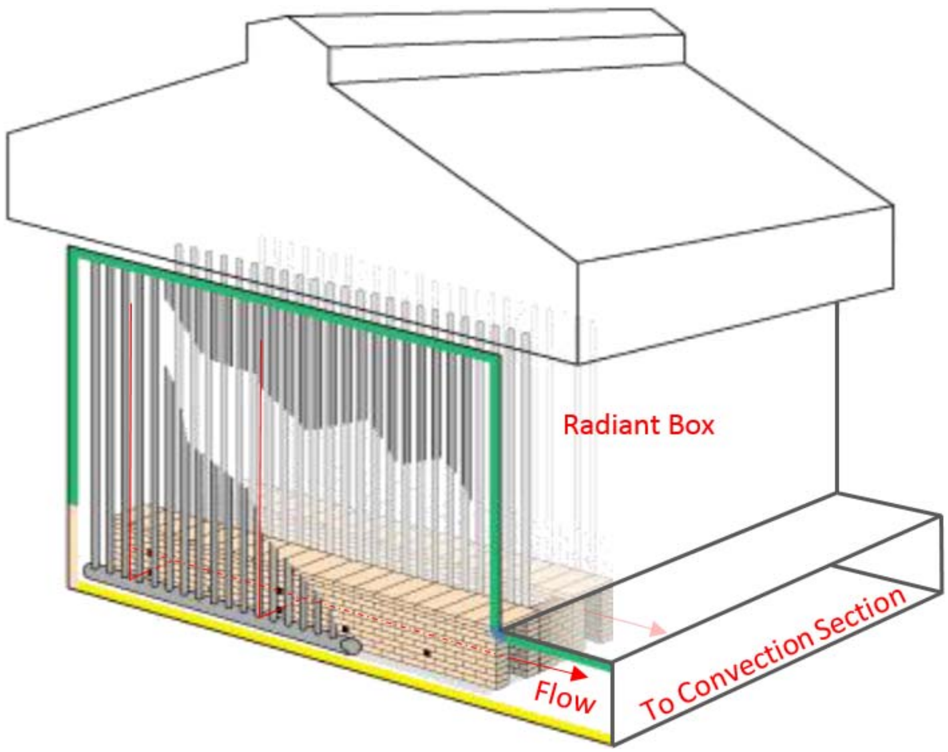

Figure 1 - Radiant Box Flue Gas Flow

Flue Gas Flow

Hot flue gas flows from the arch burners into tunnels on the floor directly below each burner row. Flue gas enters the tunnel through tunnel wall openings distributed along the tunnel length and exits the open end of the tunnel to the Convection Section for additional heat recovery (Figure 1). Ideally, radiant box flue gas flows vertically downward with uniform velocity throughout the box to achieve uniform catalyst tube heating and tube temperature and also to improve flame patterns. Consequently, the ideal total flow into each tunnel is proportional to the firing rate of their respective burner rows and the ideal flue gas flow rate into each tunnel is uniform along the length of that tunnel.

Typically, burner outer-row firing is lower than inner-row firing because the outer row of burners must heat only one row of tubes, whereas inner rows heat tubes on either side of these burner rows. As a result, outer-row burners produce less flue gas than inner-row burners (Figure 2). Therefore, proportionally less flue gas must be transported by the outer tunnels than by the inner tunnels. For example, if an outer burner row were designed to fire at 65% of the rate of an inner burner row, then the ideal outer tunnel flue gas load would be 65% of that of an inner tunnel. The ideal flow ratio between outer and inner tunnels is achieved by designing the outer tunnels with less tunnel-wall open-area and a smaller cross-section compared to inner tunnels.

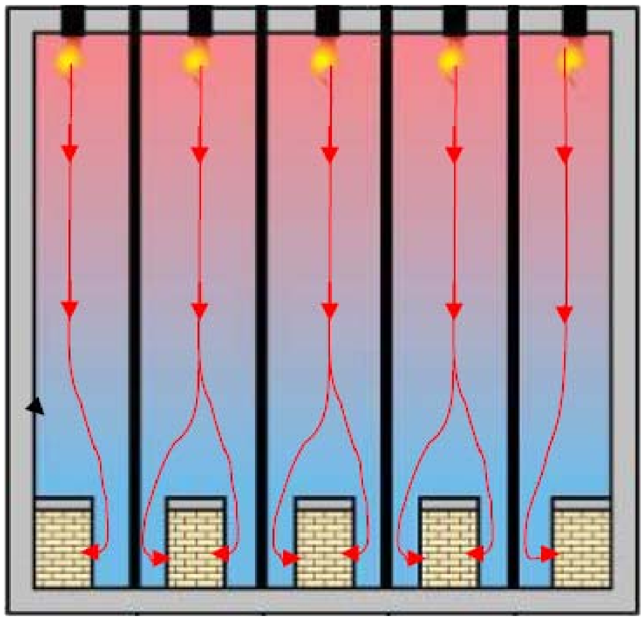

Figure 2 - Flue gas Flow into Radiant Box Tunnels

Uniform flow into a tunnel along the length of the tunnel requires less open area near the tunnel open end than near the tunnel closed end (Figure 3). Flue gas is drawn into the tunnel wall opening by the differential static pressure across the wall which is proportional to the fluegas velocity inside the tunnel. Near the tunnel closed end where the in-tunnel flue gas velocity is very low (e.g., 0 ft/s) the differential static pressure also is low, so more open area is required to draw in flue gas. Toward the tunnel open end, where the in-tunnel flue gas flowrate and velocity is high, the differential static pressure also is high, so less open area is required to draw in flue gas. Ideal tunnel wall open area decreases gradually from the tunnel closed end to the tunnel open end. Due to certain physical constraints (see below), ideal open-area distribution is not achievable for the conventional tunnel system design.

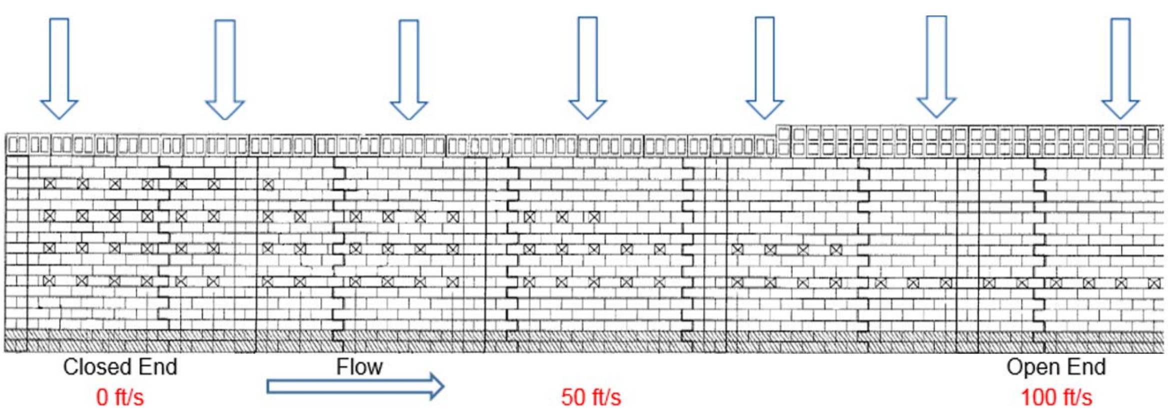

Figure 3 - Ideal In-Tunnel Flue Gas Velocity

CONVENTIONAL TUNNEL SYSTEM

Physical Characteristics

Conventional brick and mortar tunnels are typically 4 to 10 ft high, 2 to 3 ft wide, and 40 to 100 ft long. Nominal brick dimensions are 9 in x 3 in x 6 in (L x H x W). Buttresses extend from the outer wall surface for support. Discrete expansion gaps ('expansion joints') are intended to accommodate thermal expansion to avoid wall distortion ('snaking'). Tunnel-wall openings are created by removing ½ bricks (4½ in x 3 in) from the tunnel wall. Columns of openings are arranged at least 1½ to 2 brick lengths apart (center-to-center) and are distributed along the length of the tunnel to control flue gas flow into the tunnel (Figure 4). These brick tunnels historically have been a significant source of reliability concerns and tunnel section failure – even full tunnel collapse – is common. The causes of these failures can be classified into three main sources: Mass, Material Selection, and Expansion Management.

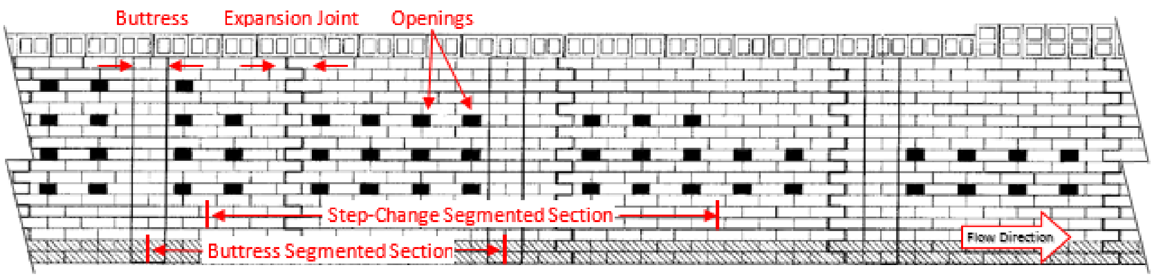

Figure 4 - Conventional Tunnel Wall Sketch

Mass

Mass is an important thermal load factor, but thermal load failures often are perceived incorrectly as static load failures. For example, after lids are broken or collapsed (Figure 5) it may be believed that a middle-of-the-lid crack is correlated to the ratio of component span to material thickness. After the replacement lid thickness is increased, however, the result is an even worse failure than before. This is because the lid failure is not a result of static load. Rather, the component stress build-up is caused by excess component mass.

Figure 5 - Lid Failure

Hand calculations coupled with computer simulation clearly prove that the static load alone imparts very little stress on the lids and will not result in failure. Consider, for example, a tunnel lid measuring 9 inches wide, 9 inches tall, and 42 inches long analyzed at a 1900˚F constant service temperature with no external forces acting upon it except its own weight (Figure 6). The result is a 10 psi maximum stress. Most of the engineered refractory material suppliers characterize the Hot Modulus of Rupture (HMOR) of their products and supply a lid material option having a sufficiently high HMOR safety factor for the static loads. Based on the Finite Element Analysis (FEA) results comparison to the published HMOR it can be concluded that most lid failures are not a result of static load alone and therefore must be the result of thermal state stresses.

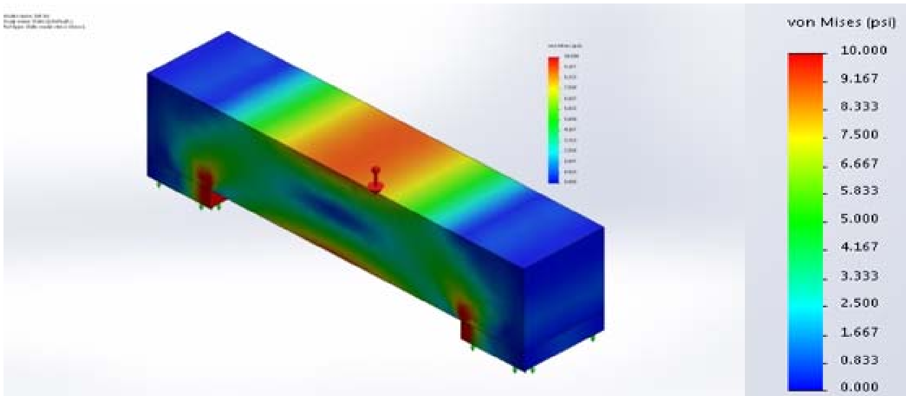

Figure 6 - FEA of Tunnel Lid at Constant 1900F

The component also can fail as a result of thermal stress. Thermal stress is not limited to instances of large upsets, but occurs during normal operation as a result of any differential temperature. Thermal stress failure results when the thermal expansion from one area of a component differs from that of another area, resulting in a stress greater than the material yield strength. If the radiant section temperature differs from the temperature inside the tunnels, even for a short period of time, thermal stress potentially is present. Consider an identical lid, for example, installed on a tunnel as before, but this time with the lid upper surface temperature increased to 1910˚F (Figure 7).

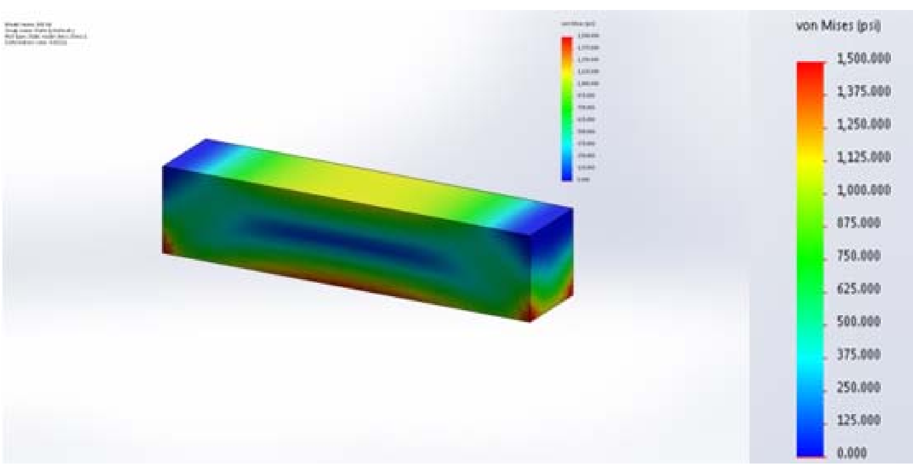

Figure 7 - FEA of Tunnel Lid at Variable Temperature between 900F and 1910F

The lid has no external forces acting upon it other than its own weight. A differential temperature of 10˚F across the lid results in a 1500 psi max stress, which is well above the HMOR of many refractory materials. In a situation where a great percentage of tunnel lids fail during the same operation period without a wall collapse, thermal stress is the most likely failure mode (Figure 8).

Figure 8 - Tunnel Lid Thermal Stress Failure Mode

Excess mass in these tunnels not only causes individual component thermal stress, but also may affect the entire reformer radiant section. Flue gas tunnel construction uses hundreds of thousands of pounds of refractory. All of this mass rests on a base layer of insulating refractory. A tunnel cross section with 6 inch wide bricks, 96 inch high tunnel walls, and a solid 9 inch thick lid represents an 11.6 psi load on the supporting insulating refractory layer. Published data using ASTM testing suggests that at these reformer furnace temperatures the insulating refractory layer will deform a full 1% under those loads in 100 hours. The insulating refractory layer deformation will translate in two ways: the deformation will result in an unstable wall, and will reduce the overall insulating value. Either of these can result in tunnel failure (Figure 9).

Figure 9 - Tunnel Failure

The effects of temperature and tunnel mass are not limited to the furnace internals, but can cause supporting furnace structure deformation, leading to a non-uniform furnace floor. Conventional tunnel design utilizes a mortared joint, effectively turning the large number of small bricks into a small number of large wall sections. These wall sections move as a single body and cannot accommodate any major dimensional change in the furnace floor, meaning that a supporting furnace structure deformation will result in tunnel collapse.

Material Selection

In order to address this thermal stress build-up, sufficiently strong material selection is essential. Two primary material properties, Creep Resistance and the HMOR, are very important. Creep occurs when a material slowly but permanently deforms under long term high stress exposure below the material yield strength. For refractory material, this commonly is referred to as Refractoriness Under Load (RUL). This property comes into play in two distinct areas: first in the lids, and second on the unsupported brick sections that span the wall openings. These unsupported sections will inevitably sag over time and as they do, stress concentrates and causes the parts to crack (Figure 10).

Figure 10 - Unsupported Brick Failure

Lid deformation has a secondary effect on the tunnel walls. The lids are designed to transfer all their weight in the vertical direction, which compliments the strength and structure of the wall. In a lid, creep will result in center span "sagging" and will change the interaction force between the lid and the tunnel walls, which eventually will lead to failure as this non-vertical force pushes apart the tunnel walls (Figure 9). Creep can be characterized with ASTM standard testing, which is representative of the use of a tunnel lid in service and is an important material selection component. ASTM tests on Super Duty Brick have published results of a 7.86% deflection at 2,600ºF.

HMOR also is an important material property. It is critical to note that knowing only the MOR at room temperature is not sufficient for proper tunnel system design. As refractories are exposed to high temperatures they begin to lose strength over time. This non-linear process will diminish over time. ASTM tests expose components to 2500ºF environments for 100 hours and then measure the MOR. The test result is called the HMOR because it indicates material strength at elevated temperatures. To put this in perspective, ASTM tests on Super Duty Brick have published results of 1100 to 1500 psi MOR, but this decreases to a HMOR of approximately 600 psi at 2,500ºF. Proper material selection should include confirmation that the modulus of rupture at the furnace service and excursion temperatures has a sufficient safety factor compared to the associated static load stresses.

Expansion Management

One of the most important design aspects of flue gas tunnels is thermal expansion accommodation. A conventional tunnel design includes expansion gaps, at approximately 6 to 10 foot tunnel length spacing. Refractory mortar is used to bond all between-gap components into a single wall section which behaves as a single body. Unfortunately, furnace temperature distribution is not uniform and differential thermal expansion occurs across a given wall section. The wall section stresses are the same as those that cause thermal shock within a singular body.

To illustrate the differential temperature stress levels, from the top to the bottom of a fully mortared wall section, consider a 10 foot fully mortared wall section, which can be treated as a single body for the purposes of this analysis. Apply 1925˚F and 1900˚F temperatures to the top and bottom of the wall segment, respectively, with a uniform temperature distribution in between. The analysis should also include simulated gravity and tunnel lid weight, with no other external forces (Figure 11). Under these conditions, the system stresses exceed the 500 psi standard refractory mortar HMOR. Because the mortar joints are the weakest wall points, they will crack to alleviate the stress. As more cracking occurs, the mortared wall sections become smaller, and stresses become lower for any one section.

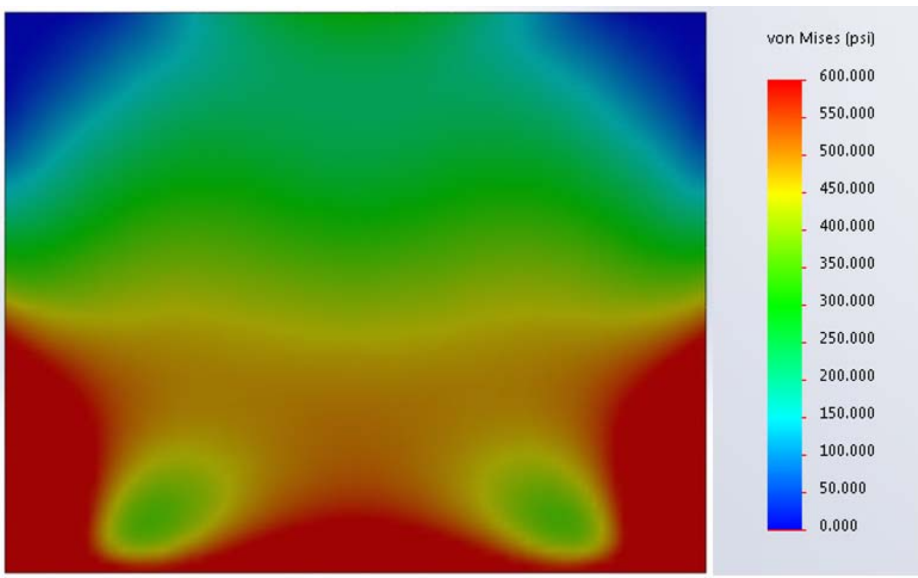

Figure 11 – FEA Results for a Fully Mortared 10' Tunnel Wall Section with Variable Temperature

Properly accommodating thermal expansion is, perhaps, the most difficult thermal application design aspect. Conventional tunnel lids and bases have differing material and design. Many tunnels are designed with low density insulating refractory or fiber board insulation in the "base" area of the tunnels. The tunnel lid can expand by as much as $^{3}/_{8}$ inch pushing apart the tunnel walls, whereas the base insulation will not impart any expansion forces on the tunnel walls. The resulting non-vertical force increases the likelihood of wall buckling and collapse.

During turnarounds, tunnel wall inspection has in some cases shown an alternating lateral movement. This more commonly is known as "snaking" and is the result of the overall tunnel attempting to expand more than the built in allowance. This movement will crack the mortar, separate walls from lids, and can separate walls from bases, all of which can lead to failure. Proper material selection and installation procedures are important to prevent "snaking." Many materials will increase in size when re-heated, increasing variability and making thermal expansion management more difficult. Because the Coefficient of Thermal Expansion (CTE) for refractory components is nonlinear, it fully must be characterized and understood to ensure that proper expansion joints are created.

Design Technique

Open-Area Distribution Design

To distribute open area along the tunnel-wall length, the tunnel is segmented into discrete lengths and the average ideal open area for each length segment is calculated. Open area then is distributed to approximate the calculated ideal distribution. Conventional tunnel lengths are segmented evenly into approximately 4 sections. Alternatively, they may be segmented at the buttresses or at the open-area step changes (Figure 12). Conventional open area is added in nominal 13½ in^2 increments (4 ½ in x 3 in) and for structural reasons cannot be located at buttresses or at expansion joints. To compensate for the lack of open area at buttresses and expansion joints, open area is increased elsewhere in the wall section. The result is non-uniform flow.

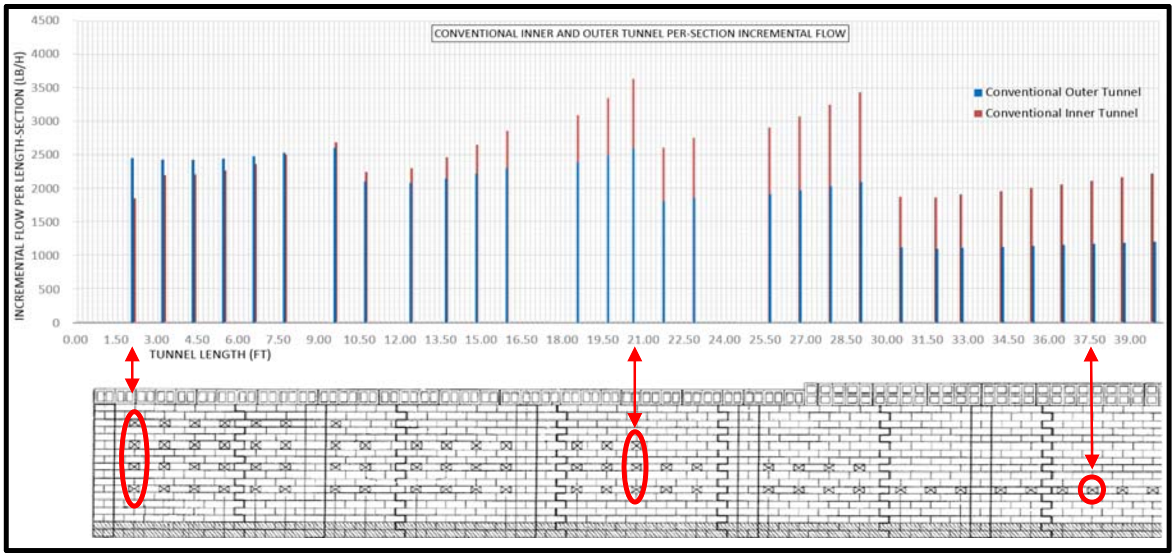

Figure 12 – Incremental Flow per Open-Area Column for Convention Inner and Outer Tunnels

Evaluation of Conventional Design

A conventional 40 ft. long tunnel system is evaluated below (Figure 12). Calculated total flow through each outer-tunnel is approximately 77% of the inner-tunnel flow, but this ratio is not constant along the tunnel length. For example, at each open-area column, the ratio of one outer-tunnel flow to one inner-tunnel flow (the 'flow ratio') is calculated. The resulting average flow ratio is 77.4% +/- 55.1%, with a standard deviation of 21.3%. Additionally, the 'high-flow' columns tend to be grouped together. For the 6 columns closest to the closed end, for example, the average outer-tunnel incremental flow is 110% that of the inner tunnels. For the 6 columns closest to the open end, however, the average outer-tunnel incremental flow is 56% that of the inner tunnels.

Also, incremental flow is non-uniform along the length of each inner or outer tunnel. Following any open-area step change, the incremental flow increases with each successive open-area column (Figure 12). As in-tunnel velocity increases along the tunnel length, incremental flow through each successive column increases until an open-area-per-column step-change reduces the open area and, consequently, the incremental flow. After the step change, incremental flow increases, again. The areas near buttresses and/or expansion joints are 'no flow' regions.

Therefore, at the tunnel closed end (Figure 12), some flue gas generated above the inner tunnels moves laterally toward the outer tunnels and toward the radiant-box center. At the tunnel open end, however, some flue gas generated above the outer tunnels moves laterally toward the inner tunnels and toward the middle of the outer tunnel. Half-way between the tunnel ends, flue gas generated above the outer tunnels moves toward the radiant-box center.

STABLOXTM INTERLOCKING TUNNEL SYSTEM

Physical Characteristics

The StaBloxTM system utilizes 5 core tunnel construction components. The construction begins with a base component that spans the bottom of the tunnel and mates to the side wall blocks. The side wall blocks are 18 inches long by 9 inches high and each block contains two 4 ½ in diameter openings. An orifice insert with an engineered inside diameter is installed in each opening (Figure 13). In addition to orifice inserts, these openings can hold ancillary parts such as tie-rods which connect the two tunnel walls and replace buttresses as a support structure.

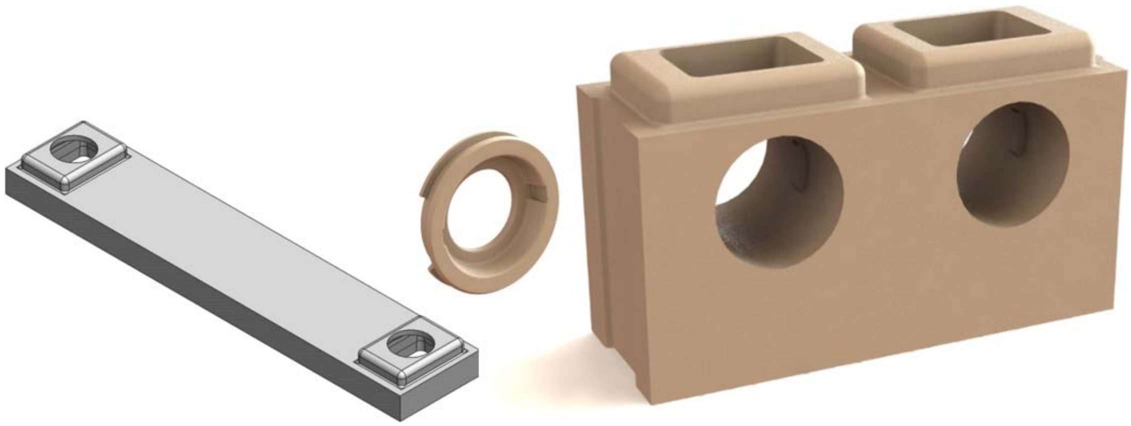

Figure 13 – StaBloxTM Base, Insert, and Block Components

These tie-rods easily can be removed and replaced during outages to allow easy access down the tunnel interior for inspection or repairs (Figure 14). At the top of the tunnel is a light weight lid that (Figure 15) mates to the side walls (Figure 14). In order to allow for a completely mortar-free construction, the lids also employ a shiplap joint to prevent any gas bypass through the tunnel lids. Every component of this system is designed to accommodate its own thermal expansion. In order to eliminate any gas bypass through the expansion joints a fiber gasketing system is employed.

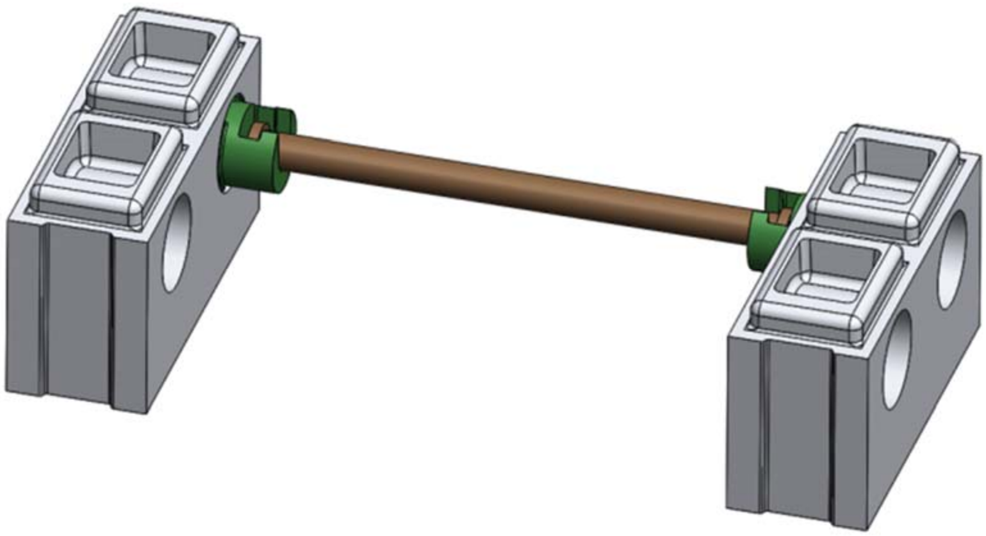

Figure 14 – Support Tie Rod

Mass

Temperature differential stresses across a body can result in thermal shock failure. The most direct way to reduce the thermal stresses to below the refractory component yield strength is to decrease the refractory component wall thickness (Figure 15) to allow the wall temperature to equilibrate more quickly and eliminate temperature differential stresses. The wall thickness should be as thin as possible without sacrificing the overall stability of the tunnel system. Because the tunnel system is self-supporting, component wall-thickness reduction decreases the overall system weight. With the StaBlox™ design, tunnel system weight can be reduced by up to 60%.

Figure 15 – Thin Walled Lid (Underside)

This weight reduction provides added benefits when selecting a suitable base insulating material. The bricks that have insulating value sufficient to keep the furnace supports from deforming are too weak to support the tunnel system, while the bricks with the higher strengths conduct too much heat. As mentioned before, a conventional tunnel cross section with 6 inch wide bricks, 96 inch high tunnel walls, and 9 inch thick solid lids, will result in an 11.6 psi load on the supporting refractory layer and a 1% deformation within the first 100 hours of use.

Decreasing the overall weight of the tunnel system by 60% will translate into a lower PSI load, and result in a deformation to the supporting refractory layer one order of magnitude less. The tunnel system design also can utilize a "base" component that distributes the wall load over an area 5 times larger than the conventional design. A light weight design coupled with a larger base component can result in a 1.4 psi load on the insulating material. This makes possible the use of highly insulating materials which would improve structural furnace support reliability and, therefore, improve overall system reliability.

Material Selection

Selected materials for tunnel system components should have the highest creep resistance reasonably available, because a reduced creep will prolong tunnel system life and prevent premature failures. ASTM tests on Super Duty Brick have published results of a 7.86% deflection at 2,600ºF. An ideal candidate to replace Super Duty Brick is Mullite bonded Alumina refractory material, which has published results of 1.11% deflection at 3,000ºF.

In addition to creep resistance, a high HMOR also is critical for these tunnels. Comparing the same mullite bonded alumina to super duty fire brick results in a similar difference in material strength properties (Figure 16). Super duty brick has a <600 psi HMOR, high grade castable can have up to an almost 500 psi HMOR, and mullite bonded alumina has a 1700 psi HMOR. A fully characterized CTE, higher HMOR, and increased creep resistance will improve the overall tunnel system reliability.

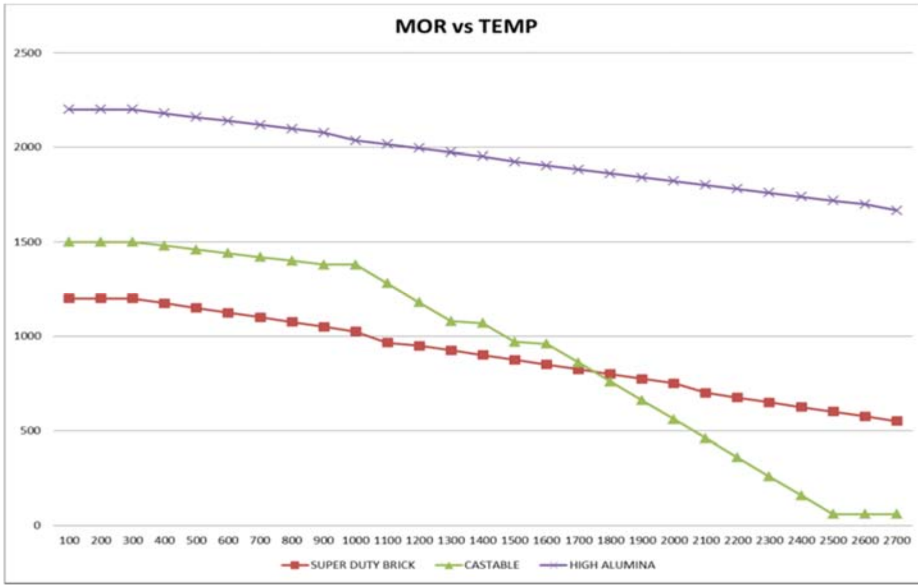

Figure 16 – HMOR Comparison of Super Duty Brick, Castable, and Mullite Bonded Alumina

Expansion Management

Reducing the component wall thicknesses is just one way to relieve thermal stress; it is also possible to reduce the tunnel system 'section' sizes to minimize single section differential temperatures. Ideally, the tunnel system sections should be only as large as the individual building components. In order for this to be accomplished every block must accommodate its own thermal expansion and the entire system must be mortar free, but for stability reasons, must be completely interconnected. With thin walled parts it is feasible to increase wall component size. An ideal size for these parts is 18 inches long and 9 inches tall. An analysis of a 10 foot wall section composed of these blocks (Figure 17), under operating conditions and external forces identical to what was analyzed previously (Figure 11), results in a peak stress of less than 65 psi.

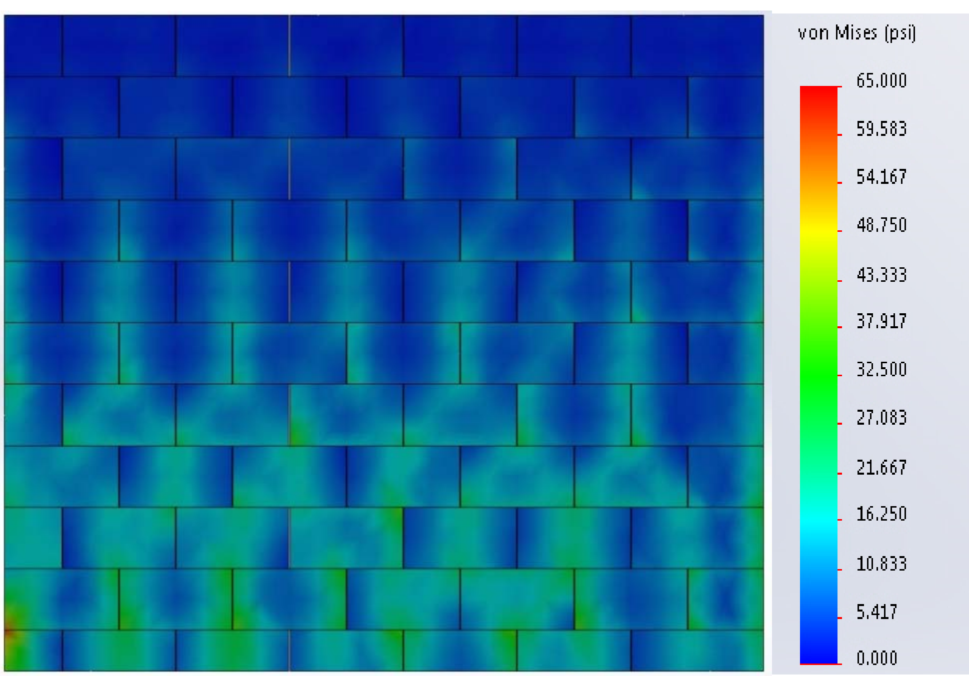

Figure 17 – FEA of a Non-Mortared 10' Tunnel Wall Section with Variable Temperature

This distributed expansion requires precision formed refractory components or an installation procedure that measures and accommodates the variability in every single component. The CTE is very important to analysis of uniformly distributed expansion allowances. For the tunnel system materials, this value should not be assumed to be a linear function. A fully characterized CTE is important to ensuring properly managed expansion and is critical for single component expansion management. Proper thermal expansion management also requires a "base" component of the same material and having dimensions similar to the "lid" component. This ensures that the tunnel expands and contracts uniformly on both the top and bottom of the wall, maintaining the overall structure and reducing stresses that may cause buckling.

Even if the thermal expansion is properly managed, buckling still may occur as a result of delayed ignition or a non-uniform furnace floor. Additional cross beam supports at predetermined locations are recommended to arrest any buckling (Figure 18). These supports replace the buttresses used in conventional tunnels and reinforce the tunnel structure by reducing the unsupported tunnel length per Euler's column equation:

$$\boldsymbol{F = \frac{\pi^2 EI}{(KL)^2}}$$

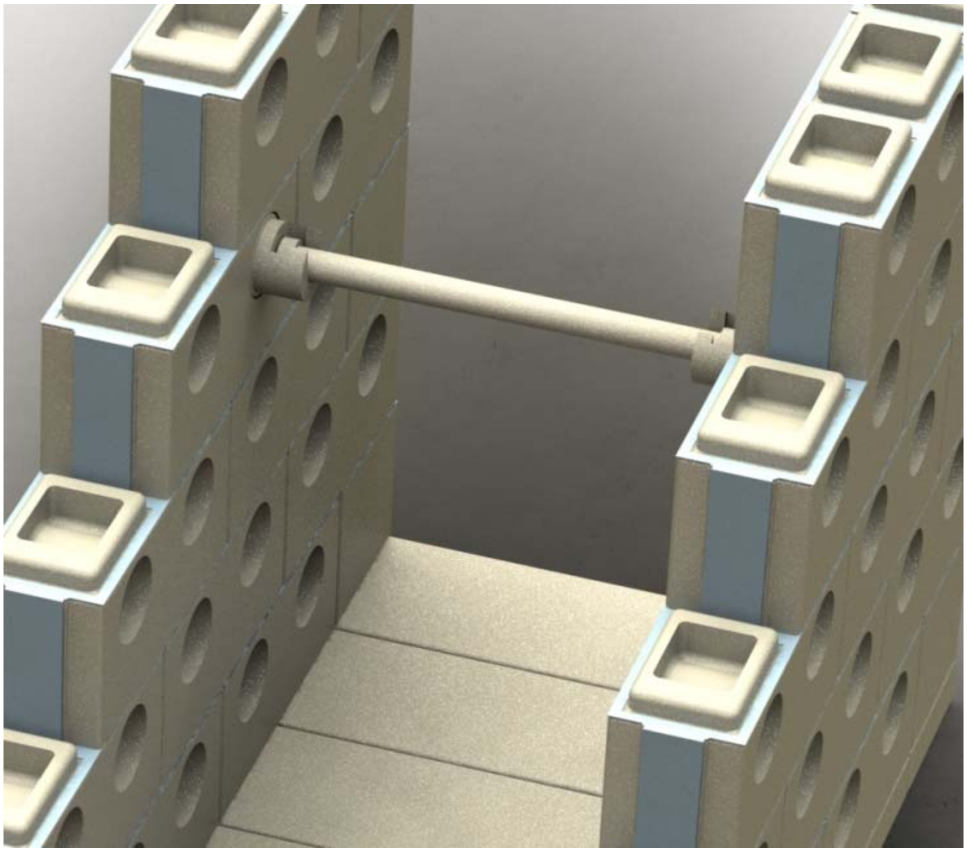

Figure 18 - Tunnel System with Support Tie Rod

Buckling also can be arrested using a tight tolerance mating feature in the wall components such that the rotation of a block in relation to the block below it results in direct contact. In order to dislodge this tight tolerance mating, an amount of stress sufficient to break the block wall is required. By contrast, a traditional tongue and groove design with a circular cross section will be effective in preventing lateral movement, but will not arrest buckling because the rotation of a block in relation to the block below it will separate the tongue from the groove, allowing a full system collapse.

Design Technique

Open-Area Distribution Design

The StaBlox™ design method is to segment the tunnel length into ½ block (i.e., 9 inch) sections, one column of openings per section. For example, a 75 ft tunnel-wall length is segmented into 100 sections with openings in every course (row). Open area is distributed along the tunnel length by specifying the orifice-insert internal-diameter for each opening, rather than by specifying the per-section opening quantity (Figure 19).

Figure 19 – StaBlox™ Interlocking Blocks with Varied Orifice Insert Diameters

Evaluation of StaBlox™ Design

The Figure 12 conventional tunnel system is redesigned using Blasch technology (Figure 20). The goal is to achieve 65% flow through each outer tunnel compared to the flow through each inner tunnel and to achieve near uniform incremental flow along each tunnel length. The inner and outer walls are segmented into 9 inch sections, one opening-column per section. Buttresses are not included and expansion gaps are evenly distributed among the blocks. Required open area per column is calculated and appropriate orifice insert diameters are selected for each opening. For illustration purposes, each orifice size is illustrated with a unique color.

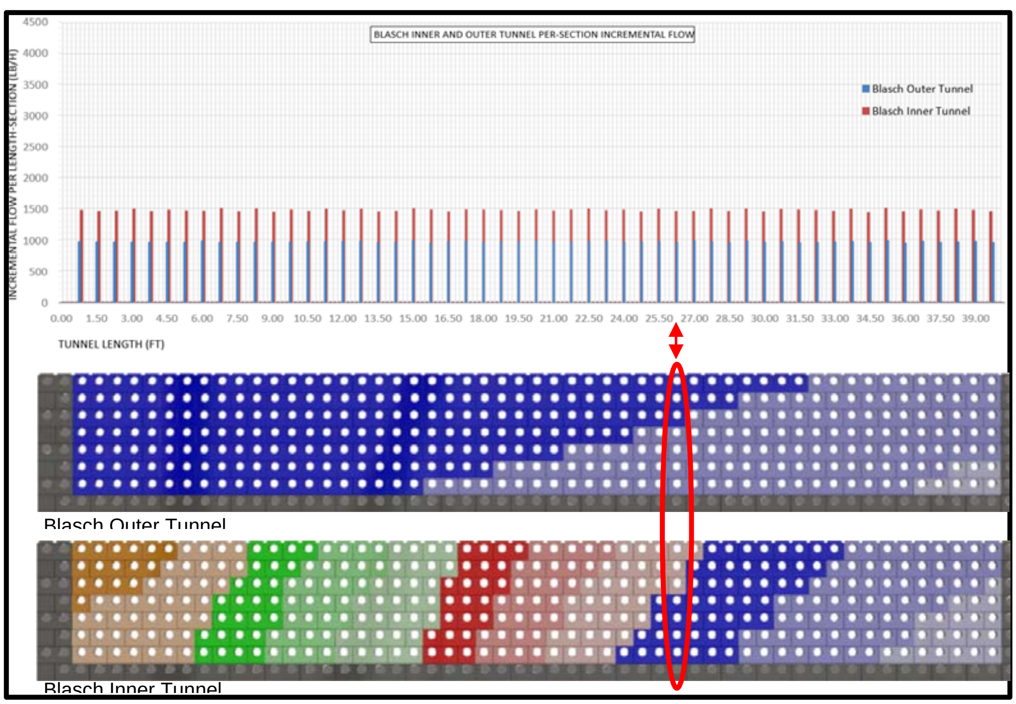

Figure 20 – Blasch Tunnel Evaluation

For each column, more than one orifice size may be specified, so the average orifice diameter per column gradually decreases closer to the tunnel open end. The outer tunnel requires very little orifice diameter change compared to the inner tunnel because the outer tunnel closed end flue gas velocity is very low. So, the outer-tunnel closed end acts somewhat like a manifold, whereas the inner-tunnel closed end develops high-velocity flow almost immediately. To be conservative, the minimum orifice-size step-change is arbitrarily specified well above manufacturing limitations. More finely tuned diameters are feasible.

Calculated total flow through each outer-tunnel is approximately 65.64% of per-inner-tunnel flow, and this ratio is approximately constant along the tunnel length. At each open-area column, for example, the ratio of one outer-tunnel flow to one inner-tunnel flow (the 'flow ratio') is calculated. The resulting average flow ratio is 65.64% +/- 1.8%, with a standard deviation of 0.7%. Also, neither high-flow nor low-flow regions are grouped together. For the 6 columns closest to the closed end, for example, the average outer-tunnel incremental flow is 65.62% that of the inner tunnels. For the 6 columns closest to the open end, the average outer-tunnel incremental flow is 65.60% that of the inner tunnels.

Additional Advantages

Reduced Pressure Drop

Because StaBlox™ tunnels do not require buttresses, the tunnel-wall footprint is narrower – typically half the conventional width. For example, a conventional tunnel wall, nominally 6 inch wide, may require buttresses that extend an additional 6 inches, a 12 inch combined wall-and-buttress footprint. A StaBlox™ tunnel wall requires only the nominal 6 ½ inch block width and no buttress width. Therefore, the StaBlox™ interior tunnel-width can be increased by 11 inches (5 ½ inches per wall) without increasing the tunnel footprint. This increased interior width results in approximately ⅓ greater cross-sectional flow area and significantly reduces pressure drop across the tunnel system.

Process Flexibility

Often, operating conditions change after tunnel-system construction. A capacity increase may be desired, for example. Typically, in such cases, the existing tunnel-wall open-area distribution no longer performs optimally. For a conventional tunnel, open-area distribution redesign may require partial or complete reconstruction, incurring material costs and possibly lengthening the turnaround schedule. For a StaBlox™ tunnel system, however, open-area redesign requires only the removal, addition, or relocating of some of the orifice inserts (a relatively quick and inexpensive procedure), re-using the wall tunnel structure in its entirety.

Reduced Heat Storage

During heat up or cool down it is important to evenly heat or cool the catalyst tubes to avoid accelerated tube aging. However, the tunnels absorb heat during heat-up and release heat during cool down, causing non-uniform heating or cooling of individual tubes. During a trip, for example, while the catalyst-tube upper ends are cooling more quickly than normal, the tunnels radiate heat to the catalyst-tube lower ends. Because StaBlox™ tunnel mass is up to 60% less than conventional tunnel mass, StaBlox™ tunnels absorb and release 60% less heat, reducing the degree and period of uneven cooling.