



Achieving optimal performance in downfired steam-methane reformers

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Down-fired steam methane reformer furnaces utilize flue gas tunnels (aka “coffins”) along the radiant section floor to collect and transport radiant section flue gas to the convection section for additional heat recovery. 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. Flue gas enters the tunnels through side wall openings which are distributed throughout the tunnel system to achieve uniform radiant flue gas flow.

Conventional tunnel system physical features constrain design efficacy, resulting in non-uniform flue gas flow along the tunnel lengths and among tunnels. Non-uniform flue gas flow is correlated to non-uniform catalyst tube convective heating, varied tube temperatures, and early tube failures. BD Energy Systems have developed a new, patent-pending Tunnel Optimal Performance (TOP) design method to achieve near-perfect radiant flue gas flow uniformity, near-perfect catalyst tube temperatures with respect to convective heating, and improved tube longevity/reliability. BD Energy Systems are pleased that TOP tunnel system(s) are in production in North America and under consideration elsewhere in the world.

This flue gas fine-tuning method has applications in Selective Non-Catalytic Reduction (SNCR) as well. Historically, radiant tunnel ammonia injection SNCR projects results have varied per reformer – some projects achieve required NO_x reduction, while others fall short of expectations. The BD Energy Systems TOP-based flue gas control method increases in-tunnel flue gas mixing and NO_x reduction, rendering ammonia injection a more predictable NO_x reduction method. This paper compares conventional design results to TOP design results, focussing on benefits to radiant tube reliability and NO_x reduction efficacy.

1 INTRODUCTION

1.1 Early Tube Failures

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 practice, 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 in which tubes degrade more rapidly, 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.

1.2 Selective Non-Catalytic Reduction (SNCR) Results Variability

At the floor of the reformer, flue gas collection tunnels carry the flue gas to the convection section for additional waste heat recovery. To decrease NO_x emissions, ammonia may be injected into the tunnels. Ideally, the injected ammonia sufficiently reduces NO_x concentrations. In practice, however, results may vary significantly. For example, in one reformer, NO_x levels may be successfully reduced without excessive ammonia slip, but identical efforts in a sister plant may yield minimal NO_x reduction. Further, failure of the ammonia to reduce NO_x may result in unacceptably high ammonia concentrations at the stack. So far, this outcome variability has rendered the SNCR method unreliable.

2 EARLY TUBE FAILURE

2.1 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.

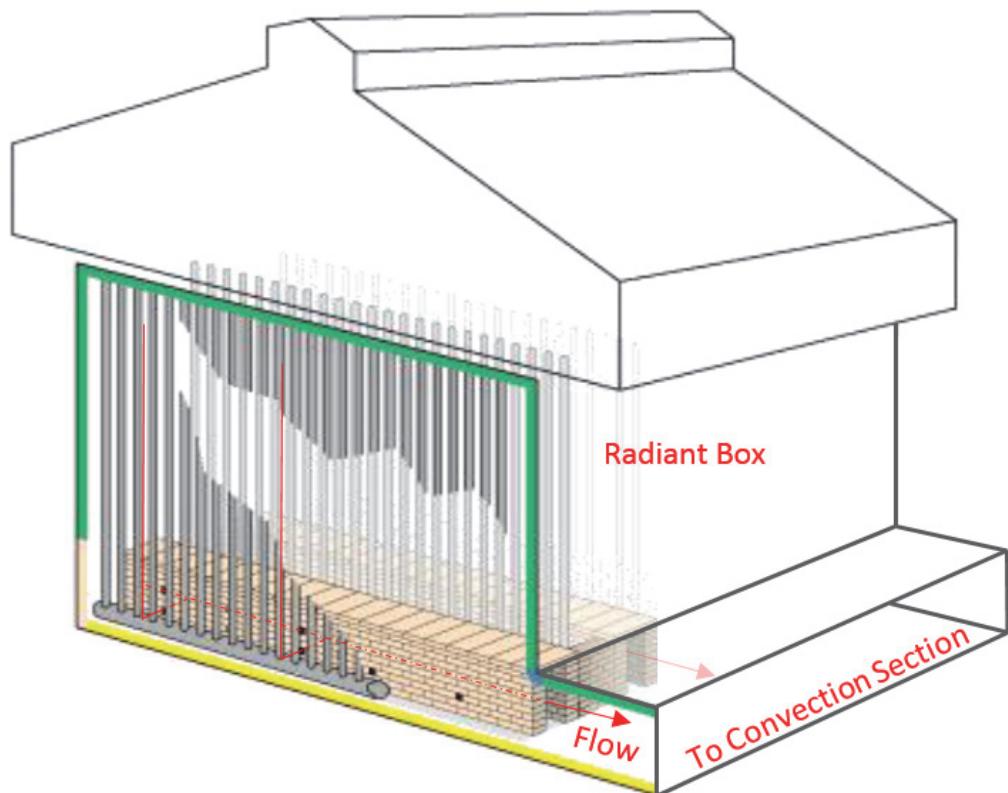


Fig. 1: Tunnels Collect & transport flue gas

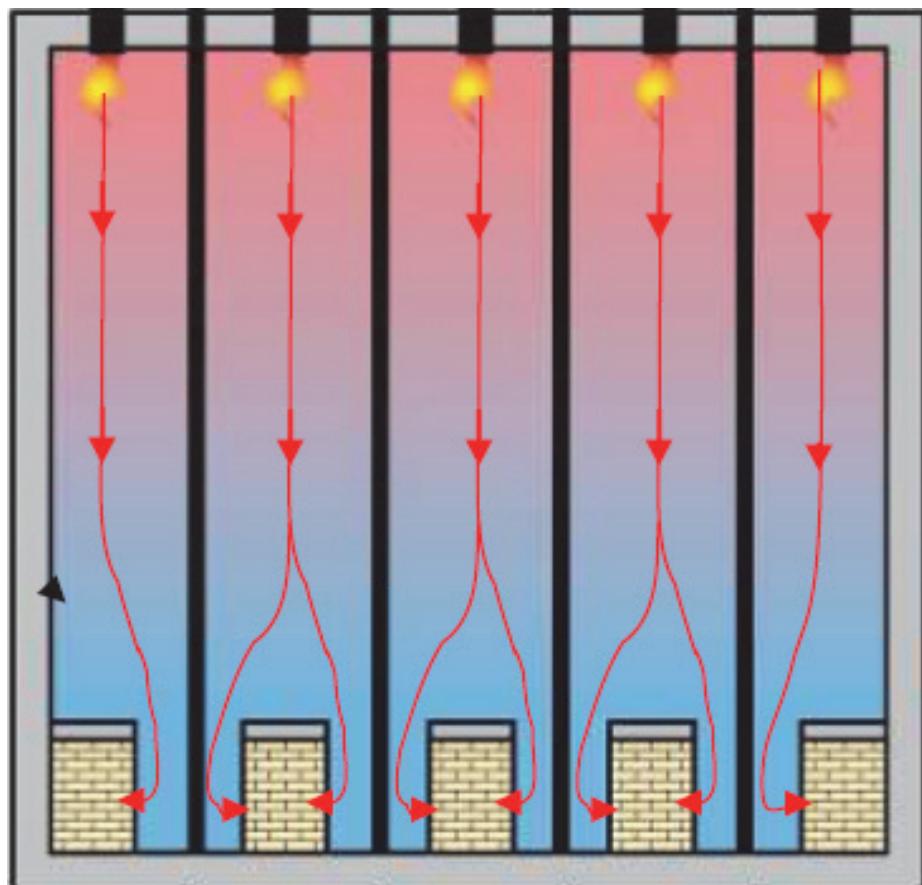


Fig. 2: Flue gas Flow into Radiant Box Tunnels

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 the correct amount of 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.

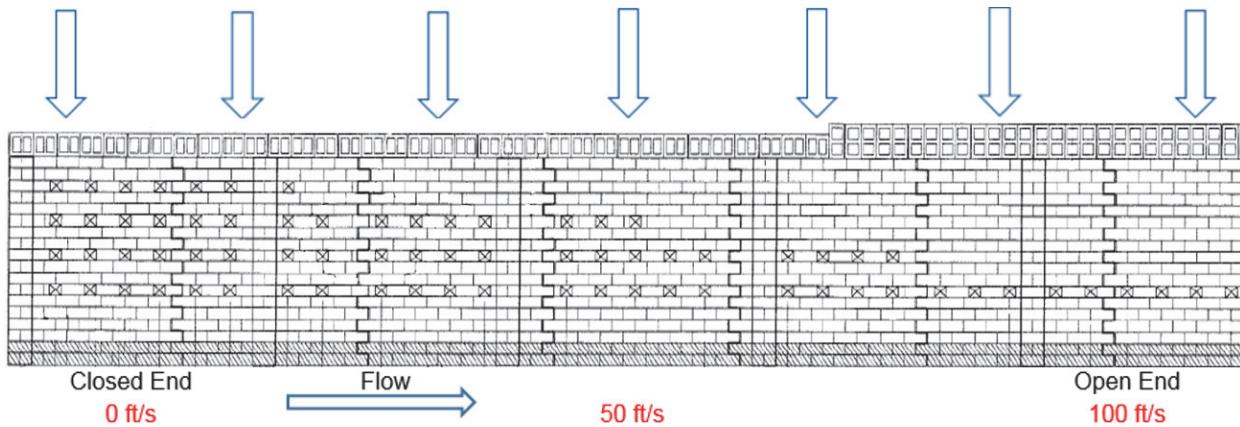


Fig. 3: Ideal In-Tunnel Flue Gas Velocity

2.2 Conventional Tunnels

2.2.1 Conventional Physical Characteristics

Typically, tunnels are 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).

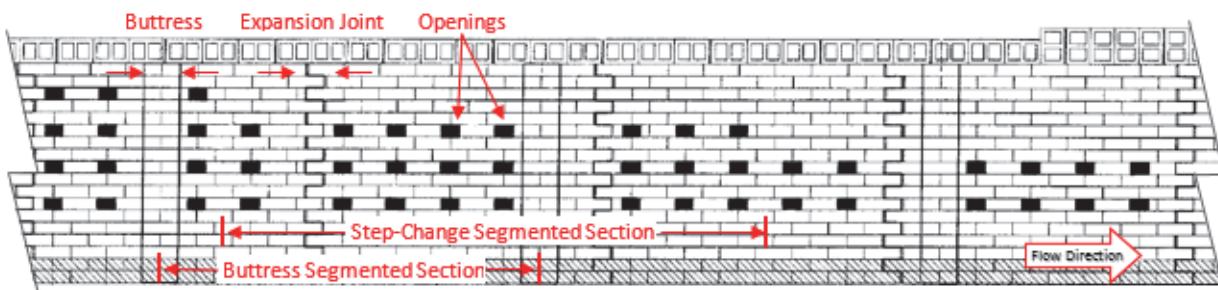


Fig. 4: Conventional Tunnel Wall Sketch

2.2.2 Conventional Design Technique

2.2.2.1 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 5). Conventional open area is added in nominal 13½ in² 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.

2.2.2.2 Flue Gas Flow Calculations

Total flue gas flow into each tunnel is calculated by summation of the flows into each tunnel's opening. The ratio of flow into one outer tunnel vs. one inner tunnel is computed. This ratio is compared to the ratio of one outer burner-row firing to one inner burner-row firing – approximately 0.65 – to determine the degree of flow uniformity among the regions between the burner rows. Flow non-uniformity among outer and inner tunnels causes lateral flue gas flow across the outer tube lanes, which tends to cause outer tube row overheating, and possibly overheating of nearby tube rows.

Total flue gas flow through each incremental tunnel length ([Figure 5](#)) is calculated. Each incremental length includes exactly one column of openings, so the incremental flow is the sum of the flows through the openings in that one column. These incremental flows are compared along the length of each tunnel to determine flue gas flow uniformity along the tunnel lengths. Non-uniform flow along the tunnel lengths causes increased convection for tubes in high-flow areas and decreasing convection for low-flow areas. In addition, this flow mal-distribution may cause lateral flow along the length of a tube lane, causing increased convection for affected tubes.

2.2.3 Conventional Design Evaluation

Typically, tunnels are 4 to 10 ft high, 2 to 3 ft wide, and 40 to 90 ft long. For a conventional 40 ft long tunnel system, flue gas flow was calculated ([Figure 5](#)). 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 $77.4\% \pm 55.1\%$, 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 and outer tunnel. Following any open-area step change, the incremental flow increases with each successive open-area column ([Figure 5](#)). 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 5](#)), 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.

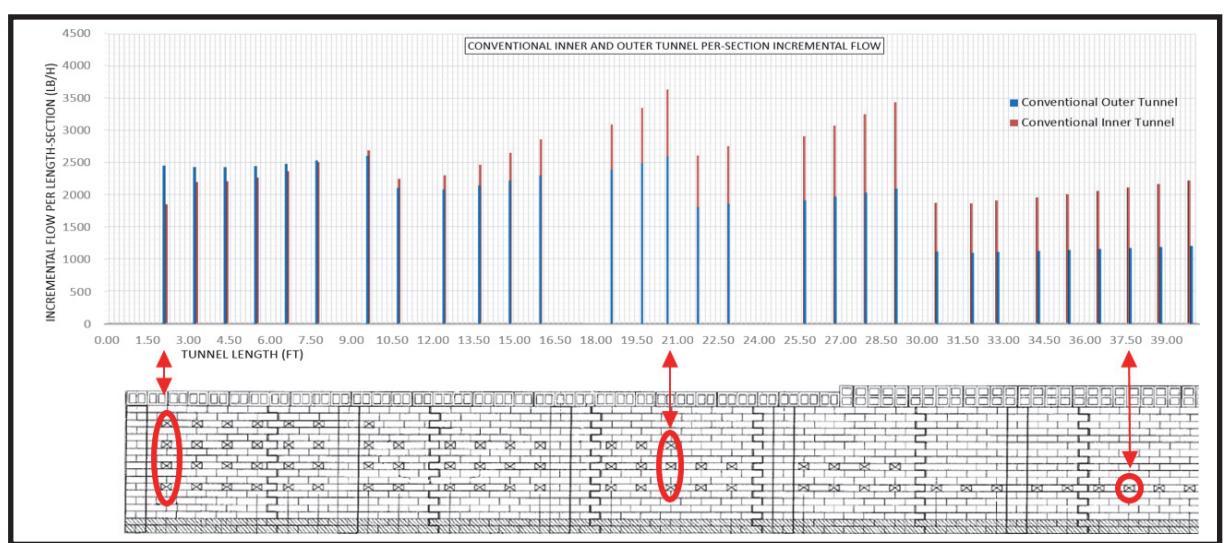


Fig. 5: Incremental Flow per Open Area Column for Conventional Inner and Outer Tunnels

2.3 Tunnel Optimal Performance (TOP) Tunnels

2.3.1 TOP Physical Characteristics

The TOP tunnel walls are constructed of firebrick. Nominal wall block dimensions are 9 inch x 9 inch x 6 inch (H x W x D), rather than 9 inch x 3 inch x 6 inch. Rather than removing half blocks to control flue gas flow, each block features an opening into which a variable-diameter flow-control orifice is inserted. The blocks are dry mortared during construction and expansion gaps are employed. Overall tunnel weight is much less than conventional tunnel systems, and the larger, lighter blocks require significantly less installation time.

2.3.2 TOP Design Technique

2.3.2.1 TOP Open-Area Distribution Design

The TOP design method segments the tunnel into 9-inch tunnel-length sections. Each segment is assigned one column of openings. Every column has the same number of openings – one per course (row). For example, a 75 ft tunnel-wall length would be segmented into 100 sections with openings in every course. 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. Using 1/16" diameter increments, orifice diameters are engineered for each opening to achieve near-uniform flue gas flow. For both the inner and outer tunnel opening layouts (Figure 6), orifice diameters are specified as the number of 1/16 inch increments. Tie-rods, which negate the need for buttresses, are indicated by 'TR'.

2.3.2.2 TOP Flue Gas Flow Calculations

To calculate flue gas flow uniformity for the TOP tunnel system, flue gas flow through each orifice is calculated simultaneously for both the inner and outer tunnels. Similar to the conventional tunnel system evaluations, the TOP design total flue gas flow into each tunnel is calculated by summation of the flows into each tunnel's openings. The ratio of flow into one outer tunnel vs. one inner tunnel is computed, and is compared, to the existing flow ratio. To achieve high flow uniformity among inner and outer tunnels, an approximate flow ratio of 0.65 ± 0.01 is targeted based on typical outer to inner burner row firing ratio of approximately 0.65.

2.3.2.3 TOP Tunnel Evaluation

For the TOP design case, calculated total flow through each outer-tunnel was approximately 65.64% of per-inner-tunnel flow, and this ratio is relatively consistent along the tunnel length (Figure 6). 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 $65.64\% \pm 1.8\%$, 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.



Fig. 6: TOP Design Flows per Column

3 NO_x REDUCTION RESULTS VARIABILITY

3.1 Conventional NO_x reduction CFD Case Study

Ammonia injection had been implemented at two very similar plants. Past results were satisfactory for one plant, but NO_x reduction results were very poor for the other plant. The poorly performing tunnel system was CFD modelled by Tridiagonal Solutions Inc. (Figure 7). Rather than the expected uniform exit velocity, results indicated tunnel-exit velocities which ranged from approximately 90 ft/s near the floor to 200 ft/s at the tunnel slabs (Figure 8). In addition, injected ammonia channelled to the top of the flue gas stream (Figure 9). This channelling inhibited mixing, decreased residence time, and resulted in poor NO_x reduction. Also, the increased excessive velocity significantly increased tunnel system pressure drop.

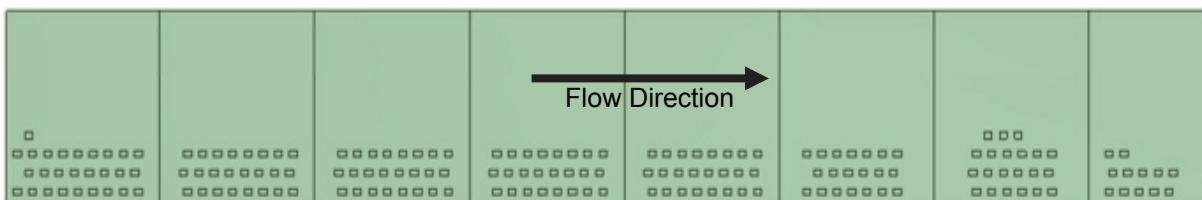


Fig. 7: Modelled Tunnel Wall Opening Layout



Fig. 8: Excessive Velocity near Top of Tunnel

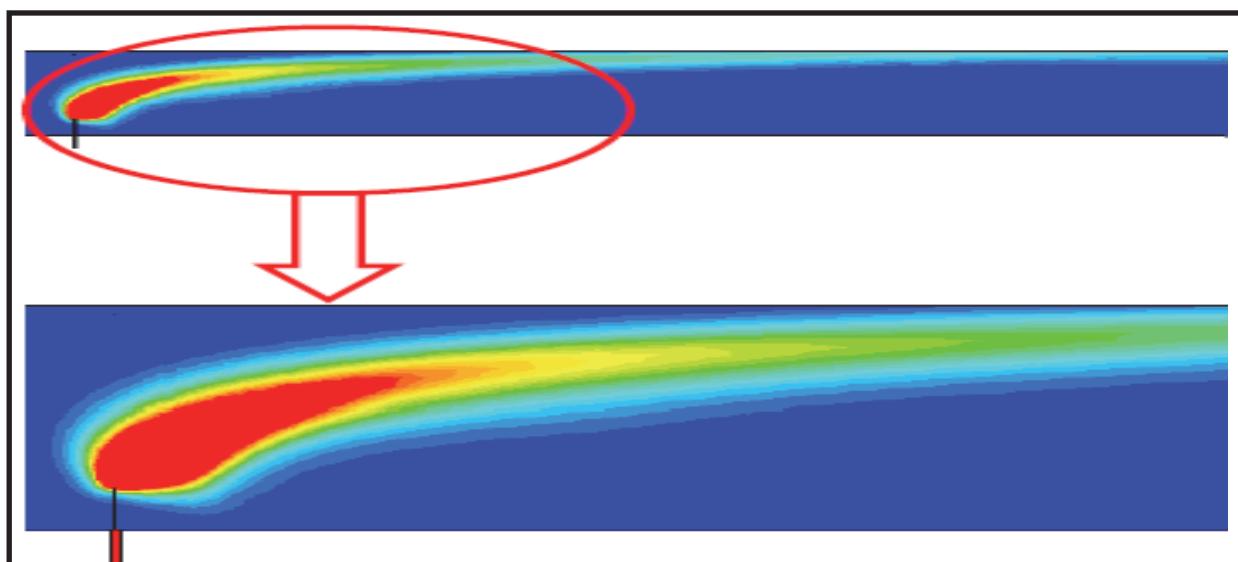


Fig. 9: Injected Ammonia Channelling Upward

To prevent channelling, while increase mixing and residence time, the nozzle was modelled to direct the flow horizontally in three small streams, rather than upward in one large stream. However, the new nozzle design failed to produce significantly different results (Figure 10). Even with the new nozzle, the tunnel-exit velocity ranged from 90 ft/s to 200 ft/s. The ammonia again channelled upward in the flue gas stream (Figure 11).

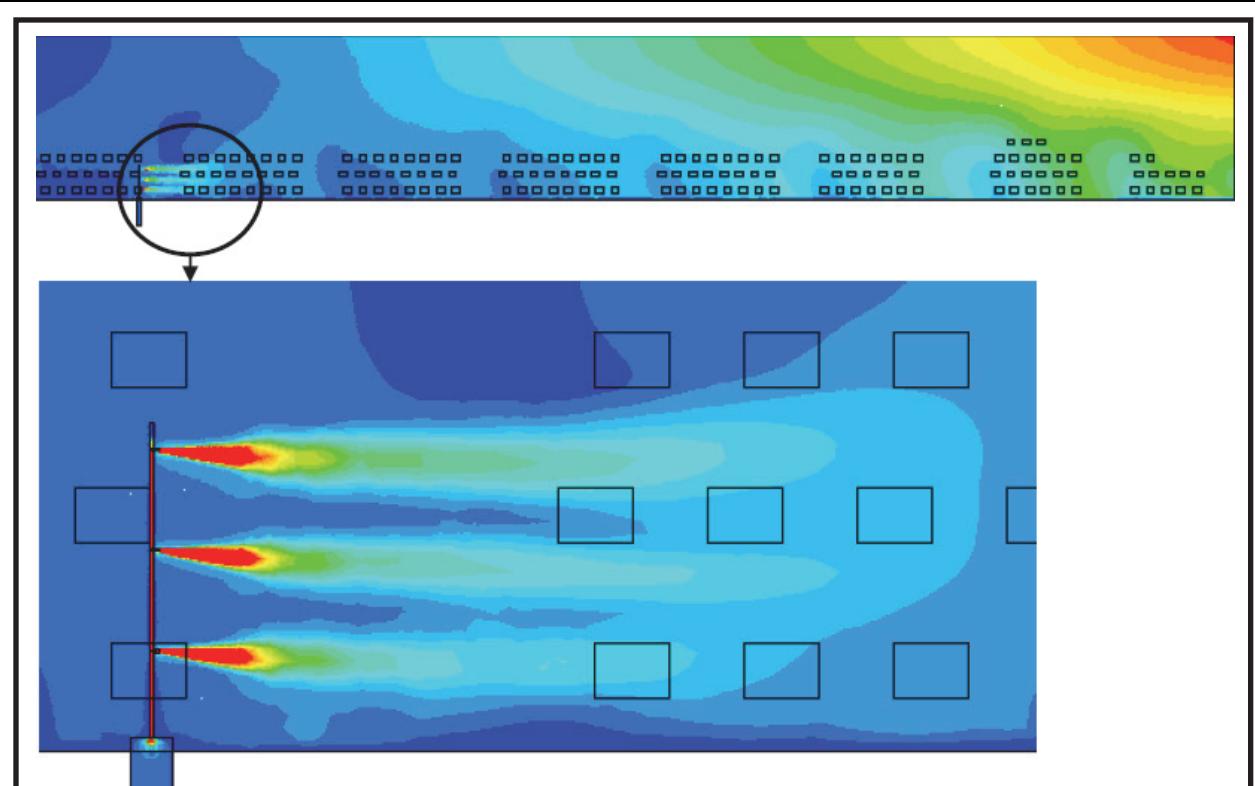


Fig. 10: Directed Injection Fails to Decrease Tunnel-Exit Flue-Gas Velocity Range

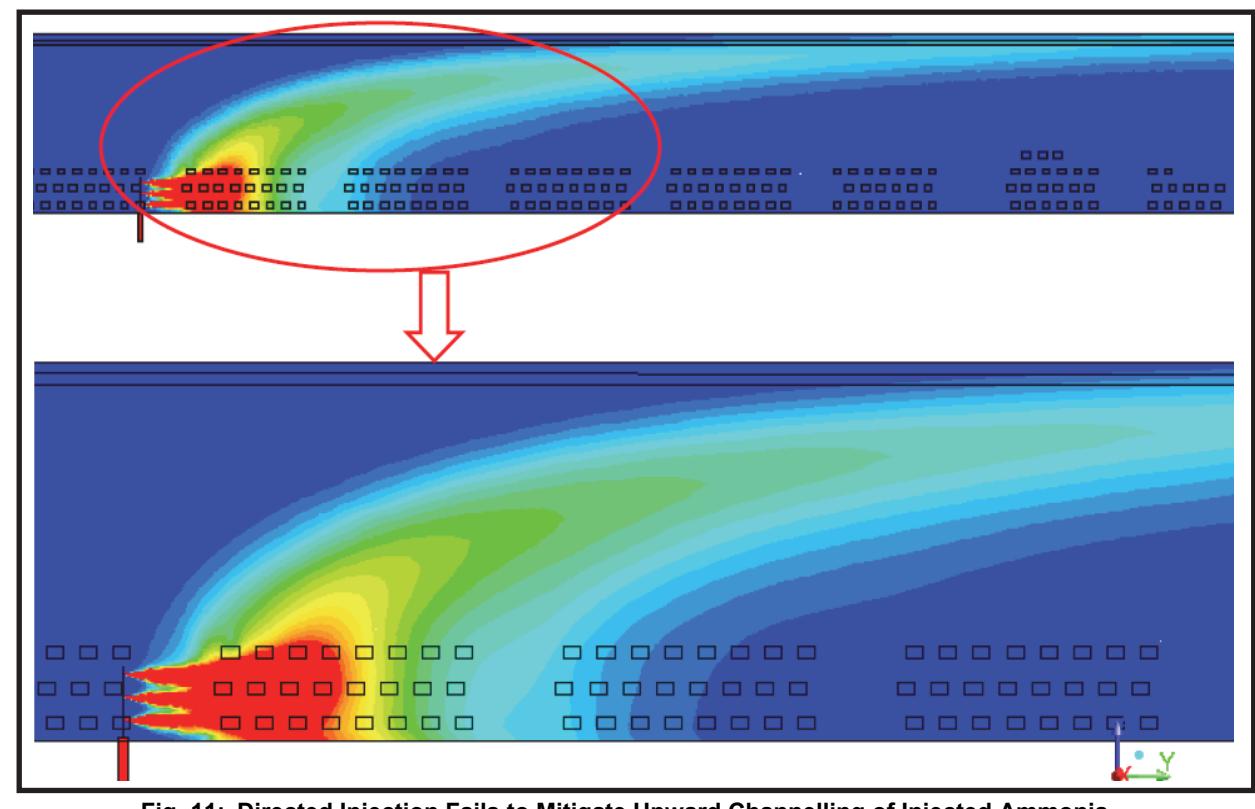


Fig. 11: Directed Injection Fails to Mitigate Upward Channelling of Injected Ammonia

To understand better the failure of the new nozzle to correct the poor tunnel performance, flue gas particle paths were traced from entrance into the tunnel to exit (Figure 12). Flue gas entering through these openings moved perpendicular to the in-tunnel flow and impeded flow toward the tunnel exit. This resistance to flow induced channelling upward to a less resistive path. In turn, this channelling caused excessive velocities away from the openings, which significantly increased pressure drop and inhibited mixing.

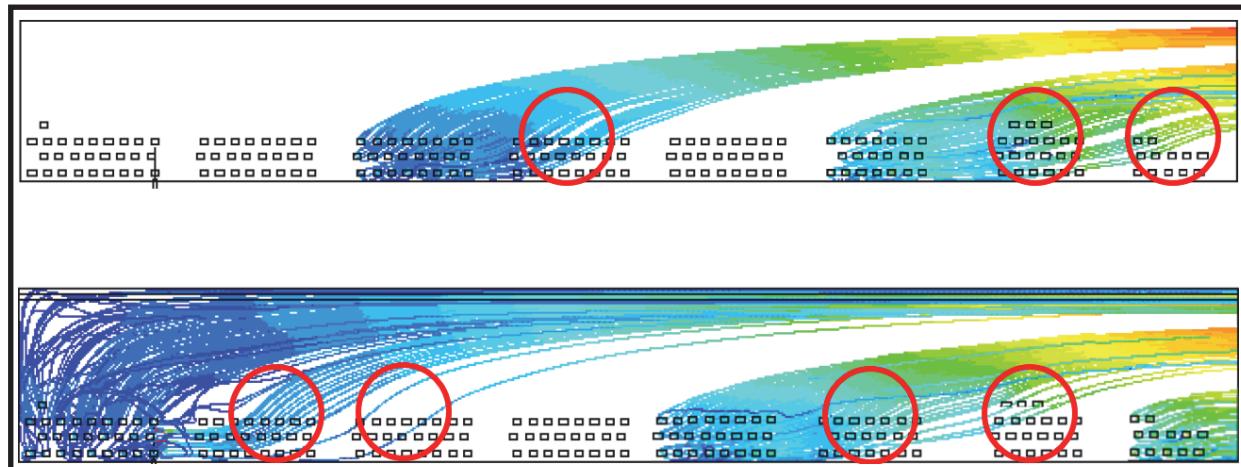


Fig. 12: Flow Turning Upward at Tunnel Openings (Circled)

3.2 TOP Tunnel System Case Study

A TOP tunnel system also was modelled. The system included outer and inner tunnels with 61 opening columns per wall (Figure 13) and openings in every course except for the lowest course. Orifice insert sizes were engineered by BD Energy Systems to achieve an inner-to-outer-tunnel flow ratio of 73.9%. The TOP program calculated flow per column to be uniform within $\pm 4\%$.

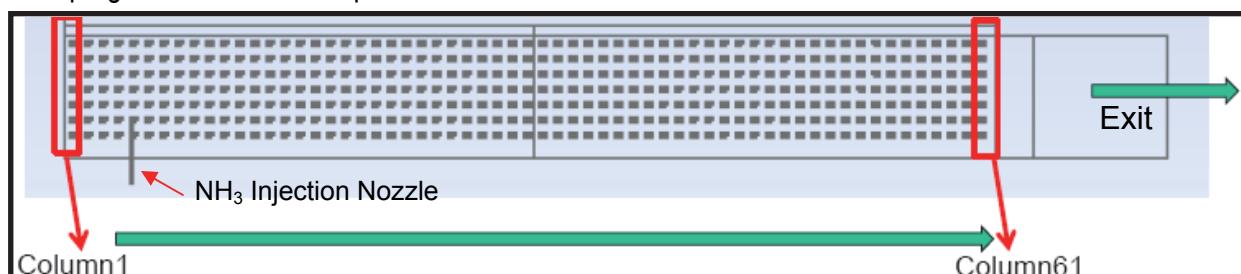


Figure 13 - TOP Tunnel CFD Model

This TOP tunnel system was modelled by Tridiagonal Solutions Inc. using the BDE specified operating conditions and tunnel-wall opening layouts. To test for channelling, a single ammonia injection nozzle was modelled with an upward trajectory (Figure 14). Despite the poor injection method, velocity uniformity increased (Figure 15) and pressure drop decreased. Path stream evaluation indicated increased mixing compared to the conventional case (Figure 16). Residence time increased as velocity uniformity and mixing uniformity increased.

The CFD model flow per tunnel matched TOP program calculations within $\pm 0.1\%$ – the CFD resulting flow ratio was 73.8% while TOP calculated flow ratio was 73.9%. CFD also validated the TOP program calculated incremental flow per column – flow was within $\pm 4\%$ of uniform for both TOP program model and the CFD model.

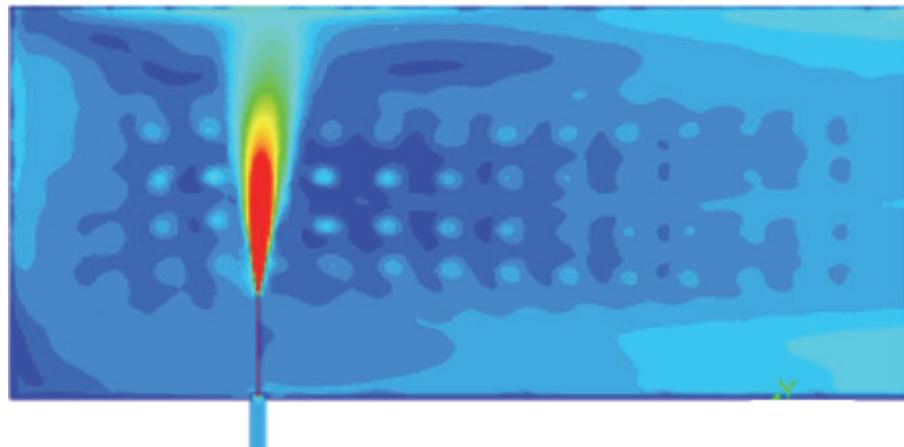


Fig. 24: Ammonia Injected Upward into Tunnel



Fig. 15: Tunnel Exit Velocity Profile is Uniform (~85 ft/s)

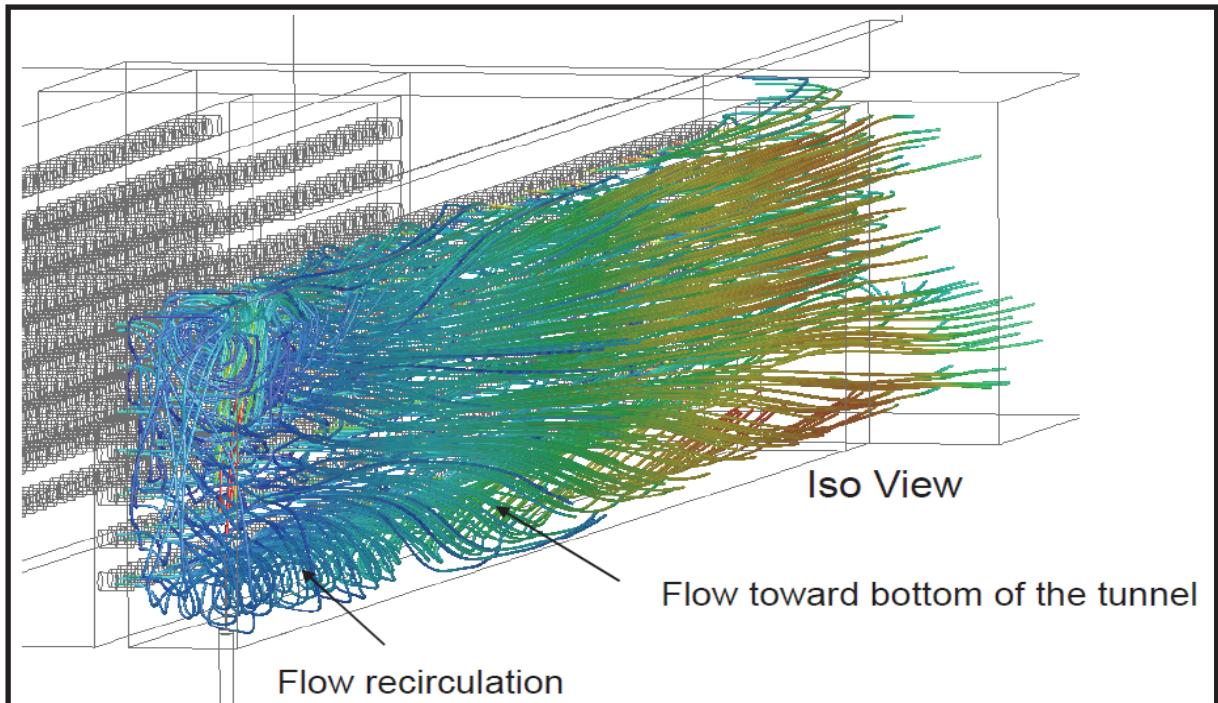


Fig. 16: Path Lines Show Improved Mixing for TOP Designed System

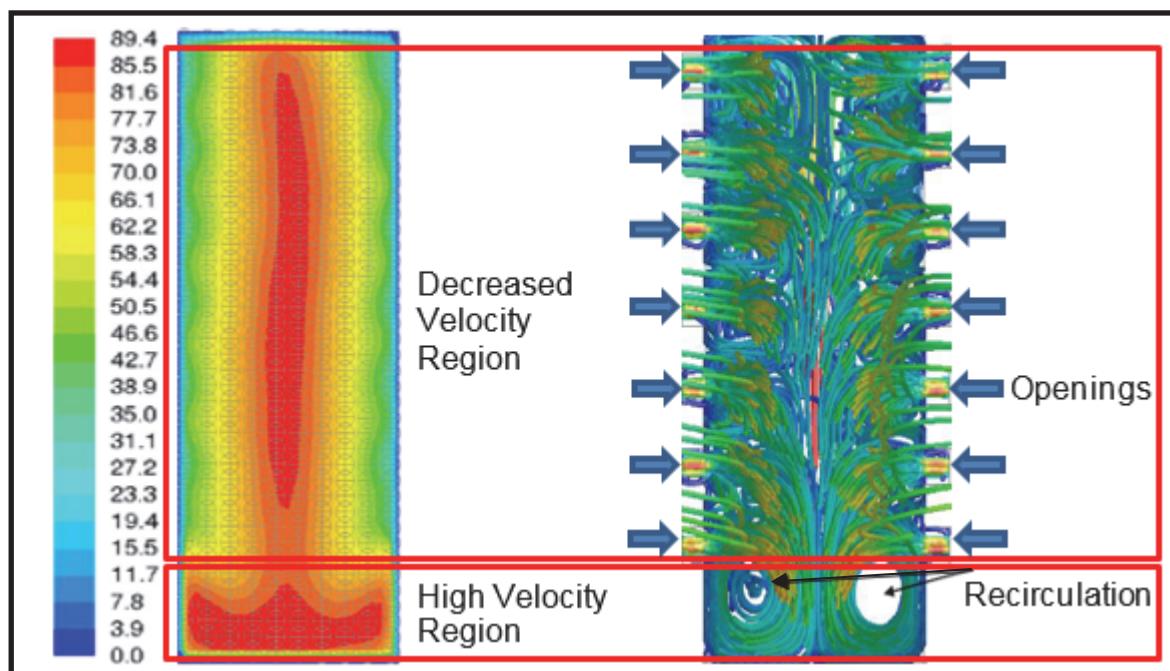


Fig. 17: Cross-sectional View of Inner Tunnel Outlet Velocity Profile (left) and Path lines (right)

Comparison of the inner-tunnel-exit cross-sectional velocity profile and path line tracing (Figure 17) indicates that tunnel-wall openings impede flow and cause channelling into less resistive regions. In the upper region of the inner tunnel, where openings are uniformly distributed, the velocity profile is near uniform, ranging approximately 80 ft/s to 90 ft/s. This narrow range increased mixing uniformity and residence time while decreasing pressure drop. In the lower region of the tunnel the absence of openings is correlated to a high velocity region (Figure 18). At the outer tunnel a similar comparison indicates near uniform flow in the region having uniform wall openings and indicates high velocity in the regions without openings, which includes both the floor region and near the wall without openings.

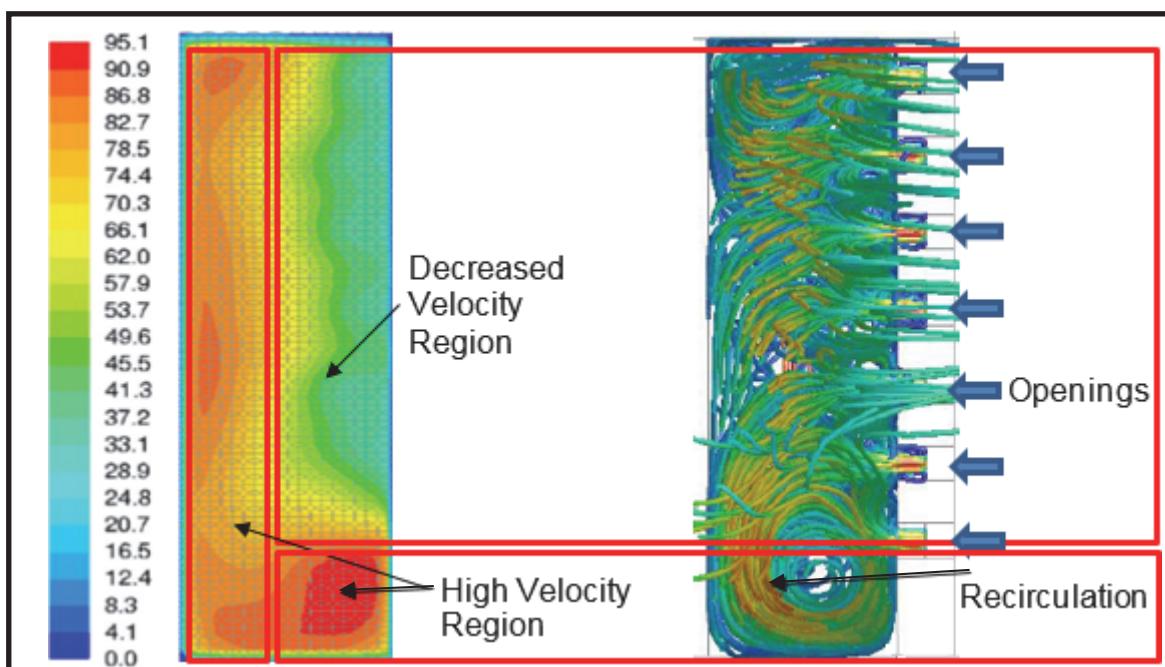


Fig. 18: Cross-sectional View of Inner Tunnel Outlet Velocity Profile (left) and Path lines (right)

4 CONCLUSION

The TOP tunnel design method results in near uniform radiant section flue gas flow. This near-uniform flow promotes near uniform catalyst-tube heating, near-uniform tube-temperatures, and increased tube reliability and useful life. CFD modelling validates the TOP calculated flows.

The TOP tunnel design method uniform opening distribution decreases in-tunnel flue gas channelling to increase cross-sectional velocity uniformity, decrease maximum velocity, and decrease system pressure drop. Also, decreased channelling results in increased ammonia mixing uniformity and residence time. The ammonia injection SNCR method results are more predictable using TOP designed tunnels.

5 CONTINUING RESEARCH

Currently, BD Energy Systems is studying methods to prevent or mitigate vortex formation in non-wall-opening tunnel regions, thus entirely preventing channelling. Further pressure drop reduction, increase mixing uniformity increase, and residence time increase are expected, but validation requires additional data collection.

Though CFD modelling validated TOP design calculations, BD Energy Systems anticipates field-data validation from the first ever TOP deigned tunnel system currently in construction.

