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# CFD ANALYSIS HELPS TSV® BURNER MEET STRICT $NO_X$ EMISSION REQUIREMENTS AT CONECTIV INDIAN RIVER UNIT 4, A DB RILEY TURBO® FURNACE

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***ABSTRACT***

*This project is the first application of low $NO_X$ circular-type burners to a "TURBO® Furnace" coal-fired utility boiler design. It is an important part of Conectiv's (formerly Delmarva Power and Light Co.) compliance strategy for the Clean Air Act Amendment of 1990 (CAAA). In project Phase 1, installation of dynamic classifiers successfully reduced flyash unburned carbon loss by nearly 50%. This paper describes Phase 2, the design and retrofit of new low-$NO_X$ burners. The two phases met all performance requirements, including a $NO_X$ guarantee of 0.42 lbs/$10^6$ Btu at 105% load.*

*Initially the Model 2 Tertiary Staged Venturi (TSV®) Burner design installed at Conectiv Indian River Station Unit 4 did not meet required $NO_X$ levels. Field observations indicated poor flame retention as well as poor flame scanner signals, particularly at lower loads. Using computational fluid dynamics (CFD) modeling and working with DB Riley Inc.'s (DBR) parent, Deutsche Babcock, DBR engineers developed a promising design solution incorporating elements of other DBR low-$NO_X$ coal burner technology into the TSV® Burner design. The CFD modeling goal was to improve burner aerodynamics in the burner near-field region to produce better flame retention while limiting hardware changes. Past experience has shown that better flame retention promotes lower $NO_X$. Although the design process consisted of a series of 2-D axi-symmetric, purely aerodynamic CFD models with no combustion or $NO_X$ calculations, several key CFD models added coal combustion for flame visualization purposes. A significant $NO_X$ improvement was expected with the final design chosen, based on significantly improved burner aerodynamics and flame attachment. This analysis ultimately proved to be correct.*

*Final operating performance for this low-$NO_X$ retrofit at 105% load is:*

*0.42 lbs NOx /$10^6$ Btu*
*11.4 wt. % unburned carbon in flyash*
*Less than 50 ppm CO emission*
*Burners are non-slagging*
*Uniform furnace and burner-to-burner flame conditions throughout the load range*
*Excellent flame attachment and flame scanner signal throughout the load range*
*Reasonable burner zone stoichiometric ratio of approximately 0.90*

*This new Model 3 low-$NO_X$ TSV®Burner design is applicable to other coal-fired TURBO® Furnaces for significant reductions in $NO_X$ emissions.*

## INTRODUCTION AND BACKGROUND

Conectiv (formerly Delmarva Power and Light Co.) Indian River Station Unit 4 (IR4), located in Sussex County Delaware, is an indoor, DB Riley Inc. (DBR) dry-bottom TURBO® Furnace, balanced draft, reheat unit commissioned in 1980. IR4 fires Eastern bituminous coal to heat 2,943,000 pph MCR main steam flow from feedwater at 485°F to superheater outlet conditions of 1005°F / 2620 psig. Reheat steam flow of 2,736,200 pph is raised from 623°F / 594 psig inlet to 1005°F / 569 psig outlet conditions. Figure 1 contains a side-elevation schematic of the furnace as equipped in 1987 with the original DBR Directional Flame (DF) burners (a non-swirl, axial flow type with two coal nozzles per burner). The 24 DF burners were arranged in a 12 side-by-side line on each of the opposed-firing walls. Each burner wall originally had 12 overfire air (OFA) ports, one per burner, to reduce burner zone stoichiometry for additional $NO_X$ reduction.

In 1987 two "wing" OFA ports were added to each burner wall near the sidewalls for a total of 14 OFA ports per burner wall, and 12 underfire air (UFA) ports were added below the burners on each burner wall as shown in Figure 1. Eventually, the UFA ports were closed off because operational experience showed they were causing high attemperator spray flows.

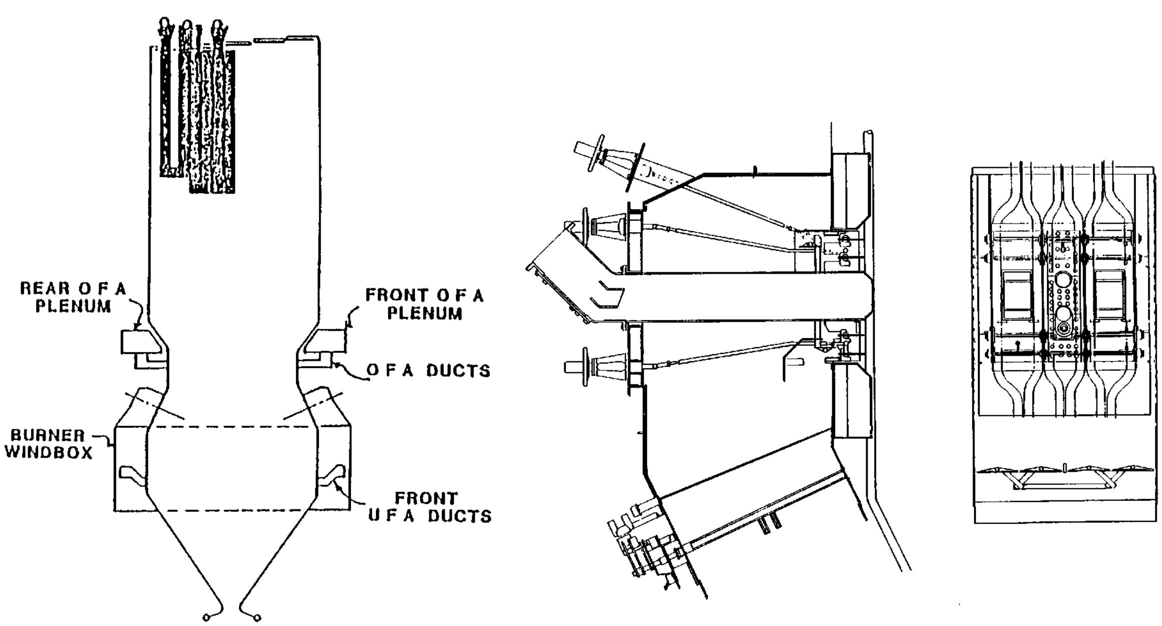


*Figure 1. Conectiv IR4 Boiler Schematic, Directional Flame Burners, OFA, and UFA - 1987*

In 1994 the original static classifiers were replaced with rotating classifiers to increase coal fineness and reduce flyash carbon loss. Due to classifier reject line pluggage when operating at increased fineness levels, the coal reject lines were enlarged and new reject line dampers were added in 1995 to allow operation at the desired classifier RPM. After the rotating classifiers were installed, DBR Baseline Testing at 3,144,400 pph steam showed emissions of 0.62 lbs $NO_X$ /$10^6$ Btu, 12 ppm CO, and 11.25% unburned carbon in the flyash. Operating conditions were 3.3% excess $O_2$ at the economizer outlet, and 14% OFA, resulting in a burner zone stoichiometry of approximately 1.0. These test results were used as the basis for burner guarantees in the project's Phase 2 low-$NO_X$ burner retrofit.

In October 1994, Conectiv awarded a low-$NO_X$ burner-replacement contract to DBR with a $NO_X$ guarantee of 0.42 lbs/$10^6$ Btu, CO emission and flyash unburned carbon dependent upon Baseline Testing, and no decrease in steam temperatures. The resulting DBR guarantees for the retrofit were then 0.42 lbs $NO_X$/$10^6$ Btu, 62 ppm CO emission, and 12.25 % unburned carbon in the flyash. The analysis of the Eastern bituminous coal for the guarantees, listed below, has a 1.9 fixed carbon to volatile matter ratio and 1.3% Nitrogen. Typically, $NO_X$ reduction is much more difficult with Eastern bituminous coals than with Midwestern or Western bituminous coals.

| **HHV and Proximate Analysis, Weight %** | | **Ultimate Analysis, Weight %** | |
|---|---|---|---|
| HHV, Btu/lb | 13,008 | Moisture (total) | 6.1 |
| | | Hydrogen | 4.7 |
| | | Carbon | 73.1 |
| Moisture (total) | 6.1 | Sulfur | 0.7 |
| Volatile Matter | 30.0 | Nitrogen | 1.3 |
| Fixed Carbon (diff.) | 56.0 | Oxygen (diff.) | 6.2 |
| Ash | 7.9 | Ash | 7.9 |
| Total | 100.0 | Total | 100.0 |

Figure 2 is a schematic of the original Model 2 Tertiary Staged Venturi (TSV®) Burner design for IR4 highlighting the following features:

- A primary air (PA) section containing the patented DBR coal nozzle with 4-bladed, 15° coal spreader and attached secondary air (SA) diverter.
- An SA section annulus with inlet swirl vanes surrounding the PA.
- A converging tertiary air (TA) section with axial swirl vanes surrounding the SA.
- Individual flow control dampers for both SA and TA flow passages.

Independent, automatic control of SA and TA flows maintains proper windbox-to-furnace differential pressure and burner air flow split as a function of boiler load. The SA and TA swirl vane positions are set manually at the burner front during optimization testing and subsequently are not changed throughout the load range.

DBR developed the Model 1 TSV® low-$NO_X$ coal burner in the early 1980's to reduce $NO_X$ emissions from DBR industrial-type TURBO® Furnace boiler designs. The burner design goal was $NO_X$ emissions less than 0.45 lb/$10^6$ Btu without a significant increase in flyash unburned carbon. This was a challenging target since the New Source Performance Standard (NSPS) limit for $NO_X$ was 0.7 lb/$10^6$ Btu at the time. The Model 1 TSV® low $NO_X$

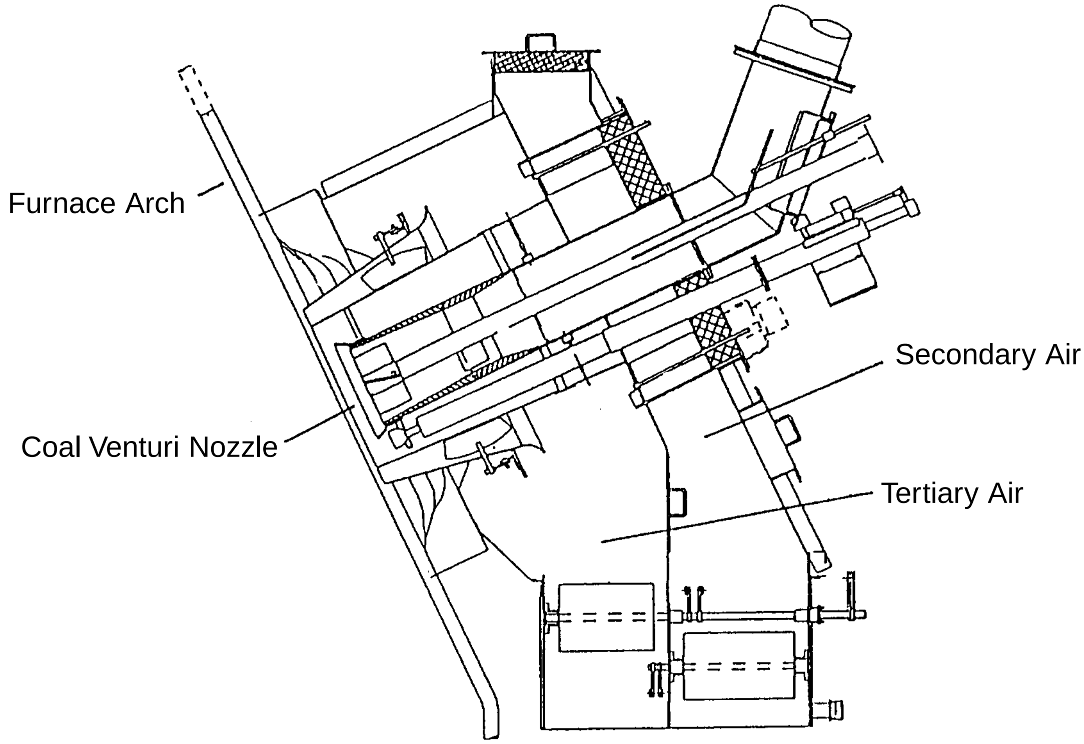


*Figure 2 Original Model 2 TSV® Burner Installed at IR4*

burner has a venturi coal nozzle and air register similar to those in DBR's Controlled Combustion Venturi (CCV®) single register low $NO_X$ burner for wall-fired applications. The Model 1 TSV® Burner also has a small number of separated, but close-coupled, TA ports surrounding the SA annulus. The venturi coal nozzle gave a fuel-rich flame core while the SA annulus and outboard TA ports produced internal burner air staging for additional control of $NO_X$ emissions. Itse and Penterson[1], Penterson and Abraham[2], and Penterson[3] described the design and operation of this TSV® Burner.

In the mid 1990's DBR developed the Model 2 TSV® Burner design for larger-sized utility TURBO® Furnaces which included a revision to the TA design due to mechanical limitations. The separated TA ports were replaced with a TA annulus surrounding the SA annulus and containing axial swirl vanes similar to the design of DBR's CCV® dual air zone burner used for reducing $NO_X$ in wall-fired applications as discussed by Ake and Penterson[4].

The Model 2 TSV® Burner was installed in IR4. However, the performance at this unit was below expectations. Numerous optimization tests ultimately showed that the guarantee $NO_X$ emissions could not be met with the original IR4 TSV® Burner design. Additionally, the optimum $NO_X$ settings at full load could not be used at lower loads while maintaining acceptable flame scanner signals. Flame retention on the coal nozzle was poor. The visible flame front typically started 3 ft from the coal nozzle end. UFA was ineffective at reducing $NO_X$ and caused increased attemperator spray flow. The variables tested during optimization included excess air, windbox pressure, SA and TA flow splits, SA and TA register vane swirl, OFA flow, UFA flow, burner air flow bias, coal spreader position, classifier speed, and effect of sootblowing. Bradshaw and Skedzielewski[5] reported preliminary results for this TSV® Burner design including the following best $NO_X$ performance at full load:

| | |
|---|---|
| Steam flow, pph | 3,038,000 |
| Excess air, % | 18.3 |
| Superheat spray, pph | 113,000 |
| $NO_X$, lbs/$10^6$ Btu | 0.5 |
| CO, ppm | ~ 4 |
| Unburned carbon in flyash, % | ~ 10 (from precipitator hoppers) |

## BURNER DESIGN MODIFICATION BY CFD FLOW MODELING

To improve burner performance with respect to flame attachment and low $NO_X$ production, an investigation of the burner design was executed via computational fluid dynamics (CFD). Design by CFD has several benefits:

- Often it is quicker and more cost effective than laboratory or field experimentation.
- It often invokes fewer approximations than laboratory experiments and produces more realistic results.
- It makes more detailed numerical results available than laboratory testing, is not limited by hard-to-reach sample locations or hard-to-acquire data, and offers easier and more complete visualization of key flow parameters and behavior.

Two fundamental ideas underpinned the CFD burner design improvement work.

1) Combustion destabilizes a swirl-stabilized burner flow field and does not cure poor burner aerodynamics. In other words, if the burner flow field without pulverized coal combustion does not display recirculation patterns necessary for good flame attachment and low $NO_X$ production, then the combustion process will not correct these deficiencies.

2) The burner near-field flow pattern, where burner-to-burner or flame-to-flame interactions may be ignored, controls flame attachment. In other words, the idealization of a single burner with its near-field flow and flame spreading down a narrow "tunnel furnace" isolated from the surrounding burners and flames is an adequate model with respect to flame holding at the burner tip.

Thus simple 2-dimensional axi-symmetric, purely aerodynamic burner CFD models were used to explore systematically the effects of burner geometry and/or operating changes. The 2-D axi-symmetry implies that circumferential flow varies with axial and radial location but is uniform around circumferentially. This technique captures the essential behavior of the swirling burner flow but implies that modest non-axi-symmetric geometrical features have negligible impact.

Figure 3 shows the CFD model burner zone of the original IR4 Model 2 TSV® Burner which is the baseline case of the design improvement task. Figure 3 highlights the flush-mount (no quarl) installation. The PA, SA, and TA inlets have axial, radial, and tangential components which establish the swirling burner flow field. The furnace walls in Figure 3 represent the actual tight burner-to-burner spacing as well as the idealized "tunnel furnace" tube containing a single burner flow and flame structure. Only the near-field or first 3 burner diameters of the tunnel furnace are significant in the model. The remaining tunnel furnace length is included to avoid distortion of the near-field zone flow behavior due to flow domain truncation and to assure no flow into the CFD model exit surface, which would invalidate the results.

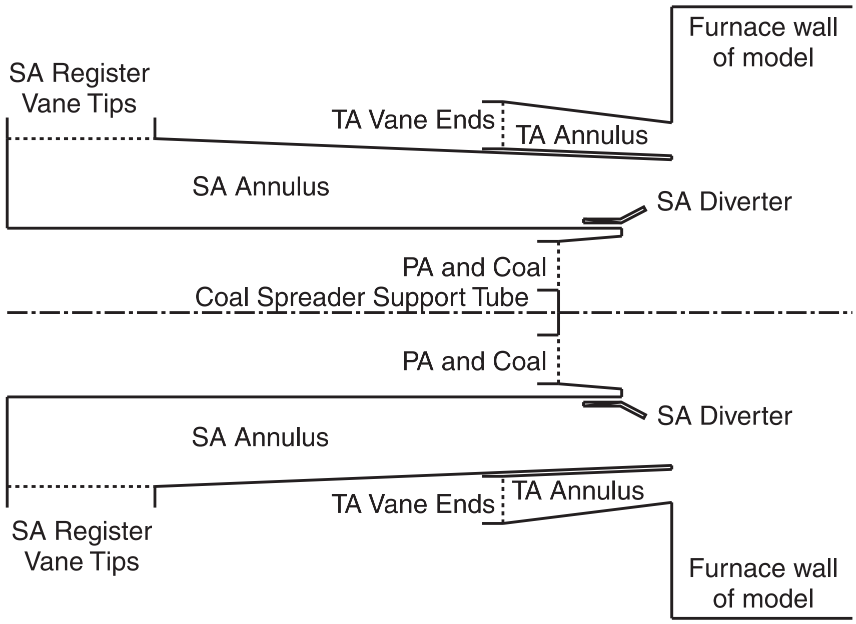


*Figure 3 Simple 2-D Axi-Symmetric CFD Model of Original IR4 TSV® Burner Model 2*

Because three computers were available and these 2-D aerodynamic CFD models typically took only one day for setup, calculation, and results analysis, a fairly systematic evaluation of effects of changes in geometry and operating conditions was possible. Figure 4 shows the aerodynamic models calculated for the IR4 TSV® Model 2 Burner. For this paper, the details in each box are not important (for example, "Mod nn" indicating historical sequence), but the tree-like structure of the boxes is. The top box is the original Model 2 TSV® Burner at IR4. Each row of boxes represents a single change of geometry or operating condition from the row above. The connecting lines show inheritance of a change from one CFD model to another. For each model the goal was to change one parameter at a time (geometrical feature or operating condition) from a previous model to build up a library of relative effects of changes. Although Figure 4 shows many aerodynamic models creating a fairly systematic evaluation structure, not all combinations were done. As modeling progressed, some combinations seemed to lead nowhere while others seemed more promising. Additionally, an overall project goal was to find a solution requiring as few changes to the burner as possible to reduce manufacturing and installation time and costs. As a result not all combinations were evaluated and the levels of complication were minimized.

Finally, although all the real burner-modification design work was done with the aerodynamic models shown in Figure 4, a few important aerodynamic models were supplemented with 2-D axi-symmetric models with coal particle combustion. Each combustion model was started from scratch with combustion active immediately rather than started from the aerodynamic solution. This assured an independent solution separate from the aerodynamic case but took two weeks of computer time to reach a reasonable convergence state, a long

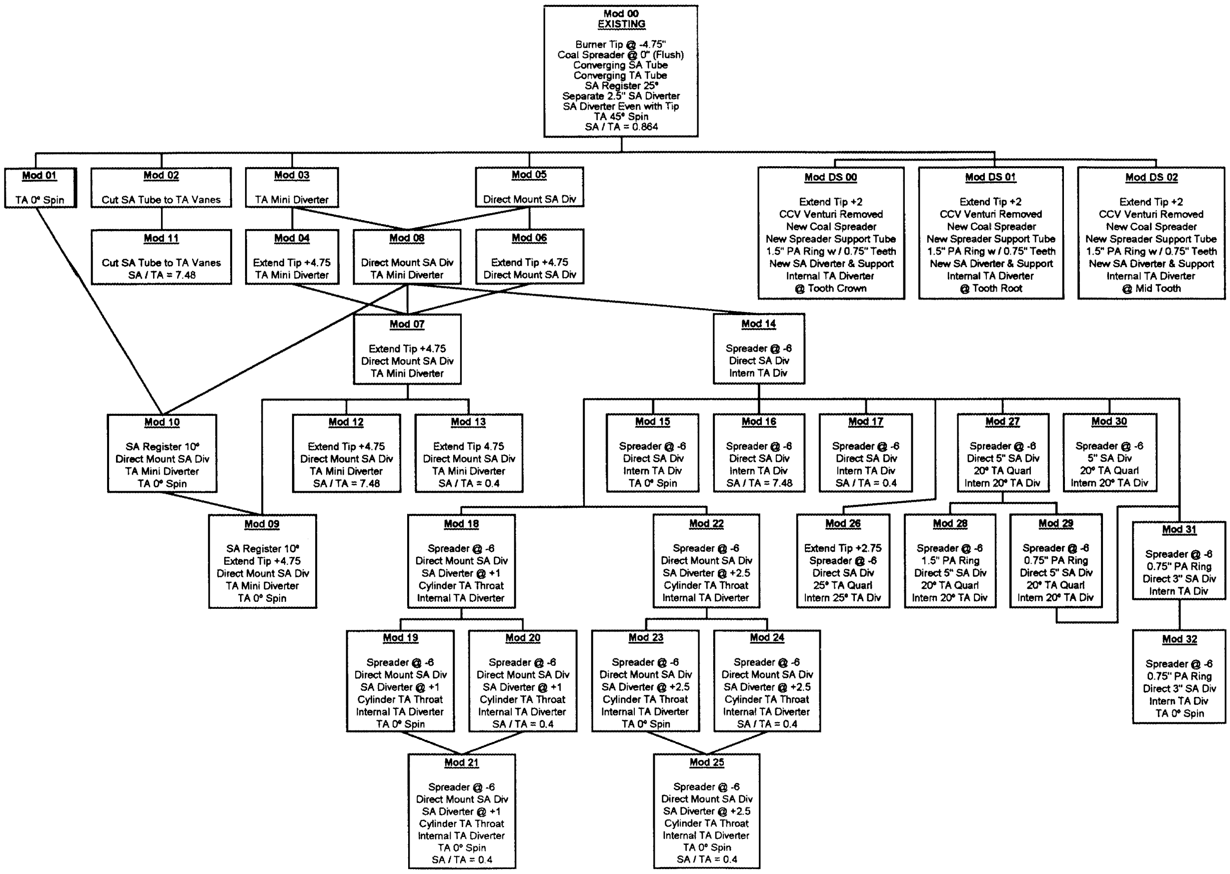


*Figure 4 Aerodynamic Modeling (Non-Combustion) of IR4 TSV® Burner Showing Lines of Inheritance of Changes between Levels of Complication*

time compared to the one day turn-around possible with the purely aerodynamic models. Such long computation times also precluded doing all the design work with combustion models. However, a few combustion models were run to demonstrate similarity of near-field flow patterns in combustion cases with those in corresponding non-combustion cases and to visualize flame attachment and flame shape. The flow pattern similarity test validated the first tenet of the modeling project (combustion does not cure bad aerodynamics) and enhanced confidence in the baseline and final design result models. Similarly, flame shape visualization provided by the combustion cases validated the baseline models against field observations and therefore enhanced confidence in all the modeling, aerodynamic as well as combustion, and the choice of the final modified design.

Figure 5 shows the computed near-field velocity vectors for the purely aerodynamic model of the original IR4 Model 2 TSV® Burner while Figure 6 shows the computed temperature field for the corresponding baseline combustion case.

The velocity vectors in Figure 5 indicate that PA from the nozzle tip swirls away from the burner axis fairly quickly to move alongside the SA and TA streams while flow returns toward the nozzle tip along the burner axis. The return flow defines the internal recirculation pattern or zone (IRZ). Figure 5 shows an “outside-in” IRZ, i.e., the combined PA, SA, and TA move downstream outside the flow structure, then move inside, and back to the burner tip along the burner axis. The IRZ of a swirl-stabilized burner holds the flame, and Figure

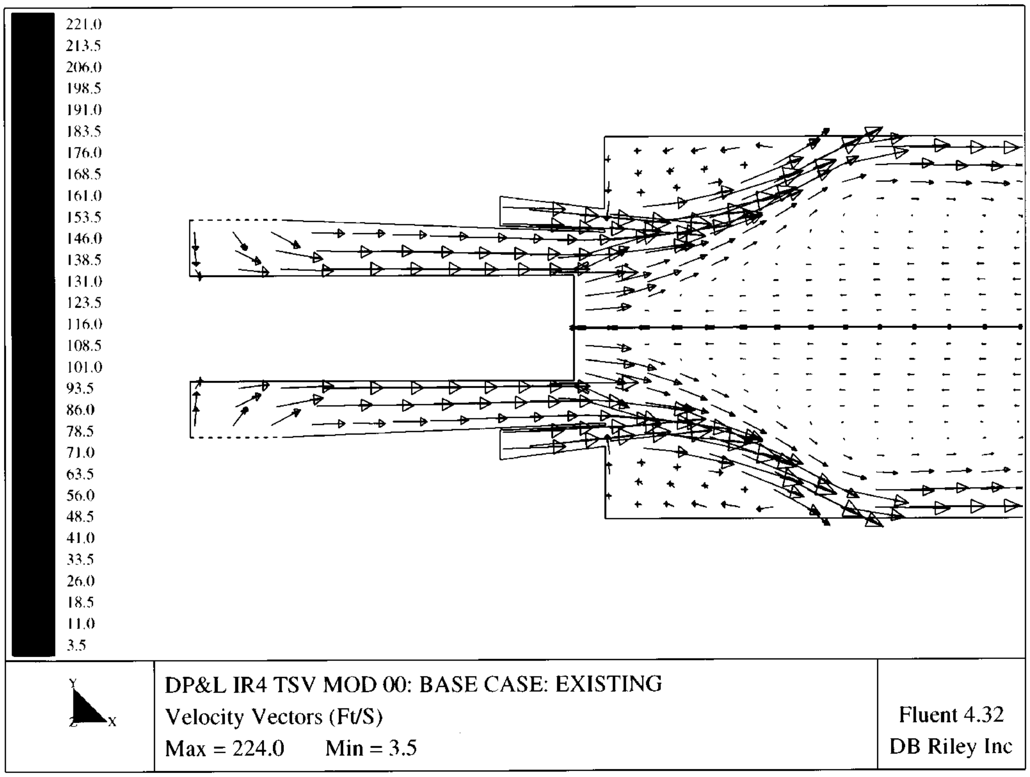


*Figure 5 Computed Near-Field Velocity Vectors for Aerodynamic-Only Original Burner Model*

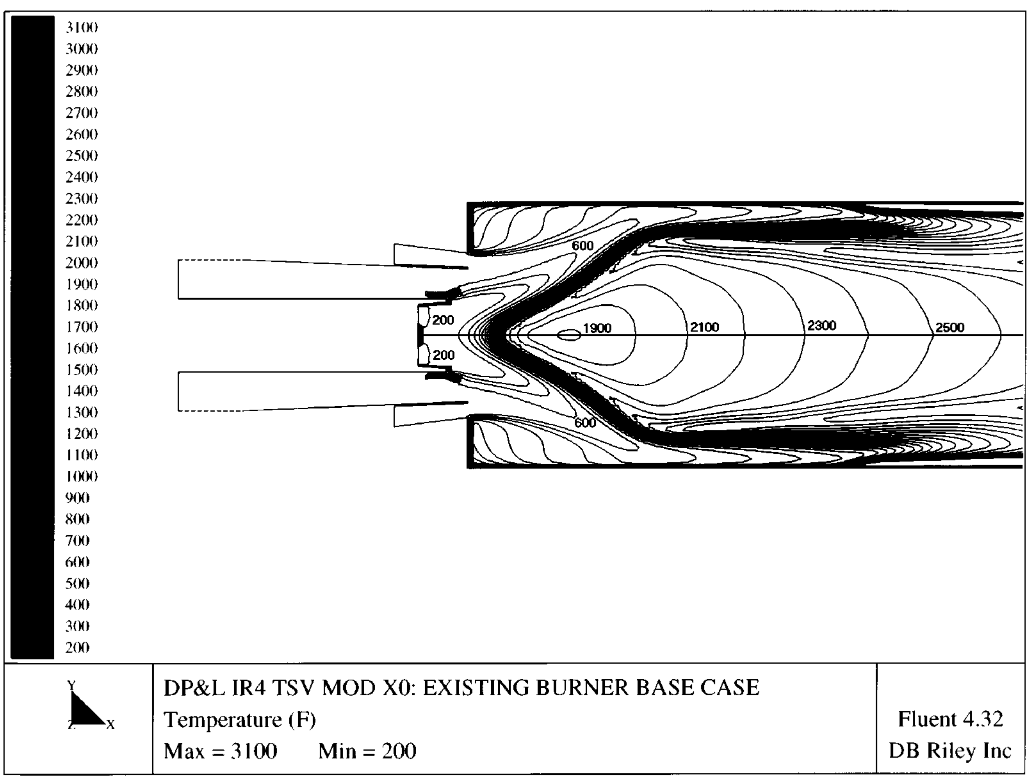


*Figure 6 Computed Isotherms for Original Burner Combustion Model*

5 suggests the outside-in IRZ of the original IR4 burner will give a detached flame at about 1/2 burner diameter off the nozzle. A detached flame will not produce low $NO_X$ since it quickly mixes SA into the primary ignition zone.

The flame boundary defines flame shape. In a CFD temperature distribution picture, the flame boundary is the narrow region where isotherms (lines of constant temperature) are spaced closely, indicating a rapid temperature change across a small distance. In Figure 6 the combustion model flame boundary corresponds closely to the IRZ limits for the aerodynamic-only model in Figure 5, which is essentially identical to the combustion model IRZ. This flow pattern agreement between aerodynamic and combustion models validates the modeling project tenet that combustion does not cure bad aerodynamics. Additionally, the flame shape in Figure 6 agrees well with field observations for detached flame location with a V-shaped flame base. This agreement between calculated and observed flame shapes gives confidence in the model results.

## MODIFIED TSV® BURNER DESIGN (NEW MODEL 3 TSV® BURNER

Figure 7 is a schematic drawing of the modified IR4 TSV® Burner, the final selected design which is the new Model 3 TSV® Burner. Figure 8 shows the CFD model burner near-field zone and highlights the small number of changes required:

- “Flame holding” ring at the end of the coal nozzle.
- TA diverter reshaping the TA annulus exit.
- New direct-mounted SA diverter.

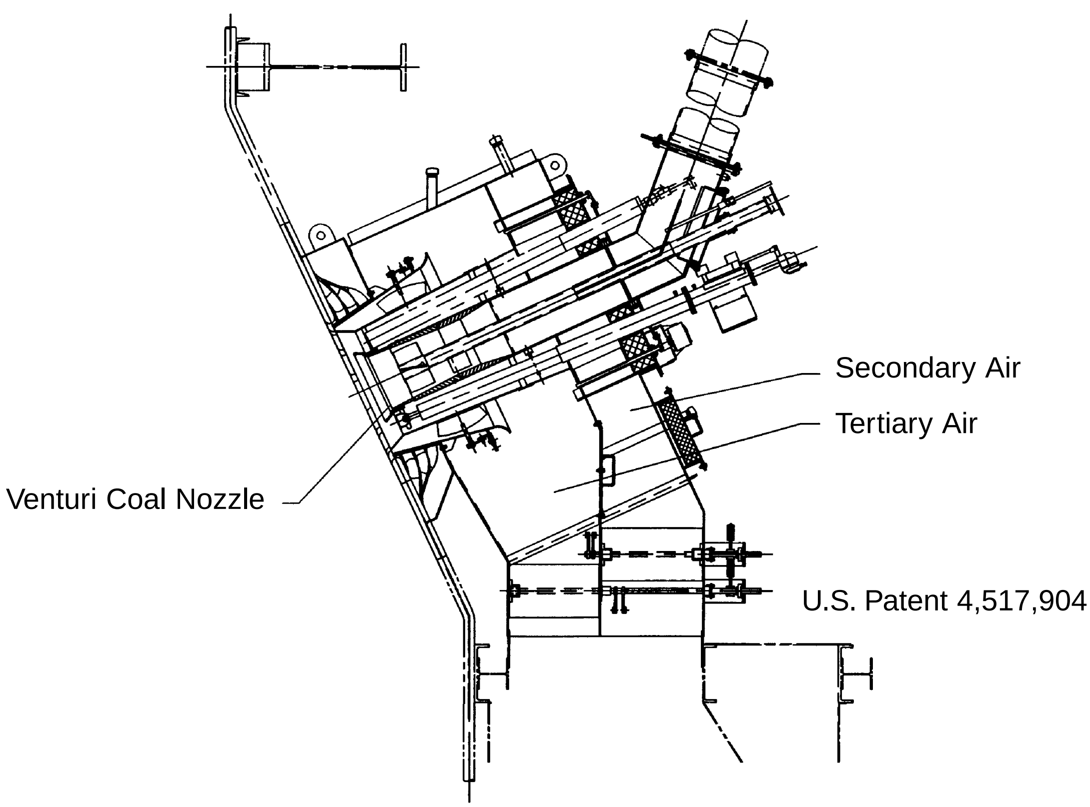


*Figure 7 Modified (New Model 3) TSV® Burner Installed at IR4*

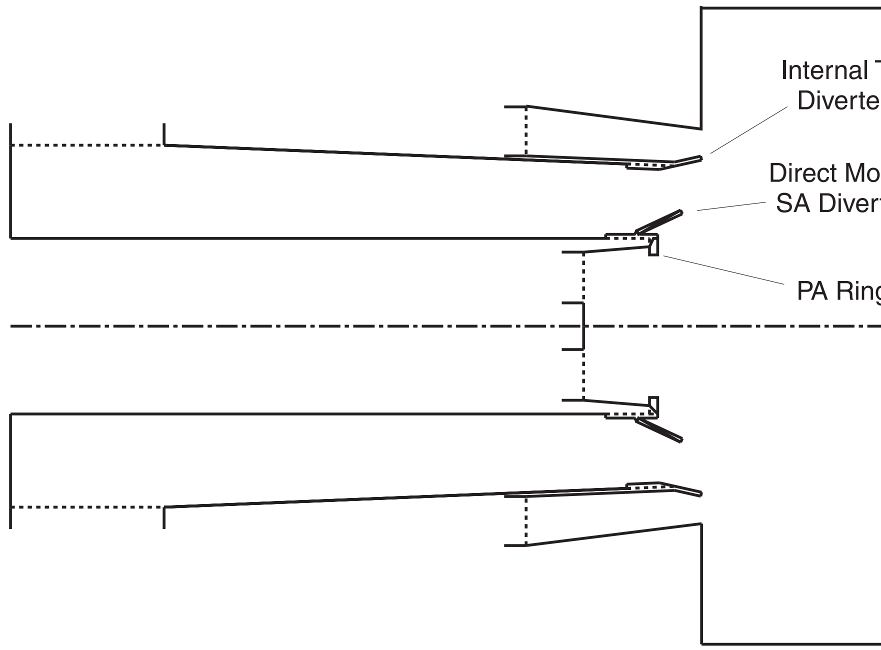


*Figure 8  Simple 2-D Axi-Symmetric CFD Model of Modified IR4 TSV® Burner (New Model 3) Highlighting Required Changes to Original Burner Model 2*

Figure 9 shows computed near-field velocity vectors of the purely aerodynamic, modified IR4 TSV® Burner model and Figure 10 shows the computed temperature field of the combustion case. Comparing Figures 9 and 10 for the modified burner to Figures 5 and 6, respectively, for the original burner, shows a dramatic change in flow pattern and flame shape. Only the geometrical changes in Figure 8 have been made to the burner. There are no operating conditions changes in PA, SA, or TA flow or swirl between these original and modified burner models.

The aerodynamic-only velocity vectors in Figure 9 show an “inside-out” IRZ compared to the “outside-in” IRZ in Figure 5. For the “inside-out” IRZ in Figure 9, swirling PA from the nozzle tip moves deep into the flame base along the burner axis before it spins out toward the SA to form a low-velocity return flow to the burner tip in an annulus between PA and SA streams. This inside-out IRZ does two important things:

1) It completely stops the SA from early or rapid mixing into the PA flow primary ignition zone deep in the flame base.

2) It provides a low-velocity return region for combustibles to produce complete and firm flame attachment to the burner tip.

In Figure 10 the combustion model flame boundary once again corresponds closely to the IRZ limits for the aerodynamic-only model in Figure 9, which again is essentially identical to the combustion model IRZ. The flame shape in Figure 10 shows complete attachment to the burner, excellent separation between SA and PA, and a slimmer flame base and finish than for the original burner in Figure 6. Unlike the poor aerodynamics of the original IR4 burner in Figure 5, the good aerodynamics of the modified IR4 burner in Figure 9 produce the desired flame characteristics. The predicted flame shape in Figure 10 agrees well with field observations and operational trials proving the good flame attachment suggested by the flame shape in Figure 10.

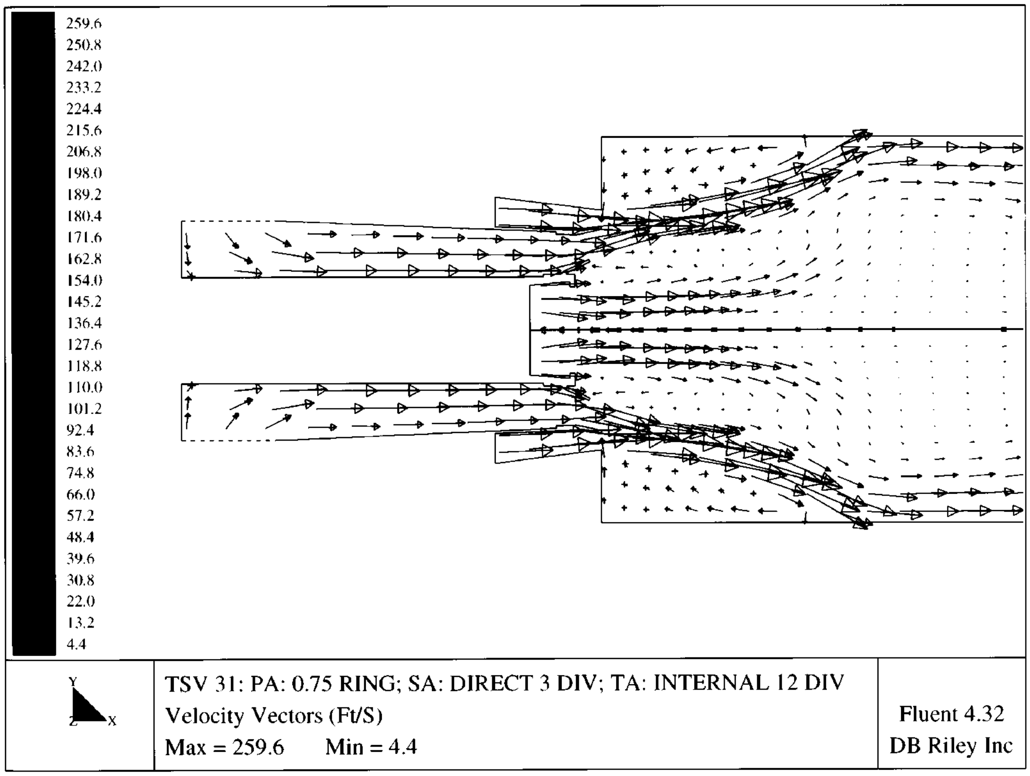


*Figure 9 Computed Near-Field Velocity Vectors for Aerodynamic-Only Modified Burner Model*

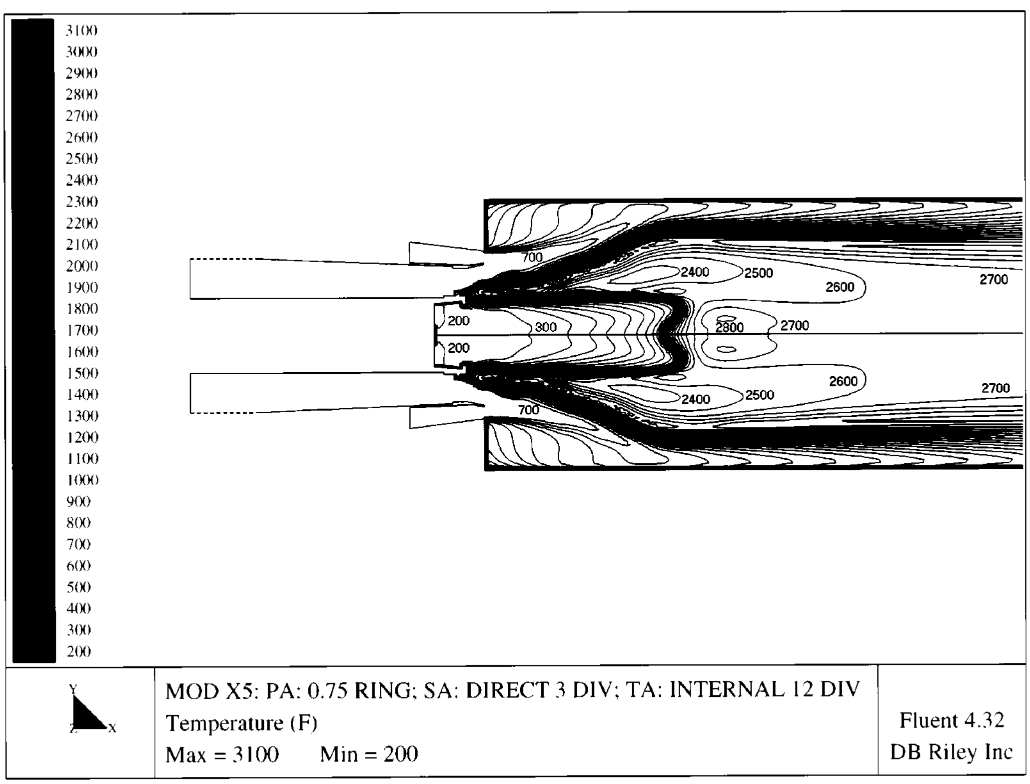


*Figure 10 Computed Isotherms for Modified Burner Combustion Model*

## ACCEPTANCE TEST RESULTS WITH MODIFIED (NEW MODEL 3) TSV® BURNERS

In late 1997 optimization tests were performed on the new Model 3 TSV® burner design at IR4 which showed promising results. The flame shape produced by the burner was observed as long and cylindrical in shape with the ignition point within 2-3 inches of the coal nozzle tip at all loads. Since the flames extended downward on a 22° inclined angle and are directly opposed, there was no concern about flame impingement on waterwall surfaces in the lower furnace. Flame scannability and stability throughout the boiler load range was excellent.

In January 1998 acceptance tests were completed successfully which showed that all guarantees were met. The final performance results are:

| | | | |
|---|---|---|---|
| Gross load, MW | 439 | 410 | 156 |
| Boiler load, % | 105 | 99 | 41 |
| Steam flow, lbs/hr | 3,108,850 | 2,907,250 | 1,216,500 |
| Coal spreader vane angle, degrees | 15 | 15 | 15 |
| Coal spreader retraction, inches from nozzle end | 6 | 6 | 6 |
| Classifier RPM | 122 | 127 | 127 |
| Secondary air swirl vane position, degrees | 35 (low swirl) | 35 | 35 |
| Tertiary air swirl vane position, degrees | 0 (no swirl) | 0 | 0 |
| Excess $O_2$, % at economizer outlet | 3.11 | 2.82 | 7.32 |
| SA/TA flow ratio | 0.94 | 0.76 | 1.21 |
| Burner stoichiometric ratio | 0.90 | ~ 0.90 | not determined |
| $NO_x$, lbs/$10^6$ Btu | 0.42 | 0.40 | 0.345 |
| CO, ppm at 3% 02 | 50 | 26 | 11 |
| Unburned carbon in flyash, % (Total carbon – carbonate carbon) | 11.4 | 9.0 | < 2.4 |
| SH outlet temperature, °F | 998 | 998 | 998 |
| RH outlet temperature, °F | 993 | 989 | 969 |
| Scanner signal intensity, % | 100 | 100 | 90-100 |

## FURTHER DESIGN IMPROVEMENTS IN NEW COMMERCIAL TSV® BURNERS

Test results in this project demonstrated that a TA swirl vane setting of 0, i.e., no TA swirl, produced acceptable burner performance. Therefore, future TSV® Burner designs may not be equipped with these axial swirl vanes and their linkages and operators to reduce burner costs.

Future commercial TSV® Burners will include Air Monitor Corp. Volu-Probes for accurate measurement of SA and TA flows in each of the burner passages to give better control of the SA/TA flow split.

Easier on-line coal spreader positioning is also featured in future commercial TSV® Burners.

An improved method of attachment for both the flame stabilizer ring at the end of the coal nozzle and the SA diverter will also be implemented in future TSV® Burner designs.

## SUMMARY

Working with DBR's parent company, Deutsche Babcock, and using CFD flow modeling, DBR developed a new TSV® Burner design incorporating elements of other DBR and DB low $NO_X$ coal burners with proven performance. The new Model 3 TSV® Burners were installed at Conectiv IR4 in the fall of 1997. The new burner design provides a well-attached flame over the complete load range in a quarl-less installation. Flame scannability is excellent over the entire unit load range. $NO_X$ emissions for this 400 MW utility TURBO® Furnace firing Eastern bituminous coal are reduced to low levels of 0.42 lbs/$10^6$ Btu (below the legislative requirement) at 105% load while CO emissions and flyash unburned carbon remained below required limits and guarantees.


## ACKNOWLEDGEMENTS

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