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Design of a High Removal Efficiency SCR System at Gallatin Fossil Plant Units 1 – 4

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ABSTRACT

Inventive designs are employed in the design and erection of four (4) Selective Catalytic Reduction (SCR) systems for the TVA Gallatin Fossil Plant located in Gallatin, Tennessee, in order to maintain adequate access requirements within the existing plant footprint while simultaneously meeting all of the design requirements.

Each TVA Gallatin SCR reactor is designed for a maximum outlet NOx emission of 0.030 lb/MMBtu with 92.5% design NOx removal efficiency at 2 ppmvd ammonia slip over a range of fuels (50/50 blend of Powder River Basin (PRB) and Illinois Basin coal to 100% PRB coal). The mixing system is designed to simultaneously achieve all requirements and meet an ammonia to NOx distribution of 2.0% RMS at full load. Riley Power Inc.'s (RPI) SCR experience, in conjunction with TVA and URS, has been utilized to meet all of the required performance parameters.

The SCR system designs for TVA Gallatin were based on a level of mixing that reduces capital and operating cost for a critical component of regulatory compliance. The tightened mixing RMS values are a result of physical flow modelling and Riley Power's exclusive Delta Wing® technology. Existing data from other units clearly demonstrates Riley Power's mixing capability and achievement of low mixing RMS values below the guaranteed performance requirements. Upon operation of these prior units, the SCR systems achieved the low mixing RMS values demonstrated in the model, thereby validating the physical flow model results. TVA is the first utility to specify and guarantee such a level and physical flow modelling has validated these results to date. Based on this, we can confidently project that the future performance of TVA Gallatin will meet the performance guarantees as specified by TVA, when constructed and operational by 2018. This paper presents an overview of the SCR system design factors for this project, including past model and full scale results demonstrating Riley Power's ability to achieve the performance guarantees we have made for TVA Gallatin.

INTRODUCTION

In December 2012, Riley Power Inc., a Babcock Power Inc. company, was contracted by TVA to supply four (4) Selective Catalytic Reduction (SCR) reactors (two (2) 250 MW and two (2) 275 MW) for Tennessee Valley Authority's Gallatin Fossil Plant located in Gallatin, Tennessee. Riley Power, in conjunction with URS and TVA, is supplying, designing and erecting the SCR reactors, ductwork, structural support steel, platforms, piping and electrical wiring. The scope of the project includes the design, fabrication, installation and commissioning of all ductwork, mixing systems, ammonia injection piping, reactors, catalyst, and instrumentation and controls for the complete SCR systems. Sonic horns are installed on each of the three (3) initially installed catalyst layers, with provisions for sonic horns on the future fourth catalyst layer. A vaporized anhydrous ammonia system is provided as the reagent source for the SCR systems. The SCR systems will be operational by 2018.

The TVA Gallatin SCR reactor designs are based in part on three (3) major factors: a wide fuel range, tight ammonia to NOx distribution, and construction and installation within the confines of the existing plant footprint. Each of these items is discussed in further detail below.

- The fuel range varies from a design blend of 50% PRB coal and 50% Bituminous coal up to a maximum of 100% PRB coal, which requires additional considerations in the catalyst design. The design blended fuel consists of an upper limit of 3.05 lb SO_2 /MMBtu while the 100% PRB coal consists of a lower limit of 0.295 lb SO_2 /MMBtu.
- The ammonia to NOx distribution guarantee is 2.0% RMS at full load (5.0% RMS at low load). Historically, the utility industry has required a 5.0% RMS guarantee at full load due to limitations in modelling and lack of perceived incentives to design to such a tight distribution. In order to make such a guarantee, it is necessary to not only model the mixing quality but also to determine from past experience the ability to achieve this performance level.
- The construction and installation of the SCR system requires modularization as well as inventive designs in order to maintain adequate access requirements within the existing footprint. The SCR structure and structural steel column locations are narrowed due to both new and existing interferences, requiring a large cantilever to carry the SCR inlet and outlet duct loads. Locations for the catalyst lifting zones are limited due to interferences. In addition, installation of all structural steel and ductwork will be accomplished by the use of a single hook roof crane given the limited access for cranes within the plant footprint.

BACKGROUND

TVA's Gallatin Fossil Plant has four (4) pulverized coal-fired boilers. Units 1 and 2 were commissioned in 1956 and 1957, respectively. Each boiler has a gross capacity of 250 MW. Units 3 and 4 were commissioned in 1959, and each has a gross capacity of 275 MW. All four (4) boilers are balanced draft, tangentially fired units supplied by Combustion Engineering and are equipped with low NOx burners.

The SCR reactors for TVA Gallatin are designed for the maximum load operating parameters summarized in Table 1 (Units 1&2) and Table 2 (Units 3&4).

Table 1. Unit 1&2 Max Load Design Operating Parameters

Parameter	Design Coal (50/50 PRB/Bit Blend)	100% PRB Coal
Boiler Heat Input, MMBtu/hr	2,400	
Flue Gas Flowrate, lb/hr	2,362,691	2,392,772
Economizer Outlet Temperature, °F	680	
Inlet SO_2, lb/MMBtu	3.05	0.295
Inlet NOx, lb/MMBtu	0.12 – 0.40	
Outlet NOx, lb/MMBtu	0.03	

Table 2. Unit 3&4 Max Load Design Operating Parameters

Parameter	Design Coal (50/50 PRB/Bit Blend)	100% PRB Coal
Boiler Heat Input, MMBtu/hr	2,640	
Flue Gas Flowrate, lb/hr	2,598,960	2,632,049
Economizer Outlet Temperature, °F	690	
Inlet SO_2, lb/MMBtu	3.05	0.295
Inlet NOx, lb/MMBtu	0.20 – 0.40	0.12 – 0.20
Outlet NOx, lb/MMBtu	0.03	

DESIGN FEATURES

Fuel Range

The planned fuels for the Gallatin plant consist of a 50/50 blend of Powder River Basin (PRB) and Illinois Basin (Bituminous) coals up to 100% PRB coal. As a result, the catalyst is designed for the complete range of fuels provided while achieving the guarantees and warranties identified in Table 3.

Table 3. Catalyst Design Guarantees

Parameter	Design Coal (50/50 PRB/Bit Blend)	100% PRB Coal
Outlet NOx, lb/MMBtu	0.03	
Ammonia Slip (end of guarantee period), ppmvd @ 3% O_2	2.00	
SO_2 to SO_3 Conversion (initial charge), mol% vol dry @ 3% O_2	0.25 per layer	0.37 per layer (Note 1)
Catalyst Life Warranty, hours	32,000 (Note 2)	24,000 (Note 3)

Note 1: Value provided for reference only; guarantee based on Design Coal.
Note 2: Based on an inlet NOx of 0.200 – 0.400 lb/MMBtu.
Note 3: Based on an inlet NOx of 0.120 – 0.200 lb/MMBtu.

Ammonia to NOx Distribution

The ammonia to NOx distribution guarantee for TVA Gallatin is 2.0% RMS at full load (5.0% RMS at low load). TVA is the first utility to specify a guarantee at such a level. The improved modelling methods and tightened mixing RMS values guaranteed for this project are a result of Riley Power's licensed Delta Wing® technology. The physical flow modelling completed for TVA Gallatin has validated the mixing requirements. Based on this, we can confidently project that the future performance of TVA Gallatin will meet the performance guarantees as specified by TVA.

Construction and Installation

The erection of the SCR reactors, ductwork and structural support steel is included in Riley Power's scope of supply. Ductwork will be modularized and shipped to the projects site via truck. Ductwork will be further modularized, erected, welded, insulated and lagged by the installing contractor on site. This will allow for a reduction in field assembly time and a significant cost savings.

RESULTS AND DISCUSSION

Fuel Range

The fuel range for the SCR reactor systems varies from a design blend of 50% PRB coal and 50% Bituminous coal up to a maximum of 100% PRB coal. In addition, specific blends of 85% PRB/15% Bituminous coal and 75% PRB/25% Bituminous coal have been identified as potential fuels. This requires additional considerations in the catalyst design for the varied NOx and Sulfur Dioxide (SO_2) in the fuel as well as the flue gas temperature range.

The inlet NOx varies from 0.12 to 0.40 lb/MMBtu, depending on the fuel blend that is burned. The catalyst life warranty of 32,000 hours applies to the design coal only, with an inlet NOx ranging from 0.20 to 0.40 lb NOx/MMBtu. By comparison, the catalyst life warranty of 24,000 hours applies to the 100% PRB coal only, with an inlet NOx ranging from 0.12 to 0.20 lb NOx/MMBtu.

The blended fuel (design coal) consists of the upper limit of 3.05 lb SO_2 /MMBtu. By comparison, the 100% PRB coal consists of the lower limit of 0.295 lb SO_2 /MMBtu. The catalyst SO_2 to SO_3 conversion rate guarantee of 0.25% oxidation per installed catalyst layer is based on burning the blended design fuel.

Variations in fuel characteristics can have a considerable impact on catalyst life. The nature of the fuel fired will dictate in large part the rate of catalyst deactivation. Historical data and past experience are key to an accurate assessment of what to expect in the future for the range of fuels provided.[1] The initial catalyst charge for TVA Gallatin, provided by Cormetech®, is designed for the properties identified in Table 4.

Table 4. Catalyst Design Criteria

Parameter	Description
Catalyst Type	Honeycomb
Catalyst Formulation	Titanium (Ti) – Tungsten (W) – Vanadium (V)
Catalyst Pitch, mm	8.2
Module Arrangement per Layer (W x D)	6 x 12
Number of Layers per SCR (Initial / Future)	3 / 1
Minimum Ammonia Injection Temperature (Maximum Duration 100 Hours), °F	600 for Design Coal 590 for 100% PRB Coal
Continuous Operating Temperature, °F	678 for Units 1&2 690 for Units 3&4
Max Catalyst Operating Temperature, °F	800

The catalyst for TVA Gallatin was designed for the complete range of fuels and expected operating conditions provided. This is crucial in order to mitigate the deactivation of catalyst and assure achievement of the performance guarantees.

Ammonia to NOx Distribution

A major factor in the design of a high removal efficiency SCR system is the ability to inject and distribute the ammonia into the flue gas stream upstream of the catalyst. The ratio of ammonia to NOx is therefore the essential design parameter for high removal efficiency SCR systems. The standard deviation of ammonia to NOx at the catalyst face is a measure of the mixing system's uniformity or performance. For 90% removal systems a standard deviation of ammonia/NOx ratio of 5% is typically chosen.[2] For TVA Gallatin, a more stringent ammonia to NOx concentration ratio of 2.0% RMS has been specified at full load (92.5% NOx removal based on an inlet NOx concentration of 0.40 lb/MMBtu). The improved modelling methods and tightened mixing RMS values guaranteed for this project are a result of Riley Power's experience with its licensed Delta Wing® technology. Retrofit SCR systems with limited space and high NOx removal requirements are ideal applications for the Delta Wing® static gas mixing systems, which were first developed and applied in Europe.[3]

Riley Power's SCR system designs utilize Delta Wing® mixing systems to provide uniform conditions across the catalyst surface. To design the Delta Wing® mixing system, 3D physical flow modeling was conducted at two (2) model scales based on the size of the full-scale application, customer requirements, and test facility capabilities. These models were used to develop a mixing system design that does not require a large ammonia injection grid and remains flexible across boiler loads.[4]

For TVA Gallatin, the physical models included a 1:30 scale flow model and a 1:18 scale dust model. The smaller flow model (Figure 1) was designed to provide for optimization of the mixing system and identification of performance parameters (ammonia to NOx distribution, etc.) and flow distribution. The larger dust model (Figure 2) was designed to provide verification of flow model test results and identification of areas of dust settlement within the ductwork and reactor. The physical flow model studies have verified the flow conditions of the SCR system performance, including the ammonia to NOx guarantee of 2.0% RMS at full load.

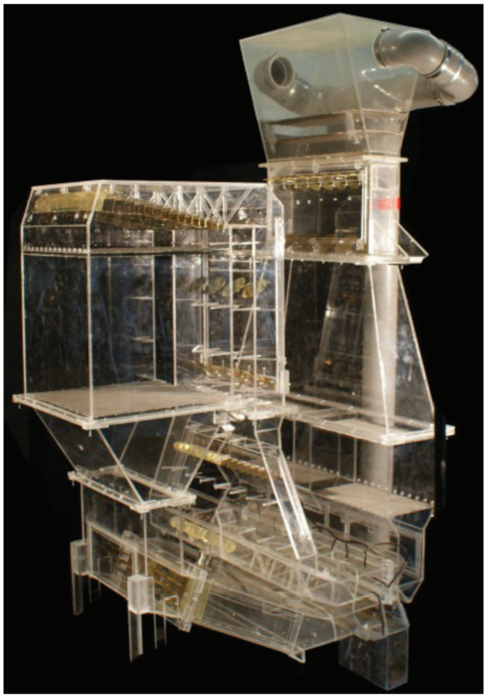

Figure 1 – TVA Gallatin SCR Flow Model
(1:30 Scale)

Figure 2 – TVA Gallatin SCR Dust Model
(1:18 Scale)

Successful modeling of an SCR system requires capability and experience in modeling as well as experience with the characteristics of the mixing system. Riley Power's SCR systems perform to standards unmatched by other SCR system suppliers in part due to the modeling work conducted for each application. The physical flow modeling for TVA Gallatin, as with all Riley Power SCR designs, was conducted by Ruscheweyh Consult GmbH (flow model) in Würselen, Germany, and Balcke-Dürr GmbH (dust model) in Ratingen, Germany.

Experience using reduced-scale physical flow models in the design of SCR gas mixing systems is important to ensure that flow patterns observed in the model are similar to those of a full-size SCR system. A number of important factors must be considered. This includes the maintenance of geometric similarity between the model and full-scale system (Reynolds Number, Euler Number and Barth Number), as well as taking into account velocities, velocity head values and the values of significant dimensionless parameters that characterize the flow.

The dimensionless parameters have a physical significance and govern the relationship between flow in the model and the full-scale SCR duct system. They represent the ratio of various forces acting on the dust laden gas flow. These parameters also account for the differences in fluid properties between the model and full size unit (i.e.: air versus flue gas) and differences in temperature (i.e.: ambient versus approximately 700°F). NOx and ammonia concentrations are represented in the SCR air flow model by an oil fog or a gas tracer (CO^2). In coal-fired applications, light hollow glass spheres are used to simulate fly ash in the SCR dust flow model.

Two (2) physical model studies were constructed for TVA Gallatin, one (1) for Units 1&2 and one (1) for Units 3&4. Each physical model was constructed from plexiglass and simulated the flow from the boiler back-pass economizer outlet flanges, including the LPA screens and economizer hoppers, to the air heater inlet flanges.

The flow model inlet boundary conditions were based on the flue gas flow, NOx and temperature profiles as summarized in Table 5. The physical flow model, as tested at three (3) operating loads (full, intermediate and minimum), determined the mixing elements needed to achieve uniform flow and velocity distributions at the catalyst face as well as to achieve proper distribution into the air heater as summarized in Table 6. The dust model was performed to establish uniform distribution of dust across the SCR and identify any areas for potential ash layout in the system.

Table 5. Physical Flow Model Inlet Boundary Conditions

Parameter	Value
Velocity	± 20% of mean
Temperature	± 28°C (± 50°F) of mean
NOx	± 30% of mean

Table 6. Performance Guarantee Distribution Requirements

Parameter	Basis (% of Surface)	Value	Location
Velocity	80% 100%	± 10% of mean ± 20% of mean	Above first layer of catalyst
NH_3/NOx	100%, full load 100%, low load	± 2.0% RMS ± 5.0% RMS	
Temperature	100%	± 10°C (± 18°F)	
Dust	100%	0.25 standard deviation from mean value	
Angle of Flow	100%	± 10° from vertical	
Velocity	100%	15% RMS	Air heater inlet

The flue gas was simulated by ambient air provided by the flow laboratory fans. The ammonia stream was simulated by an air-fog mixture to rough tune the mixing elements followed by CO_2 for the final testing. The gases were injected through six (6) nozzles at the first row of the ammonia mixer, which represent the optimum solution found by the test for the given duct geometry as shown in Figure 3. Grids at the first and last catalyst layers simulate the catalyst pressure loss and provide a proper indication of flow conditions in the catalyst bed.

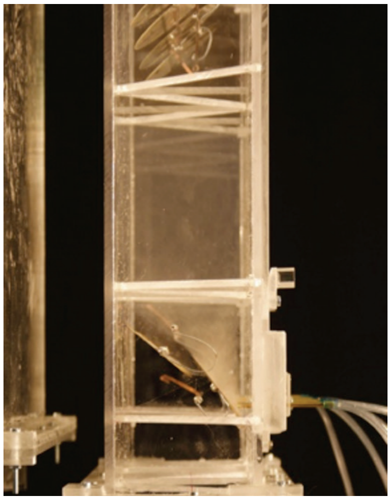

Figure 3 – Visualization of the Mixing Process at the Ammonia Mixer

The project specified ± 30% inlet NOx variation at the economizer outlet, which was reduced via the installation of Delta Wing® mixers to + 7.5% / - 6.5% upstream of the catalyst. In order to have guidelines for the adjustment of the six (6) ammonia nozzles, the influence field of each ammonia nozzle was measured, with only one (1) nozzle in operation at a time. The values were then normalized with the measured maximum value in order to maintain the same reference level for each influence field. To determine the ammonia to NOx Distribution, a computer aided superposition of the normalized NOx concentration upstream of the catalyst and the six (6) ammonia influence fields was performed. As shown in Figure 4, the resulting distribution is 1.5% RMS, which is below the contract guarantee.

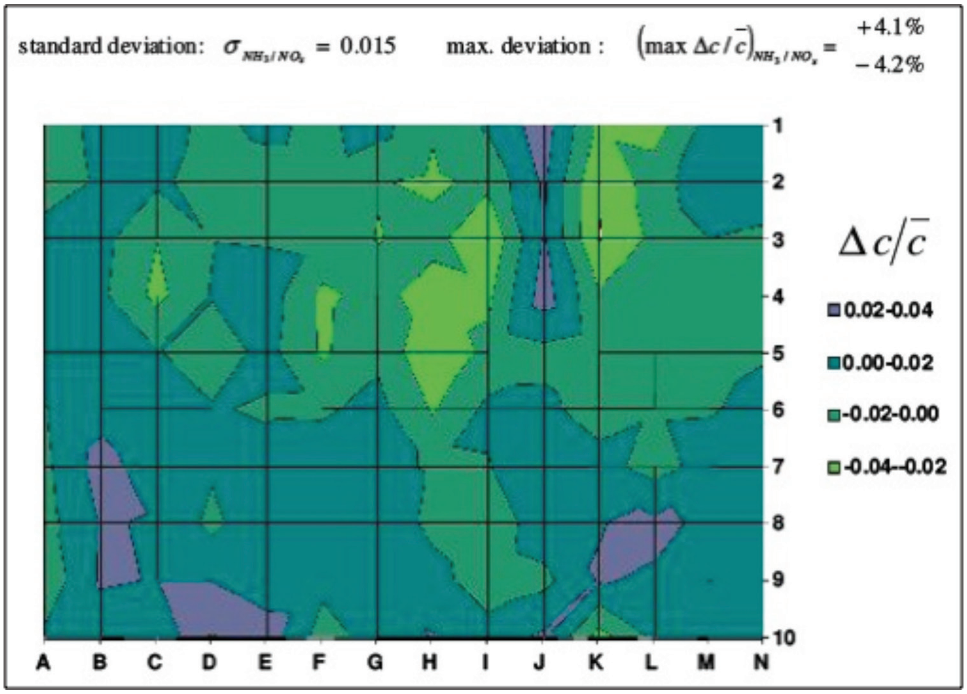

Figure 4 – Calculated Superposition of Ammonia to NOx Distribution

Riley Power has installed SCR reactor systems on more than 85 boilers, all of which have had physical flow models constructed and optimized by Ruscheweyh Consult, GmbH and Balcke-Dürr GmbH. Eleven (11) of these SCR reactor systems in the recent past have had contractual NH_3/NOx distribution guarantees. As shown in Figure 5, ten (10) out of the eleven (11) SCR reactor systems have been optimized in the flow model below the NH_3/NOx distribution guarantee. The higher distribution shown for SCR system number 4 was observed at three (3) points in one corner only, which was due to the duct geometry. Optimization and tuning of the ammonia injection valves in the model is not typically performed, however these field adjustments have shown in the past to be able to improve upon the model distributions. (SCR system numbers 12 and 13 are the TVA Gallatin Units 1&2 and Units 3&4 systems, respectively, which are not scheduled for start-up and performance testing until 2018.)

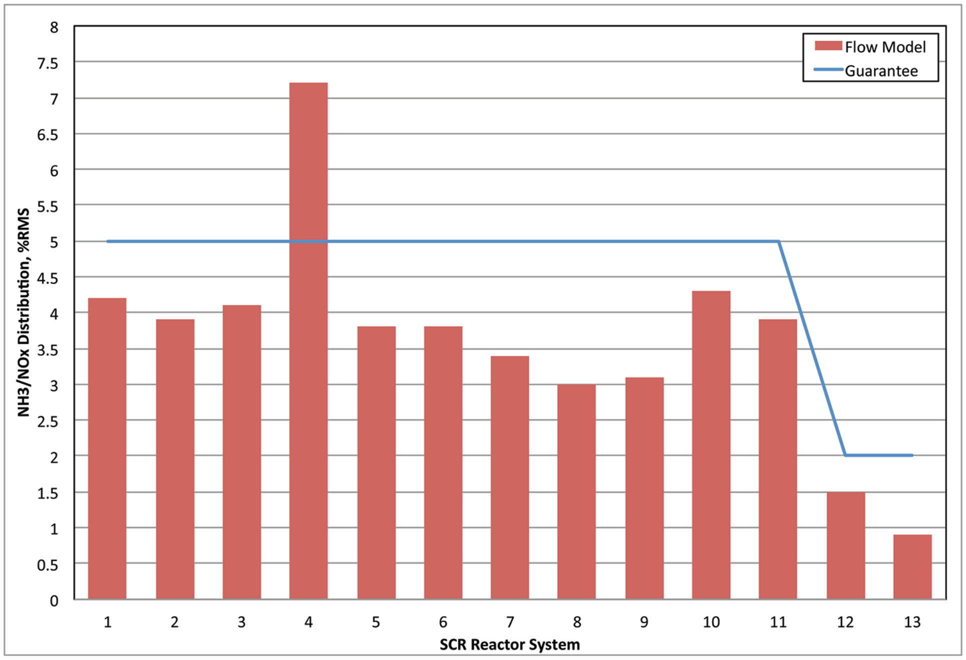

Figure 5 – NH_3/NOx Distribution Guarantees vs. Flow Model Results

As shown in Figure 6, all eleven (11) reactor systems have performed at or below the guaranteed NH_3 – /NOx distribution limits as observed during performance testing, thereby validating the physical flow model results. This historical data demonstrates the mixing capability and achievement of low mixing RMS values below the guaranteed performance requirements. Based on this, we can confidently project that the future performance of TVA Gallatin will meet the performance guarantees as specified by TVA.

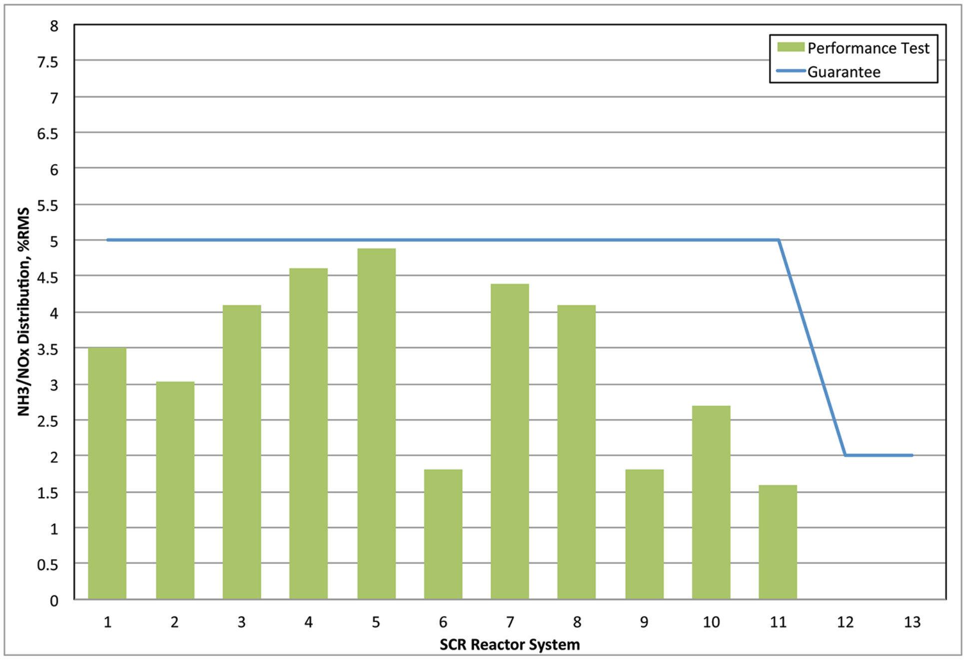

Figure 6 – NH_3/NOx Distribution Guarantees vs. Performance Test Results

Construction and Installation

In the construction and installation of the SCR reactors, the highest priority is placed on the safety of all personnel. This includes TVA plant employees, the employees of Riley Power, all other on site contractors and the general public, protection of the physical plant, protection of the environment including air, water and soil and the continuous generation of electricity. All necessary precautions will be taken to protect personnel from injury. There is an added degree of difficulty in the design of the SCR reactor systems for TVA Gallatin due to the construction and installation requirements within the limited space of the existing plant footprint. As a result, the design of the SCR reactors is focused on system modularization and constructability. Specifically, the areas of added focus are the SCR structure and structural steel column locations, installation of all structural steel and ductwork, location of the catalyst lifting zones, and modularization of the ductwork in the shop prior to shipment as well as in the field prior to installation.

SCR REACTOR AND STRUCTURAL STEEL COLUMN LOCATIONS

The SCR structure and structural steel column locations are narrowed due to both new and existing interferences, requiring a large cantilever to carry the SCR inlet and outlet duct loads. The cantilevered structure design allows for clearance of the forced draft (FD) fan intake hoods that would have otherwise obstructed the new column locations. This design is required due to the TVA plant design that locates the FD fans below grade; the concrete roof of the FD fan room would not support the column loads from the SCR support structure. This design utilizes the weight of the SCR reactor box to counterbalance the weight of the ductwork that is located in the cantilever section of the steel structure. In addition, this design reduces the structural steel weight and allows for installation of ductwork once 75% of the structure is erected.

STRUCTURAL STEEL AND DUCTWORK INSTALLATION

The structural steel is supplied galvanized and will be erected and bolted utilizing direct tension indicator (DTI) washer for proper bolt torque control. In addition, installation of all structural steel and ductwork will be accomplished by the use of a single hook roof crane given the limited access for cranes within the plant footprint. The plan is to group assemble structural steel pieces into subassemblies that will be lifted into position with the single available crane. This roof crane will have the capability to move along the boiler house roof. In addition to the roof crane, a “bogy” cart will be installed to set the pieces on the structure with a separate tower crane. Once the steel or duct section is placed on the cart, it is moved across to the location where the crane is operating. This allows for a smooth flow of construction activity.

CATALYST LIFTING ZONE LOCATIONS

Locations for the catalyst lifting zones are limited due to interferences. As a result, the lifting zones for SCR reactors on TVA Gallatin Units 2 and 3 are tucked inside the structural steel as shown in Figure 7 and Figure 8. High speed electric lifting winches raise the catalyst from the ground to the catalyst loading levels. Once at the catalyst loading elevations, Army trolleys are used to move the catalyst into the SCR reactor.

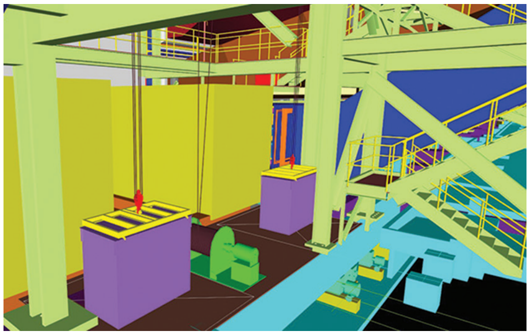

Figure 7 – Elevation View of Catalyst Lifting Zones (Units 2 and 3)

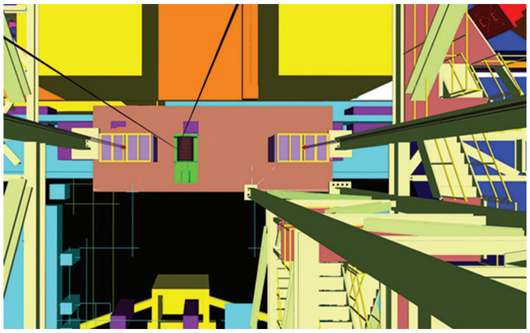

Figure 8 – Plan View of Catalyst Lifting Zones (Units 2 and 3)

DUCTWORK MODULARIZATION

The SCR ductwork is modularized to be shipped to the project site via truck (see Figure 9). Once on site, the ductwork will be further modularized, erected, welded, insulated and lagged, by the installing contractor. By maximizing the shop fabrication/modularization of the equipment, including all internal flow correction devices and necessary steel bracing and truss work in the ductwork, a reduction in field assembly time and an increase in cost savings is realized as compared to flat panel SCR systems.

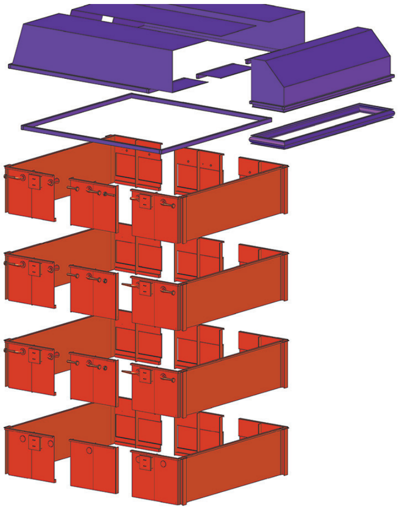

Figure 9 – Exploded View of SCR Reactor

These savings can be found through:

- Reduction of field construction labor required to ground fabricate/modularize flat panels to modularized sections
- Improvement to the overall project schedule through better labor productivities
- Higher degree of quality control (dimensional accuracy and control through shop trial fit-up of assemblies)
- Personnel safety (given the fabricator's controlled shop environment, consistent jigs, tools, and equipment versus the site's variable weather conditions, craft supplied tools and rented equipment)

These combined benefits further minimize the projects overall risk to the owner, engineer, and erector.

SUMMARY

The TVA Gallatin SCR reactor designs are based in part on three major factors: a wide fuel range, tight ammonia to NOx distribution, and construction and installation of the SCR system within the confines of the existing plant footprint. The SCR reactor system has been designed to accommodate the ammonia to NOx distribution requirements and potential fuel range. In addition, physical flow modelling has optimized the ammonia injection design in order to meet the stringent distribution requirements. We can predict with high confidence the achievement of the ammonia to NOx distribution guarantee, when the systems begin operation in 2018, based on our exclusive Delta Wing® technology, historical flow modelling and performance testing results of the installed SCR systems. The construction and installation of the SCR systems include inventive designs in order to maintain adequate access requirements within the plant footprint while simultaneously meeting all of the design requirements, guarantees and safety requirements.

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KEYWORDS

SCR Reactor, physical flow model, ammonia to NOx distribution, % RMS, ductwork modularization, catalyst