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ADAPTING THE GERMAN COAL-FIRED SCR EXPERIENCE TO THE U.S.

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ABSTRACT

There is agreement that the latest U.S.-EPA and State Implementation Plans regarding NOx reduction will require application of Selective Catalytic Reduction (SCR) Systems on utility power plants. Just as the U.S. benefitted greatly from the experience gained by European installations of Wet Flue Gas Desulfurization (WFGD) for compliance with the 1990 Clean Air Ash Conveying Technologies Amendments Phase I regulations, so too can we gain valuable insight from an examination of the European SCR installations. A detailed discussion of coal-fired SCR installations is presented. Included are discussions of the design basis, retrofit considerations, installation and construction experiences, commissioning test results and long term operating results. The plants discussed will be from the over 7,000 megawatts of installed SCR Systems experience, several with over ten years continuous operation.

INTRODUCTION

The Selective Catalytic Reduction Systems to be designed for US. installations can benefit greatly from an examination of the European Selective Catalytic Reduction (SCR) installations. The importation and adaptation of the German SCR technology and the simultaneous preservation of the core technology is the challenge that lies ahead for the designer of the future U.S. SCR Systems. The German technology holds forth the best experience base of long term performance of SCR systems on coal and should be the platform upon which we in the U.S. build.

In the past there has been a very meaningful exchange of information between the U.S. and Europe, the best recent example being the technology for Wet Flue Gas Desulfurization (WFGD) Systems. Recall that the original U.S. Clean Air Ash Conveying Technologies of 1970 stimulated the development of the limestone WFGD System which was then exported to Germany for use in response to their regulations. The German regulations of the 1980s encouraged the further development of the U.S. type WFGD system to include generation of a gypsum by-product. In turn, the 1990 U.S. Clean Air Ash Conveying Technologies Amendments for S02 control were largely met by the re-importation of the German type WFGD systems back to the U.S. with considerable success. Overall, the application of these systems in the U.S. cost less than the original projections and performed very well.

This is significant if you appreciate that the technology was re-imported to the U.S. in an atmosphere of severe cost reduction pressure and, simultaneously, in a manner that preserved the core technology.

We can successfully repeat this process of technology importation for SCR Systems. Once again, as with WFGD, the marketplace will certainly produce significant cost reduction pressure and, again, the core technology must be preserved and applied in a manner that achieves the long-term performance already demonstrated.

Why look to Germany for this SCR technology? The German SCR installations on coal-fired boilers total about 33,000 megawatts, equal to about 70% of the world's coal experience base. The Deutsche Babcock coal-fired SCR installations in Germany, that form the experience basis of this paper, had start-ups as early as 1986 and total over 5,000 megawatts.

In general, there have been three basic system configurations: SCR after economizer, SCR after precipitator, and SCR after Wet FGD. In the U.S. it appears that the SCR after the economizer arrangement will dominate due to (1) the need to operate the reactor within a certain temperature range, and (2) the high cost of the gas-gas heat exchanger if the SCR is located anywhere but directly after the economizer. In addition, even when the SCR is located directly after the economizer, an economizer by-pass may be needed to achieve operating temperatures at low boiler load, especially in retrofit situations.

Deutsche Babcock has experience with both the "SCR after economizer" and "SCR after Wet FGD" system configurations. Since the issue in the U.S. is largely coal firing and all the associated concerns with flyash, S02 conversion, etc., the focus of this paper is only those SCR Systems arranged immediately after the economizer.

SYSTEM DESIGN CONSIDERATIONS AND CONSTRAINTS

The SCR System designer is faced with many considerations and constraints, both process and mechanical arrangement, including:

- Inlet NOx Concentration
- Outlet NOx Concentration
- Operating Temperature Range
- Ductwork System Arrangement
- Fuel Characteristics
- Flyash Loading and Properties
- S02 and SO3 Concentrations
- Boiler Firing Method and Overall Operation
- System Pressure Drop and Impact on Fans
- Reagent Source and Ammonia Slip Allowable
- Reactor Support Configuration and Space Constraints

These factors are what could be termed the macro or system considerations. While some of them certainly do affect the catalyst selection and process chemistry, they go beyond that and *affect* the entire SCR and Boiler System. After all, the retrofit of an SCR System to an existing boiler is not simply the addition of a few more components (to an already complex process), but rather the modification of an entire process to generate a new set of results. In fact, on many of our projects we have considered enhancements to the boiler operation as a part of the SCR retrofit.

The following is a presentation of several SCR Systems installed and operating for some time. Important lessons were learned and are presented here in the hope that they are not repeated as the technology is incorporated into the future U.S. SCR System installations. The presentation is sequential along a time line for clarity; but in reality, many of the events occurred in parallel.

This paper presents four projects: KW Reuter, Munchen Nord, Dormagen, and Nordjyllandsvaerket.

KW REUTER PROJECT

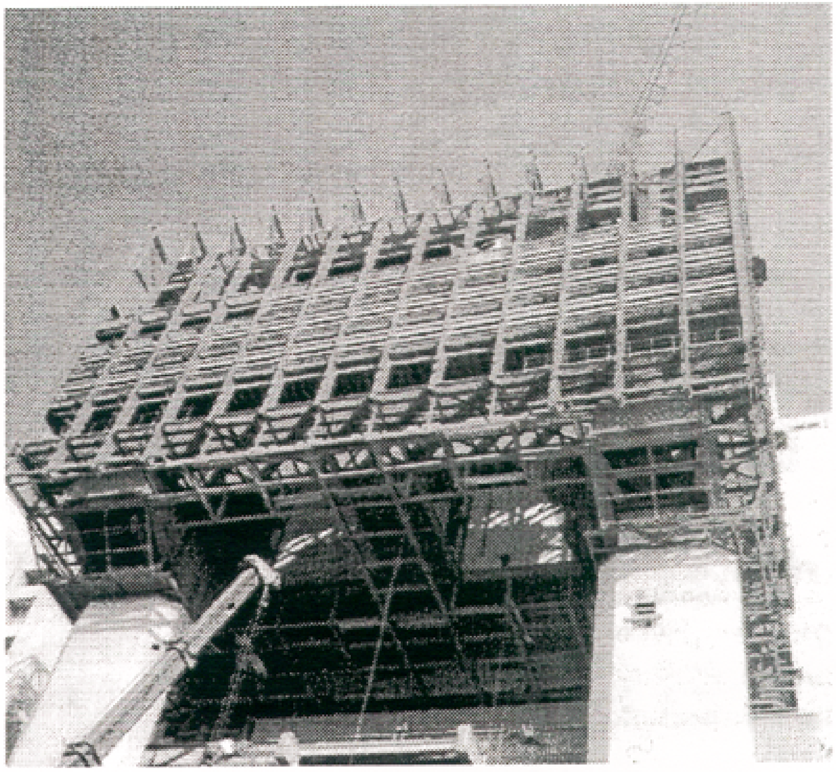
The KW Reuter Project is a retrofitted SCR System to each of two 300 MW pulverized bituminous coal-fired boilers. The SCR Systems started up in November 1988 and January 1989 respectively. The SCR reactors are top-supported and located immediately after the economizer. Anhydrous ammonia is injected through a multi-nozzle grid and the catalyst is honeycomb type with a 7.5 mm pitch. (This pitch dimension is roughly the length of one side of the square opening through which the gas flows.) The inlet NOx is about 650 mg/Nm^3 (0.52 Lbs/10^6 Btu) and the reduction is 77% to 150 mg/Nm^3 (0.12 Lbs/10^6 Btu). The end-oflife ammonia slip guarantee was 5 ppm at 20,000 hours. The flyash loading is fairly typical at 11, 700 mg/Nm^3 (about 6 gr/dscf).

This project was designed, constructed, and successfully put into operation. Unfortunately the ductwork configuration contained a relatively short, but nevertheless troublesome, horizontal run. During prolonged low load boiler operation the gas velocity was not sufficient to keep all the flyash in suspension and some of the flyash settled out on the floor of the horizontal duct. When there was a rapid increase in load from very low to very high, the flyash traveled as a moving dune and flowed at very high concentrations into the reactor. This high flyash loading overwhelmed the catalyst to the point that the flyash accumulated on a section of the uppermost surface of the catalyst face and greatly restricted gas flow. The pressure loss became excessive and load was curtailed to unacceptably low levels.

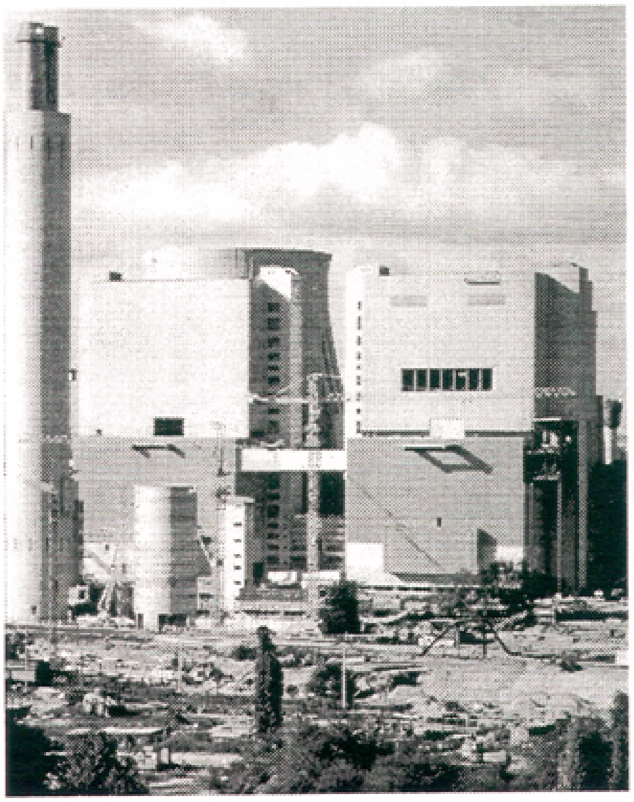
The solution was not elegant but was very effective. Ash hoppers were installed immediately upstream of the reactor entrance. This configuration diverted the ash flow from the reactor and catalyst face and allowed satisfactory operation.

The lesson learned here is that the ductwork has to be approached and designed as integral to the SCR-Boiler System and made compatible with, or better yet, an enhancement to, the SCR System performance.

Now, ten years later, it may seem obvious that an ash hopper should have been installed in the first place, but during the design phase it is never that clear. The designer must fully understand the ash characteristics and loading under normal full-load operation, part-load operation, when sootblowing, or when other unusual occurrences may need to be considered. A reason to want to avoid such hoppers may be based on the general experience with econ-



KW Reuter SCR during construction



KW Reuter SCR

omizer hoppers, which may well be the most difficult ash hoppers in the boiler system to maintain in a flowing condition. In addition, introducing a second set of hoppers immediately upstream of the SCR Reactor, operating under similarly difficult conditions as the economizer hoppers, may decrease reliability. On the other hand, hoppers may prove necessary.

We have found the best solution to be a total ductwork system approach. Utilizing the known characteristics of the ash, ash samples if available, and the loading information under normal and unusual operating conditions, a system configuration is developed that considers these factors and takes a total ductwork system approach to develop the plant con-figuration. Next, using the proposed ductwork and reactor configurations, a system three-dimensional flow model is produced that can, through empirical evaluation, detect and eliminate flyash accumulations both in the ductwork and on the face of the catalyst. The plant arrangement is then finalized incorporating the knowledge gained from the flow model. In extreme cases hoppers may be the best solution, but often they can be avoided through optimizing the ductwork configuration. This achieves overall system cost reduction and simplified system operations.

At KW Reuter, after a few years of operation, the owner had experienced problems with low boiler exit temperature operation. Operation below a minimum temperature can cause ammonia salts to deposit on the catalyst surface. The owner elected to retrofit an economizer by-pass to keep the gas temperature higher at low loads. The retrofitted economizer by-pass introduced two new problems; a non-uniform NOx concentration profile in the flue gas and a flue gas flow mal-distribution. Attempts were made to improve performance, adjusting the ammonia injection flow among the 130 nozzles that make up the grid. This did not correct the situation. Ultimately, three years after initial start-up, a new technology was retrofitted that did correct the situation. This new technology is an improved injection and mixing technology developed at another plant, the details of which are discussed later in this paper.

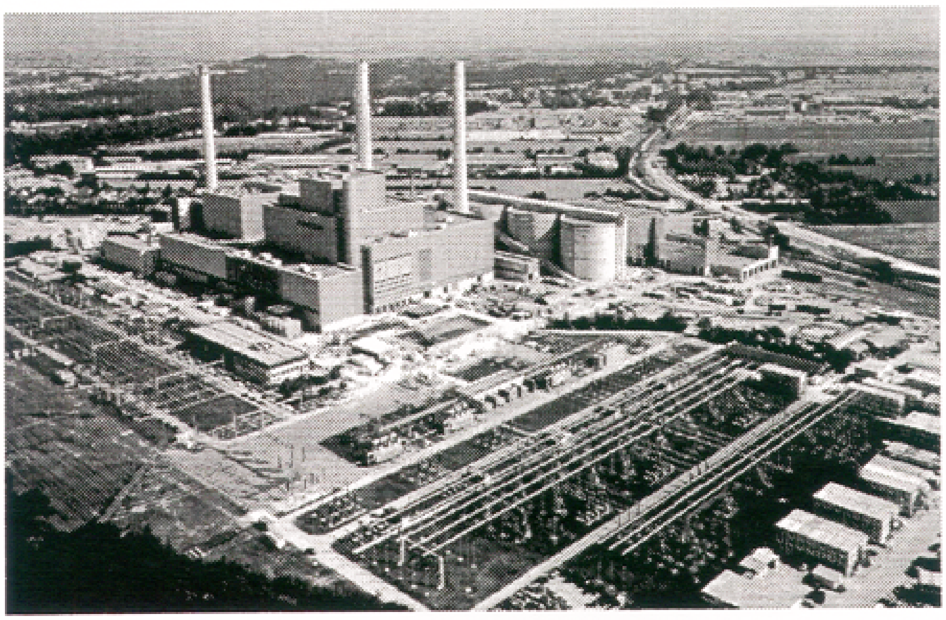
MUNCHEN NORD PROJECT

The Munchen Nord Project is a SCR System on a new 300 MW pulverized bituminous coal- fired boiler that achieved commercial operation in 1991. The SCR reactor is top-supported and located immediately after the economizer. The anhydrous ammonia was originally to be injected through a grid system but this method was modified as discussed below. The catalyst is the plate type with a 5.2 mm pitch. The inlet NOx is 700 mg/Nm^3 (0.56 Lbs/1 0^6 Btu) and the reduction is 85% to 100 mg/Nm^3 (0.08 Lbs/10^6 Btu) with an ammonia slip of 5 ppm. The flyash loading is 14,000 mg/Nm^3 (about 7 gr/dscf).

This unit also has an economizer by-pass, thought to be necessary at the time for low load operation, and an SCR reactor by-pass, thought to be necessary at the time for catalyst heating during cold start-up.

The Munchen Nord Project is huge. It incorporates three pulverized coal-fired boilers, a waste-to-energy facility, and sewage sludge incineration. There were German federal, state and city of Munchen regulations to meet formidable emission limits. In Germany, there are few permitted landfills for the waste products. This requires the equipment suppliers to develop processes which will utilize all waste streams into useable by-products. Much time was spent in the planning and permitting process. This time was well utilized by the system designers.

Part of this time was used for the development of new technology for the injection of ammonia that would replace the multi-nozzle grid system. This technology was developed and proven on a smaller facility called Dormagen which was entirely built and started up while the München Nord Project was being planned and permitted.



München Nord Project Site

DORMAGEN PROJECT

The Dormagen Project is a smaller, lignite-fired facility with the SCR reactor located directly after the economizer. It has relatively high flyash loading due to the low heating value and high ash content of the lignite fuel. Due to the fuel and firing method, the temperature at the boiler exit was predicted to be highly unbalanced.

For this project a new static mixing technology, called a Delta Wing Mixer, was used to achieve a uniform flue gas temperature leaving the boiler and entering the SCR reactor inlet duct and catalyst face. During the engineering phase a flow model was built and the Delta Wing Mixer was tested in the boiler outlet duct. Uniform temperatures were ultimately achieved by installing a set of delta-shaped static mixers at a strategic location in the boiler outlet duct.

While modeling was being conducted it was also observed that the injection of the ammonia by the grid type system was really just another component of the flow that was non-uniform. This non-uniformity was due to a combination of the characteristics of the grid and the characteristics of the gas flow at part-load conditions. A second set of Delta Wing Mixers was added to the model downstream of the grid and strategically located to provide a uniform concentration of ammonia over the entire cross section of the reactor inlet duct.

In addition, flyash testing was conducted on the Dormagen model. This was determined to be necessary from the experience of the KW Reuter project. It was observed that immediately upstream of the reactor a down-flow diverging section of duct created stagnant flow zones that allowed the accumulation of flyash on the uppermost catalyst face. The addition of a third Delta Wing Mixer to this section of duct eliminated the flyash accumulations. Dormagen was a successful installation that started up in August of 1990. The actual system performance was well predicted by the modeling work. During actual plant operation there was a uniform temperature profile and the catalyst face was free of flyash accumulations. The technology of the Delta Wing Mixer, developed during this projects engineering phase, was available for application to Munchen Nord and other installations.

As mentioned above in the KW Reuter discussion, this Delta Wing Mixer technology was also retrofitted to the KW Reuter project three years after initial start-up. The value of this retrofit proved to be the elimination of the 130-nozzle injection grid and improved performance at all loads and operating conditions. That is, gas temperature, ammonia concentrations, gas flow distribution and all other constituents in the gas were made more uniform improving overall performance. This was accomplished by flow model testing and ultimately locating two Delta Wing Mixers in the duct. Each mixer has one injection nozzle. Since the time of this retrofit, the owner has been operating trouble free over the full load range.

MUNCHEN NORD - CONTINUED

Continuing the discussion of the Munchen Nord Project, the lengthy planning and permitting process allowed that project to utilize the Dormagen project's developments and in fact provided an opportunity to advance it one step further. The Delta Wing Mixer was recognized as a gas mixer that thoroughly mixed all components and characteristics of the flue gas: the incoming flue gas temperature; the NOx concentration; the flyash, oxygen, and water vapor concentrations, as well as making the overall flow or velocity profile at the catalyst face more uniform.

The Munchen Nord Project was designed to utilize a single set of Delta Wing Mixers to thoroughly mix all the components of the incoming flue gas as well as the injected ammonia. The complex ammonia injection grid system was eliminated and a single nozzle was used at each static mixer. The system started up in 1991 and achieved all guarantee requirements.

The lessons learned from this project are really two-fold. First, the three dimensional modeling is very valuable and can be conducted in a manner that accurately reflects the operating conditions found in the actual system. In this time period the modeling of the over-all system, and in particular, the modeling of the effects of the Delta Wing Mixer, gained significant credibility.

Secondly, to achieve the higher NOx reduction efficiencies and simultaneously achieve the lower ammonia slip requirements the flue gas and injected ammonia must be homogenized by thorough mixing and the flow profile made uniform before entering the catalyst.

In addition, experience gained with an economizer by-pass and SCR system by-pass brought about further changes to the system as we will discuss in our next example.

NORDJYLLANDSVAERKET PROJECT

This project, located in Denmark, has been chosen for discussion because it utilizes the latest SCR System features and also introduces valuable construction technique innovations.

The Nordjyllandsvaerket Project is a new installation at 415 MW firing pulverized bituminous coal. The project is now under construction with start-up scheduled for the fall of 1998. The SCR reactors are bottom-supported and located immediately after the economizer.Te anhydrous ammonia is injected using a Delta Wing Mixer. The catalyst is *honeycomb* with a 6 mm pitch. The inlet NOx is 635 mg/Nm^3 (0.423 Lbs/10^6 Btu) and the reduction is 80% to 127 mg/Nm^3 (0.085 Lbs/10^6 Btu) with an end of life ammonia slip of 5 ppm. The fly-ash loading is 14,000 mg/Nm^3 (about 7 gr/dscf).

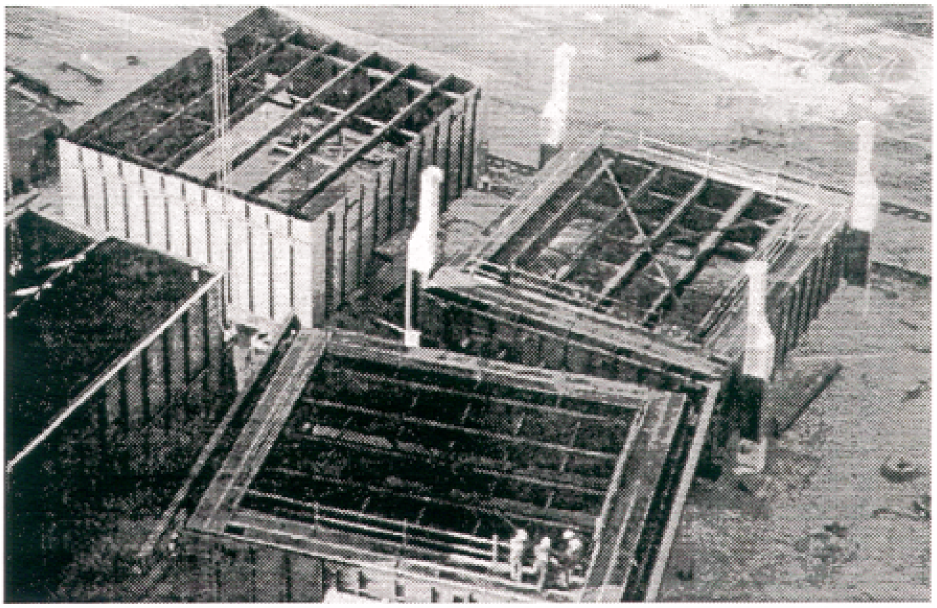
There is one large SCR reactor treating the full boiler flue gas flow. This project utilizes the as-modeled locations of Delta Wing Mixers as determined by the flow model for ammonia injection and gas mixing and flow uniformity. In addition it does not utilize an economizer by-pass or SCR System by-pass. The economizer by-pass is not required due to the con sistently high load operation of the boiler. The SCR by-pass is not needed because the boiler is planned to have very few cold starts per year.

The construction schedule for this project required that the entire SCR reactor shell be erected within one week. The one-week window for the SCR reactor was bounded by the prior activities of air heater erection and erection of the support steel for the SCR to be located above the air heater. After the SCR Reactor was in place, the subsequent activities were erection of the SCR Reactor inlet duct support steel and duct itself The SCR Reactor inlet duct came from a high boiler exit typical of the European design.

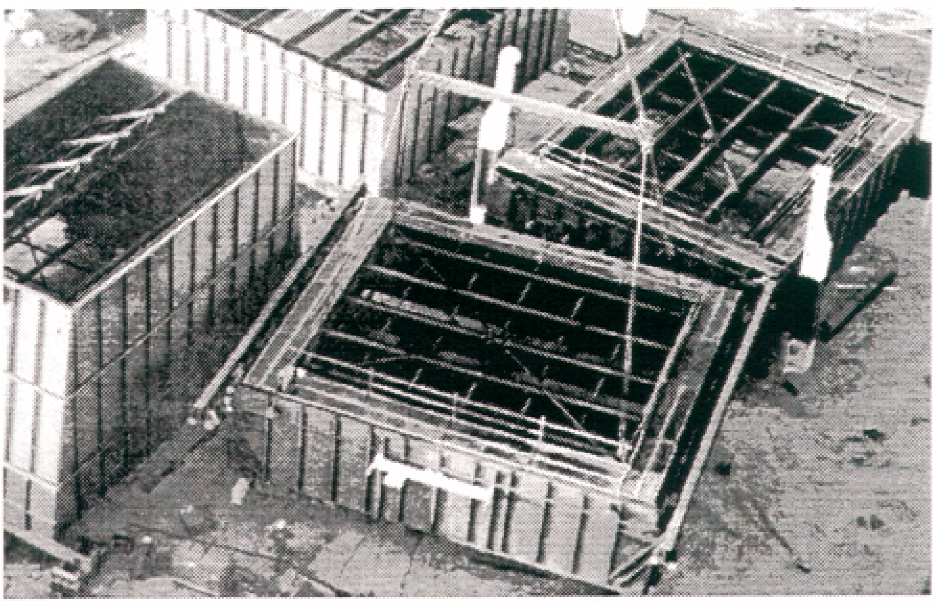
The SCR reactor, as prefabricated modules, was brought onto the site and situated near the final position. Each module consisted of the reactor shell with external stiffeners and support legs, as well as all the interior catalyst support structure. The catalyst will be installed during start-up. From grade, the modules were lifted and placed on the finished structural steel. As each successive module was lifted, it was placed on top of the lower module in the structure. This method accomplished the construction of the reactor vessel in one week.

The lessons learned on this project transferable to the U.S. market are the value of the innovative construction techniques that can be used to minimize the boiler outage time, and the value of keeping the SCR System simple. Recalling that there is no economizer by-pass and no SCR reactor by-pass, the overall gas path configuration is greatly simplified. This was, of course, a new facility. This enabled the boiler to be designed to achieve the appropriate exit temperature over a wide range of load. On the other hand, a retrofit project in the U. S. could minimize the boiler outage by employing an SCR reactor by-pass. Once the by-pass gas path is in place, the boiler can be operated while the SCR Reactor construction continues.

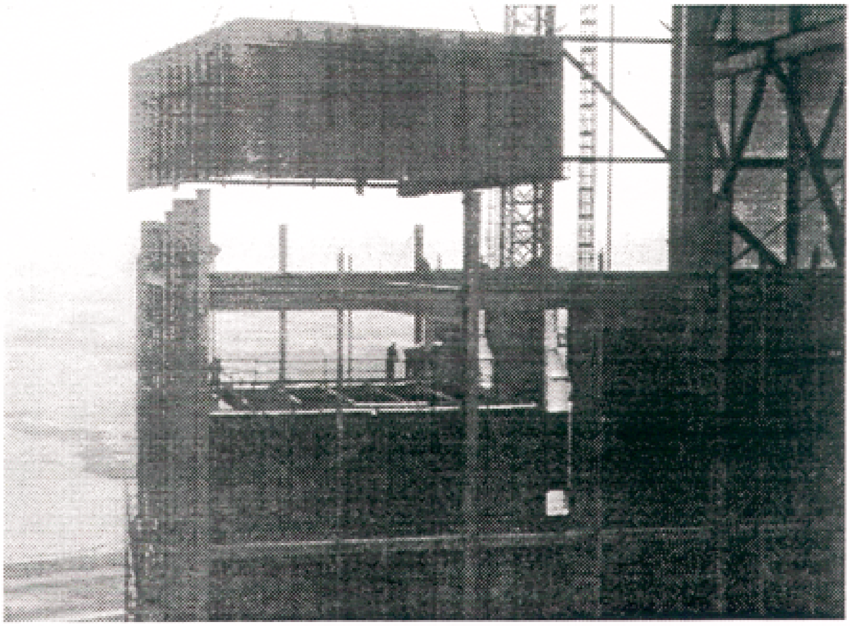
Again, the Delta Wing Mixer is used to insure uniformity of all gas constituents at the catalyst face over the entire load range with the resulting good performance and long catalyst life expected.



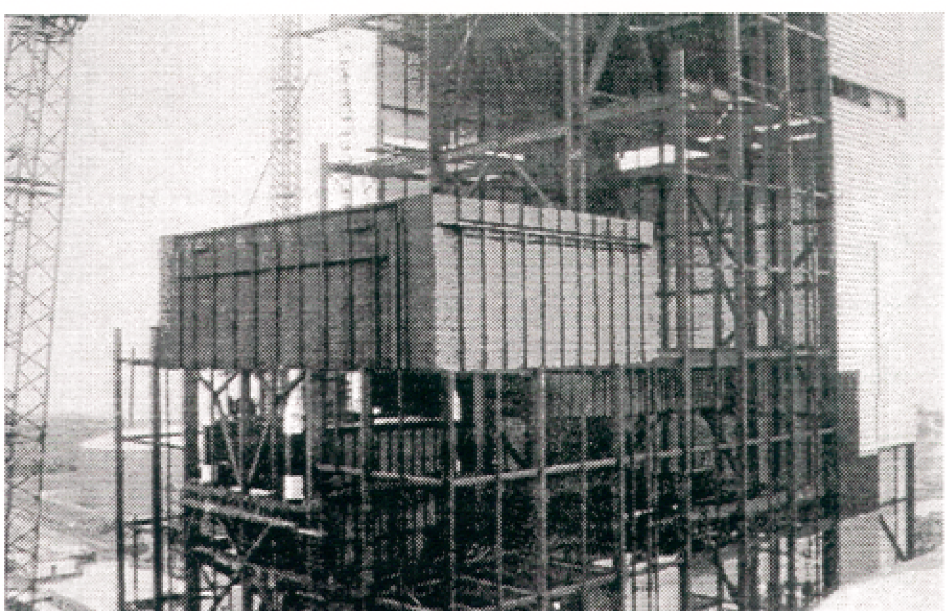
Nordjyllandsvaerket Project SCR layers ready for installation



Layer being lifted as complete section



Layer section being lowered into steel structure



Final alignment of section in steel

Nordjyllandsvaerket Project with completed SCR

FLUE GAS MIXING

Why do this mixing? Can't good flow distribution and uniform grid injection of ammonia insure sufficiently uniform distribution to achieve the system performance goals?

There is general agreement that uniformity of operating conditions ensures the best SCR System performance for NO_x reduction, ammonia utilization, and catalyst life. The designers of these systems will certainly be faced with elaborate specifications and test methods to prove that the as-built system achieves the specified uniformity of gas flow and ammonia concentration. But such testing gives little insight as to what is happening at other operating conditions. Furthermore, it does not help achieve optimal performance over the range of boiler loads or operating conditions.

For best results, other important parameters should also be uniform, such as flue gas temperature, oxygen concentration, moisture and flyash concentrations, and of course NO_x concentration. However, these variables are very dependent on the boiler firing conditions. At full load under well-controlled conditions there may be a brief period of time wherein reasonably uniform conditions are perceived to exist at the boiler outlet(s). But what happens to this uniformity as the boiler fouls or operates at part load? What happens when a pulverizer or burners are out of service and the unit operates at non-uniform conditions? Furthermore, most of the flue gas constituents that are unbalanced are not known to be unbalanced because they are not actively measured. If they are not measured they cannot be responded to by any process control system.

It is our contention that positive steps must be taken to thoroughly mix all the constituents of the flue gas in the region between the boiler outlet and the SCR Reactor catalyst face. Furthermore it must be done in a manner that accomplishes thorough mixing over the entire range of gas flows and boiler firing conditions. The core technology lies in the technique used to accomplish the thorough mixing efficiently, while simultaneously satisfying all other system design requirements.

SUMMARY

The SCR System is just that, a system. It is not an accumulation of disconnected components added onto the existing boiler system. The ductwork and reactor arrangement must be analyzed as a system and when done in this manner, can produce optimal performance results.

The best system analysis tool is a three-dimensional flow model. It is capable of demonstrating the degree of gas mixing achieved, the gas flow distribution, and the flyash distribution over a wide range of operating conditions.. It can accomplish this with the accuracy needed and within the time frame of the overall projects needs.

The best performance-enhancing device is the Delta Wing Mixer. It is adaptable to any ductwork system configuration and has been demonstrated on numerous commercial installations since 1988. It provides the thoroughly mixed gas necessary to achieve the level of performance required of the future SCR Systems.

PROJECT SUMMARIES

KW REUTER, UNITS D AND E

Client	**BEWAG**	
Size	2 at 300 MW each	
Boiler Fuel and Firing Method	Bituminous Coal, Pulverized	
SCR Arrangement	After Economizer	
Status	Commercial Operation 1988/1989	
Flue Gas Flow	*930,000 Nm^3/Hr*	(-580,000 *scfm,wet)*
Reagent	Anhydrous Ammonia	
Mixer Type	Originally Grid — Retrofit Delta Wing Mixer	
Reactor Support	Top Supported	
Catalyst Type	Honeycomb	
Catalyst Pitch	7.5 mm	
Temperature	385°C (725°F)	
Flyash Loading	11,700 mg/Nm^3	(-6 gr/dscf)
SOx	2000 mg/Nm^3	
NOx Inlet	*650 mg/Nm3 @ 6%* 02	*(0.52 Lbs/10^6 Btu)*
NOx Outlet	150 mg/Nm^3 @6% 02	(0.12 Lbs/10^6 Btu)
NOx Removal Efficiency	77%	
NH3 Slip, End of Life	5 ppmv	

DORMAGEN UNIT 7

Client	Bayer	
Size	125 rnt/hr	
Boiler Fuel and Firing Method	Lignite (Brown Coal) After	
SCR Arrangement	Economizer Commercial	
Status	Operation 1990	
Flue Gas Flow	*200,000 Nm^3*/Hr	*(-580,000 scfm,wet)*
Reagent	Anhydrous Ammonia	
Mixer Type	Delta Wing Mixer	
Reactor Support	Top Supported	
Catalyst Type	Honeycomb	
Catalyst Pitch	7.0 mm	
Temperature	370°C	(700°F)
Flyash Loading		
SOx		
NOx Inlet	600 mg/Nm^3	(0.37 Lbs/10^6 Btu)
NOx Outlet	200 mg/Nm^3	(0.12 Lbs/10^6 Btu)
NOx Removal Efficiency	66%	
NH3 Slip, End of Life	5 ppmv	

PROJECT SUMMARIES

MUNCHEN NORD, UNIT 2

Client	City of Munich	
Size	300 MW each	
Boiler Fuel & Firing Method	Bituminous Coal, Pulverized	
SCR Arrangement	After Economizer Commercial	
Status	Operation 1991	
Flue Gas Flow	1,050,000 Nm3/Hr	(-653,000 scfm,wet)
Reagent	Anhydrous Ammonia	
Mixer Type	Vortex Mixer Top	
Reactor Support	Supported Plate	
Catalyst Type	5.2mm	
Catalyst Pitch	400°C (750°F)	
Temperature	14,000 mg/Nm^3	(-7 gr/dscf)
Flyash Loading	40 mg/Nm3	
S03	700 mg/Nm^3 @ 6% 02	(0.56 Lbs/10^6 Btu)
NOx Inlet	100 mg/Nm^3 @ 6% 02	(0.07 Lbs/10^6 Btu)
NOx Outlet	85%	
NOx Removal Efficiency	5 ppmv	
NH3 Slip, End of Life		

NORDJYLLANDSVEARKET

Client	NJV	
Size	415 MW	
Boiler Fuel & Firing Method	Bituminous Coal, Pulverized	
SCR Arrangement	After Economizer	
Status	Commercial Operation, Fall 1998	
Flue Gas Flow	1,268,500 Nm3/Hr	(-790,00 scfm,wet)
Reagent	Anhydrous Ammonia	
Mixer Type	Vortex Mixer	
Reactor Support	Bottom Supported	
Catalyst Type	Honeycomb	
Catalyst Pitch	6 mm	
Temperature	370°C	(700°F)
Flyash Loading	14,000 mg/Nm^3	(-7 gr/dscf)
S03	30 mg/Nm^3	
NOx Inlet	635 mg/Nm^3 @ 3% 02	(0.423 Lbs/106 Btu)
NOx Outlet	127 mg/Nm^3 @ 3% 02	(0.085 Lbs/106 Btu)
NOx Removal Efficiency	80%	
NH3 Slip, End of Life	5	