# POST COMBUSTION CONTROL OF OXIDES OF NITROGEN (NOx) EMISSIONS FROM A 900 TPD PROCESSED REFUSE FUEL BOILER

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## ABSTRACT

The SEMASS Resource Recovery Facility was developed by Energy Answers Corporation (EAC) to provide an integrated approach to solid waste management, primarily in southeastern Massachusetts. The Facility is privately owned by a partnership, SEMASS Partnership, in which EAC is the Managing General Partner. The Facility, located in the town of Rochester, Massachusetts, is operated by Bechtel SEMASS Operations under contract with the Partnership.

Waste is received at the Facility mainly from communities who have executed long term contracts with SEMASS. The waste is processed on-site through a single shredding stage to reduce the material size to less than a nominal 6″ which allows for more efficient combustion in the Facility's "Shred and Burn" technology (1), and a magnetic separation stage for the recovery of ferrous material for re-cycling. The resulting stream known as Processed Refuse Fuel or PRF consists of approximately 97% of the incoming waste, and retains practically all of the heating value of the raw fuel. The PRF is then fed to the three steam boilers for the generation of more than 80 MW of electricity.

Two of the existing three boilers, Boilers 1 and 2, designed for burning PRF at approximate full load firing rates of 900 tons per day (tpd) per boiler, began commercial operation in February 1989. With additional commitments from communities located in the southeastern re-

gion, an expansion of the SEMASS Facility was planned and undertaken in 1990. This expansion included the installation of one additional 900 tpd PRF fired boiler and improvements and expansion of the refuse processing facilities. For the third boiler (Boiler 3), control of oxides of nitrogen (NOx) emissions, was required under the New Source Performance Standards (NSPS) issued under the revised Clean Air Act in 1990. The Nalco Fuel Tech NOx-OUT® Process was chosen as the best available control technology (BACT) for NOx reduction on the third boiler.

In accordance with the design basis provided by EAC, the SEMASS Facility was designed and constructed by Bechtel Corporation of Gaithersburg, Maryland and the boilers were supplied by Riley Stoker Corporation of Worcester, Massachusetts. The successful application of the NOx control process at the SEMASS Facility required close coordination, detailed design review and cooperation between EAC, SEMASS Partnership, Nalco Fuel Tech, Bechtel Corporation and Riley Stoker. This paper discusses how the SEMASS NOx control system was designed to meet the NSPS and how the process was applied on the Riley Stoker specially designed boiler.

To help in determining design and operating parameters, including the prediction of urea consumption and injection locations to meet the specified NOx control levels while minimizing $NH_3$ slip, Nalco Fuel Tech performed Computational Fluid Dynamics (CFD), Chemical Kinetics Modelling (CKM) and temperature mapping on the existing boilers prior to design and installation of the NOx Control

system on the third boiler. The results of these predictive models are shown and compared to actual operating conditions documented during startup and optimization conducted in May of 1993.

Since the optimization of the NOx system at SEMASS, the emissions in Boiler 3 have been effectively controlled to levels below the NSPS of 180 parts per million of dry volume (ppmdv), corrected to 7% $O_2$, under all furnace operating conditions. This controlled level makes SEMASS Boiler 3 one of the lowest NOx emitting municipal solid waste combustors in the United States.

The observed performance of the NOx control system on Boiler 3 also indicates a potential for generation of Emission Reduction Credits (ERC) for the purposes of banking and trading. The State regulations governing these issues are geared towards improving air quality while allowing economic growth.

## PLANT OVERVIEW

The SEMASS Resource Recovery Facility is one of the largest solid waste processing facilities in the United States. This facility processes and disposes of up to 3000 tons per day of municipal solid waste (MSW). In addition to producing steam for power production from its three boilers, this plant is unique in that EAC's proprietary ash processing plant achieves total resource recovery of recyclable materials from the post combustion waste streams. (Figure 1)

The three combustion boilers are of a travelling grate design manufactured by Riley Stoker. Each boiler is normally operated at a steam production rate of 280,000 lbs/hr. For controlling odors, all of the combustion air supplied by the forced draft fans is drawn from the Receiving Building of the Facility where the incoming waste is stored.

Back-end air pollution control equipment includes a spray dryer absorber (SDA) for removing up to 80% of $SO_2$ and 95% of HCL from the flue gas streams from each boiler. Particulate is collected downstream of the SDAs through an electrostatic precipitator (ESP) provided for Boilers 1 and 2 and a pulse-jet baghouse provided for Boiler 3. The NOxOUT System is designed to provide up to 50% reduction, and control at or below 180 ppmdv corrected, which is the permitted level, with less than 20 ppm ammonia slip, under boiler load ranges of 170,000 to 340,000 pph steaming rates.

## NOxOUT PROCESS DESCRIPTION

The SEMASS NOx control system employs the selective non-catalytic reduction (SNCR) technology which utilizes a stabilized urea-based solution. This reagent is injected into the post combustion furnace gas stream, where it reacts chemically with the NOx emissions to basically form nitrogen and water.

The selective non-catalytic reduction of NOx using urea was initially studied and patented by the Electric Power Research Institute (EPRI). Currently, Nalco Fuel Tech is the exclusive licensing agent for this technology under the trade name of NOxOUT®. The SEMASS System includes several improvements and Nalco Fuel Tech's patented enhancements to extend and expand the applicability of the basic technology. These improvements include chemical enhancers, scale inhibitors, stabilizers, injection systems and computer modelling techniques.

The overall chemical relation for reducing NOx with urea is:

$$CO(NH_2)_2 + 2NO + \tfrac{1}{2}O_2 \rightarrow 2N_2 + CO_2 + 2H_2O$$
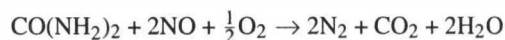
Urea + Nitric Oxide + Oxygen → Nitrogen + Carbon Dioxide + Water

The above chemical reaction indicates that one mole of urea is required to react with two moles of NOx. Results of test data indicates that reagents greater than stoichiometric quantities must be injected to achieve a desired removal efficiency. The sum of many gas phase equilibrium reactions result in the reduction of NOx and produce primarily $N_2$ and $H_2O$. Some trace quantities of ammonia, carbon monoxide and nitrous oxide can be formed; controlling the emissions of these byproducts while achieving high NOx reductions is a key consideration in the design and analysis undertaken by Nalco Fuel Tech in applying the NOxOUT Technology.
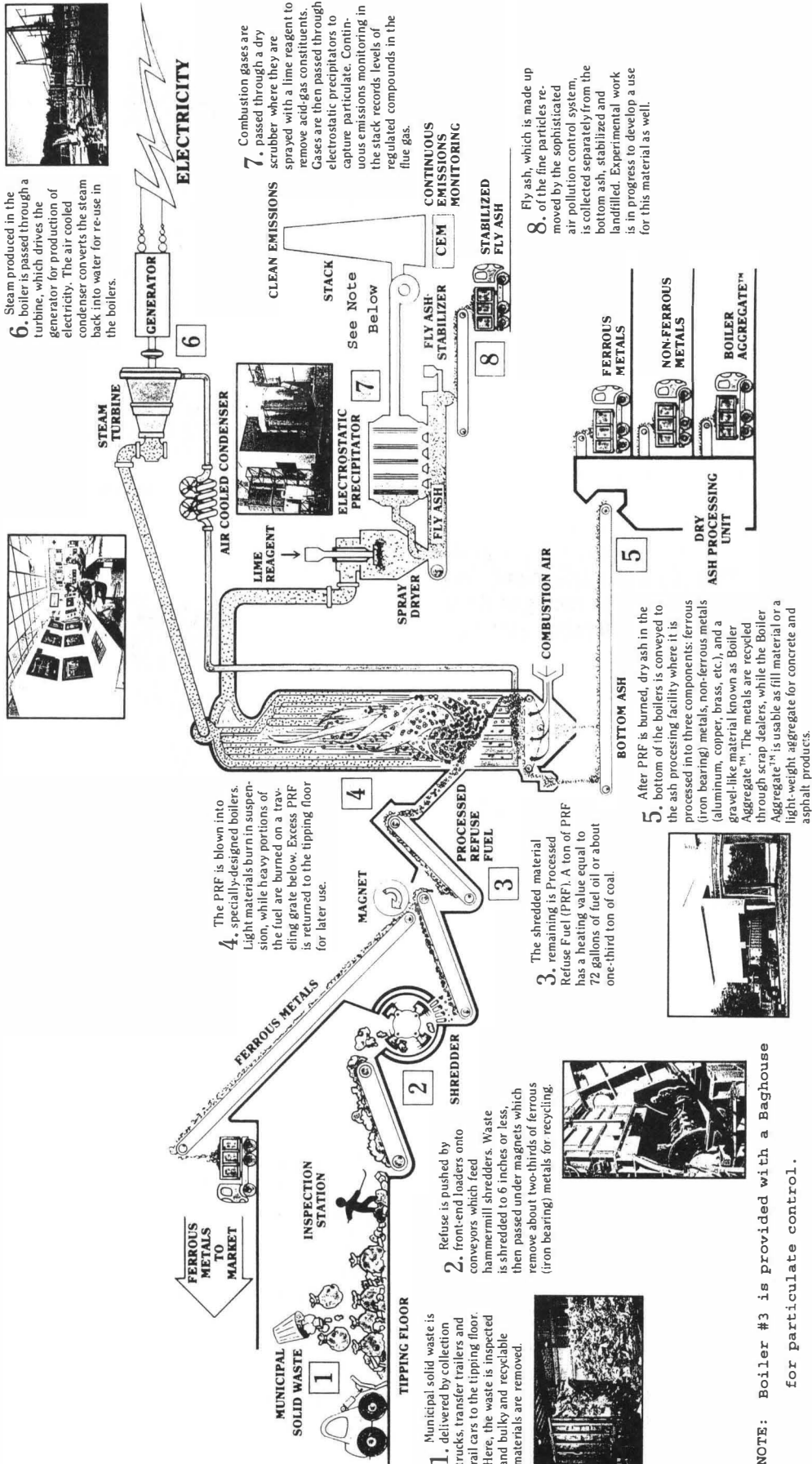
The relationship between NOx removal efficiency and reagent utilization has been tied together by a variable known as the Normalized Stoichiometric Ratio (NSR). The NSR is defined as follows:

$$NSR = \frac{\text{Actual Molar Ratio of Reagent to Inlet NOx}}{\text{Stoichiometric Molar Ratio of Reagent to Inlet NOx}}$$

The relationship between reagent utilization, NSR and NOx removal efficiency is as follows:

$$\%\text{Utilization} = \frac{\%\text{NOx Reduction}}{\text{NSR}}$$

Reagent utilization is the key factor used to gauge process performance, verification of the optimum injection location and strategy, and to determine that byproduct formations are controlled at minimum levels.

**MUNICIPAL SOLID WASTE**

**TIPPING FLOOR**

**1.** Municipal solid waste is delivered by collection trucks, transfer trailers and rail cars to the tipping floor. Here, the waste is inspected and bulky and recyclable materials are removed.

**INSPECTION STATION**

**FERROUS METALS TO MARKET**

**2.** Refuse is pushed by front-end loaders onto conveyors which feed hammermill shredders. Waste is shredded to 6 inches or less, then passed under magnets which remove about two-thirds of ferrous (iron bearing) metals for recycling.

**SHREDDER**

**MAGNET**

**FERROUS METALS**

**PROCESSED REFUSE FUEL**

**3.** The shredded material remaining is Processed Refuse Fuel (PRF). A ton of PRF has a heating value equal to 72 gallons of fuel oil or about one-third ton of coal.

**4.** The PRF is blown into specially-designed boilers. Light materials burn in suspension, while heavy portions of the fuel are burned on a traveling grate below. Excess PRF is returned to the tipping floor for later use.

**COMBUSTION AIR**

**BOTTOM ASH**

**5.** After PRF is burned, dry ash in the bottom of the boilers is conveyed to the ash processing facility where it is processed into three components: ferrous (iron bearing) metals, non-ferrous metals (aluminum, copper, brass, etc.), and a gravel-like material known as Boiler Aggregate™. The metals are recycled through scrap dealers, while the Boiler Aggregate™ is usable as fill material or a light-weight aggregate for concrete and asphalt products.

**DRY ASH PROCESSING UNIT**

**FERROUS METALS**

**NON-FERROUS METALS**

**BOILER AGGREGATE™**

**6.** Steam produced in the boiler is passed through a turbine, which drives the generator for production of electricity. The air cooled condenser converts the steam back into water for re-use in the boilers.

**STEAM TURBINE**

**AIR COOLED CONDENSER**

**GENERATOR**

**ELECTRICITY**

**LIME REAGENT**

**SPRAY DRYER**

**ELECTROSTATIC PRECIPITATOR**

**FLY ASH**

**7.** Combustion gases are passed through a dry scrubber where they are sprayed with a lime reagent to remove acid-gas constituents. Gases are then passed through electrostatic precipitators to capture particulate. Continuous emissions monitoring in the stack records levels of regulated compounds in the flue gas.

**CLEAN EMISSIONS**

**STACK**

**See Note Below**

**CONTINUOUS EMISSIONS MONITORING**

**CEM**

**FLY ASH STABILIZER**

**STABILIZED FLY ASH**

**8.** Fly ash, which is made up of the fine particles removed by the sophisticated air pollution control system, is collected separately from the bottom ash, stabilized and landfilled. Experimental work is in progress to develop a use for this material as well.

**FIG. 1 PROCESS SCHEMATIC**

**NOTE:** Boiler #3 is provided with a Baghouse for particulate control.

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Various factors effect the overall performance and successful application of the urea based SNCR NOx reduction process. These factors include:

- Fuel Type
- Initial NOx Concentration
- Flue Gas Makeup
- Excess $O_2$
- CO Concentrations
- Furnace Geometry
- Gas Velocities and Distribution
- Furnace Temperature Profile
- Load Changes

In evaluating the application of the process on a new or existing unit, each of these factors are analyzed to determine the most reliable, safe and economical injection strategy necessary to achieve the NOx reduction goals and optimum process performance. To accomplish these goals at SEMASS, Nalco Fuel Tech used its applications data base, and CFD and CKM Modelling. The results of these modelling studies are outlined in the following sections.

## SEMASS CFD AND CKM MODELLING RESULTS

The PHOENICS CFD program (CHAM, Ltd) was used for the SEMASS Project, supplemented with a number of proprietary subroutines developed at Nalco Fuel Tech for estimating process parameters specific to the combustion of PRF. This in combination with the CKM data base and applications data base provided Nalco Fuel Tech with the information necessary to predict and guarantee the process performance. The CFD models of the SEMASS boiler were generated as part of the Nalco Fuel Tech engineering design process. Five cases were examined: (1) 280 klbs/hr steam waste fired at 100% excess air; (2) 340 klbs/hr steam waste fired at 100% excess air; (3) 170 klbs/hr steam waste fired at 100% excess air; (4) 280 klbs/hr steam waste fired at 45% excess air; and (5) 280 klbs/hr steam firing waste at (40%) and oil at (60%) at approximately 30% to 40% excess air. Based on the model results, injector ports were recommended and installed at 120 ft elevation (8 ports) and the 145 ft elevation (8 ports). Note: The SEMASS grate is at elavation 97′.

The objective of the CFD model is to predict flow patterns, temperatures, gas velocities and chemical distributions within a process unit. The CKM analysis determines the location where the chemical reaction needs to be initiated. This determination is based on predicted NOx, $O_2$ and CO levels, and temperature versus residence time in the furnace. Through this model, the effects of residence time, temperature, treatment rate, baseline NOx, and
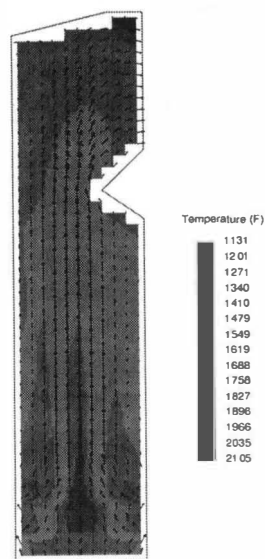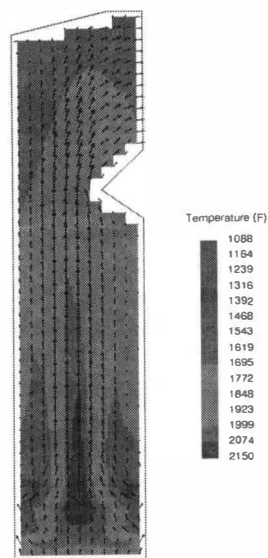


**FIG. 2**



**FIG. 3**

CO concentrations are determined. In addition, the lowest achievable NOx reduction is predicted for a given application or set of conditions.

Figures 2 and 3 show the predicted side-sectional temperature and flow profiles for case 1 and 2. The temperatures predicted by the model are consistent with field data taken in early 1992. However, the horizontal distribution of the flame zone was found to favor the rear wall of the furnace due to relatively higher air flows in the front section of the furnace.

Two levels of injection were shown to be sufficient to treat the SEMASS unit. It was determined that the lower
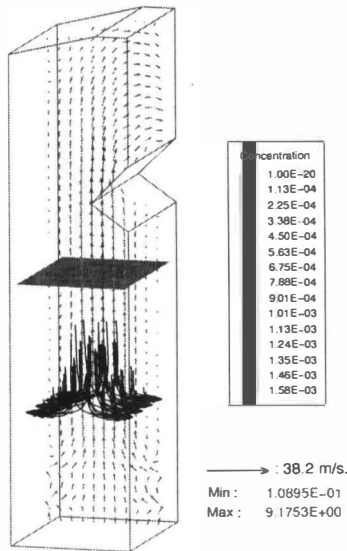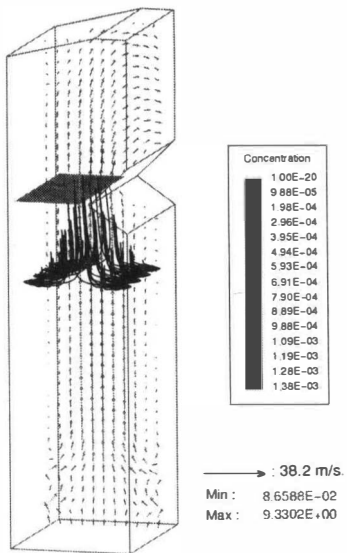
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**FIG. 4**



**FIG. 5**

level should be located around 120 ft elevation, and should include four ports along the front and back wall, as shown in Figure 4. The second level should be around 145 ft elevation, again with four nozzles along the front and rear walls as shown in Figure 5. In case the back wall is not completely accessible at 145 ft elevation, an alternate arrangement would be to move the outer two nozzles from the rear wall to the two side walls. The side wall injectors could be located approximately eight feet from the rear wall. The results shown are for sprays with an average droplet size of 250 micron.

## BOILER DESCRIPTION AND OPERATION

The waste is burned in the SEMASS boiler in suspension and on the grate which is located at the 97 ft elevation, whereas oil used for start-up is fired through two burners at the 131 ft elevation. The furnace has a depth of 21 ft 8 in, a width of 29 ft 8 in, and a total height of approximately 93 ft (above grate). Overfire air ducts are located on the front and rear walls at approximately 101 ft elevation and 107 ft elevation. The boilers have a bullnose extending 8 ft out from the rear wall at elevation 162 ft.

The design operating conditions when firing PRF are: 75,000 lbs/hr fuel, 515,310 lb/hr undergrate air (UGA) plus overfire air (OFA) flow at 100% excess air, and 35,950 lb/hr distributor air which is provided to pneumatically spread the PRF into the combustion zone and over the grate. The "reference" PRF pertains to the design higher heating value (HHv) and ultimate fuel analysis. The total OFA and UGA flow rate at 45% excess air is 366,110 lb/hr. The air distribution is approximately 53% UGA, 40% OFA, and 7% distributor air. Design air preheat temperatures range from 380 F at 100% excess air to 415 F at 45% excess air. The air preheat temperatures may be higher depending on the position of the pre-heater bypass dampers.

The boiler is capable of firing #2 fuel oil to supplement the PRF fuel if necessary.

When firing PRF at 280 klbs/hr steam load, the temperatures in the furnace are predicted to be between 1900F and 1600F, and at 340 klbs/hr the range is from above 2000 F to 1700 F. The gas in the center of the unit is predicted to be approximately 150 F hotter than that near the front and rear walls.

## NOx CONTROL SYSTEM DESCRIPTION

The standard NOx Control system employed at SEMASS incorporates a reagent storage and delivery system to inject the urea based solution into the combustion gases of the boiler. With the number of injectors, and injection levels determined from the modelling results, the mechanical portion of the system was designed. In addition, chemical feed rates, distribution requirements and injector flow rates to achieve the specific NOx reduction levels were determined.

A description of the SEMASS Boiler 3 NOx Control System is presented below. (See Figure 8)

The reagent storage tank is a closed-top vertical, heat-traced and insulated fiberglass tank with a nominal capacity of 8000 gallons. This capacity provides a fourteen day storage supply based on the predicated maximum usage rate of the reagent. The tank is also designed to maintain the chemical at or above 80°F, to prevent crystallization of the special 50% concentrate urea-based solution also known as NOxOUT A.

A Circulation Module is provided to serve two purposes. The primary purpose is to supply chemical to the Metering Module. The secondary purpose is to keep the reagent at a temperature of >80°F through constant recirculation and the use of an inline heater. The Circulation Module is skid mounted and fully shop tested prior to shipment and consists of two full flow redundant stainless steel centrifugal pumps, an inline electric heater, duplex filter strainer, local control panel, with tank level, pressure and flow instrumentation. Outputs for alarm and monitoring are provided for integration into the plant Distributed Control System (DCS).

The Metering Module is a skid mounted self contained unit used to supply the metered and dilute chemical to the four injector Distribution Modules. The metering rate of the product is based on reduction demand and boiler load and is controlled from the plant DCS. (Figure 10) The unit supplied for the SEMASS boiler includes two (2) full flow chemical metering pumps, two (2) full flow water boost pumps, flow, pressure, control and monitoring instrumentation, auto and manual valving, and local controls for operation of the module.

Mixed reagent is transported from the Metering Module to the appropriate Distribution Module, which distributes and controls the flow to each injector. Each Distribution Module serves four injectors. Injector atomizing and cooling air supplied from the plant service air system is also distributed and controlled from each Distribution Module. A total of four Distribution Modules are provided, two at the 120 ft elevation and two at the 145 ft elevation.

Independent flow meters, flow control valves, pressure indication and air regulators are provided for controlling droplet size and velocity from each injector. Level select solenoids are provided on each distribution panel to provide for isolation of banks of injectors.

The sixteen injectors are equally spaced and oriented on the front and rear walls of the boiler and are designated levels 1 and 2. These injection points were determined through the CFD and CKM modelling, and are designed to provide optimum NOx reductions over the full range of operating loads.

The injectors developed by Nalco Fuel Tech is specially designed to provide precise distribution of the reagent into flue gas stream, which ensures and maximizes reagent utilization and control of byproduct formations. Due to high chlorides concentrations in the flue gas stream, which is inherent to the combustion of solid waste, the injectors for the SEMASS boiler are provided with ceramic coated Hastelloy C cooling shields, to ensure a longer operating life.

## NOxOUT PROCESS PERFORMANCE

In May of 1993 SEMASS and Nalco Fuel Tech completed the Startup and Optimization Testing of the NOx Control System installed on Boiler 3. Parametric testing was conducted at load conditions ranging from 170 to 340 k lbs/hr steam rates. The majority of the tests were conducted firing the boiler on PRF. Other tests were conducted on mixed fuels containing a small fraction of Auto Shredder Residue (ASR). During these test $NO_x$ baselines as indicated on the plant Continuous Emissions Monitoring Systems (CEMs), ranged from 140 to 180 ppmdv, corrected to @7% $O_2$. This correlates to a lb/MMbtu value of .24 to as high as .33 lbs.

The specified $NO_x$ reduction for this application was to control $NO_x$ at or below 120 ppmdv, corrected with <20 ppm ammonia slip, as measured at the stack CEMs. This target was met under all load conditions, higher reductions were achievable with less than 20 ppm ammonia slip. These increased reductions were achieved with chemical feed rates higher than those that would normally be needed to meet the permit levels.

The lower load test conditions initially resulted in higher NH3 slips as measured at the economizer outlet. The NSR had to be increased to 1.5 to compensate for the corresponding higher CO levels in the furnace. Higher CO levels effectively shifts the process performance window requiring adjustments to be made in the injections strategy or an increase in chemical feed rates. Later, the higher CO levels at low loads were reduced thorough combustion control adjustments. This eliminated the need for higher NSRs at lower loads. The resulting system performance at all load conditions was 50% $NO_x$ reduction at a NSR of 1 this equates to a chemical utilization of 50% which is on the high end of Chemical Kinetics Performance Curves. Figures 6 and 7 show typical performance curves for reductions and ammonia slip, from other municipal solid waste applications as compiled in the Nalco Fuel Tech data base.

It was observed in the optimization tests that the combustion air distribution (overfire, undergrate) and the air leakages into the boiler directly affect the flue gas flow geometry. In comparison with the modelling results, actually the flame was more directed towards the rear wall of the boiler. Also, the distribution air source was not input in the computer program. This air, which comes into the furnace across the front wall of the boiler through the five fuel distributors, also tends to push the combustion flame towards the back wall. This condition effectively increases the flue gas temperature at the rear wall injection points, beyond the optimum $NO_x$ reduction window. It was therefore decided that the rear wall injectors will not be used, or used at much lower reagent injection rates, for normal operation of the system.

The best $NO_x$ reduction performance was achieved using the front wall level 1 and 2 injectors in the configuration detailed in Figure 9. The level 2 injectors produced best results at the high load conditions and a combination of levels 1 and 2 at the mid and low load conditions. Chemical usage rates ranged between 9 and 18 gph over
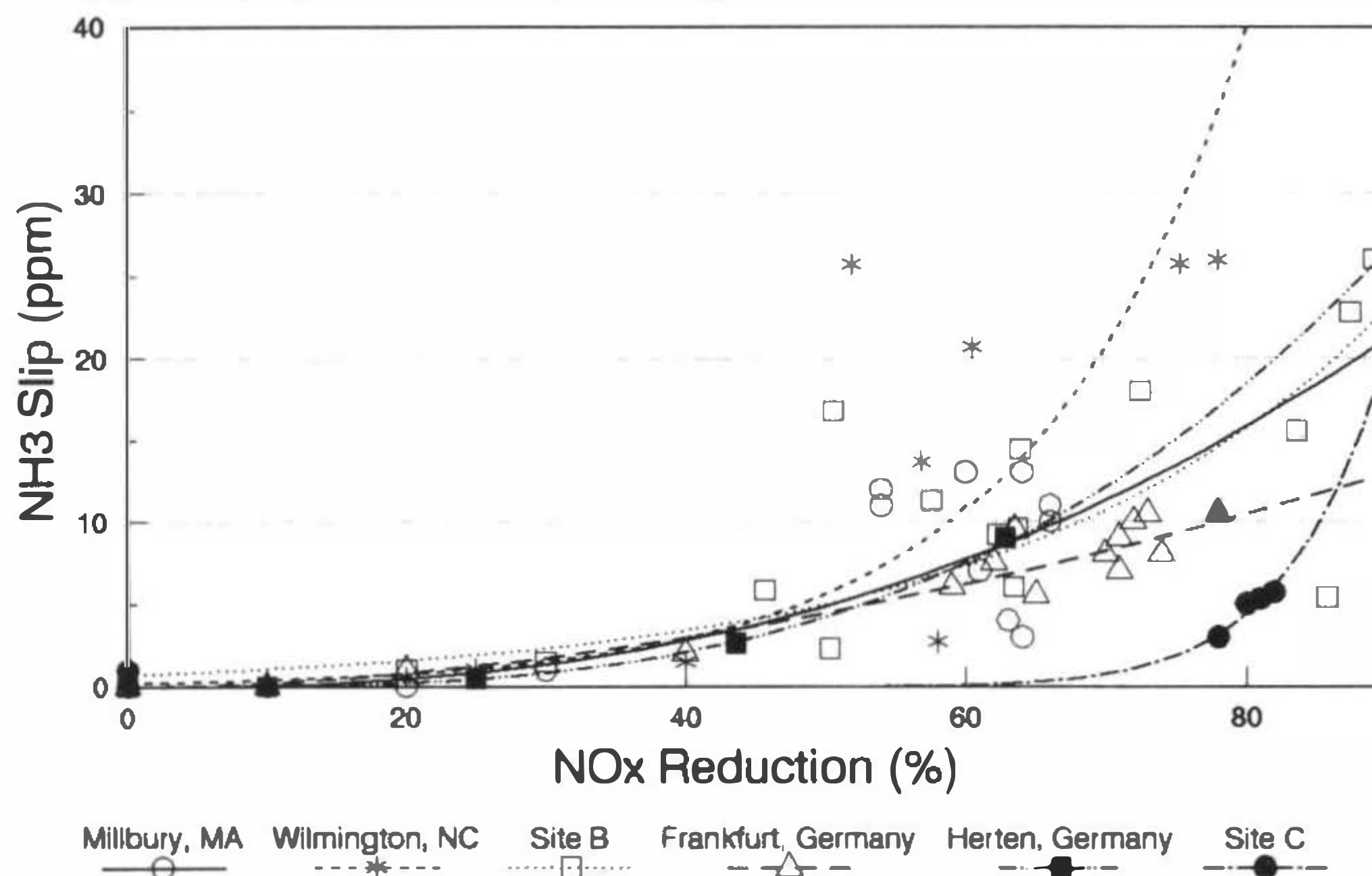
**FIG. 6   NH₃ SLIP AS A FUNCTION OF NOx REDUCTION**
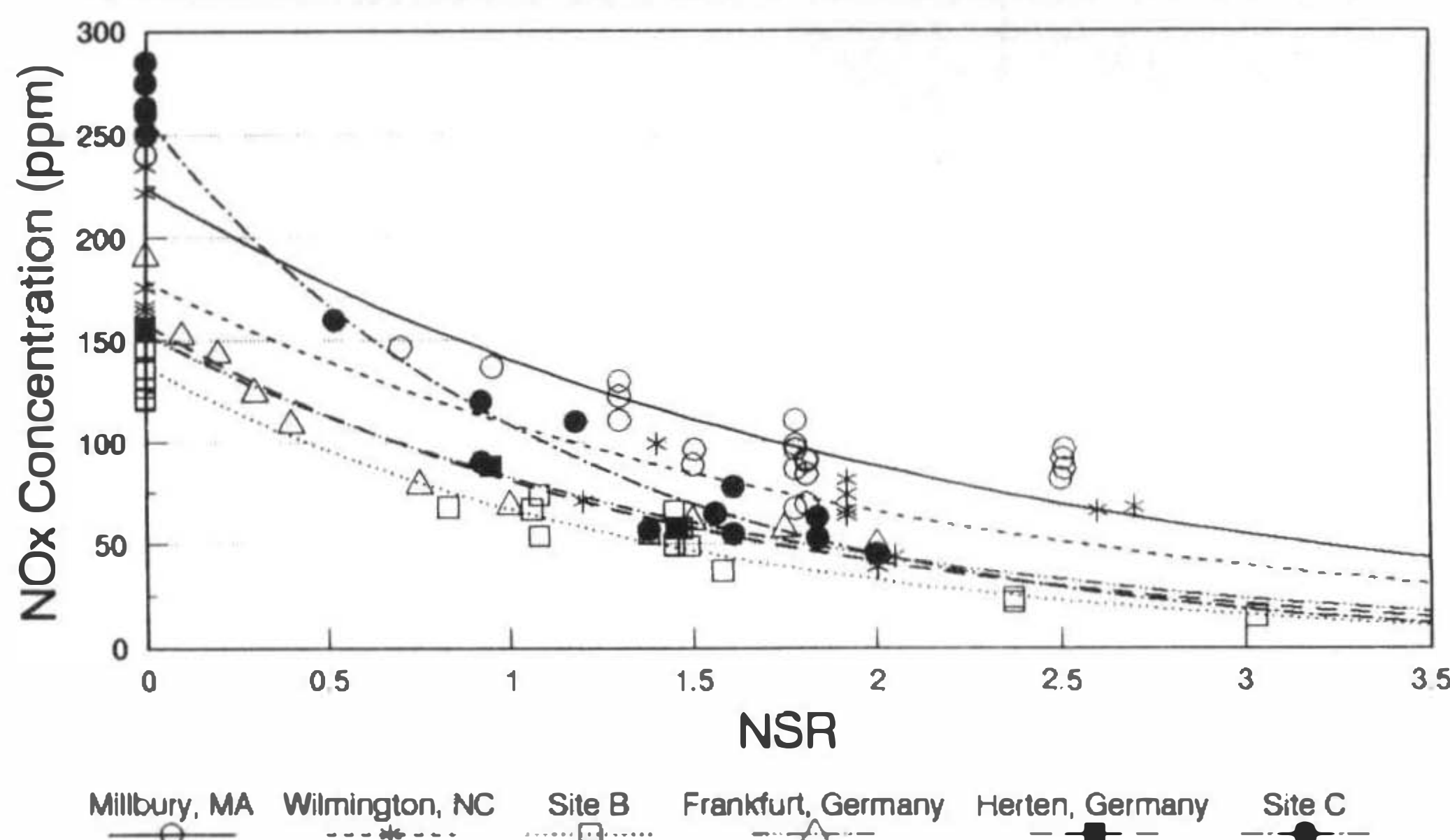
**FIG. 7   NOx REDUCTION AS A FUNCTION OF NSR**

the full range of loads. This flow was well below the predicted maximum flow of 31 gph.

Since the optimization tests of May 1993, SEMASS has further reduced its CO emissions to well below the permitted levels at all load conditions. This was accomplished though the implementation of a specially developed CO minimization plan. SEMASS and Nalco Fuel Tech are conducting re-optimization testing of the $NO_x$ Control System to fine tune the process for this lower set of CO levels.

## OVER-CONTROL OF $NO_x$ TO CREATE EMISSION REDUCTION CREDITS

SEMASS Boiler 3 currently operates under a 180 ppmdv $NO_x$ limit. At the date of this paper, the Commonwealth of Massachusetts has yet to finalize or promulgate a $NO_x$ limit for municipal waste combustors, but is expected to follow EPA guidelines.

The Commonwealth of Massachusetts has promulgated a very innovate and broadly endorsed program to create emissions reduction credits (ERCs) under Chapter 310 CMR 7.00 Appendix B of State Regulations. This program allows sources to over- control emissions of Volatile Organic Compounds (VOC), Oxides of Nitrogen ($NO_x$) and Carbon Dioxide ($CO_2$), and subsequently register and sell the surplus "credits".

The system provided at SEMASS has "dial-up" capability. That is by increasing urea reagent feed to the upper furnace through existing or additional zones of injection, $NO_x$ emissions may be reliably reduced below the current control limit of 180 ppmdv. Thus, from a perspective of creating $NO_x$ ERCs, the SEMASS Facility is capable of generating hundreds of tons of credits.
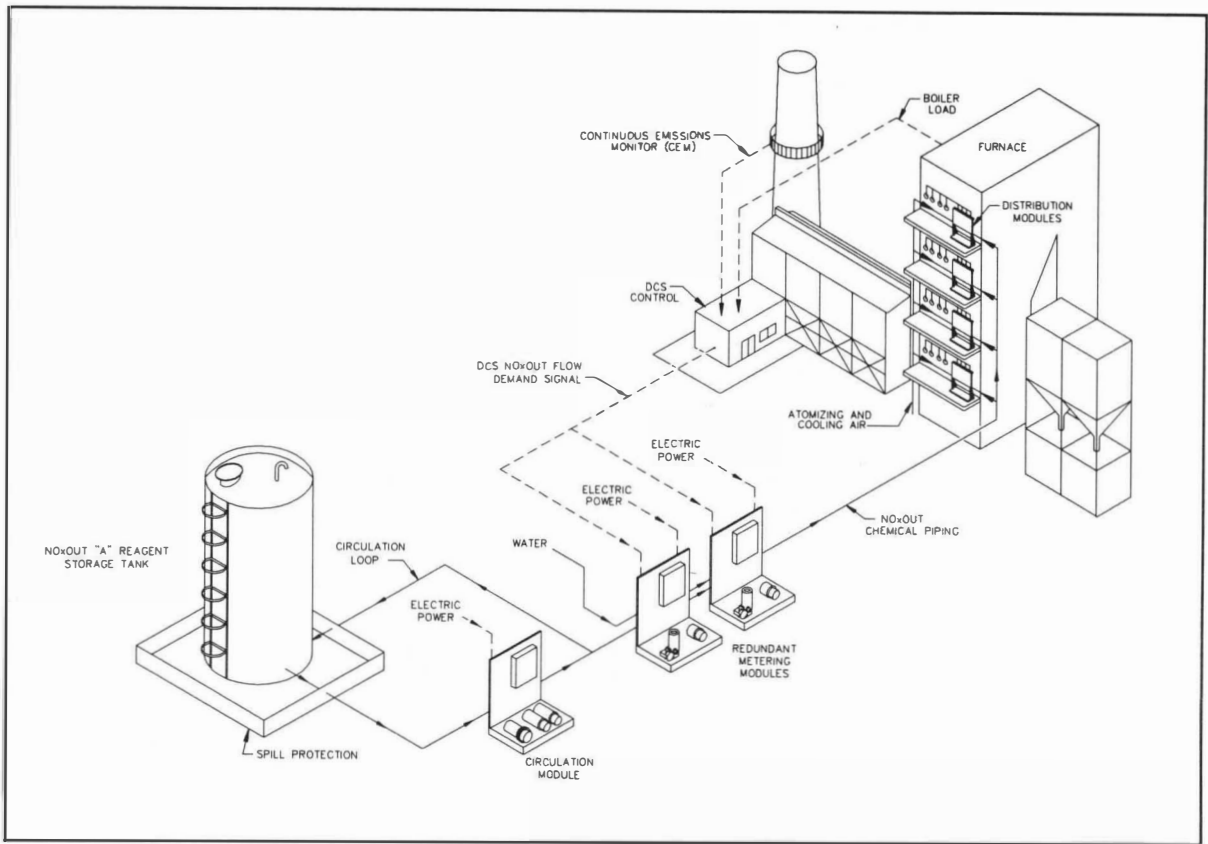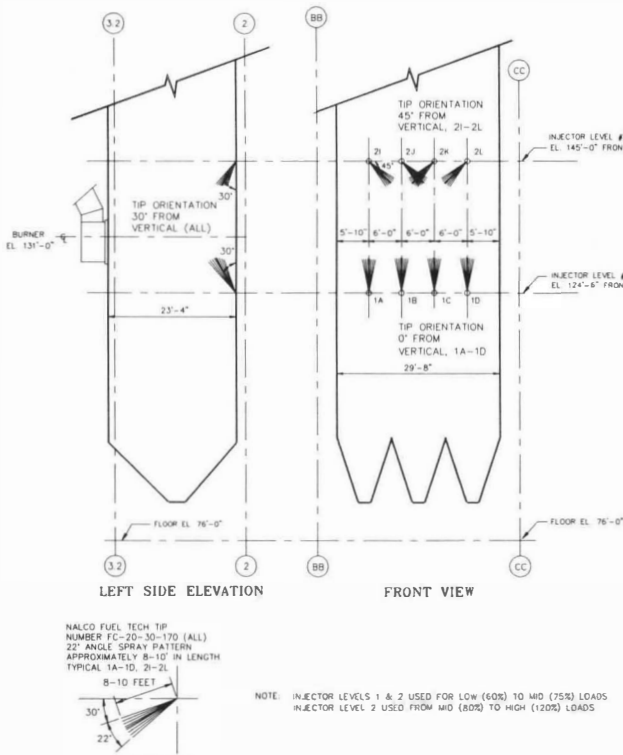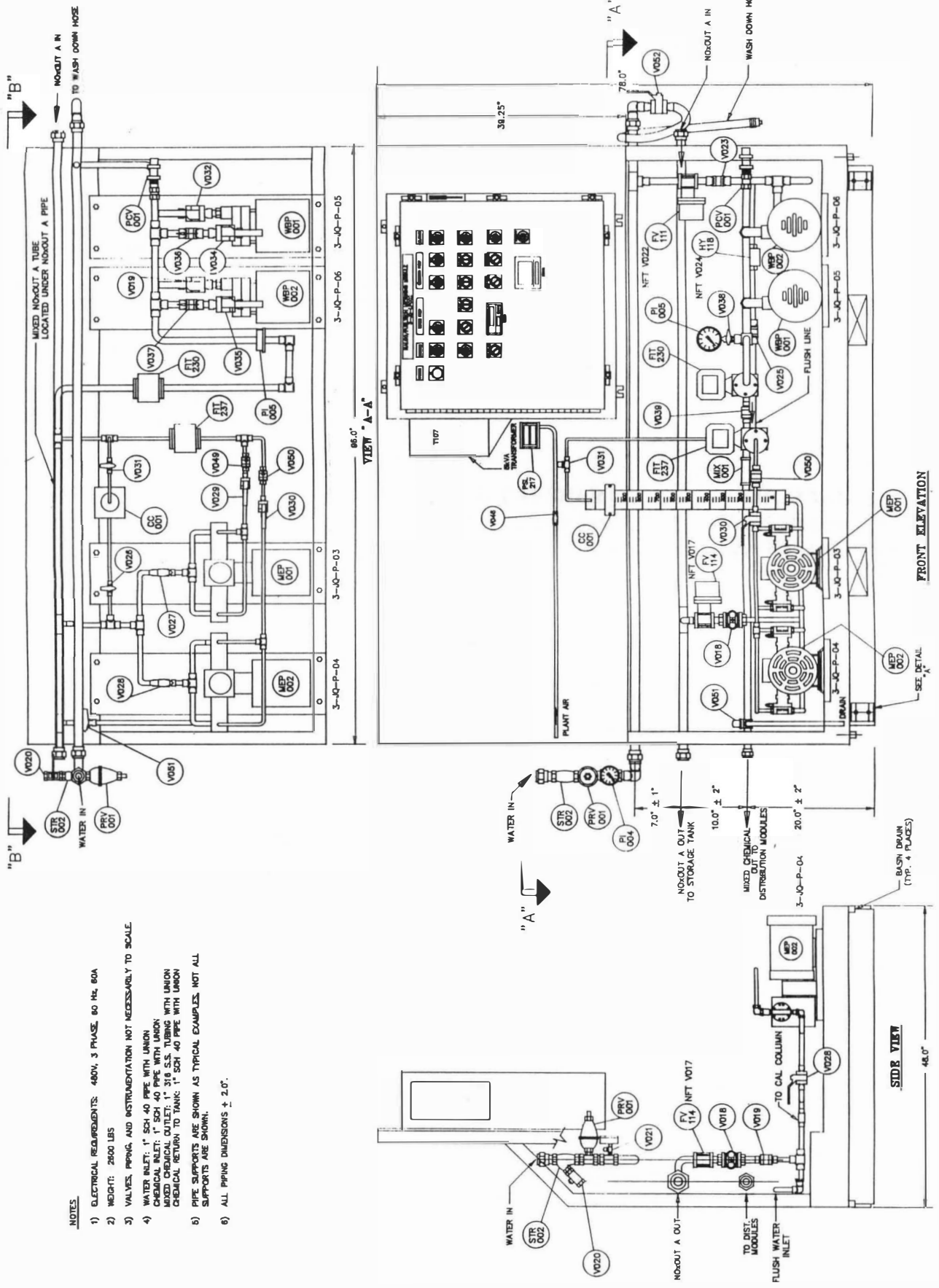
**FIG. 8**



LEFT SIDE ELEVATION        FRONT VIEW

NALCO FUEL TECH TIP
NUMBER FC-20-30-170 (ALL)
22° ANGLE SPRAY PATTERN
APPROXIMATELY 8-10" IN LENGTH
TYPICAL 1A-1D, 2I-2L

NOTE: INJECTOR LEVELS 1 & 2 USED FOR LOW (60%) TO MID (75%) LOADS
INJECTOR LEVEL 2 USED FROM MID (80%) TO HIGH (120%) LOADS

**FIG. 9    BECHTEL SEMASS — INJECTOR TIP INDEX FRONT INJECTORS ONLY EL 124'6" AND 145'-0"**

## SUMMARY

- The furnace temperature profiles and operating data collected from one of the two existing SEMASS boilers was input into CFD and CKM computer models. The resulting analysis provided reliable design data for the detailed engineering of a $NO_x$ control SNCR system for an identical new boiler.

- The SNCR system installed on the new boiler was optimized at part and full load conditions. The fine tuned system consumed 10-18 gph of the urea based reagent, obtaining up to 50% $NO_x$ reduction at a NSR of 1. The reagent consumption was observed to be 50% lower than originally predicted.

- After the first optimization tests, SEMASS was able to considerably lower its CO emissions well below the permitted levels which has prompted the need for further optimization of the $NO_x$ control system. The system incorporates adequate design margin to allow further fine tuning.

- The $NO_x$ control data obtained from the new boiler indicates that substantial potential exists at the SEMASS Facility to generate hundreds of tons of Emissions Reduction credits (ERC) for potential banking and trading purposes.

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FIG. 10 METERING MODULE

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## ABBREVIATIONS:

ASR    auto shredder residue
BACT    Best Available Control Technology
CFD    Computational fluid dynamics
CKM    chemical kinetics modelling
DCS    distributed control system
ERC    Emissions Reduction Credits
ESP    electrostatic precipitator
GHI    gross heat input
K lbs    1000 lbs
NSPS    New Source Performance Standards
NSR    normalized stoichiometric ratio
OFA    over-fire air
ppmdv    parts per million dry volume

PRF    processed refuse fuel
SDA    spray drier absorber for acid gas control
SNCR    selective non-catalytic reduction
tpd    tons per day
UGA    under grate air

## REFERENCES

[1] J. Zackaria, G. L. Sutin "The SEMASS Shred-and-Burn Technology — A Well Proven Resource Recovery System" ASME 16TH Annual National Waste Processing Conference and Exhibition and NAWTEC-II, the 2nd Annual North American Waste to Energy Conference, Boston Ma, June 5–8 1994.

[2] W. Sun, P, Stamatakis, J.E. Hofamann, Nalco Fuel Tech "Reaction Kinetics of Selective Non-Catalytic NOx Reduction with Urea."