United States
Environmental Protection
Agency

Industrial Environmental
Research Laboratory
Research Triangle Park NC 27711

Research and Development

EPA-600/S7-84-076 Sept. 1984

EPA

Project Summary

Evaluation and Demonstration of Low-NO_x Burner Systems for TEOR Steam Generators - Design Phase Report

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A program to translate design criteria developed in bench- and pilot-scale combustors to a 16 MW commercial grade prototype burner that can be retrofitted to existing thermally enhanced oil recovery (TEOR) steam generators is currently in progress.

Laboratory- and pilot-scale data have been used to develop a low-NO_x burner, capable of operating with high-nitrogen liquid fuels such as crude oils and synthetic fuels. Emissions of NO_x can be minimized by application of a staged combustion process in which the first stage is thermally isolated and provides long residence time under high temperature, optimally fuel-rich conditions. The design criteria for this process were developed in a previous EPA-sponsored study, carried out in a 21 kW (70,000 Btu/hr) tunnel furnace and applied to two pilot-scale prototype burners at 0.6 MW (2×10^6 Btu/hr) and 3 MW (10×10^6 Btu/hr).

The report summarized here describes results of the design development tests and compares results of all three scales of experiment. Firing a heavy fuel oil containing above 0.6 percent bound nitrogen, test results indicate that NO_x emissions below 85 ppm (at 3 percent O_2) are possible while CO and smoke are low. Translation of the design requirements to practical burner designs, and additional requirements for initial fuel/air contacting and second-stage air addition are presented and discussed. Data obtained over a scale range of 30:1 show that residence time and temperature in the first stage are the most important scaling parameters for this low-NO_x burner design and that aerodynamic effects are second order parameters. Detailed design of the 16 MW prototype burner is also discussed, which was selected to meet the design criteria as well as requirements for commercial-grade oil field equipment. Key aspects of the hardware design are the use of commercial primary burner equipment, a refractory-lined first stage chamber which is regeneratively air-cooled, and variable second-stage air injection to optimize emissions and flame shape. Discussion of the detailed design includes retrofit requirements and specifications for primary throat/atomizer design, first-stage residence time and temperature, refractory lining design, and preliminary requirements for second-stage air injection. The burner will be briefly evaluated in a test furnace prior to retrofit and performance testing in a field-operating steam generator in Kern County, California.

This Project Summary was developed by EPA's Industrial Environmental Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Enhanced oil recovery processes are applied to oil field production in order to extract heavy, viscous crude oil and tar sands which cannot otherwise be produced. A significant fraction of total U.S.

oil reserves require application of enhanced oil recovery in order to be realized. Thermally enhanced oil recovery (TEOR) involves injection of wet steam which is produced by combusting crude oil in oil field steam generators, typically ranging in size from 7 to 15 MW capacity. More than 90 percent of all oil field steam generators in the United States are located in California, one-third (approximately 1000 units) of which are located in Kern County. Approximately one-third of the produced crude oil is consumed by the steam generator, amounting to over 200,000 barrels of crude oil consumed per day at full capacity. The crude oils which are fired in these steam generators are typically high in nitrogen (~0.8 to 1.0 percent) and sulfur content. Uncontrolled emissions of NO_x and SO_x can therefore reach high levels and potentially worsen ambient air quality.

Local legislation regulating emissions of NO_x from oil field steam generators threatens to limit oil production unless NO_x control methods are applied. A ceiling on total NO_x emissions from all steam generators in Kern County has been established which limits total emissions to 1979 levels; thus new generators cannot be brought on line without reducing emissions from existing ones. New generators are required to have "best available control technology" (BACT) which may include low-NO_x burners, postflame NH_3 injection, or other postflame treatment methods. In addition, if ambient NO_2 level in Bakersfield exceeds a specified level, the total NO_x ceiling is lowered to the equivalent of 0.14 lb $NO_x/10^6$ Btu (60 mg/MJ) or 105 ppm NO, corrected to 3 percent oxygen, if all steamers are in operation. Enhanced oil recovery operations are projected to expand through 1995. The level of NO_x control required to meet both growth and air quality goals has typically been difficult to achieve with available technology while maintaining acceptable CO and particulate emissions and practical flame conditions within the steamer.

This program addresses the need for advanced NO_x control technology for oil-field steam generators, and concerns the development of a full-scale burner system, for which the concept is based on fundamental studies. The burner will be retrofittable to existing steam generators and will produce acceptable emissions of CO and particulate while maintaining a flame form compatible with the steamer design. The emission goals for NO_x are to achieve less than 85 ppm NO_x at 3 percent excess oxygen.

The major elements of this program are:

1. Conceptual design development—to verify and refine design scaling criteria developed under previous EPA contracts in order to develop hardware designs.
2. Detailed burner design and construction—to produce a commercial-grade full-scale burner suitable for retrofit on an existing steam generator.
3. Burner optimization and evaluation—to minimize pollutant emissions in a field-operating TEOR steam generator firing high-nitrogen crude oil and evaluate performance over an extended period of time.

The report discusses the first two elements of the project, through completion of the detailed engineering design of the full-scale (16 MW) commercial prototype burner.

NO_x Formation and Control

NO_x emissions from stationary combustors can be reduced by combustion modification techniques which involve staging the heat release process. However, optimization of these techniques to control NO_x emissions from liquid-fuel-fired combustors has proven difficult because of the limited knowledge of the controlling phenomena and the problems associated with the scaling of combustion systems.

Many studies have been carried out to determine the mechanism of NO formation in flames, both from molecular nitrogen (thermal NO) and from nitrogen contained in the fuel (fuel NO). Field test data and laboratory studies have established the importance of fuel NO to the total emission of NO_x from residual fuel oil flames. Thermal NO formation is strongly dependent upon temperature, and its formation can be reduced by decreasing flame temperatures by techniques such as the addition of cooled combustion products to the combustion air (flue gas recirculation). However, since most NO formed in residual fuel oil flames is fuel NO and its formation is not strongly dependent upon temperature, flue gas recirculation is not an effective NO_x control technique. Fuel NO formation is very sensitive to reactant stoichiometry. Fuel-rich conditions promote the formation of molecular nitrogen from fixed nitrogen species ($NO + NH_3 + HCN$) which are formed as the liquid fuel decomposes. Consequently, staged combustion (involving the formation of a fuel-rich zone either by delaying fuel/air mixing or by dividing the combustion air supply into two and injecting one portion downstream from the burner) is the most effective NO_x control technique for residual fuels.

In a previous study, parameters controlling the effectiveness of staged combustion for a wide range of liquid fuels containing bound nitrogen were defined in a series of bench-scale studies which were carried out in a refractory tunnel furnace. Exhaust NO levels from a staged combustion system depend on:

1. *First-Stage Processing.* Total fixed nitrogen (TFN) is minimized if the residence time of the fuel-rich reactants is maximized at high temperatures and at an optimum stoichiometry which is temperature dependent.
2. *Mixedness.* Since stoichiometry must be controlled, it is important that the reactants are well mixed.
3. *Second-Stage Processing.* Exhaust NO levels are the sum of thermal NO formation and conversion (or retention) of TFN species to NO during heat release in the second stage, and the second stage must be designed to minimize these effects.
4. *Fuel Properties.* The rate of evolution of nitrogen species from the liquid fuel droplets has an impact because it dictates the time available for N_2 formation in the first zone. This can be overcome by minimizing droplet size.

This information has been used to construct bench- and pilot-scale combustors having NO_x emissions below 100 ppm (corrected to 0 percent oxygen) and acceptable emission levels for CO and smoke when firing fuels containing greater than 0.5 percent fuel-bound nitrogen.

The bench-scale tests indicated that TFN concentration is minimized most effectively by increasing the temperature of the fuel-rich zone. The combination of high first-stage temperature, optimum stoichiometry, and long first-stage residence time resulted in exhaust NO_x levels below 100 ppm regardless of the nitrogen content of the liquid fuel. To translate this information into a full-scale (i.e., 18 MW) burner design requires information on how the controlling parameters scale. The approach used was to obtain experimental data with 2×10^6 Btu/hr (0.6 MW) and 10×10^6 Btu/hr (3 MW) prototype combustors, and thereby confirm the appropriate criteria for the design and fabrication of the full-scale combustor. In addition, isothermal (cold flow) spray/flow field tests were conducted to assess mixing and atomization characteristics produced by full-scale hardware in the region near the burner throat.

Pilot-Scale Development

Prototype Combustors

Two prototype low-NO_x burners, shown in Figure 1, were constructed with nominal design firing rates of 2 x 10^6 Btu/hr (0.6 MW) (small pilot-scale or SP) and 10 x 10^6 Btu/hr (3 MW) (intermediate pilot-scale or IP). Each test burner contains three major elements

1 An air/fuel injection system
2 A fuel-rich holdup zone.
3 A secondary air injection section

The primary zone is constructed from high temperature refractories and insulation to minimize heat loss through the walls and permit near-adiabatic conditions in the primary zone Fuel and primary air are injected at the entry of a divergent which forms the initial section of the fuel-rich holdup zone. The residence time in the fuel-rich zone, calculated at a first-stage stoichiometric ratio of 0.7, is approximately 0.50 sec for the SP burner and 0.42 sec for the IP burner. The primary products are directed through a convergent section which serves to minimize radiative heat loss, ensure complete mixing of the primary products, and minimize backmixing of secondary air into the primary zone Secondary air is injected parallel to the burner axis annularly around the primary exit

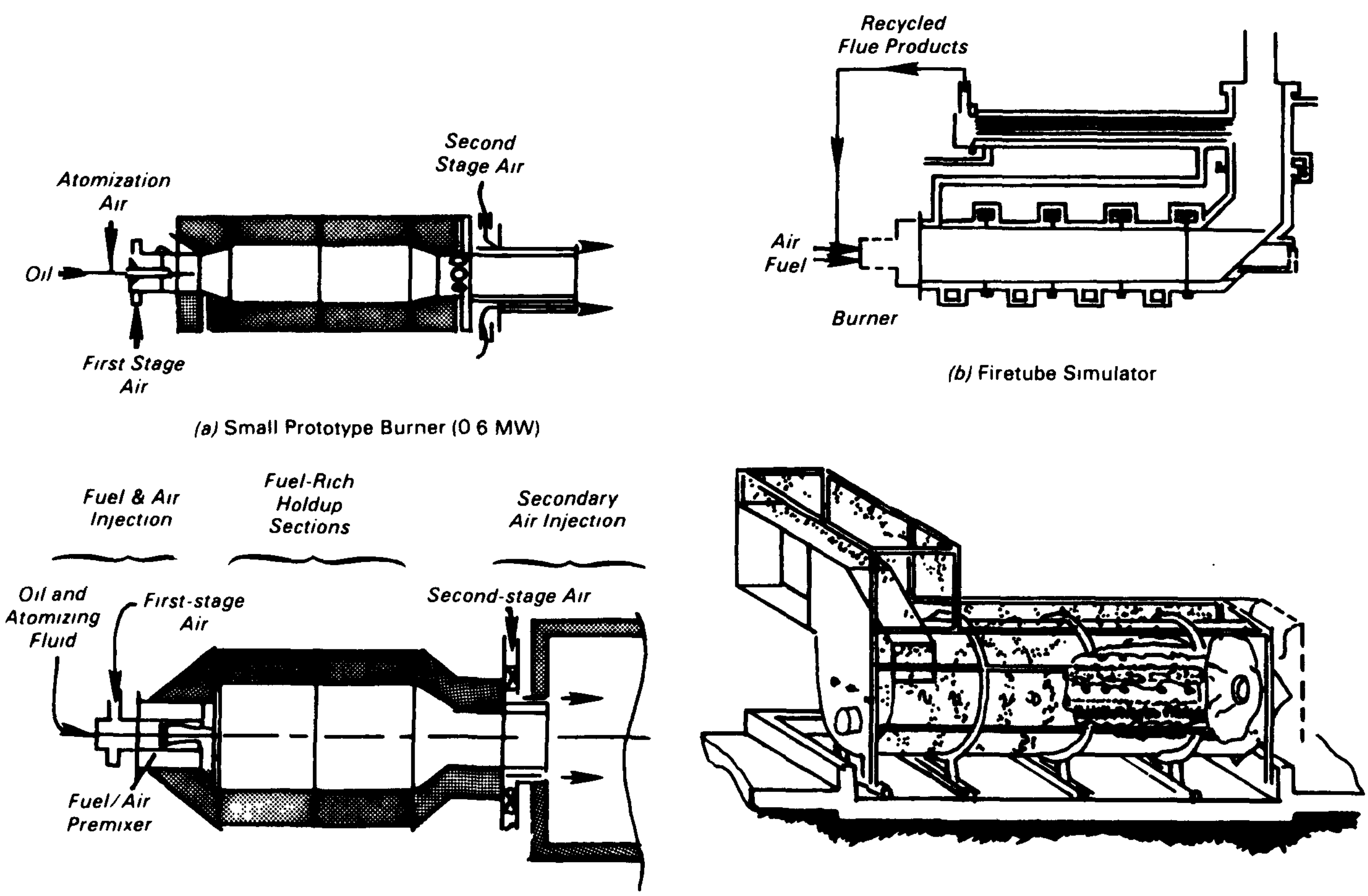
Fuel Injection

A number of different commercial atomizers were used in the two combustors. Most of the data were, however, obtained with an ultrasonic, air-assist atomizer and an internal-mixing steam-assist atomizer. At the 0.6 MW scale, the ultrasonic atomizer produced droplets with a narrow size distribution about a mean diameter of 20 μm, and the internal-mixing atomizer produced droplets with a much broader size distribution about a mean diameter of 40 μm At larger scales the ultrasonic atomizer has been found to produce droplets with a mean size greater than 120 μm.

Several air/fuel injection hardware changes were investigated during the 3 MW burner testing. Table 1 summarizes the first-stage hardware variations which were evaluated. Most of the configurations were variations on the fuel/air premixer concept with different exit geometries. The premixer design is scaled up on the basis of constant velocity and swirl numbers from the 0.6 MW design utilized in the small pilot-scale prototype.

Second-Stage Design

Second-stage mixing effects were extensively evaluated in the 3-MW studies, to determine limits of additional NO reduction possible through variations in the second-stage mixing and to develop practical information on the tradeoffs between NO_x/smoke emissions and flame shape. In addition to the first-stage exit sleeve shown in Table 1,



(a) Small Prototype Burner (0 6 MW)

(b) Firetube Simulator

(c) Intermediate Prototype Burner (3 MW)

(d) Small Watertube Simulator

Figure 1. *Prototype burners and experimental test furnace*

several air injection port configurations were tested to vary second-stage mixing. The number of ports, diameter (yielding two velocity levels), and distance from the centerline were varied. Figure 2 illustrates the different hardware configurations used.

Test Facilities

The pilot-scale burner tests were conducted at two test facilities:

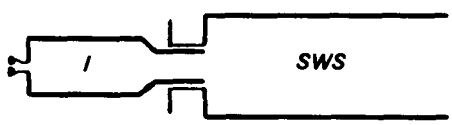
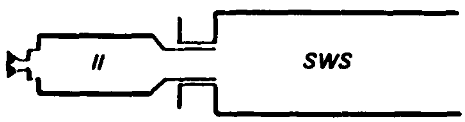
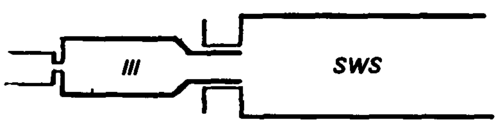
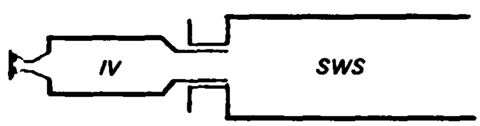
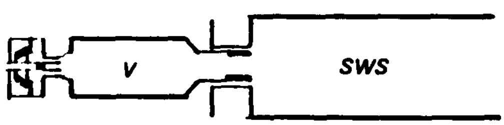
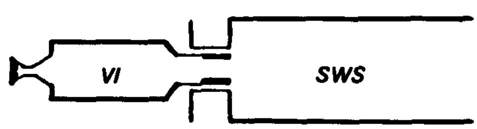
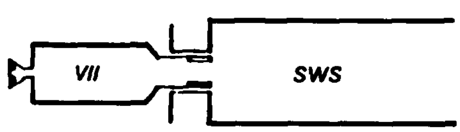
- *Firetube Simulator (FS) (Previous Study).* The combustion chamber is 3.2 m long with an internal diameter of 0.6 m. The chamber is composed of calorimetric sections cooled by heat transfer fluid and has a nominal wall temperature of 230°C. Only the SP burner was tested in this facility.
- *Small Watertube Simulator (SWS) (This Study).* The furnace is 5.2 m in length and 1.8 m inside diameter, is externally spray-cooled, and has a partial refractory lining. The total heat extraction is controlled by varying the percentage of internal surface which is covered by refractory. Both the SP and IP burners were tested in this facility.

Pilot-Scale Results

First-Stage Parameters

Figure 3 shows the influence of the first-stage stoichiometric ratio (SR_1) on exhaust emissions from the bench-scale studies carried out in the tunnel furnace and the prototype tests with different residual oils containing approximately 0.6 percent nitrogen. The curves are generally lower but similar in shape to those obtained in other staged combustion studies. As SR_1 decreased, NO_x emissions decreased rapidly until a minimum was reached and then increased. Smoke and CO emissions from the SP burner were low for $SR_1 > 0.7$, but under more fuel-rich conditions emissions increased sharply. CO was less than 100 ppm and smoke number was generally less than 5 at the point where the minimum NO_x level occurred. CO and smoke emissions from the IP burner were also low for SR_1 greater than the point where minimum NO_x occurred. CO and smoke emissions from the IP burner were also low for SR_1 greater than the point where minimum NO_x occurred; however, for many of the configurations tested, the sharp increase in emissions below this point was less severe. Differences in second-stage thermal environment between the 2 x 10^6 Btu/hr (0.6 MW) firetube simulator and the 10 x 10^6 Btu/hr (3 MW) small watertube simulator may contribute to the observed difference in burnout of CO and smoke. Comparison

Table 1. *First-Stage Hardware Configurations in 3 MW Tests*

Configuration	*First-Stage*	*Second-Stage*
 I — SWS	— *Premixer* — *Swirl (S=0.4)* — *Parallel Exit*	— *Axial Air Injection* — *Annulus Injector* — *51 CM First-Stage Exit Diameter*
 II — SWS	— *Premixer* — *Swirl (S=0.4)* — *Set Back Parallel Exit*	— *Axial Air Injection* — *Annulus Injector* — *51 CM First-Stage Exit Diameter*
 III — SWS	— *Premixer* — *No Swirl* — *Parallel Exit*	— *Axial Air Injection* — *Annulus Injector* — *51 CM First-Stage Exit Diameter*
 IV — SWS	— *Premixer* — *Swirl (S=0.4)* — *Divergent Exit (L/D=2.6)*	— *Axial Air Injection* — *Annulus Injector* — *51 CM First-Stage Exit Diameter*
 V — SWS	— *2 Channel (Low Velocity)* — *Swirl* — *Divergent Exit (L/D=1.1)*	— *Axial Air Injection* — *Annulus Injector* — *36 CM First-Stage Exit Diameter*
 VI — SWS	— *Premixer* — *Swirl (S=0.4)* — *Divergent Exit (L/D=2.6)*	— *Axial Air Injection* — *Annulus Injector* — *36 CM First-Stage Exit Diameter*
 VII — SWS	— *Premixer* — *Swirl (S=0.4)* — *Parallel Exit*	— *Axial Air Injection* — *Annulus Injector* — *36 CM First-Stage Exit Diameter*

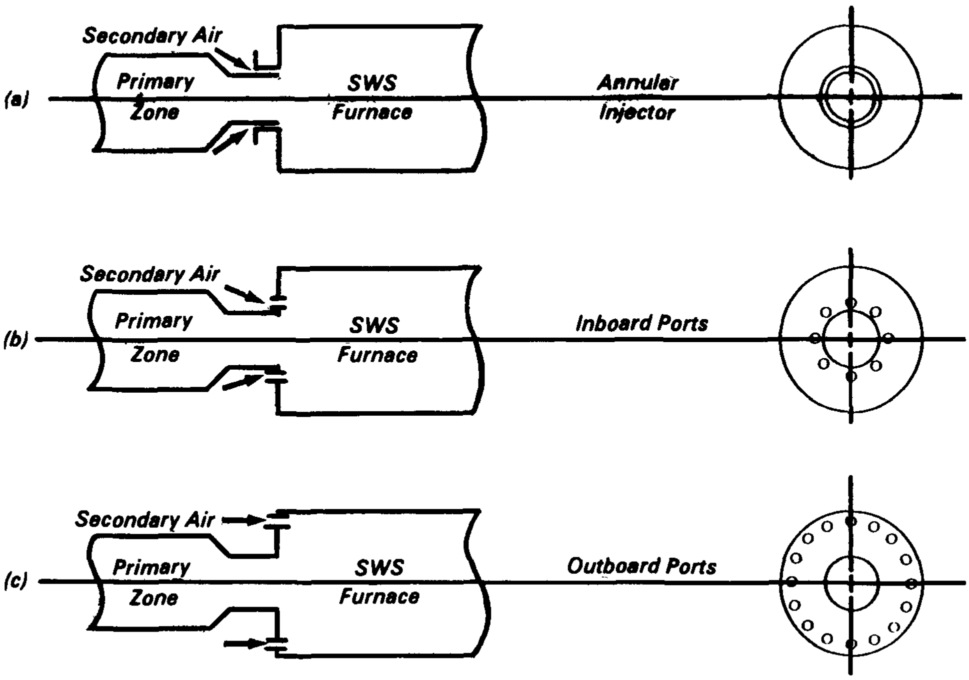


Figure 2. *Secondary air injection configurations investigated with 3 MW pilot scale burner (ports shown in axial orientation).*

of the three sets of results indicates that concept scaleup shifted the optimum SR_1 from 0.8 to 0.7 in going from 70,000 Btu/hr (0.02 MW) to 2 x 10^6 Btu/hr (0.6 MW), and to 0.56 in going to 8 x 10^6 Btu/hr (2.5 MW). This shift can be attributed to reduced heat losses and therefore higher temperatures, and to changes in fuel/air mixing characteristics, associated with the increase in scale.

The influence of burner load with the IP burner is shown in Figure 4 with and without air preheat. Fuel flowrate was varied above and below the baseline load from 2.3 MW to 3.5 MW throughput. Minimum NO_x emissions increased with load, ranging from 95 ppm to 77 ppm at 3.5 to 2.3 MW load, respectively, without first-stage air preheat. With first-stage air preheat, minimum NO_x ranged from 88 to 63 ppm at the same loads, respectively. The optimum stoichiometry in the first stage was not shifted significantly. Optimum SR_1 varied from 0.54 to 0.56 with preheat and from 0.55 to 0.57 without preheat. Smoke emissions were insensitive to load.

The effect of atomizer and air distribution variations can be seen in Figure 5. NO_x emissions increased substantially when the swirl vanes were removed from the premixer assembly (Configuration III). Optimum stoichiometry was also shifted to the fuel-lean side. The steep dependence of NO_x on SR_1 was somewhat reduced at high primary air preheat for Configuration III; however, only limited data was obtained. Observation of the flame from the rear of the SWS indicated that a rather bright, narrow jet flame was formed in the first stage chamber. Utilization of available volume for residence time is probably very poor in this configuration, accounting for the increased NO_x emission.

The experimental narrow-angle Y-jet atomizer and ultrasonic atomizer produced similar NO_x emissions under equivalent conditions, although slightly higher than baseline in both cases. Smoke numbers from the Y-jet and internal-mixing atomizer were 2 for all data shown in Figure 5.

Second-Stage Effects

The method of secondary air injection can potentially impact exhaust NO_x levels, and different modes of injection have been examined in both prototype burner systems. The standard annular (parallel) air injection system provided a relatively slow mixing rate and resulted in long diffusion-type flames. In the small prototype burner, rapid mixing was obtained by injecting the second-stage air radially through a water-cooled boom inserted along the firetube axis from the rear. NO_x emissions remained essentially constant when the ratio of air between the axial and radial injectors was varied: however, smoke emissions were substantially decreased as secondary air was transferred from the parallel injector to the radial injector. Similar results were obtained in both prototype burners when swirl vanes were added to the annular second-stage air injection system, suggesting a relative insensitivity of NO_x emissions to changes in mixing while providing some measure of control over flame shape. In larger practical-scale burner systems, however, mechanical considerations may well preclude the use of narrow annular passages for secondary air injection. To overcome this limitation the potential use of discrete secondary air injection ports has been investigated in the IP burner. Typical data are presented in Figure 6a, and show that with axial injection there is no difference in minimum NO_x between the annulus and discrete ports; with radial injection to induce rapid mixing, an increase of some 25 ppm NO_x was observed. This configuration produced short intense flames and, although the level of smoke emission was generally low, the range of operation over which low smoke could be maintained was extended. The reason for this apparent increased sensitivity to mixing at the larger scale is not immediately apparent from the data, but is believed to be due to increased formation of thermal NO_x in local high-intensity combustion zones close to the air jets.

Figure 6 shows the results of doubling the velocity of first-stage combustion products entering the second stage. This was accomplished by adding a sleeve to the first-stage exit. The flame produced by this configuration was very short without a visible smoky trail. The increase in velocity by a factor of 2 decreased flame length by a factor of 3 to 4, and increased NO_x emissions to 95 ppm from 72 ppm. Further optimization of exit velocity and swirl level may be possible to improve NO_x and flame shape characteristics with the annular air injector.

All the TFN which exists in the first stage does not result in NO in the combustion products of the second stage. Thus, it is important to design the second-stage air injection system to minimize NO formation from TFN species. In addition, thermal NO formation must be minimized which requires that second-stage flame temperatures must be maintained below some critical threshold. Heat extraction between the fuel-rich zone and the secondary air injection system allows some control over temperature in the

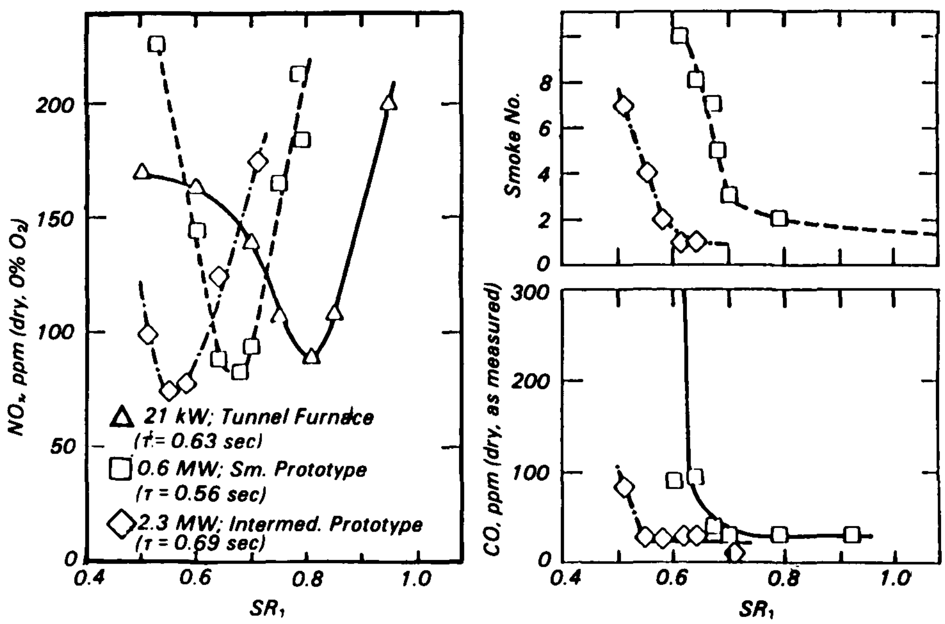


Figure 3. *Influence of scale on combustor performance.*

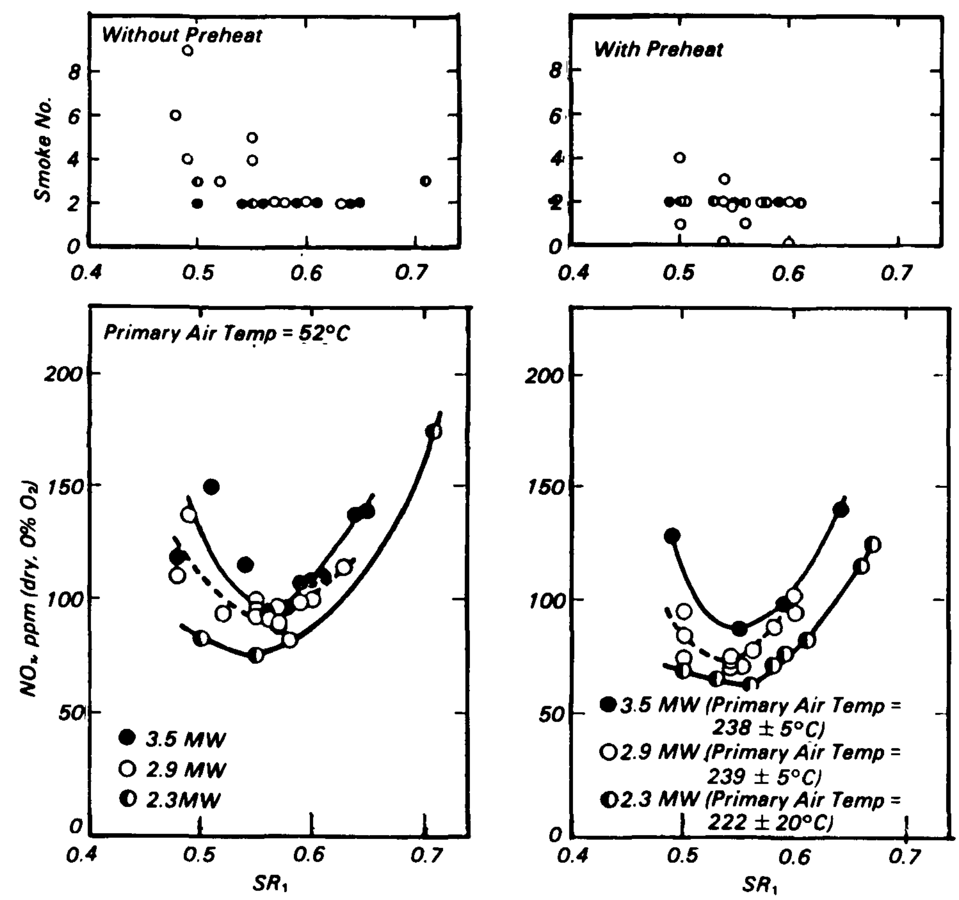


Figure 4. *Influence of load on emissions from IP burner.*

second stage. Tests in the SP burner showed that interstage cooling, in the form of coils around the periphery of the second-stage throat (approximately 6 percent of the heat input was removed), decreased the minimum exhaust NO_x by approximately 20 ppm. Exactly analogous results were achieved when 40 percent flue gas recycle was introduced with the second-stage air ($\Delta NO_x = 18$ ppm). In both tests there was a minor impact on smoke emissions; thus, it appears that at the optimum operating conditions, second-stage thermal NO_x formation accounts for approximately 20 percent of the total exhaust NO_x emissions. Use of interstage cooling may become more important in subsequent scaleup if air preheat is added and/or rich-zone heat loss is reduced further. Tests in the IP burner at 3.8 MW in which excess air was varied from 0.3 to 4.5 percent produced a 16 ppm variation in NO_x, suggesting about the same order of magnitude for thermal NO_x formation as in the SP tests.

Scaling and Full-Scale Burner Design

Design Criteria

The experimental work carried out on the bench and prototype combustors has provided an understanding of the controlling mechanisms of NO_x formation and control in staged liquid fuel combustion. The data suggest that application of these concepts can be achieved in a staged burner which consists of three major components with the following characteristics:

- Fuel Injection System
  - — High quality atomization to produce a small mean droplet size.
  - — Rapidly mixed fuel and air.
  - — Minimal heat extraction and air preheat to maximize fuel vaporization rate.
- First-Stage Fuel-Rich Zone
  - — Stoichiometric ratio approximately 0.7 or lower to minimize TFN concentration.
  - — Residence time in excess of 400 msec to allow sufficient TFN decay.
  - — Control of heat loss to produce a first-stage exit temperature in excess of 2600°F (1425°C).
- Second-Stage Air Injection
  - — Partial quenching to minimize thermal NO formation in the second stage.
  - — Refractory choke to prevent backmixing and reduce heat loss.
  - — Intermediate second-stage mixing

to reduce smoke formation without affecting minimum NO_x.

The residence time in the fuel-rich zone required to achieve the desired TFN concentration is an important practical design parameter. Figure 7 summarizes minimum exhaust NO_x and TFN data for the tunnel furnace and the prototype burners firing in both the firetube simulator and the small watertube simulator as a function of the first-stage residence time. At both bench and small pilot scales, increasing the first-stage residence time significantly decreased exhaust NO_x because of an associated decrease in TFN. (Increasing first-stage residence time allows HCN, NH_3, and NO to decay further toward equilibrium values.) Both the exhaust NO_x and the TFN from the SP burner were lower than from the tunnel furnace because of the increased rich-zone temperature associated with the increase in scale.

The first-stage residence time was varied in the SP burner/firetube simulator tests by altering the firing rate, and in the SP burner/watertube simulator tests by changing the reactor length at a fixed firing rate. A strong correlation between the two sets of experiments suggests that the controlling processes are dominated by kinetic effects (time and temperature) and not by aerodynamics and that the principal influence of firing rate is on residence time. Clearly, increasing firing rate also increases first-stage temperature, but this effect is small because even at 2×10^6 Btu/hr (0.6 MW) the prototype heat losses were low. First-stage exit temperatures measured at SR_1 of 0.7 were 2950°F (1620°C) compared to calculated adiabatic flame temperature of 3180°F (1750°C).

The key elements in these design characteristics are the requirements for a high-temperature, optimally fuel-rich, primary combustion zone with a long residence time. A number of the remaining parameters are scale-dependent and must be optimized at the burner scale under consideration. The mean droplet size produced by a given atomizer design, for example, does not remain constant with scale, but tends to increase as size increases. Drop-size distributions produced by full-scale (18 MW) atomizers under isothermal conditions showed that the mean drop size was similar for an ultrasonic atomizer and a Y-jet atomizer (Figure 8); however, radial distribution of fuel mass within the swirling flow field was very different. While small droplets are more favorable, combustion conditions are such that droplet size alone does

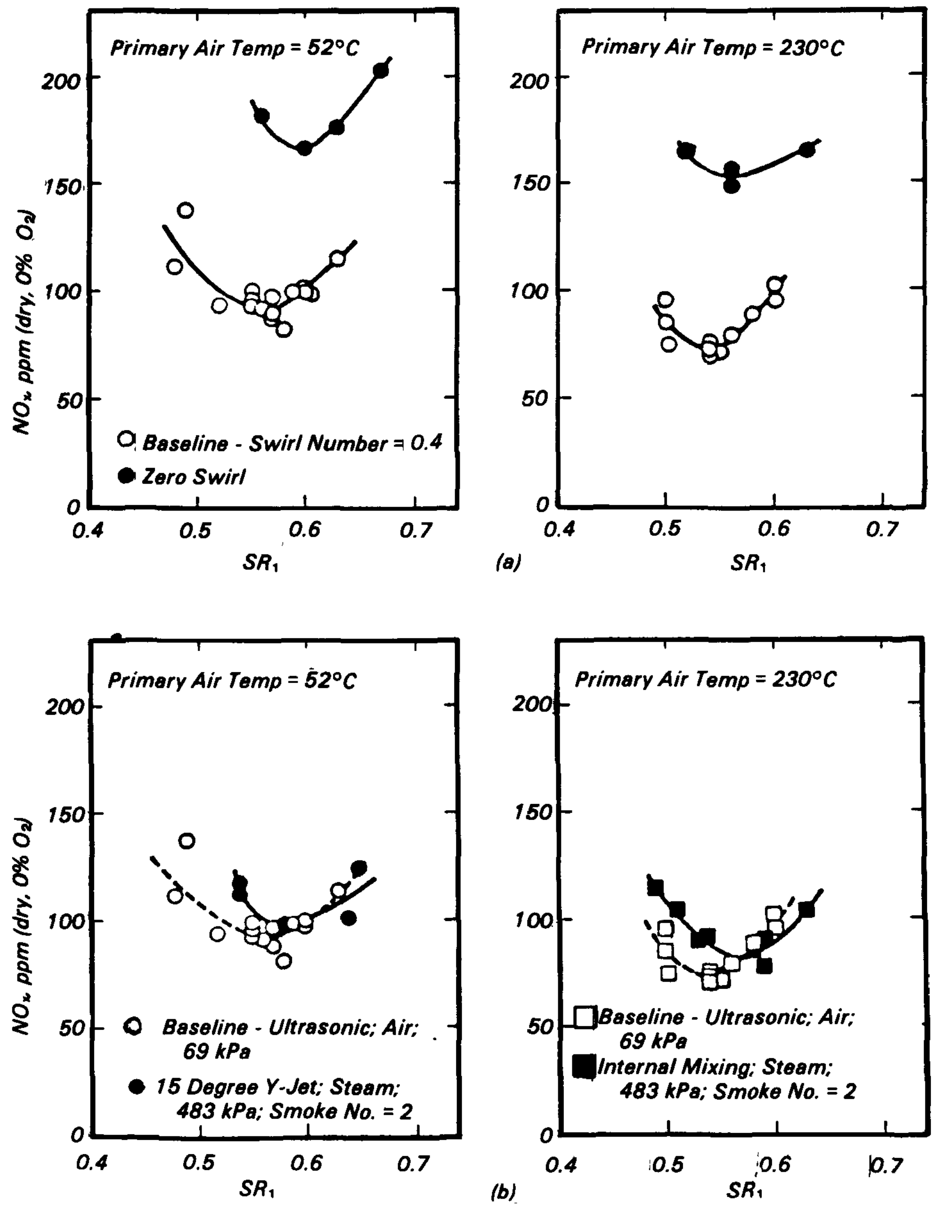


Figure 5. Effect of (a) swirl and (b) atomizer type on NO_x emissions.

not have a large impact on minimum NO_x. Rather, increased droplet size leads to greater sensitivity to those parameters which control fuel/air mixing and spray penetration. For practical applications, optimum results are obtained by selecting and matching spray angles and air register designs to provide for uniform distribution and rapid mixing.

Similarly, the overall burner performance has been shown to be more sensitive to the mode of secondary combustion air injection at larger burner scales. Rapid mixing is required to suppress smoke formation, but may impact minimum NO_x performance. In practical applications a major additional concern is the shape of the second-stage flame and its interaction with its heat transfer surroundings, which can be strongly influenced by mixing. Final designs of secondary air injection will therefore represent a compromise between NO_x emissions, flame shape, and other pollutants such as particulates and CO.

The impact of fuel type on the ability of such burners to achieve low-NO_x emissions is also important. The influence of fuel-nitrogen content on the performance of the small-scale low-NO_x prototype burner was established by conducting

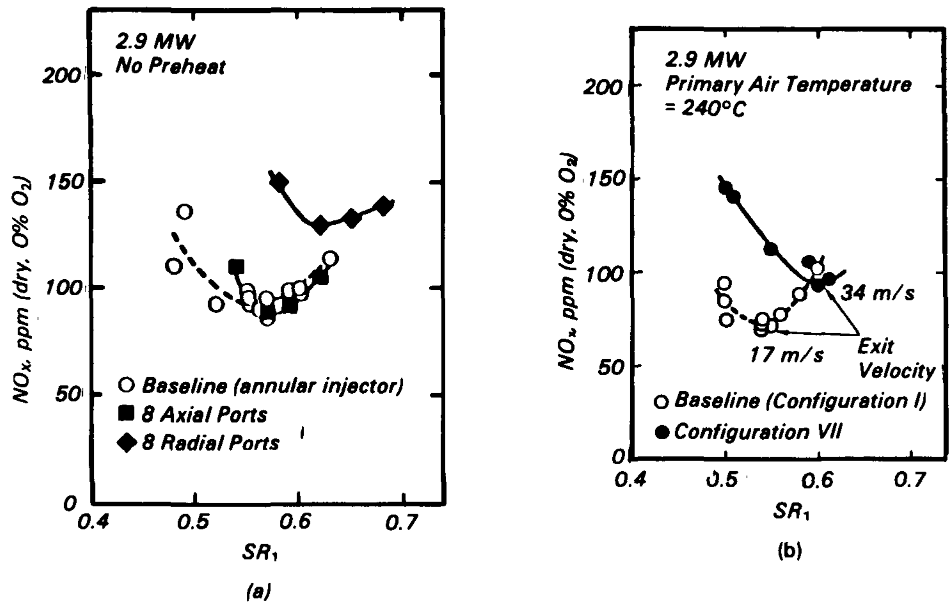


Figure 6. *Second-stage mixing effects.*

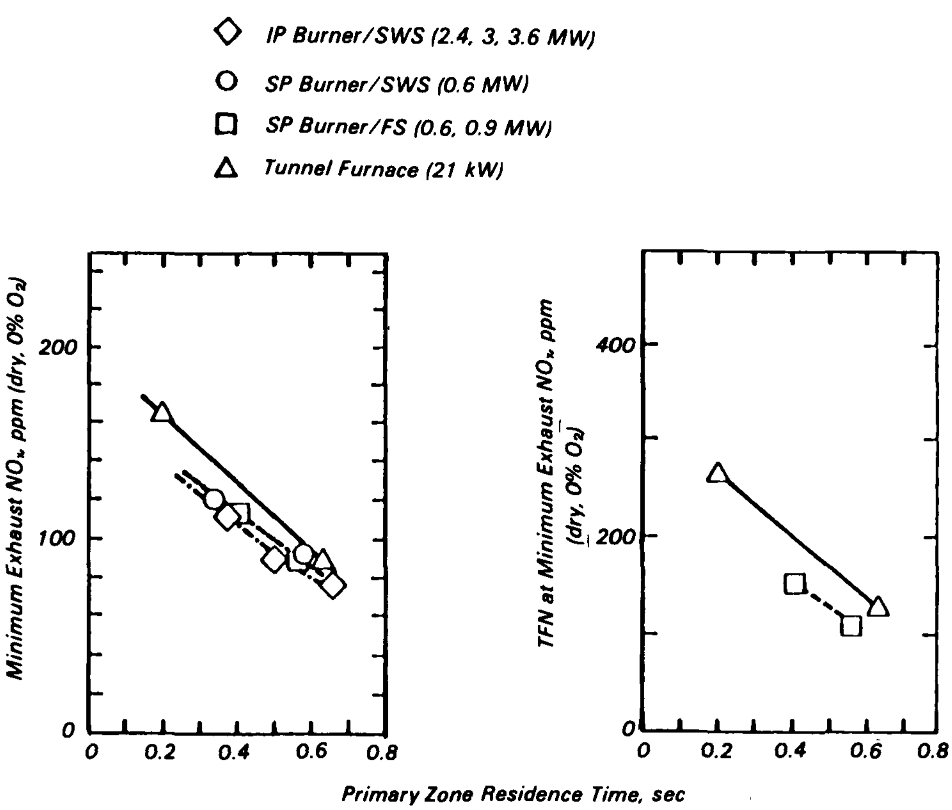


Figure 7. *Second-stage NO_x production and first-stage TFN decay for bench scale and pilot scale.*

tests with a distillate oil, residual oils, a coal liquid, and propane + NH_3. Data obtained in these tests are shown in Figure 9 which indicates that with the SP burner minimum NO_x emissions are only weakly dependent upon total fuel nitrogen content. Figure 9 also summarizes data obtained in the small-scale tunnel furnace, and in the larger 10×10^6 Btu/hr (3 MW) prototype. Concept scaleup reduced the dependence on fuel-nitrogen; this is probably because of the increased fuel-rich temperature. Thus this low NO_x concept should be capable of producing NO_x emissions less than 100 ppm at 0% O_2 (85 ppm at 3% O_2) even when firing the high-nitrogen crude oils typical, for example, of the Kern County oil fields.

Final Engineering Design

Two full-scale design concepts evolved from the detailed engineering design study. The first utilized a multilayer, castable refractory lining to insulate the first stage, similar to the pilot-scale prototypes. Analysis of this design proved that, although the criteria for temperature and residence time could be achieved, the refractory lining would be excessively prone to failure due to thermal stresses, especially during start-up and shutdown. This is primarily due to the large thermal inertia of the thick monolithic refractory lining. An alternate design was developed which utilizes a thin refractory lining contained by a hallow cylindrical shell which is cooled by the primary combustion air. This "regenerative" design, based in part on a commercial direct-fired air heater design, was selected for construction after consideration of several factors, including structural integrity of the refractory lining, heat loss to surroundings, temperature profile within the first stage, space-efficiency (compactness), and transient performance. Both concepts employ commercially available primary burner components, and secondary air is injected through two sets of discrete ports, oriented axially and radially, to allow control over second-stage flame shape. .

Figure 10 illustrates the basic construction of the regenerative burner design. The refractory lining is made up of 15 cm (6-in.) thick, 90 percent-alumina brick installed directly against the inner stainless steel shell. Primary air enters the hollow shell near the burner exit and flows toward the primary burner throat, cooling the shell and gaining preheat (hence the term "regenerative"). Materials and dimensions were selected commensurate with the design operating conditions outlined in Table 2. A substantial degree of conservatism was incorporated in the final design. The outer shell is externally insulated to reduce heat losses and personnel safety hazard. Second-stage air is injected through a separate module and can be mixed radially or axially at the first-stage exit. After optimization of the secondary air injection, the variable components can be fixed to reduce complexity. Second-stage air injection will be optimized for velocity and radial/axial split.

Commercial-grade control equipment has been used to accommodate the additional control requirements of the burner and provide simple interfacing with the existing steam generator controls. The control system is designed to maintain first-stage stoichiometric ratio and flue gas oxygenations through closed-loop control. The system uses a pneumatic primary control loop with a feedback trim signal generated by a programmable controller and flow measurement instrumentation.

Construction of the burner was completed in May 1983, with commissioning in the field in October 1983. The burner will be briefly evaluated in an experimental test furnace prior to the field installation.

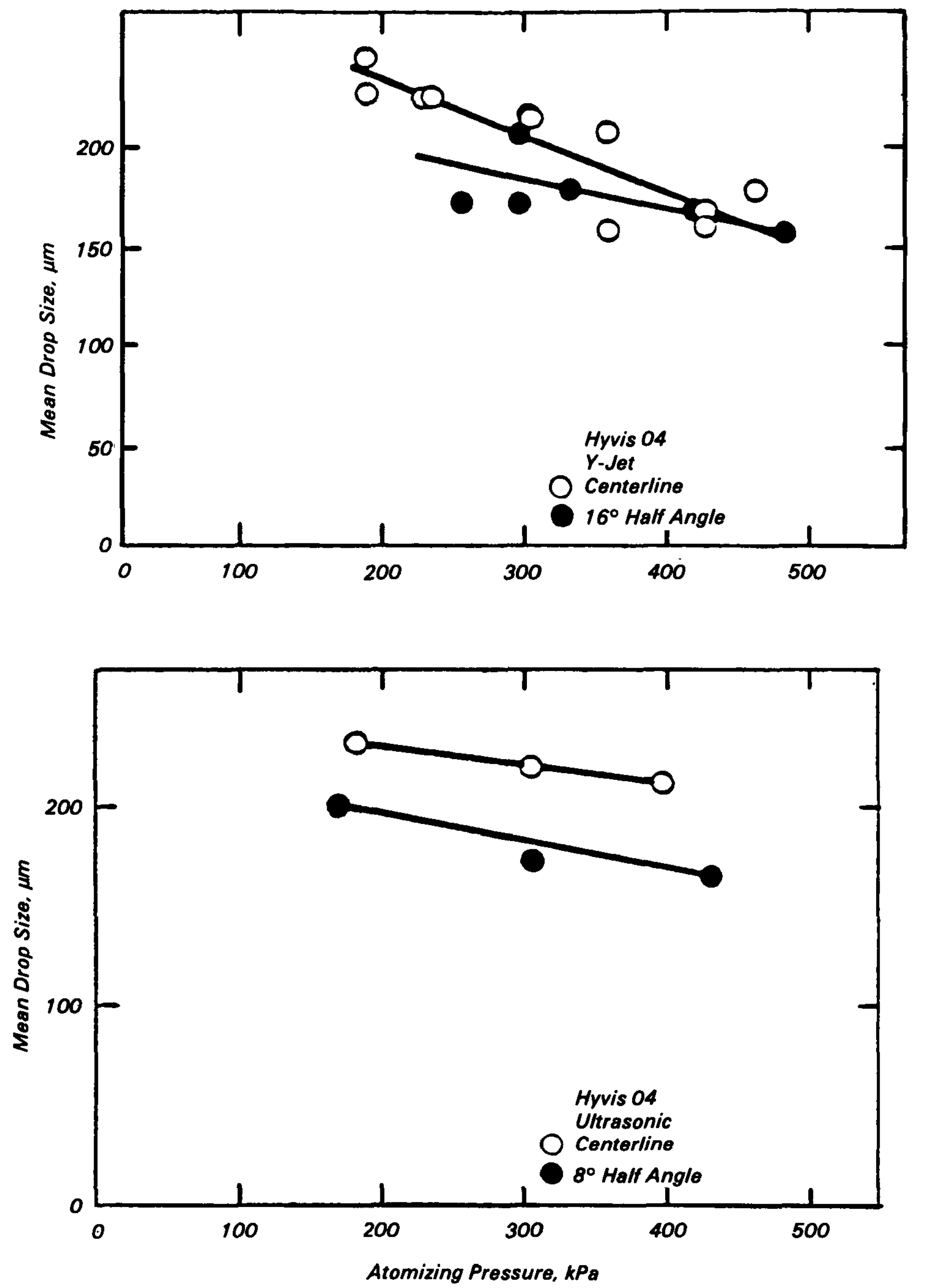


Figure 8. Drop size from ultrasonic and Y-jet atomizers.

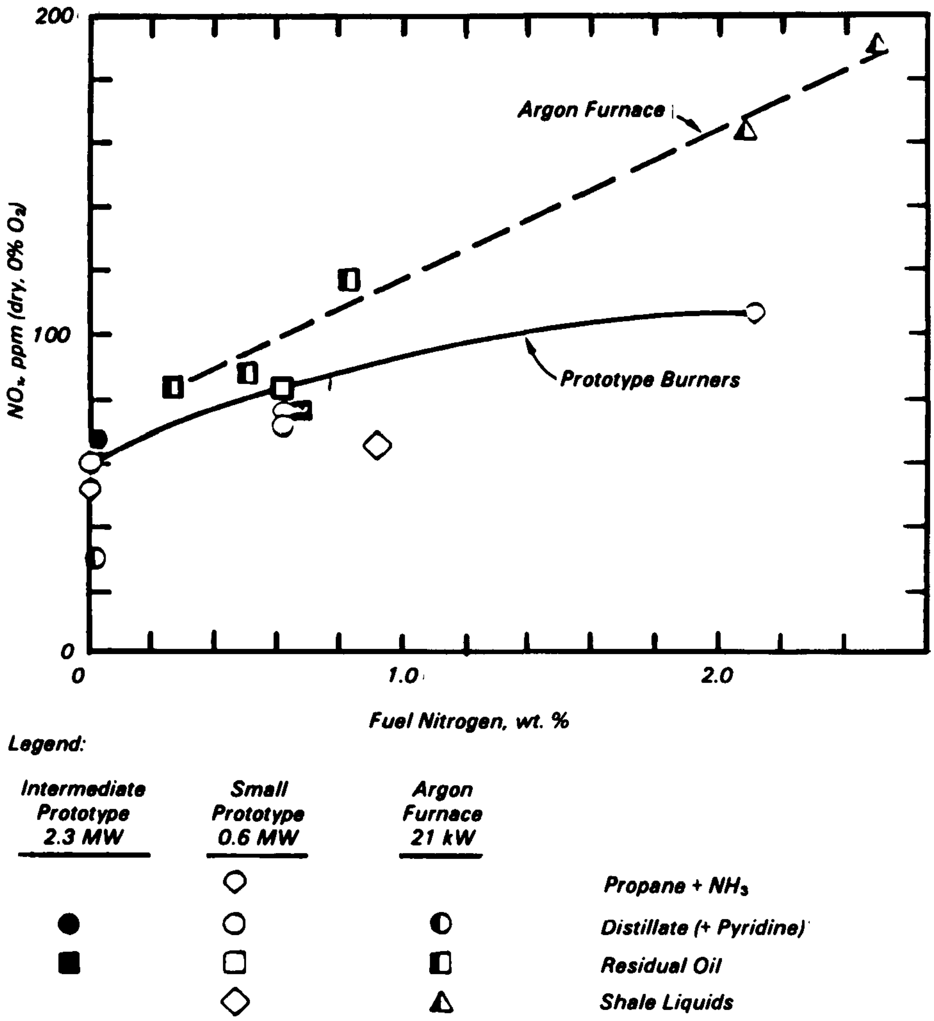


Figure 9. *Influence of fuel nitrogen on second-stage NO_x - bench- and pilot-scale data.*

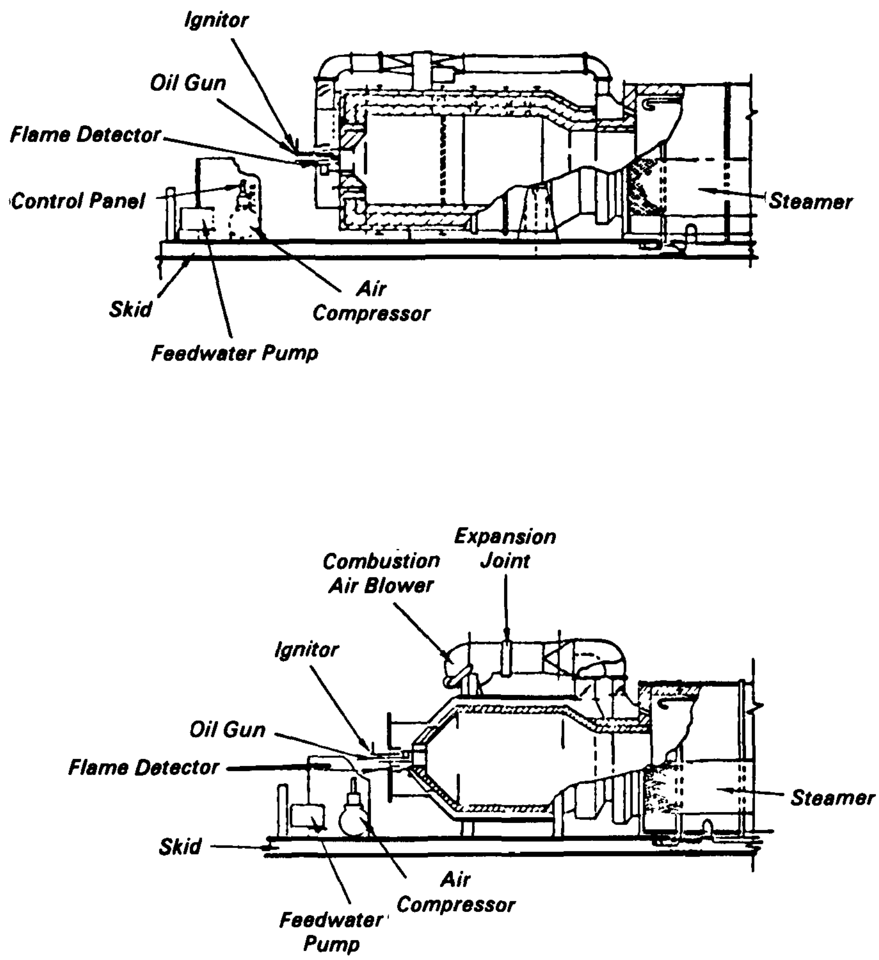


Figure 10. Conceptual burner designs for TEOR steam generators.

Table 2. First-Stage Design Specifications and Performance

	Configuration	Horizontal Cylinder Flat Wall Entrance 30-Degree Convergent Exit Cone
	Volume	$18.3\ m^3$ ($650\ ft^3$)
	Inside Diameter	213 cm (7.0 ft)
	Outside Diameter	262 cm (8.6 ft)
	Overall Length	554 cm (18.0 ft)
	Refractory Lining Thickness	15 cm (0.5 ft)
	Primary Burner Throat Diameter	38 cm (1.25 ft)
	First-Stage Exit Diameter	130 cm (4.25 ft)
Performance at Design Operating Point	Load	18 MW (60×10^6 Btu/hr)
	First-Stage Stoichiometric Ratio	0.60
	Gas Temperature	1650°C (3000°F)
	Hot-Face Refractory Temperature	1560°C (2850°F)
	Inner Shell Temperature	335°C (650°F)
	Primary Air Velocity at Primary Throat	40 m/s (130 ft/s)
	Exit Gas Velocity	16 m/s (50 ft/s)
	Mean Residence Time	0.8 s

*USGPO: 1984-759-102-10677

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The complete report, entitled "Evaluation and Demonstration of Low-NO_x Burner Systems for TEOR Steam Generators—Design Phase Report," (Order No. PB 84-224 393; Cost: $28.00, subject to change) will be available only from:
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
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The EPA Project Officer can be contacted at:
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