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A STUDY OF AIR POLLUTANT EMISSIONS FROM RESIDENTIAL HEATING SYSTEMS

Office of Research and Development
National Environmental Research Center
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A STUDY OF AIR POLLUTANT EMISSIONS FROM RESIDENTIAL HEATING SYSTEMS

by

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ABSTRACT

This document presents a comprehensive collection of recent EPA research work into the problem of air pollutant emissions from small scale combustion systems. Major factors for controlling emission levels were found to be: excess air, residence time at high temperature, combustion-air-handling components of burners, and burner maintenance. Recommendations for minimizing emissions from new and existing equipment are given, based on the research results obtained. Data illustrating the effects of combustion parameter changes on emission levels are given both for experimental combustors and for residential heating equipment currently in use in the U. S. Future work directed toward reduction of emissions is also outlined.

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ACKNOWLEDGEMENTS

It is our pleasure to acknowledge the Environmental Protection Agency employees who contributed to various aspects of the program. R. P. Hangebrauck and G. B. Martin assisted with the air/fuel stoichiometry and residence time studies, respectively. Project engineers for the work with combustion improving devices and many of the flame retention burners were M. H. Hooper and D. P. Howekamp. We also express appreciation to C. H. Bernhardt, N. L. Butts, R. A. Mueller, and R. E. Thompson, the engineering technicians who helped perform the tests.

SUMMARY

MAJOR RESULTS

This study showed that excess air, residence time, flame retention devices, and maintenance are major factors in the control of air pollutant emission levels and equipment performance of residential heaters. It was shown that carbon monoxide (CO), gaseous hydrocarbons (HC), smoke, and particulate emissions pass through a minimum point as excess air is increased from stoichiometric. Oxides of nitrogen (NO_x) behave in the opposite manner, however: as excess air is increased, NO_x emissions pass through a maximum point.

A longer residence time was found to significantly reduce emissions of CO, gaseous HC, smoke, and particulates. However, NO_x emissions were increased slightly.

A study of combustion improving and flame retention devices showed that flame retention can be used both to reduce total emissions and to increase furnace efficiency. Although most flame retention devices tested increased emissions of NO_x, one device reduced them. Combustion improving devices, other than one utilizing flame retention, had little effect on pollutant emission levels.

This study and related field tests showed that burner and furnace maintenance affect burner performance and emission levels. Old, worn out, poorly constructed, or maladjusted burners are responsible for unnecessarily high levels of air pollutant emissions.

Ignition systems, nozzles, and combustion chamber shape and material were found to be less significant variables in the control of air pollutant emissions. NO_x was the only pollutant affected by ignition systems. It was found that some ignition systems increased nitric oxide (NO) emissions by about 10 percent, but one unit tested had no effect on them.

Nozzles were found to have a small effect on emissions of smoke, gaseous HC, CO, NO, and carbon dioxide (CO_2). However, differences for nozzles within the same brand as well as for nozzles of different brands indicated that burners should always be readjusted when nozzles are replaced.

Combustion chamber material was found to affect all emissions. When firing into a steel-lined chamber, the excess air had to be increased to obtain acceptable levels of CO, gaseous HC, and smoke. Thus, the efficiency was reduced. The combustion chamber shape had little effect on the emission levels, as long as the chamber dimensions were not changed significantly.

Gas burners, which had a rating equivalent to the oil burners discussed above, were also tested. These tests provided a comparison between emissions of gas and distillate oil burners. It was found that emissions from gas burners are about the same as those from most equivalent-size, high-pressure, atomizing-gun oil burners.

MINIMIZING EMISSIONS FROM EXISTING EQUIPMENT

The results discussed above can be used to minimize air pollutant emissions from existing equipment. Excess air, one of the major variables in reducing emissions, should be set as low as possible to provide high efficiency; however, it should not be set so low that it creates excessive amounts of CO, gaseous HC, smoke, and particulates. The burner should be set so the smoke level at hot running condition is no higher than No. 1 on the Bacharach scale*. A more detailed explanation is given in Appendix A. A refractory-lined combustion chamber, as opposed to a steel-lined chamber, will allow burner operation at a lower excess air level.

Since longer residence time has a positive effect in reducing overall emissions, existing furnaces should be underfired; i.e., a nozzle, slightly

*The Bacharach Smoke Number to which reference is made throughout this paper, is used for convenience and because most readers are familiar with it. The Bacharach Smoke Number is actually the "Smoke Spot Number" described in ASTM D 2156-65.

smaller than the one which originally came with the furnace, should be installed. The smaller nozzle will help reduce emissions in two ways: it will provide longer residence time; and it will reduce cyclic-based emissions since the burner will have to remain on longer to provide a given heat load. The number of cycles per unit time will be reduced. Of course the nozzle must have the capacity to supply a sufficient quantity of oil when the heating demand is greatest.

Since flame retention devices were found to improve furnace efficiency and reduce overall emissions, flame retention should be utilized. The flame retention concept is not limited to new or replacement equipment. The components which create the flame retention effect (e.g., the end cone and the retention ring or cone) can easily and inexpensively be installed on existing burners in the field. One such device, which increased efficiency and reduced all air pollutant emissions except NO_x, was the Union flame control device. Of the flame retention burners tested, the ABC Mite and Beckett Bantam burners increased efficiency and reduced emissions most effectively. The ABC Mite was the only burner tested which significantly reduced NO_x emissions, however.

Since air pollutant emissions can be reduced significantly if all burners are properly maintained, boilers and furnaces should be serviced by an authorized serviceman at least once a year, normally just prior to the heating season. Nozzles should be replaced yearly, with readjustment of the burner. If the heater malfunctions, the serviceman should be recalled. The serviceman should always adjust the furnace by checking the CO_2 level, draft, and the Bacharach Smoke No. with proper instruments, not by "eyeing" the flame. Old, worn out units which cannot be adjusted properly should be replaced.

The above recommendations can result in the following new-burner emission levels:

CO:	0.5 g/kg fuel
Gaseous HC:	0.06 g/kg fuel
NO;	0.8 g/kg fuel
Bacharach Smoke No.: (after 10 minutes of operation)	1.0

If the heater is properly serviced these levels should be maintained.

FUTURE WORK

These studies indicate that further work is required in several areas. Long-term performance tests are needed to accurately determine the effect of time on burner emissions once the burner is adjusted. Tests are also needed to more accurately determine the effect of underfiring burners both to increase residence time and to lower cyclic emissions.

A study is needed to determine whether improvement of furnace efficiency by using better heat exchangers is an economical way of reducing air pollutant emissions. If better heat exchangers are used, less fuel will be required for a given heat load; thus, the total emissions will be reduced.

Studies of methods to reduce cyclic emissions are also needed. A pilot or modulating burner should be investigated.

Critical burner and furnace design factors need further investigations. Such a study is presently being performed by the Rocketdyne Division of Rockwell International for distillate oil burners, under EPA Contract 68-02-0017. Similar programs are needed for other types of burners; e.g., residual oil burners and mixed fuel burners.

Burners or components which offer possible reductions in air pollutant emissions and improved efficiency should be investigated further. This includes burners such as "blue flame" and other unique burners, compact heating systems, and components such as sonic nozzles.

More refined instrumentation is needed for servicemen when adjusting burners. For example, a portable instrument which could measure CO_2, stack temperature, draft, and smoke at the same time would be beneficial. Perhaps a rating (such as good, fair, or poor) could be provided which would integrate the CO_2, stack temperature, draft, and smoke measurements. This could either be provided as part of the instrument or on a separate chart. Reasonably priced and portable instruments for accurately measuring gaseous HC, CO, and NO_x should be developed. Such instruments would help the serviceman to adjust heaters for low emissions and maximum efficiency. As a followup, training should be provided for the serviceman. If he is not familiar with the instruments and does not know either how to use them properly or how to evaluate the results, they will be of little use.

INTRODUCTION

The residential heater project was established because seasonal and geographic surveys indicate that significant amounts of air pollution result from domestic heating[1,2]. It has been estimated that air pollution from residential and commercial heating sources constitutes approximately 10 percent of the total air pollution in the United States. However, since pollution from these sources occurs only during the heating season at ground levels and in highly populated areas, the pollution problem is more significant than indicated by the 10 percent estimate. Therefore, the U. S. Environmental Protection Agency (EPA) initiated several projects related to the reduction of air pollution from residential heating. The early work was performed with an experimental furnace to determine the effects of air/fuel stoichiometry and residence time on air pollution emissions. Later, specific commercially manufactured furnaces, combustion improvers, flame retention burners, and prototype burners were investigated to identify the designs with low emissions. Most of this work was performed with a commercially available furnace.

The study concentrated on distillate oil and natural gas heaters which account for over 90 percent of the residential heating units in the United States. Specifically, this study was planned to determine: the burner design variables, components, and process conditions which are critical for control of air pollutant emissions; what can be done with present technology to control pollutant emissions; and research requirements to eliminate pollutant emissions from residential heaters.

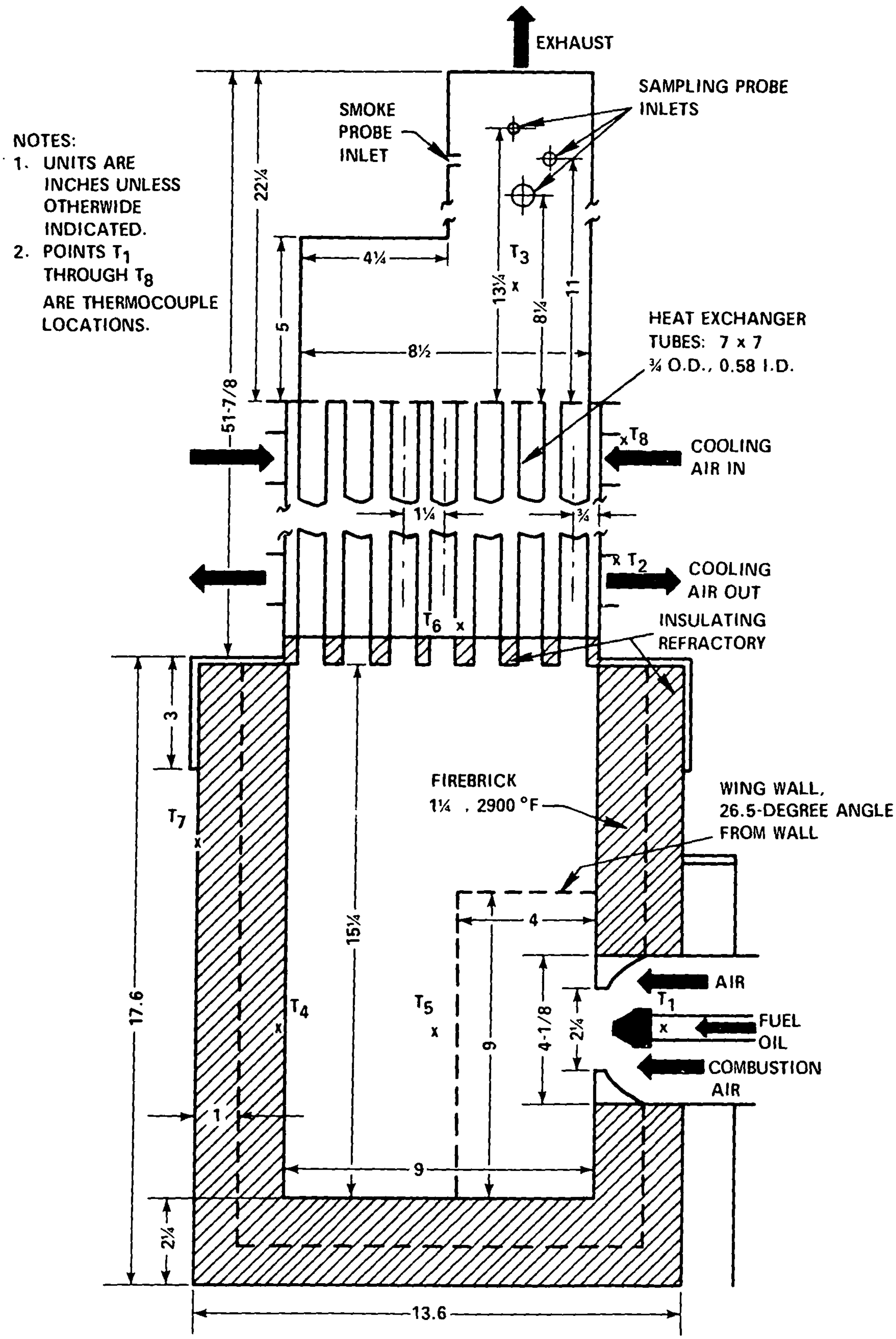

Figure 1. Experimental furnace, interior detail.

EXPERIMENTAL EQUIPMENT

EXPERIMENTAL FURNACE

The experimental furnace shown in Figures 1 and 2 was built for the initial studies. The design was dictated by several criteria: the equipment must be able to control the fuel, air, and other process variables; the internal geometry of the combustion chamber and heat exchanger must be simple enough to permit the high-temperature residence time of the combustion gases to be estimated and varied, and deposits to be removed; and the unit must be flexible enough to allow for changes in equipment and methods of operation.

An ABC Model 55J-1 oil burner equipped with a 1 gph*, 80-degree hollow-cone nozzle, was chosen for these studies. It is a popular-make, high-pressure atomizing-gun burner: in 1962, over 87 percent of the domestic oil burners in the United States were of this type[3] and 1 gph was an average domestic furnace firing rate; and by 1970, about 95 percent of the domestic oil burners were the high-pressure atomizing-gun type[4]. The combustion chamber for this burner was designed so the interior dimensions and wing walls conformed to recommended sizes for this capacity burner[5,6,7]. The air-cooled, steel heat exchanger was a shell-and-tube type in which the combustion gases passed through the tubes.

CONVENTIONAL RESIDENTIAL FURNACE

The part of the program in which commercially available and prototype equipment were tested required a furnace that was both representative of commercially available furnaces and adaptable to a large percentage of the burners to be tested. A survey was made to determine the burner size most widely used and the furnaces adaptable to that burner size. As a result of the survey, it was decided to test burners with a 0.75 gph firing rate, using a Williamson Temp-O-Matic Lo Boy Furnace for the tests. The furnace is shown schematically in Figure 3. Instrumentation used with the furnace is shown in Figure 4. The Williamson burner which originally accompanied the furnace (a conventional high-pressure atomizing-gun ABC Model 45 burner with a 0.75 gph, 80-degree hollow-cone nozzle) was used as the standard of comparison.

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*Although it is EPA policy to use the metric system, this publication uses certain non-metric units for convenience. Those more familiar with metric units should refer to Appendix E for the proper conversion factors.

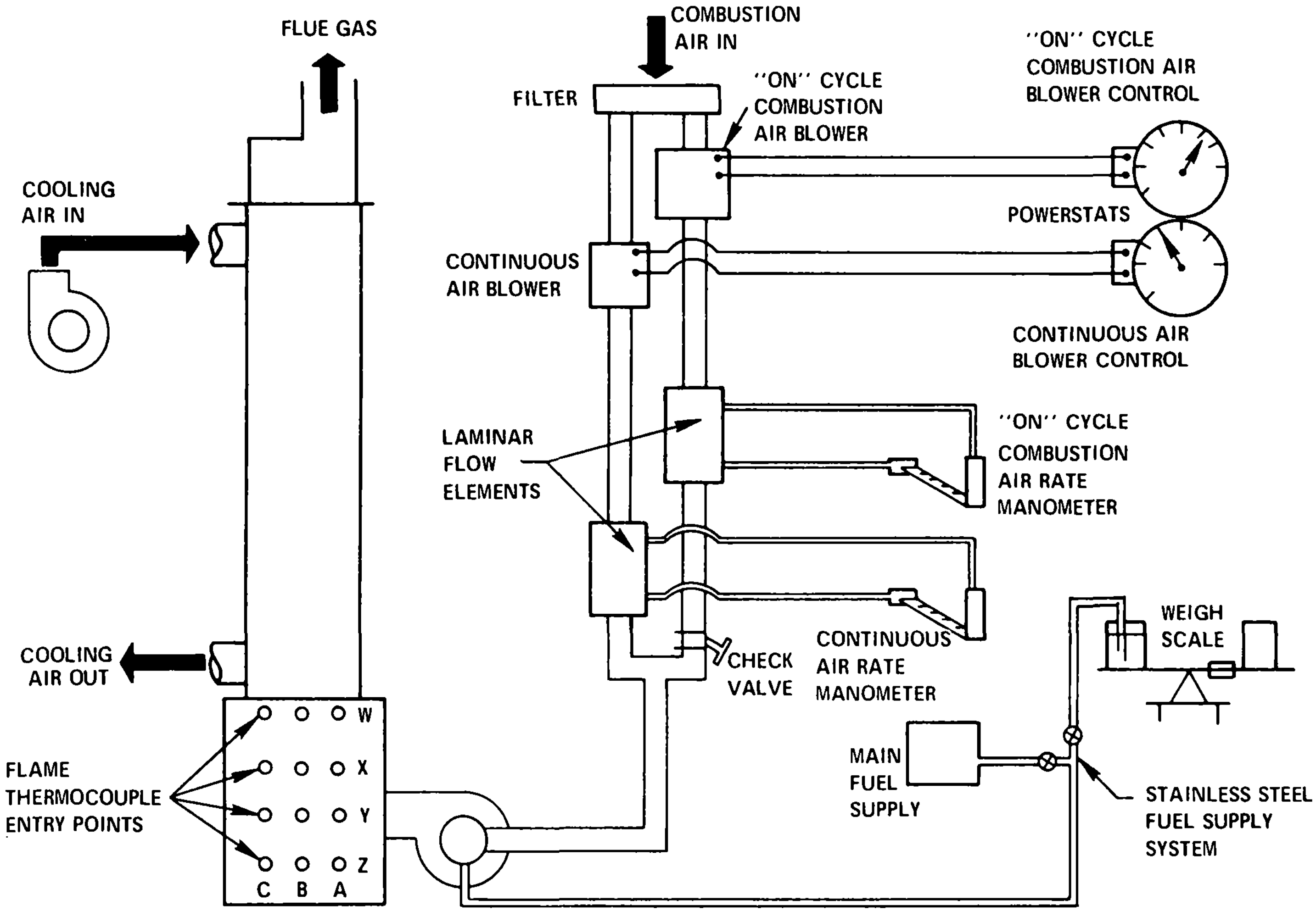


Figure 2. Experimental furnace, schematic.

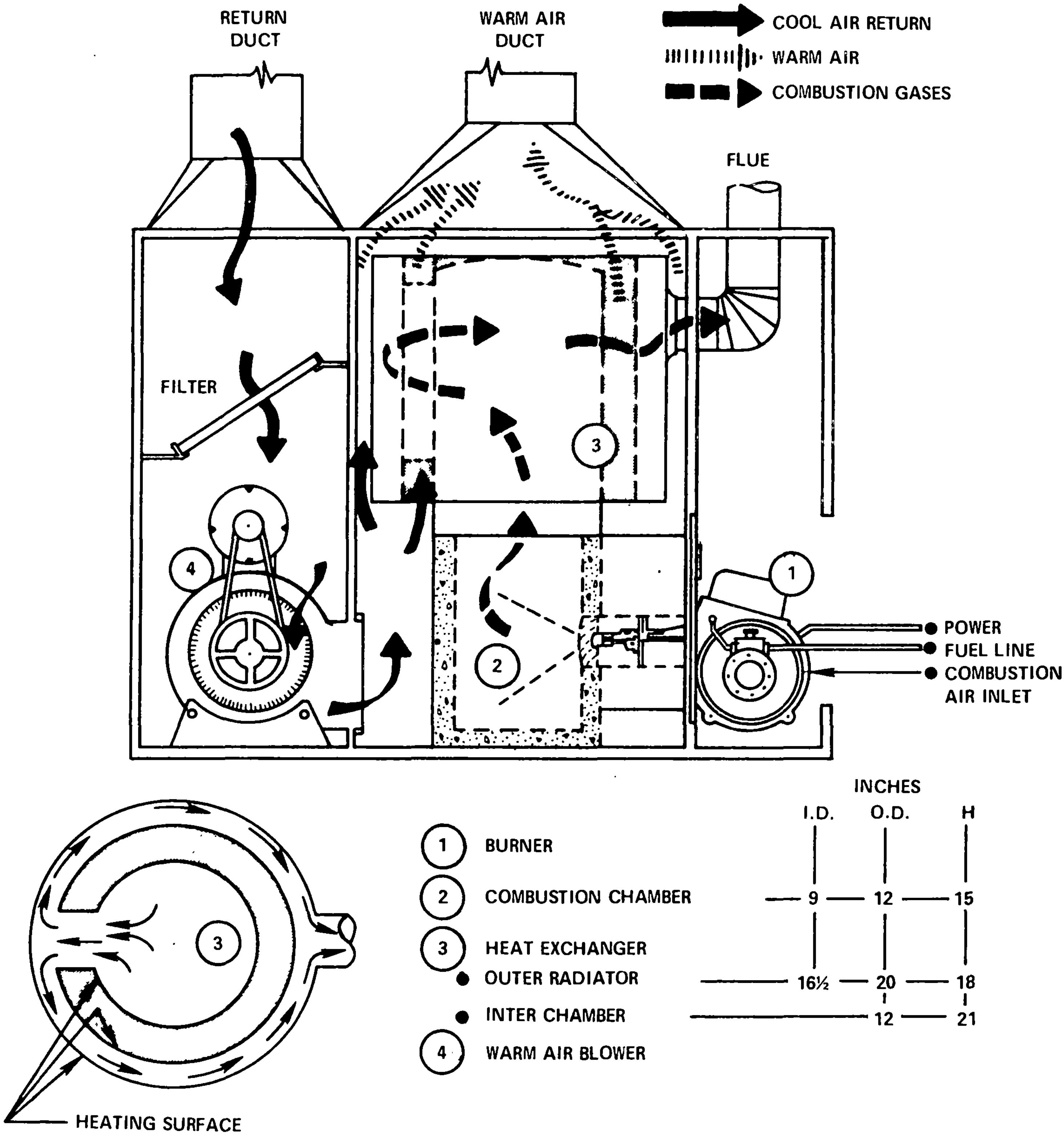


Figure 3. Conventional domestic furnace.

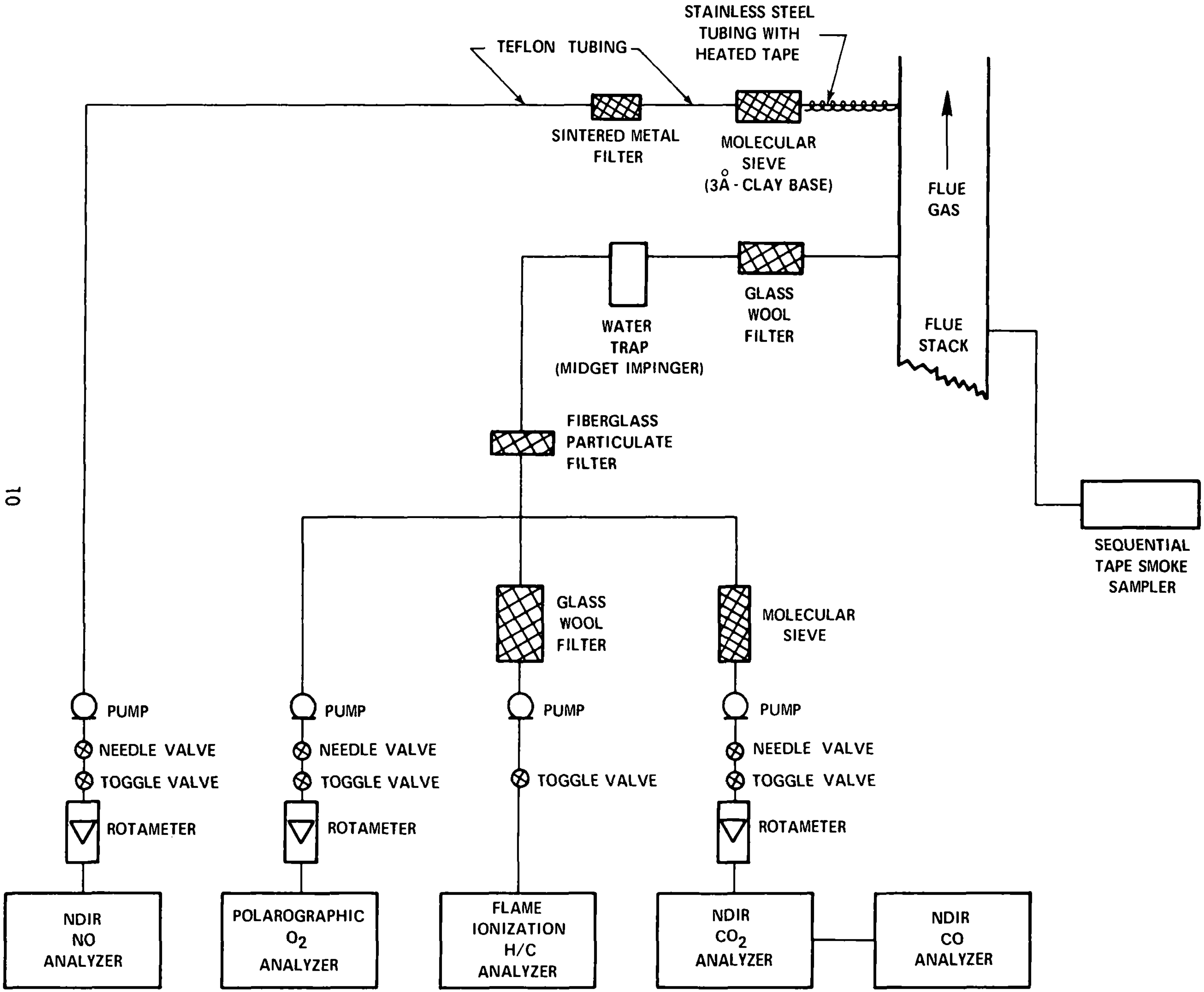


Figure 4. Domestic furnace instrumentation schematic.

An operating cycle of 30 minutes with a burner on-time of 10 minutes was selected as a result of a previous field test[8] which showed that oil burners operate cyclicly and burn about a third of the time during the heating season.

TEST FUEL

The test fuel, No. 2 distillate fuel oil, was a blend of catalytically cracked and straight-run stocks derived from a Gulf Coast crude. It had an API gravity of 35 degrees, aromatic content of 25 percent, carbon/hydrogen ratio of 6.62:1, and a nitrogen content of less than 0.01 percent. A complete fuel analysis can be found in Appendix B.

To provide a fuel of uniform quality, the oil was stored under a blanket of pure nitrogen.

COMBUSTION CHAMBERS

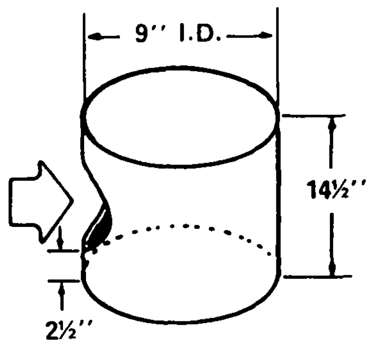
In order to determine the effect of combustion chamber configuration and material, three different combustion chambers were tested. Two were refractory lined; the third was steel with no refractory. As shown in Figure 5, one refractory lined chamber was cylindrical, fired into radially, and lined with a soft refractory material. The square chamber was lined with light brick refractory. The steel cylindrical chamber, with no refractory, was fired into axially.

COMBUSTION IMPROVERS

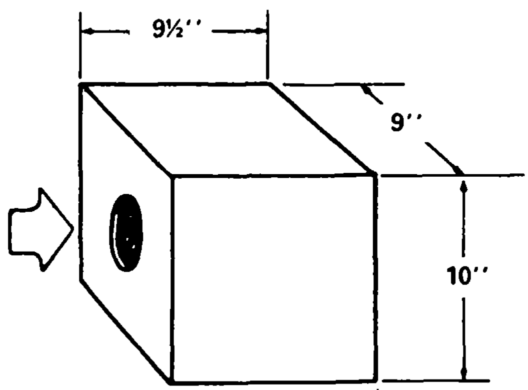
Combustion improving devices are designed to improve performance of older burners by providing better air/fuel mixing. It was desired to determine their effect on new, more efficient burners. Five commercially available combustion improving devices for high-pressure atomizing-gun burners were chosen for the study.

The devices were installed on the standard ABC Model 45 burner. In each case, the same standard burner chassis was modified by installing the combustion improving device to be tested. The tests were made in the conventional domestic furnace described above.

CYLINDRICAL (ROUND)
(SOFT REFRACTORY)



SQUARE
(LIGHT BRICK REFRACTORY)



CYLINDRICAL HORIZONTAL
(STEEL LINED)

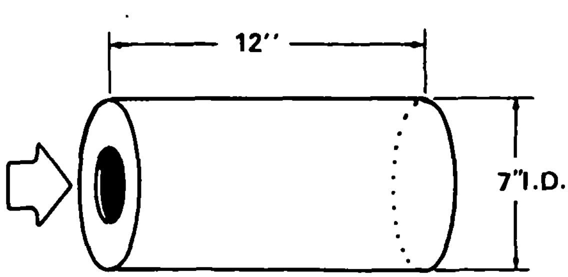


Figure 5. Typical combustion chambers.

A schematic of the fuel nozzle and air/fuel mixing assembly of the unmodified ABC Model 45 burner is shown in Figure 6. Schematics of the Monarch G-81-C combustion head, Delavan FlameCone, Shell combustion head, Gulf Econo-Jet, and Union (formerly Pure) flame control device are shown in Figures 7 through 11, respectively.

Each of these devices except the Delavan FlameCone utilized swirl mixing to some degree. The Delavan FlameCone and Union device used flame retention. Thus the Union device was the only one which incorporated both swirl and flame retention. It was also the only device which controlled inlet air by sliding an air shield within the blast tube rather than by manipulating shutter vanes on the burner housing.

FLAME RETENTION BURNERS

High-pressure atomizing-gun burners which utilized flame retention were also tested. All of these burners except one were available as an entire burner. The one exception was the Union device which was actually a combustion improving device that utilized flame retention, the same device that was described previously as a combustion improving device. As with the other combustion improvers, the Union flame control device was installed on the ABC Model 45 burner. This device should not be confused with the Union flame retention burner, which actually is a Beckett burner fitted with the Union flame control device.

The flame retention burners tested included: ABC Mite, Beckett Bantam, Esso Model 40, Sun-Ray, U. S. Carlin, Union, Union flame control device installed on an ABC Model 45 burner, Wayne, and White-Rogers. Schematics of the ABC Mite, Beckett Bantam, and Union flame control device are shown in Figures 12 through 14, respectively.

Each device utilized flame retention to hold the flame to create a more stable, compact, intense flame. The ABC Mite and Union device also incorporated swirl mixing.

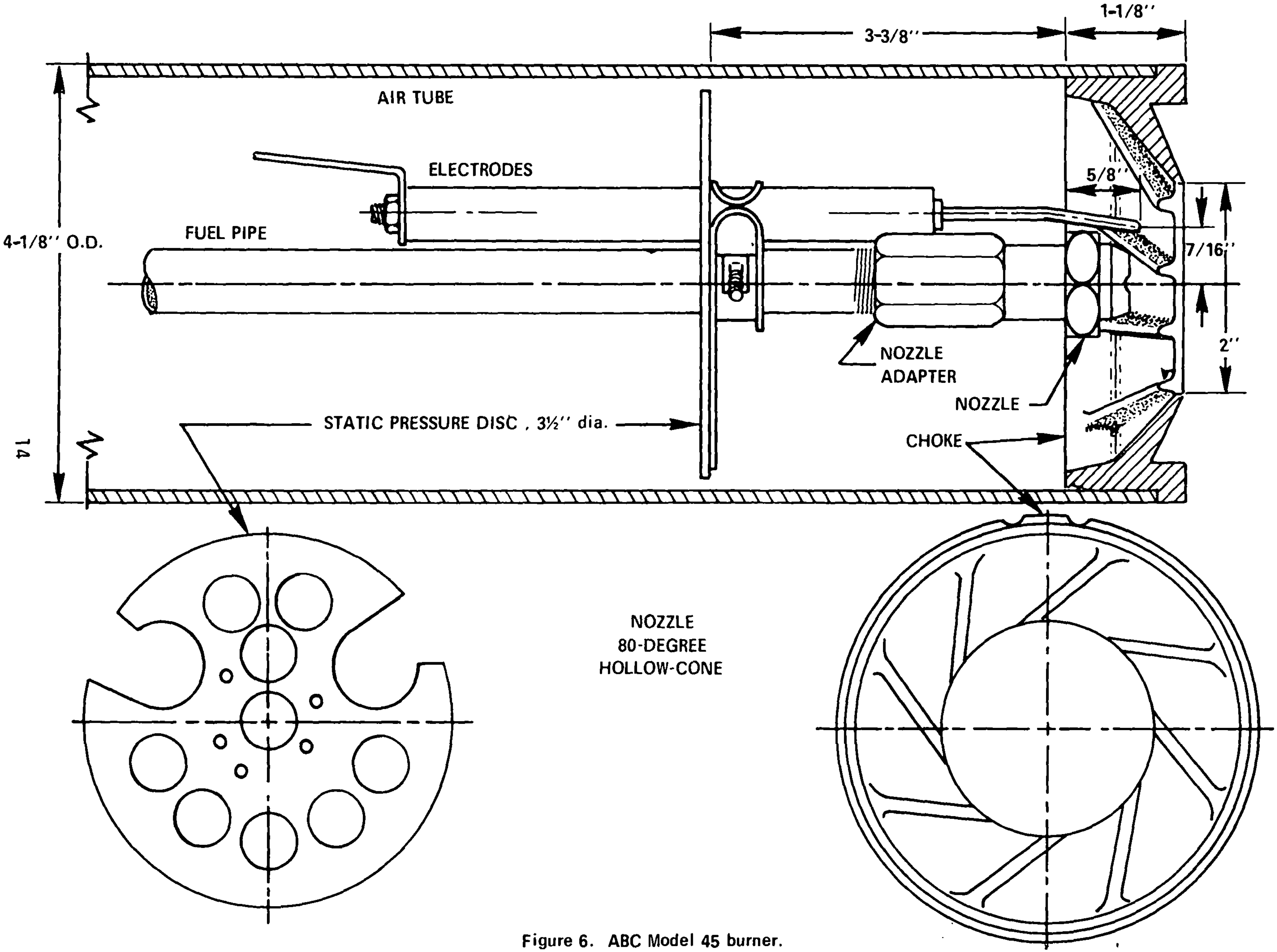


Figure 6. ABC Model 45 burner.

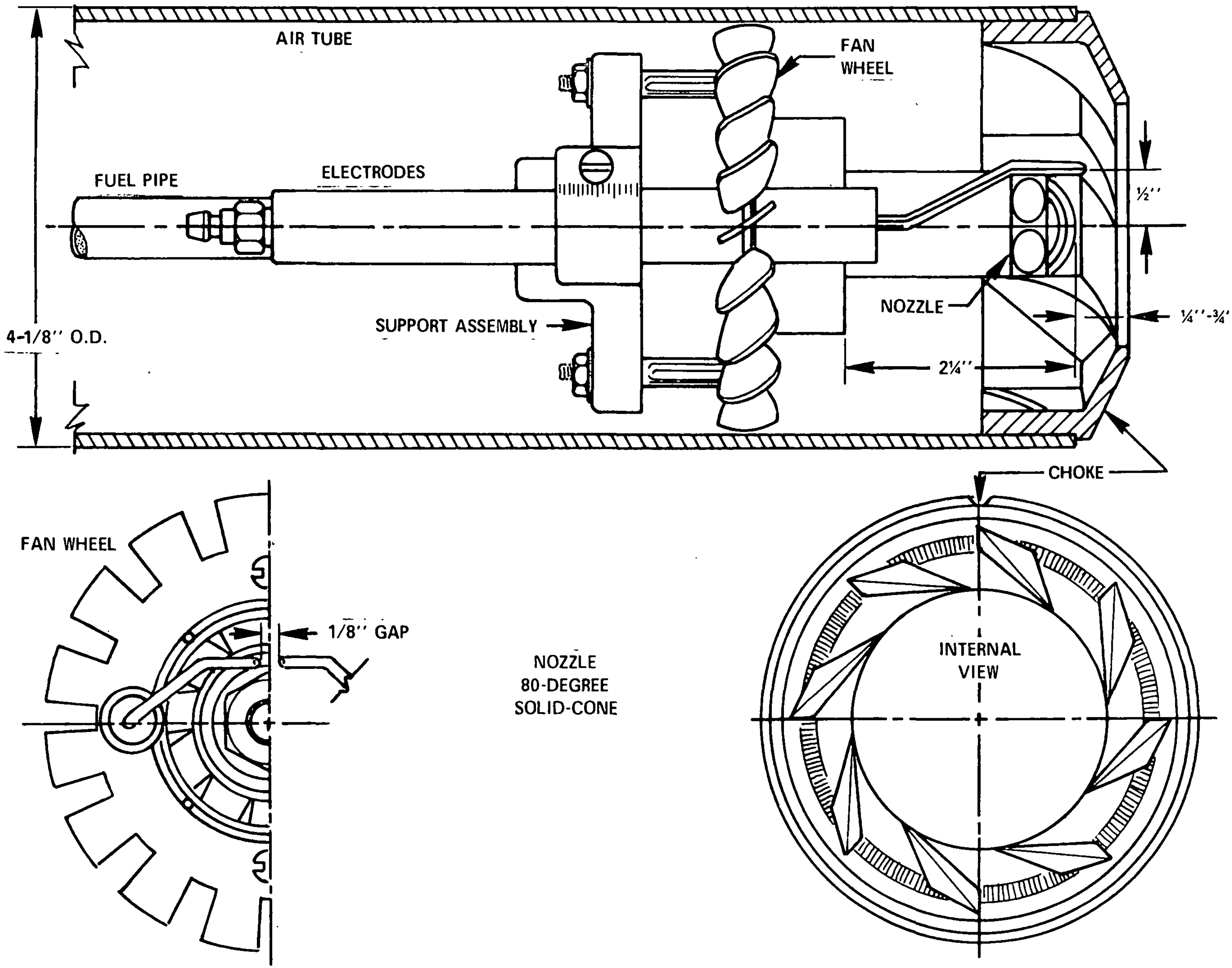


Figure 7. Monarch G-81-C combustion head.

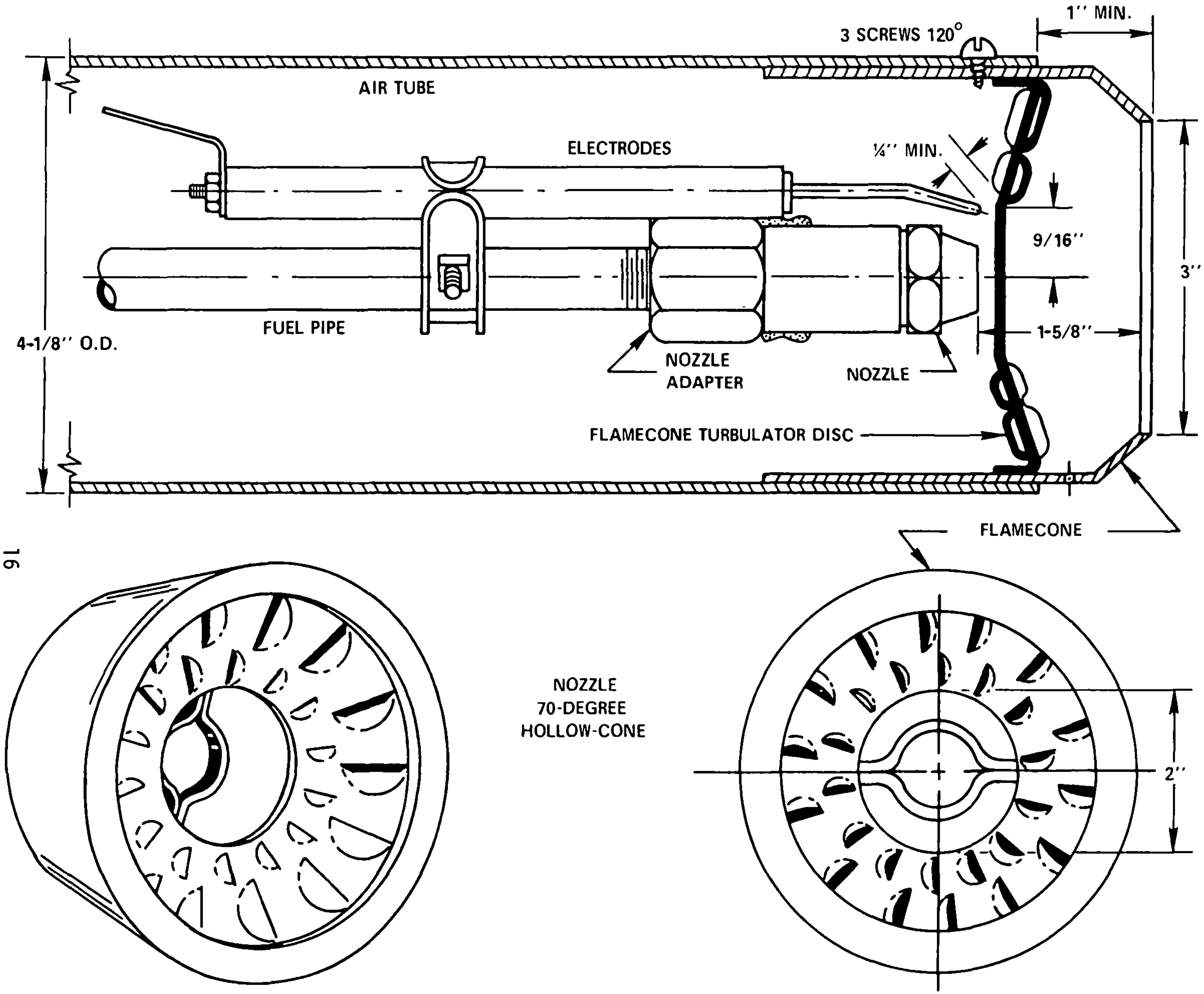


Figure 8. Delavan FlameCone.

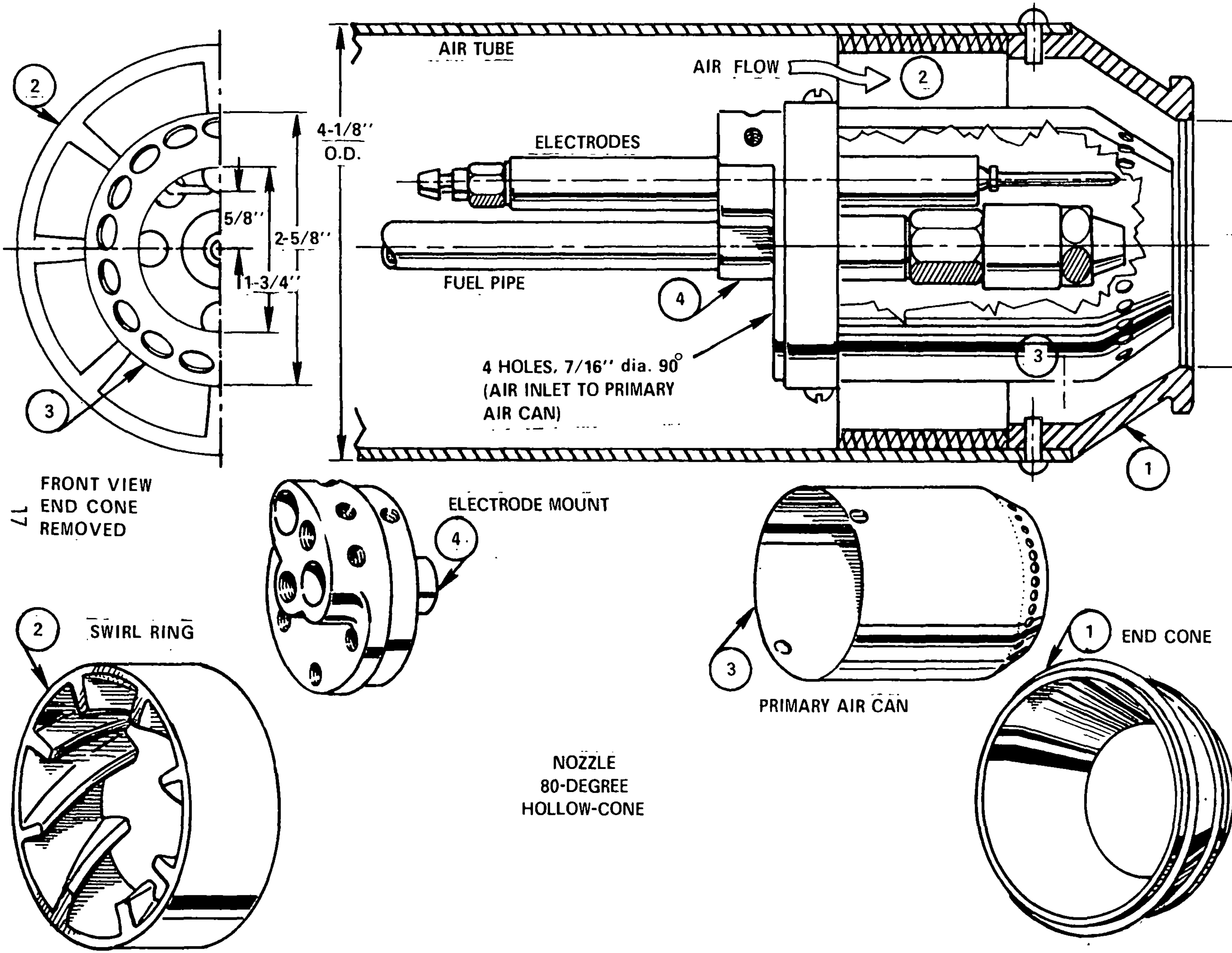


Figure 9. Shell combustion head.

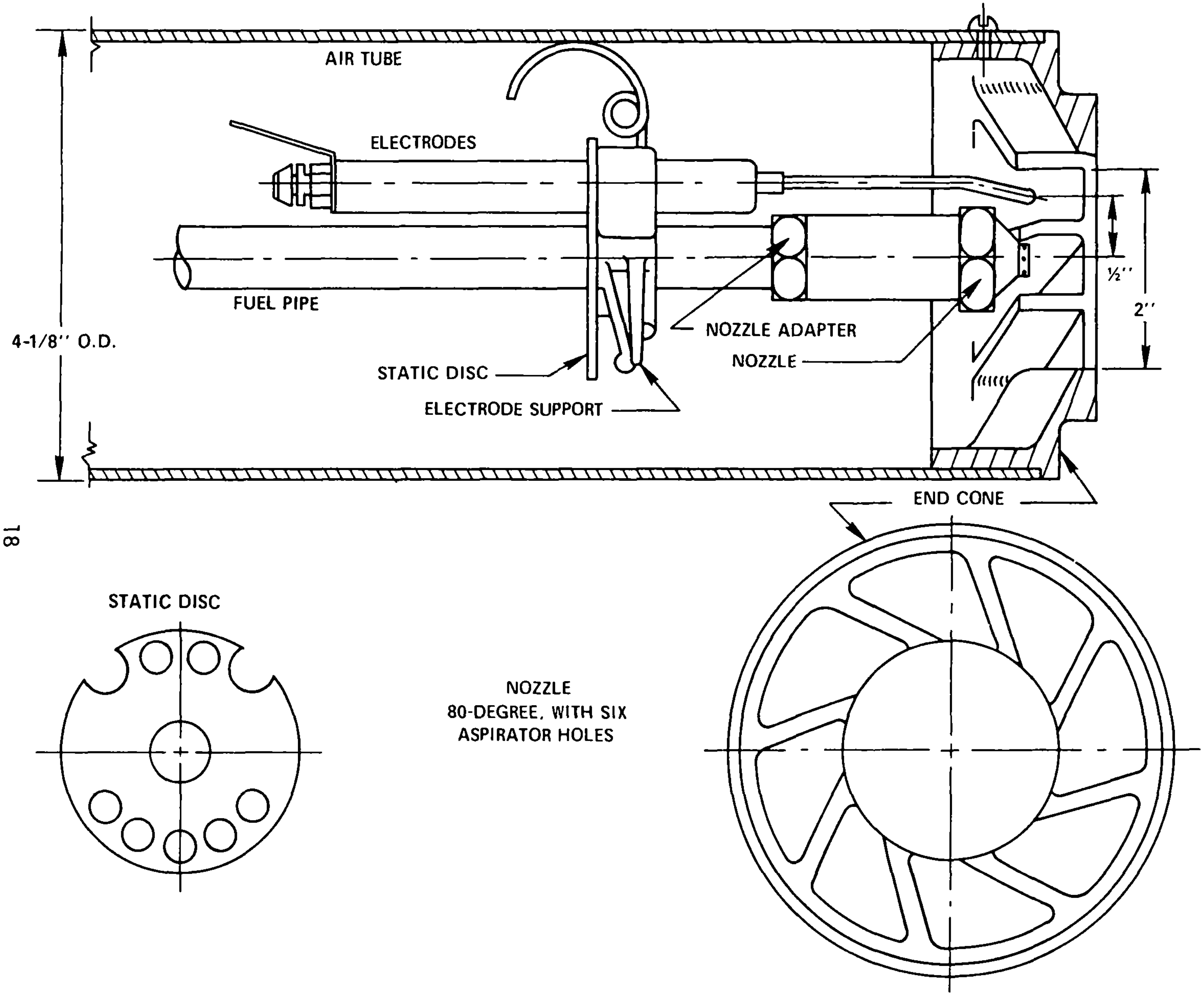


Figure 10. Gulf Econo-Jet.

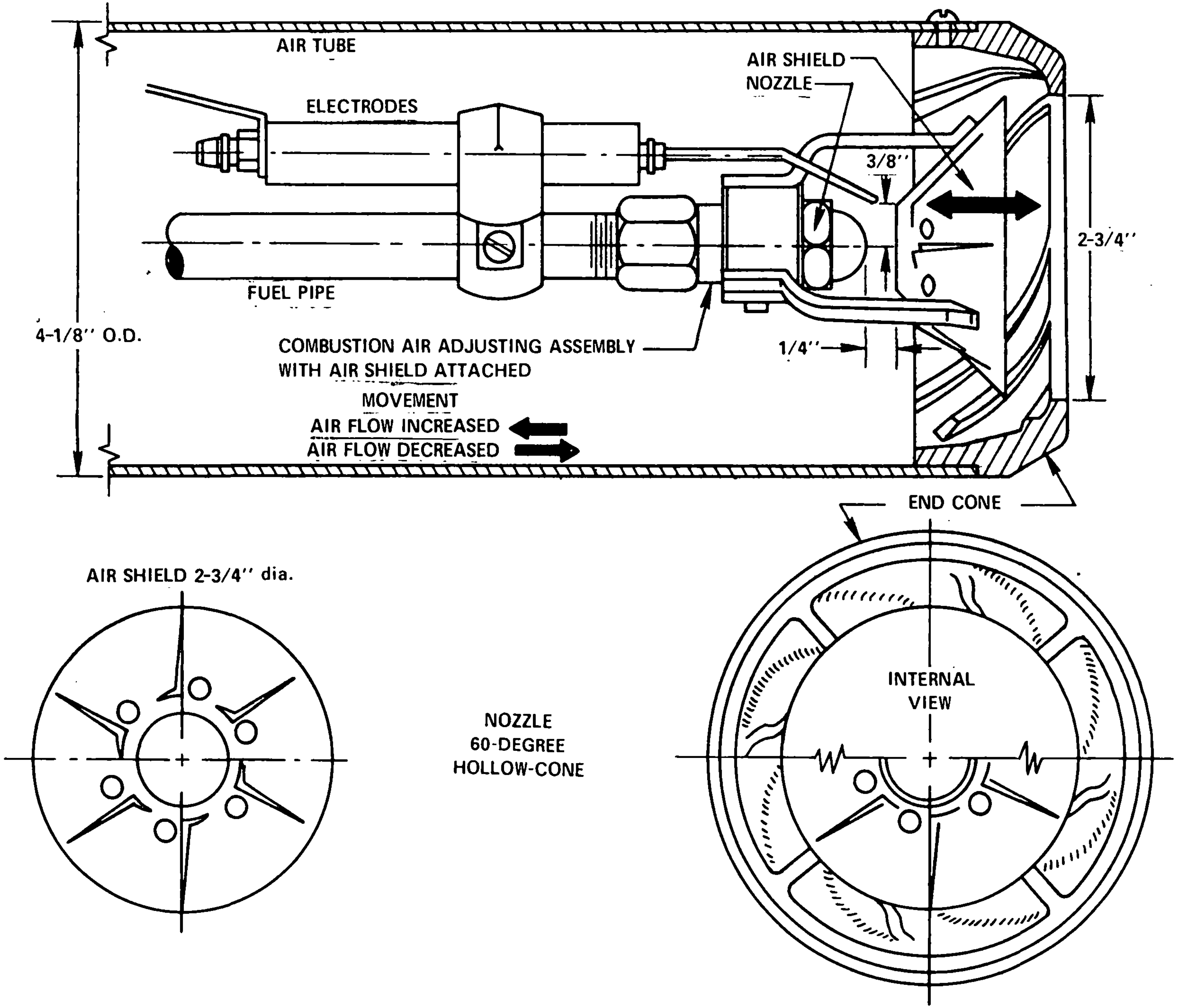


Figure 11. Union (Pure) flame control device.

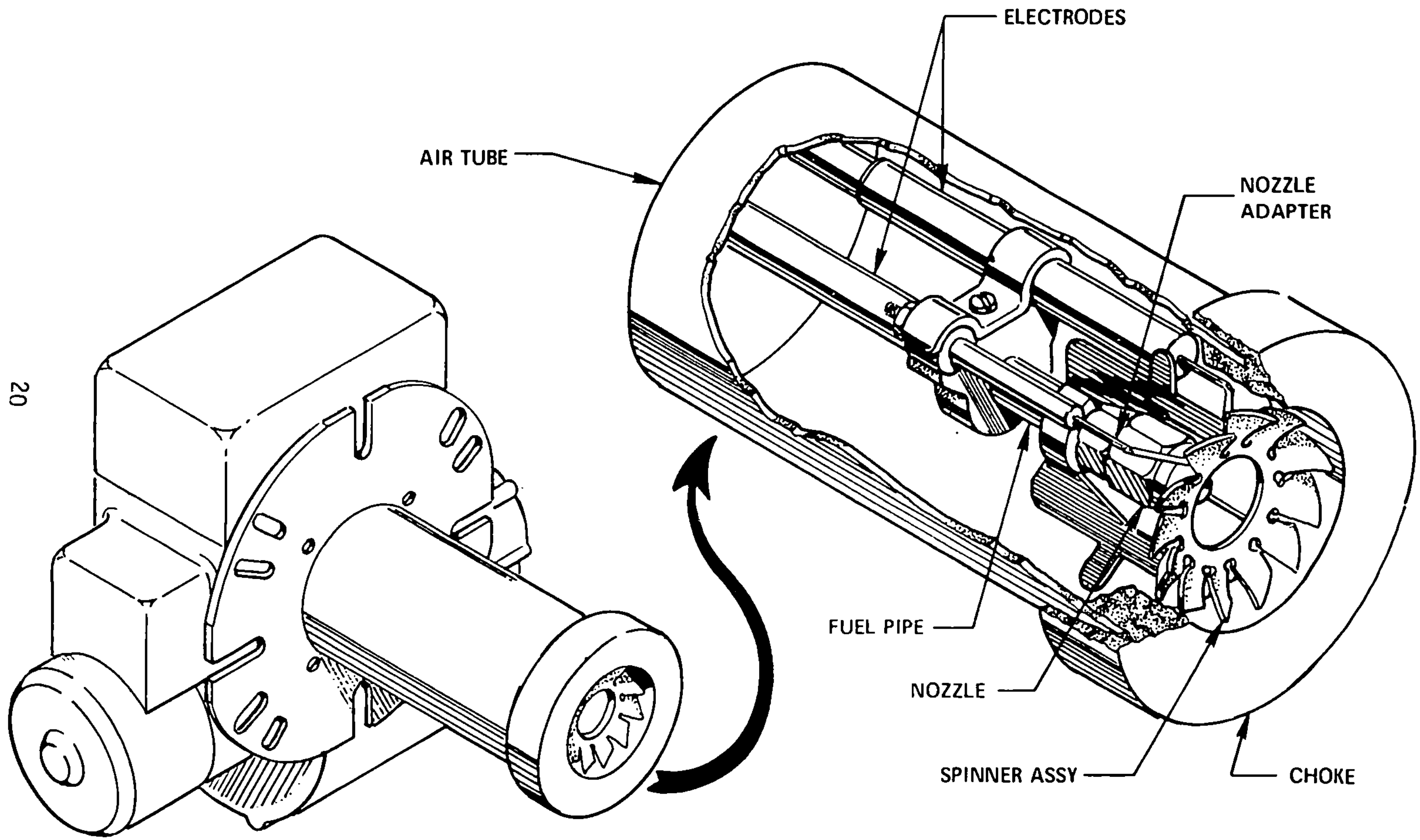


Figure 12. ABC Mite burner (model S).

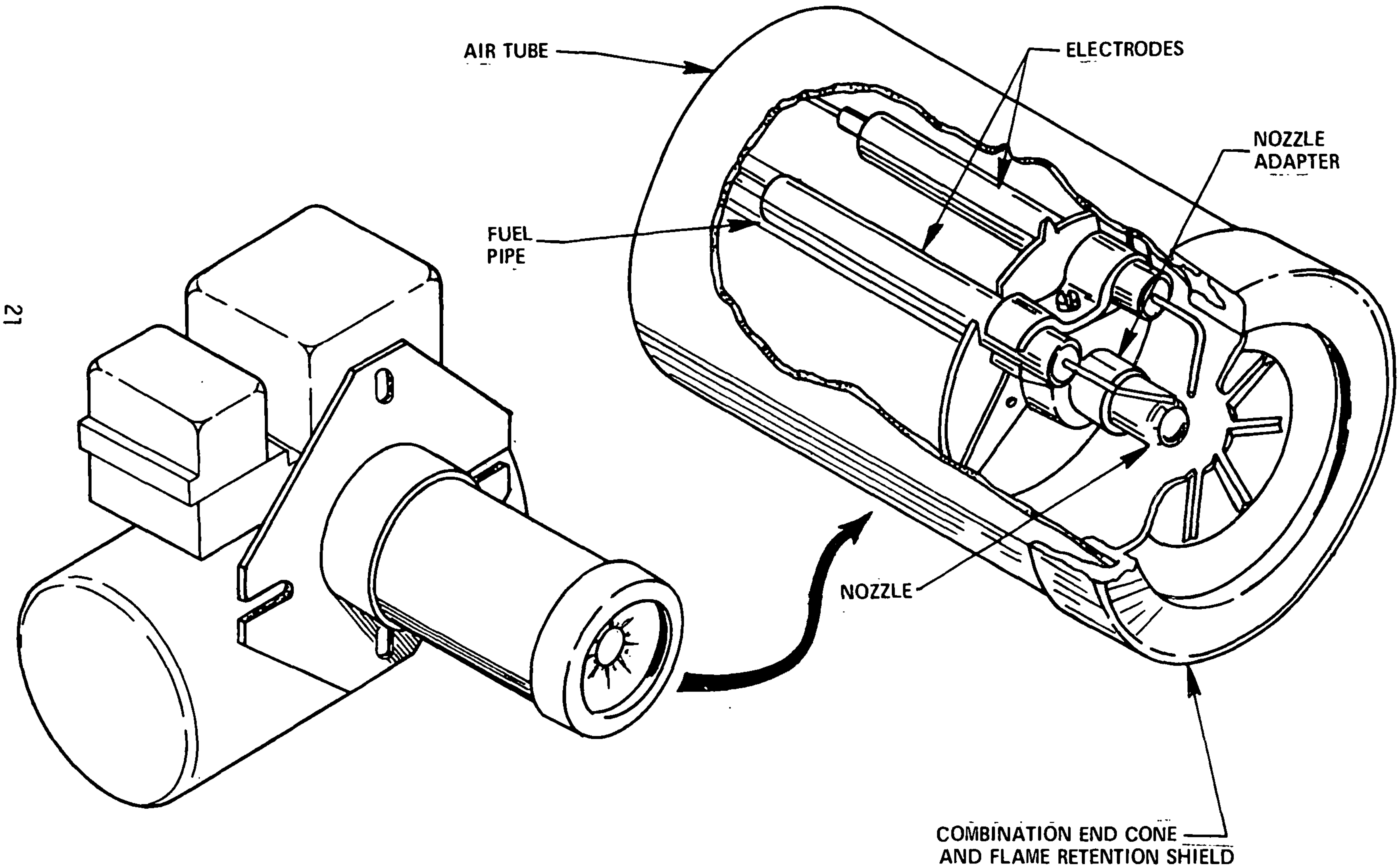


Figure 13. Beckett Bantam burner (model AF).

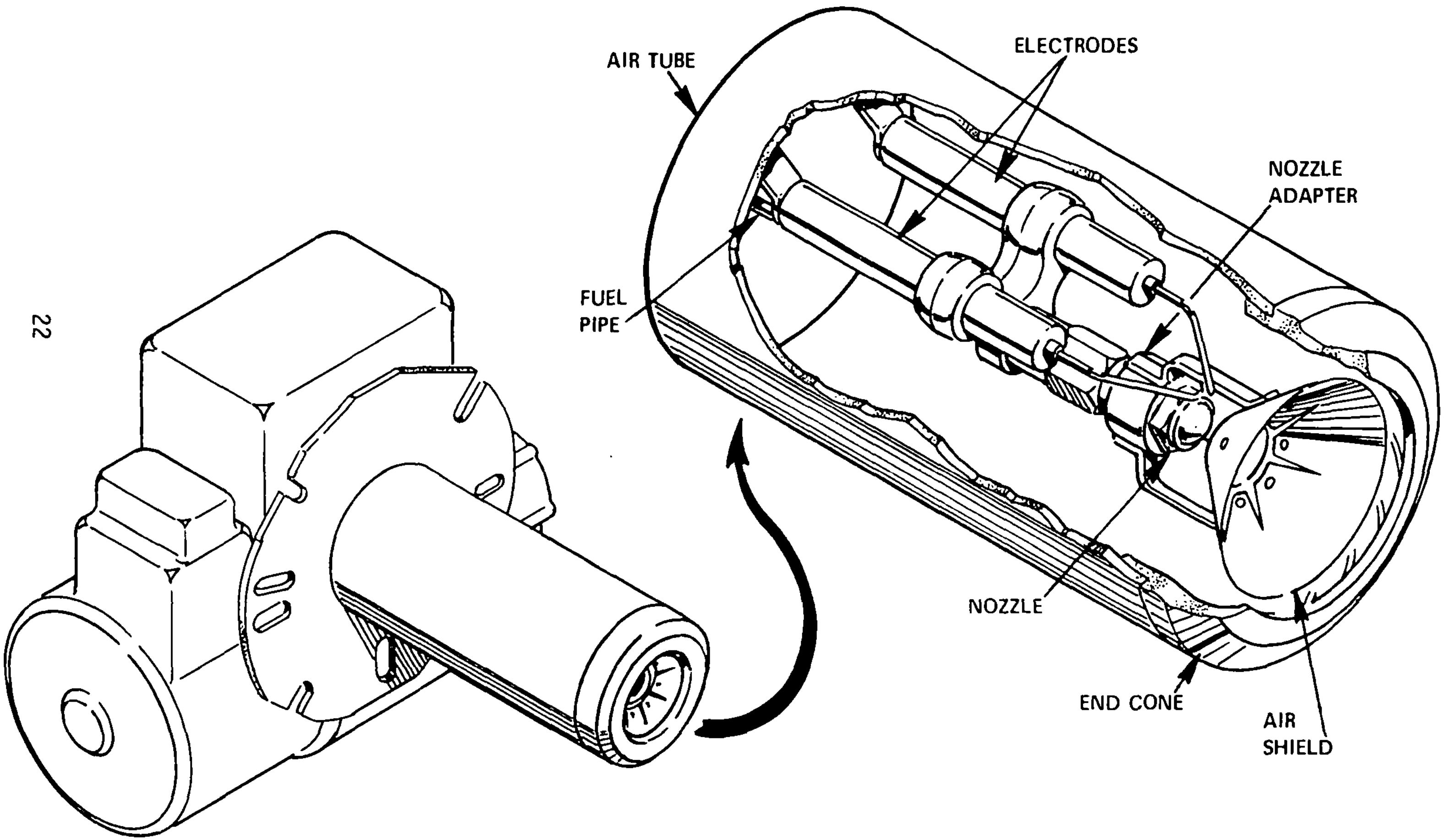


Figure 14. Union flame control device installed on ABC model 45 burner.

GAS BURNERS

Two types of natural gas burners were chosen for tests in which gas burner emissions could be compared with oil burner emissions. A Williamson Mono-Port burner and a Bryant Sectionalized burner were tested. Both were rated at 100,000 Btu, the same as the oil burners.

OTHER OIL BURNERS

Distillate oil burners other than the high-pressure atomizing-gun type were also tested. The objectives of these tests were to compare operation and emissions of the various types of burners with those of conventional burners.

Other burners tested included four low-pressure burners, one vaporization rotary-type burner, and four blue flame burners. Two of the blue flame burners utilized induced internal recirculation; the third utilized external recirculation of flue gases; the fourth did not have recirculation.

IGNITION SYSTEMS

Three ignition systems were tested to determine their effect on oil burner emissions. Two of the systems were manufactured by the France Manufacturing Company: Franceformer (Cat. LKJ) ignition system was installed on an ABC Model 45 burner, and a Franceformer (Cat. 4LACYU-4) was installed on a Beckett Bantam burner. The third ignition system tested was a Prestolite O-120 installed on an ABC Mite burner.

OIL NOZZLES

Four major brands of oil nozzles (Delavan, Monarch, Hago, and Steinen) were tested for variation of emissions and flow rate of new nozzles. All were 0.75 gph, 80-degree, hollow-cone nozzles. Variations in the nozzle distributors can be seen in Figure 15.

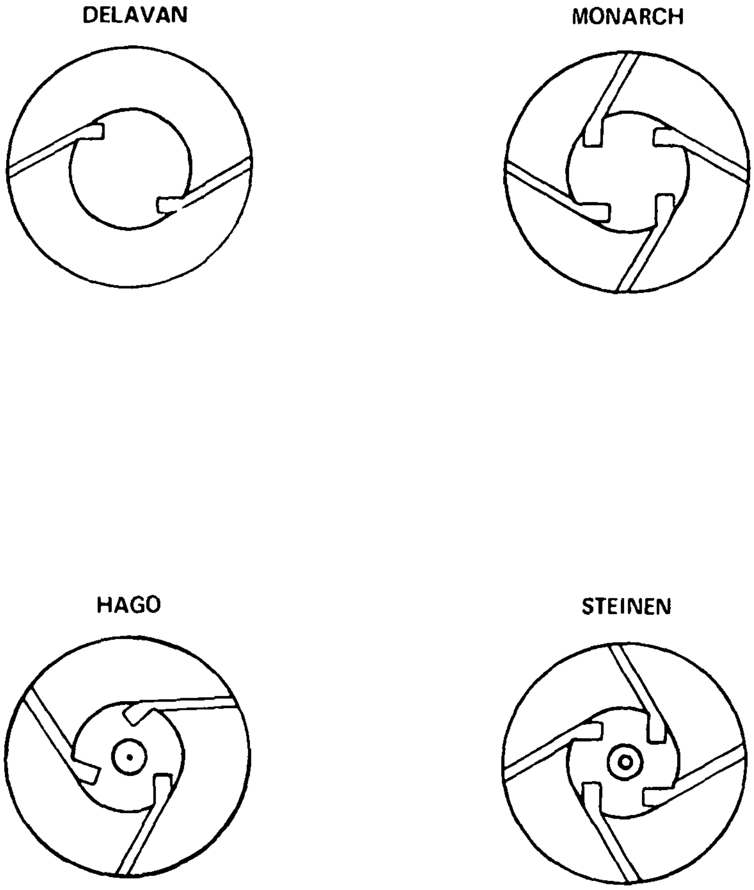


Figure 15. Nozzle distributors.

ANALYTICAL INSTRUMENTATION AND PROCEDURES

Emission measurements were made over a wide range of stoichiometric air/fuel ratios for each burner. Automatic analyzers and recorders continuously monitored temperatures (inlet, outlet, and flue), O_2, CO_2, CO, NO, and gaseous HC (as methane). Bacharach smoke spots were taken once a minute during the on-period and measured on a reflectance photometer. SO_2 and particulate weight were only measured during tests with the experimental furnace.

The actual data were the average of the emissions from the entire on-cycle and thus included any startup or shutdown peaks. Emissions were not measured during the off-period of the operating cycle. A detailed description of the equipment and methods used for analysis can be found in Reference 9.

Oxygen was measured with a polarigraphic analyzer; NO was measured by the phenoldisulfonic acid (PDSA) method, as described in Reference 9, during the earlier stages of the program. Later NO was measured with a long-path non-dispersive infrared (NDIR) analyzer. Since results between the two methods were in agreement, the wet chemical method was replaced by long-path NDIR analysis. Hydrocarbons were measured by flame ionization, and NDIR analyzers were used for measuring both CO and CO_2. The efficiency of each burner was calculated by dividing the total amount of heat (Btu) coming from the heat exchanger by the net heating value (Btu) of fuel burned for each cycle.

Smoke numbers are reported as 10th minute and average. The 10th minute smoke number refers to the one smoke spot taken over a 1-minute period after the burner had been on for 9 minutes. In other words, this is the level of smoke produced at "steady state" (or hot running) conditions. It was used to determine operating air settings for burner comparison (see Appendix A). However, to determine a number indicative of the total amount of smoke or carbon particulate produced, an average smoke number was calculated by averaging Bacharach values for the ten measurements taken during the entire on-period.

Table 1. AIR/FUEL STOICHIOMETRY

Combustion product	Range of emission	
	Minimum	Maximum
Particulate, g/kg fuel		
Filterable	0.04	33.40
Condensable	0.17	1.70
Carbon monoxide, g/kg fuel	0.86	96.60
Gaseous hydrocarbons, g/kg fuel	0.03	17.00
Oxides of nitrogen, g/kg fuel	1.08	2.41
Sulfur dioxide, g/kg fuel	1.46	1.96
Sulfur trioxide, g/kg fuel	<0.02	<0.02
Oxygen, vol %	5.5	12.8
Carbon dioxide, vol %	5.9	9.6
Smoke No., Bacharach	0	9 +
Smoke density, Cohs/1000 ft	7.0	>1230

EXPERIMENTAL RESULTS

SUMMARY OF RESULTS

The experimental data is summarized in Tables 1 through 8. All tests were made with No. 2 oil or natural gas.

Table 1 contains the results from the initial studies of the effects of air/fuel ratio on air pollutant emissions (CO, HC, SO_2, NO, NO_2, smoke and particulates) from an oil-fired test furnace. The range of air/fuel ratios investigated was 1.0 to 2.5, corresponding to excess air levels of 0 to 150 percent, at a constant fuel rate of 1.0 gph. The gaseous measurements were obtained in units of parts per million (ppm) but were converted to emission factors in units of grams of pollutant per kilogram of fuel burned.

The results of the tests to investigate residence time are contained in Table 2. Data for the short residence time were obtained from the tests to determine the effects of air/fuel stoichiometry described above. A longer residence time was achieved by increasing the height of the combustion chamber, thus increasing the volume by a factor of 1.8. With that exception the tests were identical to the air/fuel stoichiometry tests.

Table 3 contains the results of tests with various combustion chamber configurations and materials to determine the effect on CO_2, O_2, and emissions of CO, HC, NO, and smoke. The data presented in this table are based on burner adjustment to a No. 1 smoke number at hot running conditions (see Appendix A). The range of air/fuel ratios for these tests was 1.1 to 2.6, at a constant fuel rate of 0.75 gph.

The results of tests to determine the effect of combustion improving devices on burner performance (furnace efficiency, CO_2 and O_2 levels, and emissions of CO, HC, NO, and smoke) are given in Table 4. Five combustion improving devices were compared to a standard high-pressure atomizing-gun burner, using the method described in Appendix A. The burners were operated

Table 2. RESIDENCE TIME

Pollutant emission	A/F ratio	Residence time	
		Short	Long
Filtered particulate, g/kg fuel	1.00	33.40	10.840
	1.25	5.40	0.146
	1.50	0.34	0.024
	1.75	0.06	0.027
Carbon monoxide, g/kg fuel	1.00	96.60	1.380
	1.25	8.87	0.458
	1.50	0.86	0.612
	1.75	1.20	1.107
Hydrocarbons, g/kg fuel	1.00	17.00	0.288
	1.25	1.82	0.068
	1.50	0.03	0.059
	1.75	0.07	0.103
Nitric oxide, g/kg fuel	1.00	0.70	0.61
	1.25	0.81	0.88
	1.50	1.05	1.18
	1.75	1.30	1.37
Sulfur dioxide, g/kg fuel	1.00	1.46	1.56
	1.25	1.80	1.75
	1.50	1.86	1.84
	1.75	1.96	1.94

Table 3. COMBUSTION CHAMBER EFFECTS

Burner	Pollutant emissions and Stoichiometric Ratio	Cylindrical refractory	Square refractory	Horizontal steel
Williamson	Stoichiometric ratio	1.52	1.52	1.65
	10th min smoke, Bacharach	1.0	1.0	1.0
	Avg smoke, Bacharach	2.6	3.5	2.2
	HC, g/kg fuel	0.02	0.14	0.08
	CO, g/kg fuel	0.6	0.7	0.4
	NO, g/kg fuel	1.26	1.32	1.55
Pure	Stoichiometric ratio	1.18	1.20	1.37
	10th min smoke, Bacharach	1.0	1.0	1.0
	Avg smoke, Bacharach	1.1	1.1	3.5
	HC, g/kg fuel	0.08	0.11	0.06
	CO, g/kg fuel	0.6	0.4	0.3
	NO, g/kg fuel	1.63	1.92	1.76
Monarch	Stoichiometric ratio	1.63	1.38	2.03
	10th min smoke, Bacharach	1.0	1.0	1.0
	Avg smoke, Bacharach	2.4	4.0	1.6
	HC, g/kg fuel	0.04	0.08	0.15
	CO, g/kg fuel	0.5	0.6	2.3
	NO, g/kg fuel	1.26	1.08	0.94

Table 4. COMBUSTION-IMPROVING DEVICES

	Standard ABC burner	Monarch combustion head	Delavan Flame-Cone	Shell combustion head	Gulf Econo-Jet	Union (Pure) flame retention head
A/F ratio producing No. 1 smoke	1.53	1.66	1.80	1.60	1.40	1.20
Air setting, % CO_2	9.9	9.1	8.2	9.4	10.8	12.6
Efficiency of furnace, %	76.6	71.5	70.5	76.0	75.0	83.0
Gaseous HC, g/kg fuel	0.06	0.06	0.03	0.06	0.06	0.06
CO, g/kg fuel	0.5	0.6	0.6	0.3	0.6	0.5
NO, g/kg fuel	1.11	1.25	1.30	1.68	1.69	1.25
Ave smoke, Bacharach No.	2.9	2.0	1.3	2.0	3.0	1.2

over a range of air/fuel ratios from 1.0 to 2.6, at a fuel rate of 0.75 gph.

Table 5 contains the results of the studies which were designed to determine the effect of flame retention devices on burner performance. These tests were identical to those with combustion improving devices.

The results of comparing emissions of CO, HC, and NO from natural gas burners with emissions from equivalently rated oil burners are given in Table 6. Since the air/fuel adjustment on the gas burners was limited, the range of air/fuel ratios for the gas burners was very narrow. The gaseous measurements were made in units of parts per million (ppm) but were converted to emission factors in units of grams of pollutant per million calories input.

Table 7 indicates the effects of ignition systems on emissions of NO. The tests were made with three different ignition systems, with and without combustion taking place. Therefore, the NO emissions are given in parts per million (ppm).

Table 8 indicates effects of nozzles on air pollutant emissions (CO, HC, NO, and smoke) and furnace efficiency. The tests were made at a constant air/fuel ratio of 1.60 to allow more reliable comparison and analysis of the data. Estimated experimental errors are included in the table.

ESTIMATE OF EXPERIMENTAL ERROR

To estimate the experimental error in the test data, a statistical analysis was performed on one combustion improving device for 10th minute and average smoke, CO, gaseous HC, NO, and efficiency. The product of this analysis is an estimate of the standard deviation, defined as S, and is shown for each set of data in Table 9. To determine if the experimental error had changed after a period of 2 years, another analysis was made as part of the nozzle testing program. This data is also given in Table 9. Since the difference between the

Table 5. FLAME RETENTION BURNERS

	ABC Model 45[a]	ABC Mite[b]	Beckett Bantam[b]	Union modification[b]
Air setting, % CO_2	9.9	10.9	11.6	12.6
Efficiency of furnace, %	75.0	79.5	81.1	83.0
Gaseous HC, g/kg fuel	0.06	0.06	0.06	0.06
CO, g/kg fuel	0.5	0.5	0.5	0.5
NO, g/kg fuel	1.10	0.77	1.40	1.25
Ave smoke Bacharach No.	2.9	2.0	2.5	1.2

[a]Conventional burner

[b]Flame retention burner

Table 6. NATURAL GAS AND OIL-FIRED BURNERS

Burner	Stoichiometric ratio	NO, g/10^6 cal input	HC, g/10^6 cal input	CO, g/10^6 cal input
Gas-fired:				
Williamson furnace	1.20	0.084	0.0007	0.022
Bryant boiler	1.40	0.115	0.0014	0.099
Bryant furnace	1.60	0.112	0.0075	0.032
Oil-fired:				
Union (Pure)	1.20	0.115	0.0055	0.046
ABC Mite	1.38	0.071	0.0055	0.046
ABC Standard (Model 45)	1.53	0.102	0.0055	0.046

Table 7. EFFECT OF IGNITION SYSTEMS ON NITRIC OXIDE EMISSIONS

Ignition system	Burner	Run No.	Status	NO level, ppm	Reduction		Average Reduction		Combustion
					ppm	%	ppm	%	
Franceformer (Cat. LKJ)	Williamson (standard ABC)	1	ON	67.0	7.0	10.4	7.0	10.4	Yes
		2	OFF	60.0					
	Williamson with Union (Pure) device	1	ON	123.0	9.75	7.9	7.8	7.1	Yes
		2	OFF	113.25					
		3	ON	117.5	6.5	5.5			
			OFF	111.0	7.0	5.9			
			ON	118.0	6.5	5.5			
			OFF	111.5					
		4	OFF	65.5	8.0	10.9			
			ON	73.5					
		5	OFF	2.25	9.5	. . .	9.0	. . .	No
			ON	11.75					
			OFF	3.00	8.75	. . .			
			ON	11.75	8.75	. . .			
Franceformer (Cat. 4LACYU-4)	Beckett Bantam	1	ON	88.5	9.0	10.2	9.0	10.2	Yes
		2	OFF	79.5					
Prestolite (0-120 ignition system)	ABC Mite	1	ON	74.0	0.0	0.0	0.0	0.0	Yes
		2	OFF	74.0					

Table 8. NOZZLE EFFECTS

	Nozzle				Experimental error estimated (Standard deviation)
	Delavan	Monarch	Hago	Steinen	
10th minute smoke, Bacharach No.	1.9	1.73	2.47	4.61	0.24
Average smoke, Bacharach No.	2.93	3.03	4.59	6.19	0.23
Gaseous HC, g/kg fuel	0.080	0.082	0.086	0.113	0.01
NO, g/kg fuel	1.13	1.11	0.96	0.95	0.06
CO, g/kg fuel	0.34	0.34	0.32	0.42	0.05
CO_2, %	9.20	9.58	9.37	9.28	0.19
Efficiency of furnace, %	68.16	64.78	72.21	74.52	3.11

Table 9. EXPERIMENTAL ERROR

Data set	Standard deviation(S)	
	Combustion improving device tests	Nozzle tests
10th minute smoke, Bacharach No.	0.13	0.24
Average smoke, Bacharach No.	0.15	0.23
CO, g/kg fuel	0.05	0.05
Gaseous HC, g/kg fuel	0.01	0.01
NO_x g/kg fuel	0.09	0.06
Efficiency, %	2.17	3.11

S value is very small for each data set, it is assumed that the experimental error given in Table 9 is representative of the error for the entire program.

The standard deviation can be used to make a confidence statement about the average response. Defining $\bar{x}$ as the average of several readings taken at the same excess air setting, one can state with 95 percent confidence that the true average of the data points at this setting will lie within the the interval $\bar{x}$ plus or minus approximately 2 standard deviations.

DISCUSSION OF RESULTS

OXIDES OF NITROGEN (NO_x)

In each of the studies discussed below it is important to understand the mechanism of formation of oxides of nitrogen (NO_x) which represent the combination of NO and NO_2. NO_x is formed from both free nitrogen in the atmosphere at high temperatures and from bonded nitrogen in the fuel. Atmospheric nitrogen reacts with oxygen at elevated temperatures to form NO and to a lesser degree NO_2. Nitrogen which is bonded in the fuel reacts as part of the fuel and is not considered to be as temperature dependent. Since the nitrogen content of the fuel used in this work is less than 0.01 percent, the maximum amount of NO_x formed from fuel nitrogen is about 13 ppm at 3 percent O_2(16 percent excess air), or 0.23 g NO/kg fuel. This assumes 100 percent conversion which may not occur in actual practice. Therefore, it is assumed that any change in NO_x emissions in subsequent discussions is related only to the NO_x formed from high-temperature fixation of atmospheric nitrogen.

OXIDES OF SULFUR (SO_x)

Oxides of sulfur (SO_x) are formed from chemically bonded sulfur which reacts with oxygen during the combustion process. SO_x is present as SO_2 and SO_3. During the combustion process SO_2 is much more prevalent than SO_3. Since 95 percent or more of the fuel sulfur is converted to SO_x, SO_x was not measured during most of this work. The sulfur which does not oxidize to SO_x is emitted with the particulate matter.

CARBON MONOXIDE (CO)

CO is a product of incomplete combustion. If combustion is complete, the carbon in the fuel will be oxidized to CO_2. Therefore, properly designed and well-maintained burners will not emit very high levels of CO.

HYDROCARBONS (HC)

HC emissions are also a product of incomplete combustion. If combustion is complete, the hydrogen will be oxidized to form H_2O and the carbon will be oxidized to form CO_2. As with CO, HC emissions should be very low if the burner is properly designed and maintained well.

SMOKE AND PARTICULATES

Smoke is generally considered to consist of carbon particulates and is therefore a product of incomplete combustion. However, some particulates are the result of non-combustible material in the fuel. Smoke was measured for all tests made during this study. However, particulate by weight was only measured during tests made with the experimental furnace. Particulates were not measured during the entire program because particulate sampling[10] is time consuming and difficult.

AIR/FUEL STOICHIOMETRY

The initial studies with oil burners were performed in the experimental furnace with the ABC Model 55J-1 burner described earlier. The main objective was to establish the effects of air/fuel stoichiometry on air pollutant emissions. Four critical parameters (oxygen concentration, flame temperature, inlet combustion air velocity (turbulence), and mean gas residence time) which are known to affect the quantity of pollutants formed are plotted for a range of stoichiometric ratios in Figure 16.

Flame temperature was measured by dividing the combustion chamber into three vertical zones: A, B, and C (Figure 2). Entry ports are positioned along the centerlines in each of these three zones and labeled W, X, Y, and Z from top to bottom (row W was not used during these tests). Temperatures were recorded at 1-inch intervals through the chamber from wall to wall at each entry port. Every height level was traversed with three probes operating simultaneously. Fine wire thermocouples (0.003 inch, iridium and iridium with 40 percent rhodium) were used to minimize error due to conduction and radiation. These temperatures and maximum refractory temperatures are shown in Figure 17. Flame temperatures, except for point maximums, were below the theoretical adiabatic flame temperature. The point maximums were above adiabatic at stoichiometric ratios greater than 1.6 in Figure 17 because of poor mixing in localized regions. Even though the overall ratio was 1.6 or more, the air/fuel ratio at points can be much lower or higher.

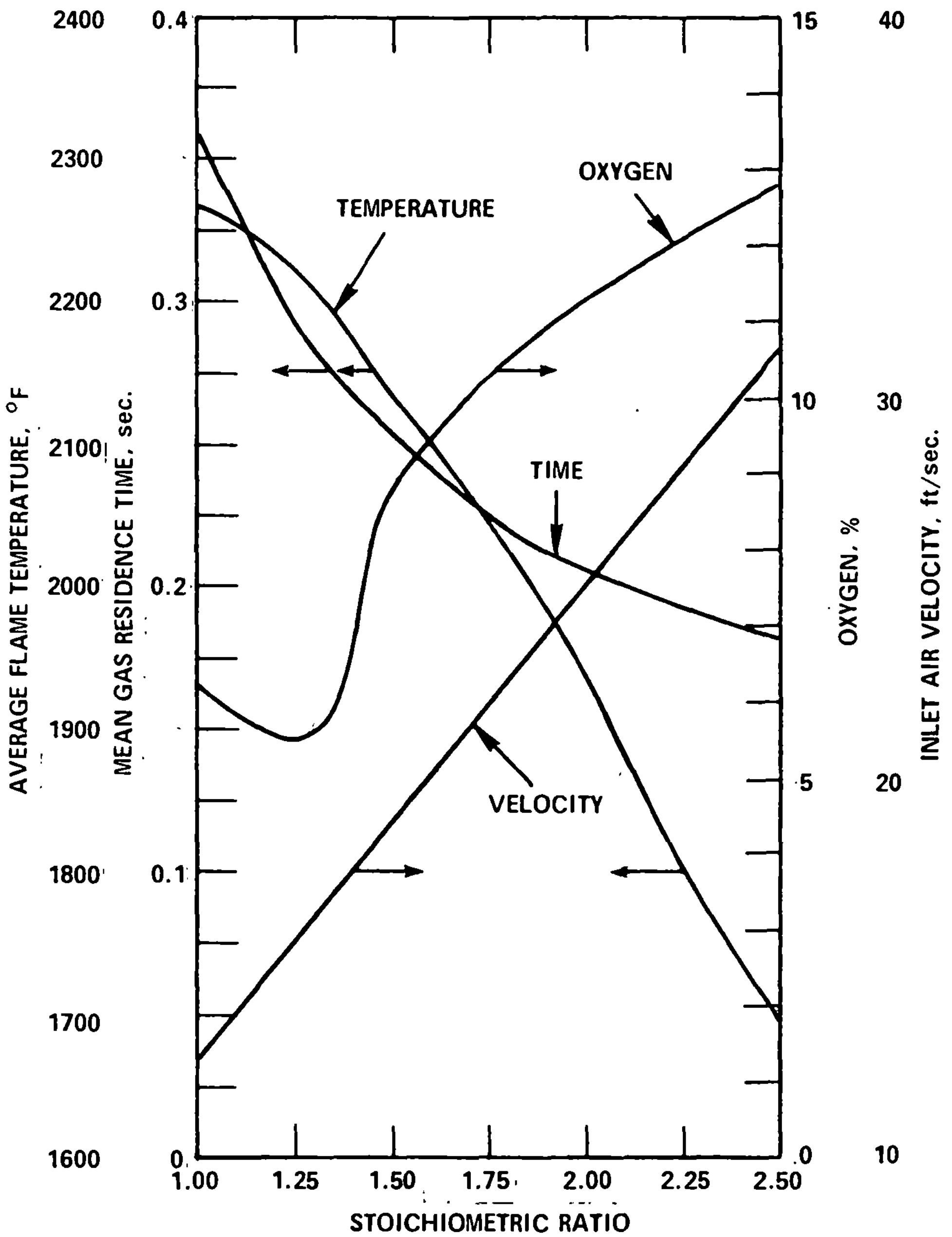


Figure 16. Critical parameters affecting pollutant formation.

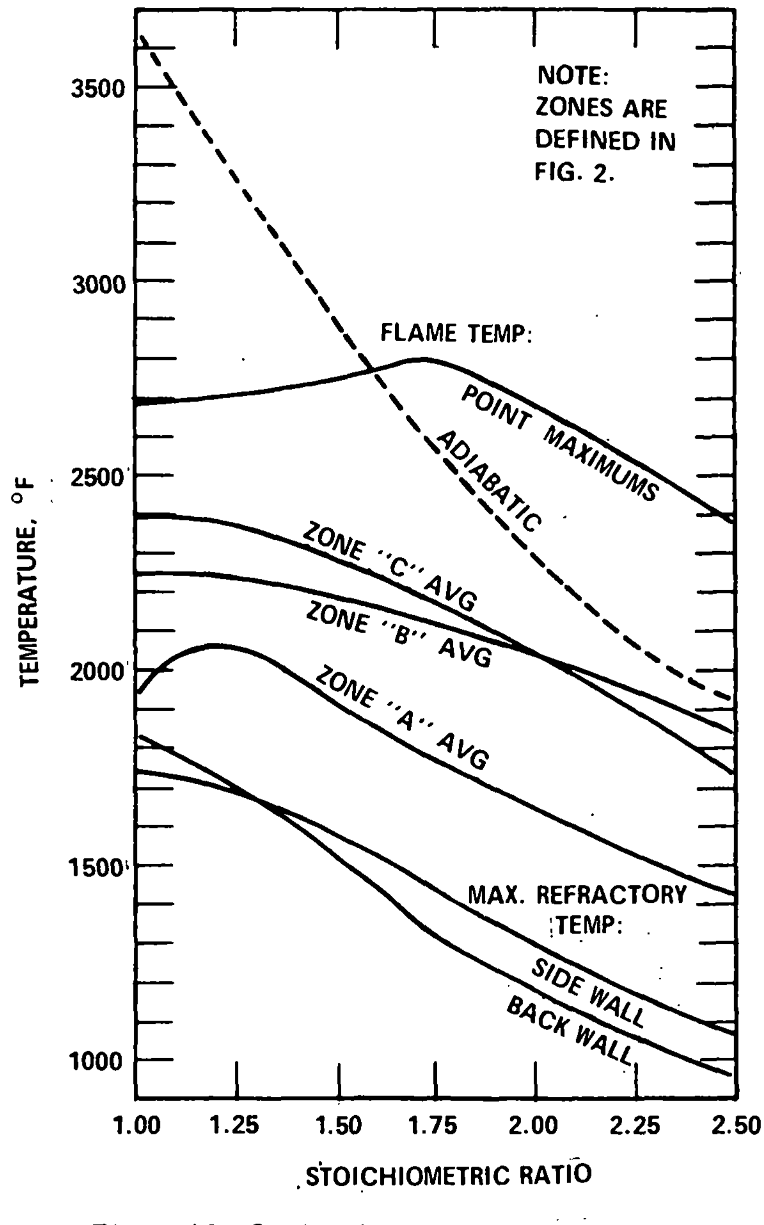


Figure 17. Combustion chamber temperatures versus stoichiometric ratio.

The temperature of the refractory, flue gas, tube sheet, and heated air typically increased over the burner-on cycle, as shown for an air/fuel ratio of 1.75 in Figure 18. Note that only the refractory temperatures do not reach steady state during the 10-minute on cycles.

The trends for emissions of particulates, smoke, CO, and gaseous HC can be seen in Figures 19 through 22, respectively. These emissions were all minimized at air/fuel ratios between 1.65 and 2.00. Emissions of NO_x and SO_2, Figures 23 and 24, respectively, decreased as the air/fuel ratio decreased. The reduction in SO_2 at low air/fuel ratios is attributed to the lack of available oxygen and sorption by the large amounts of carbon soot produced.

Relative curves for heat balance and operating efficiency of the experimental furnace are shown in Figure 25. Efficiency was calculated by subtracting the heat lost both in the flue gases and through incomplete combustion based on a carbon balance, from the net heat input. This calculation resulted in a maximum heating efficiency of 73.6 percent at an air/fuel ratio of 1.25. The maximum CO_2 reading was obtained at this same ratio, which verifies the setting for maximum heating efficiency.

Adding the amount of heat gained by the cooling air passing through the heat exchanger to these losses in Figure 25 leaves some heat which is not included. This heat is considered as being absorbed by and radiated from the combustion chamber refractory and is included as a positive factor in computing efficiency.

By comparing the trends of each pollutant with the four parameters shown in Figure 16, the levels of air pollutant formations can be explained. Combustion was complete at levels between 1.65 and 2.00. At levels above 2.00 the flame temperature and combustion gas residence time in the furnace were too low for complete combustion. At low air/fuel ratios, the high flame temperatures together with poor air/fuel mixing due to low inlet air velocity resulted in thermal cracking of the fuel droplets, thus yielding carbon soot, CO, and unburned HC. NO emissions were minimized at the

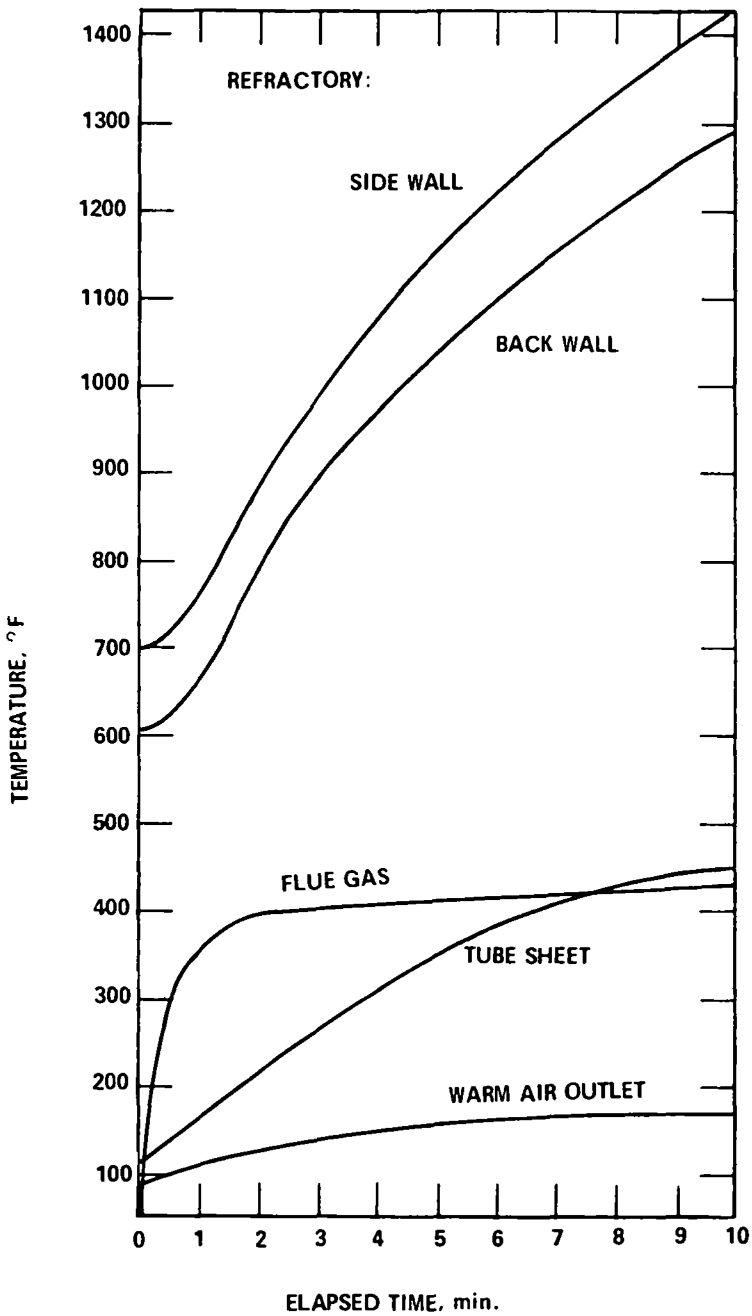


Figure 18. Furnace temperatures at air/fuel ratio of 1.75.

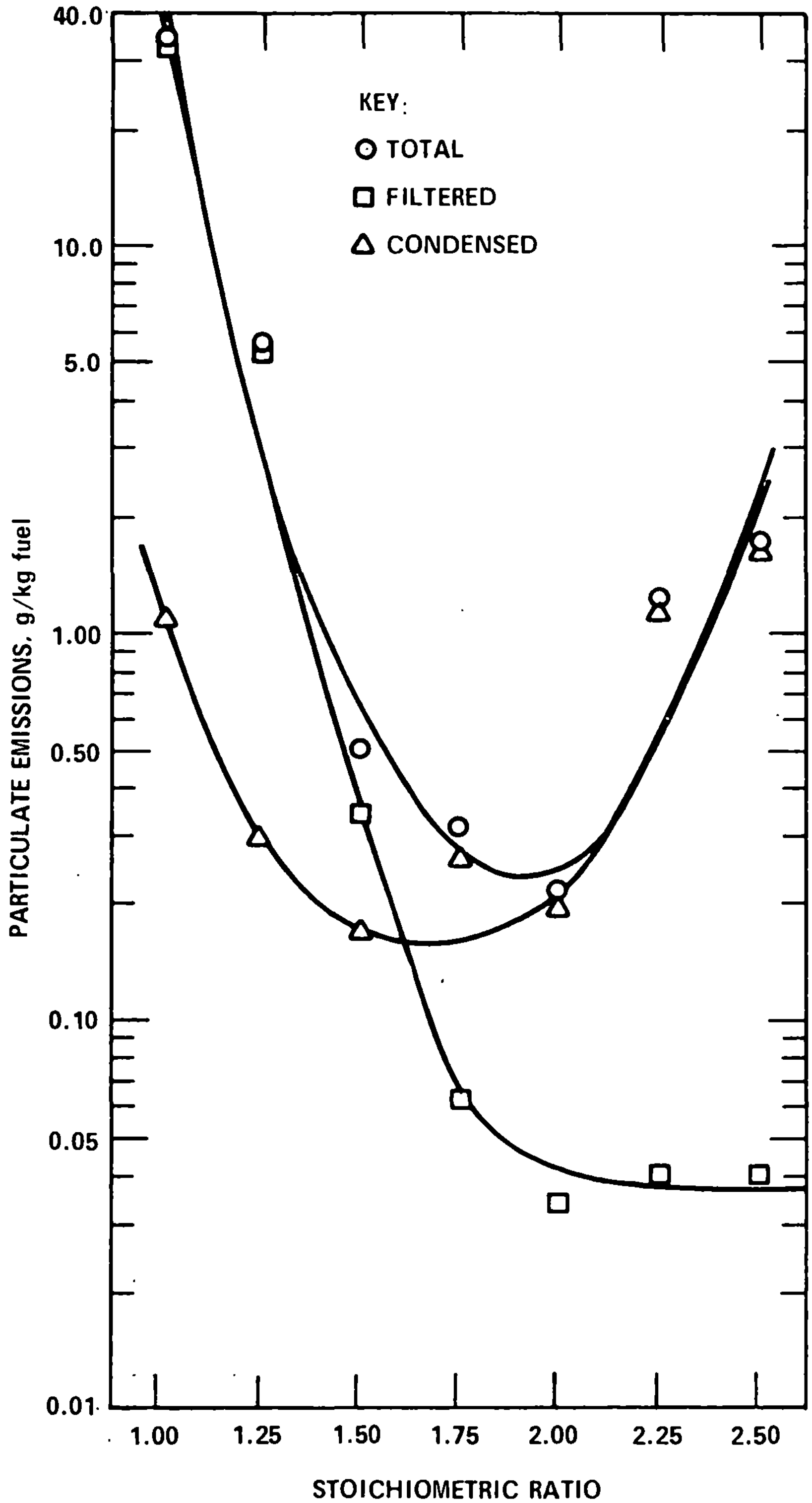


Figure 19. Particulate emissions versus stoichiometric ratio.

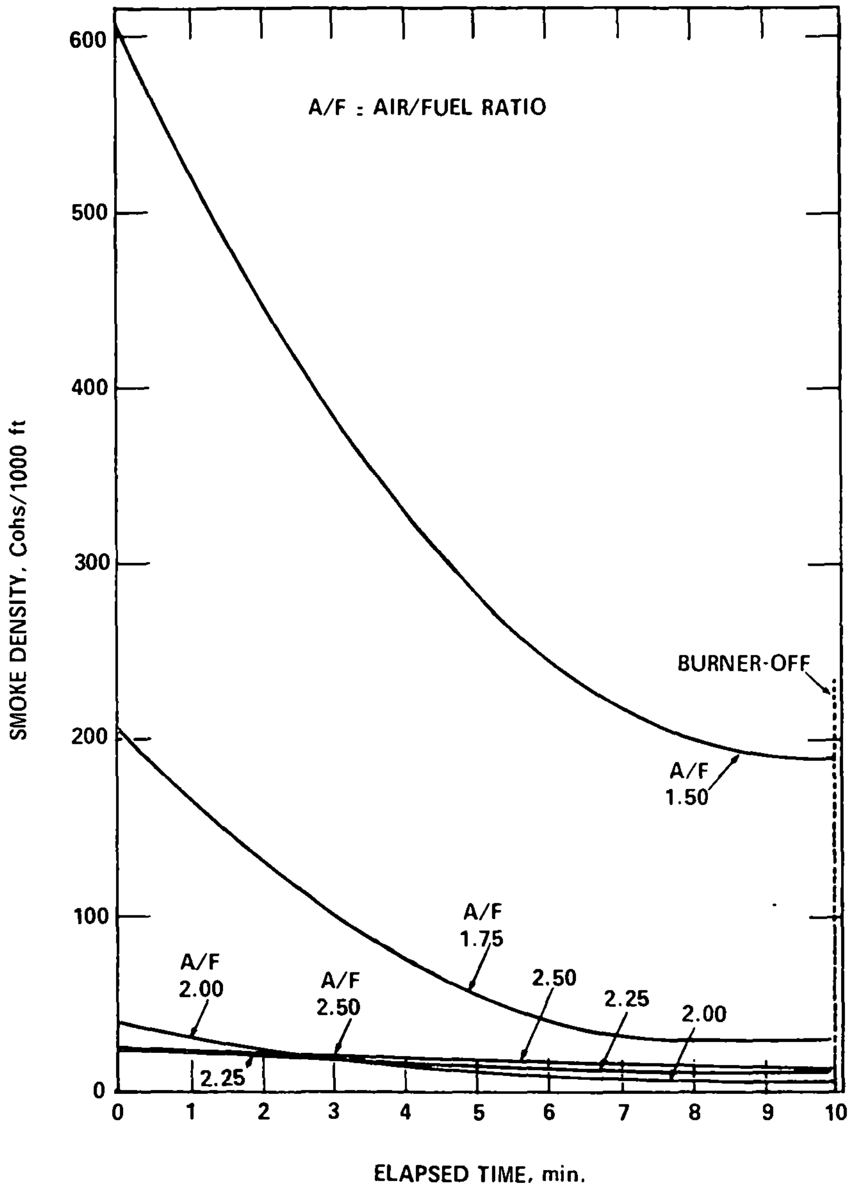


Figure 20. Smoke emissions versus time for various stoichiometric ratios.

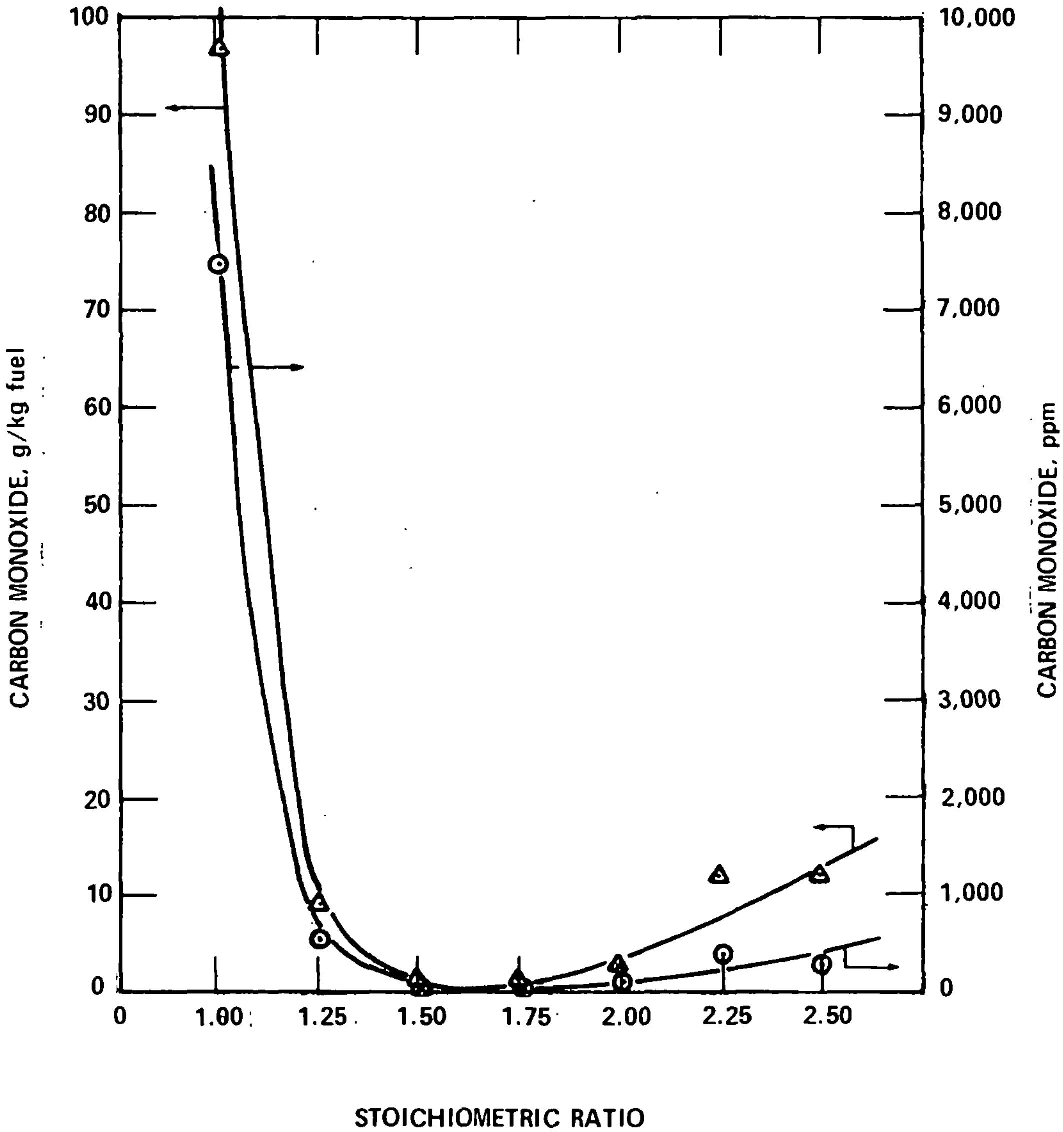


Figure 21. Carbon monoxide emissions versus stoichiometric ratio.

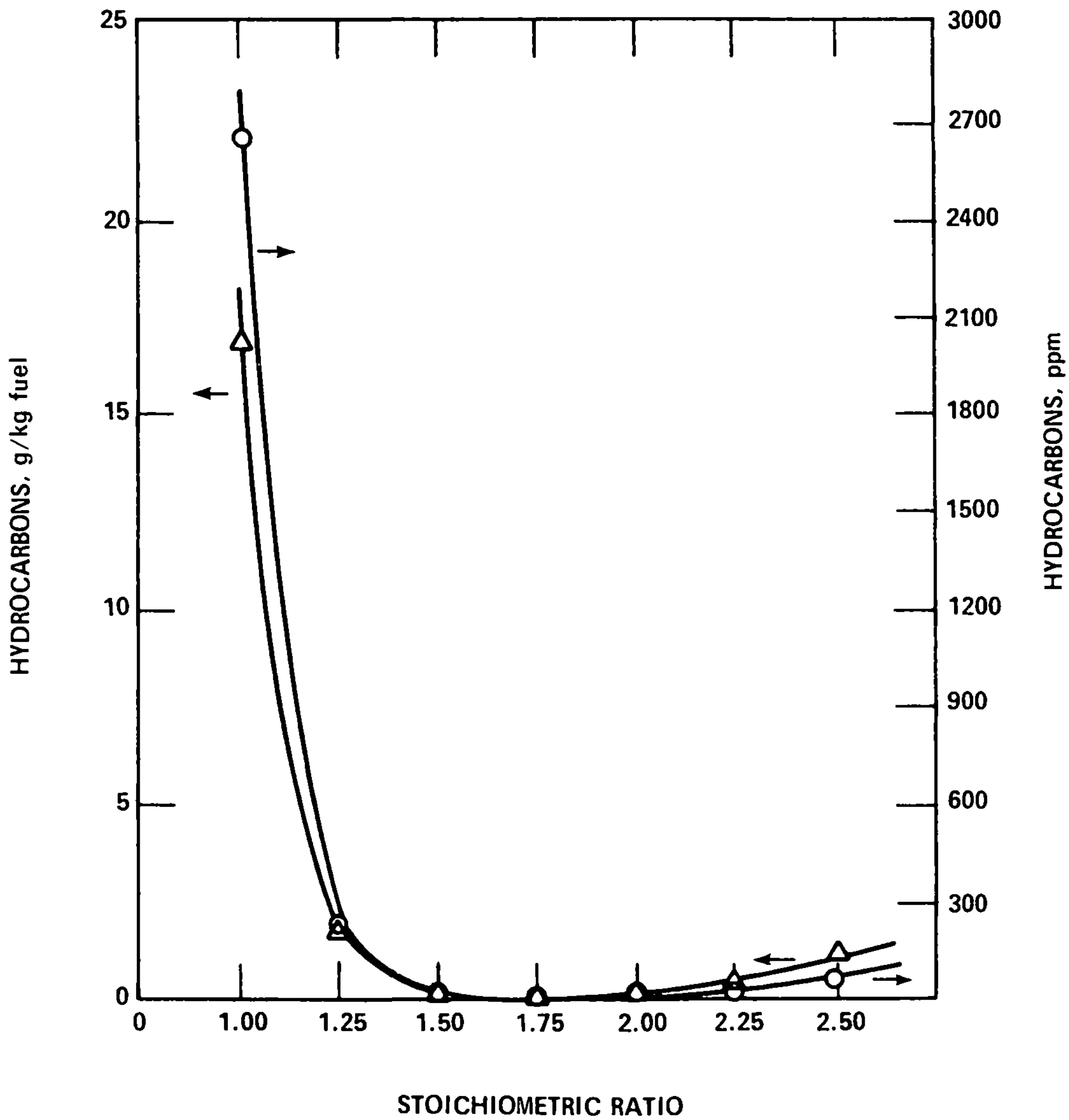


Figure 22. Gaseous hydrocarbon emissions versus stoichiometric ratio.

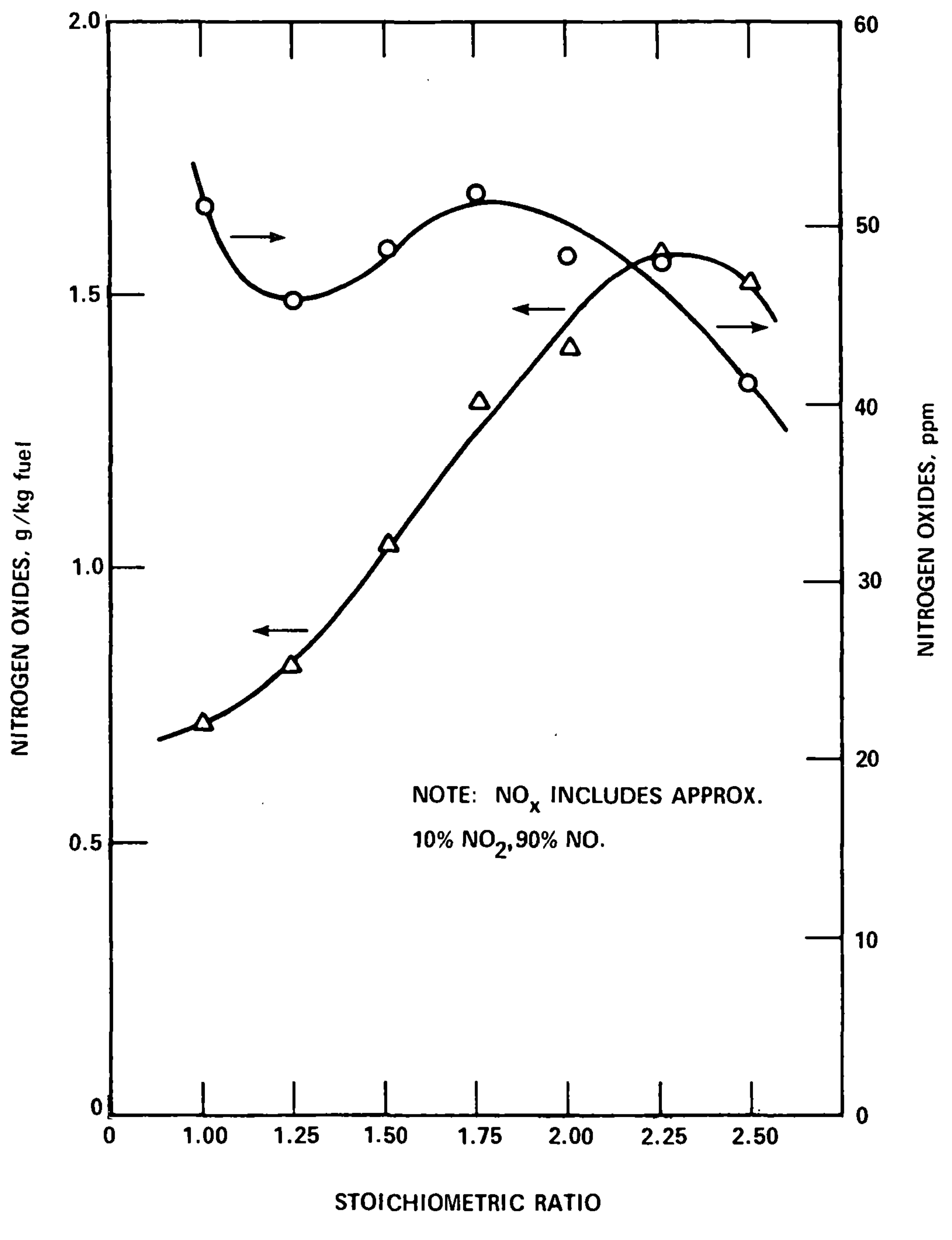


Figure 23. Nitrogen oxides emissions versus stoichiometric ratio.

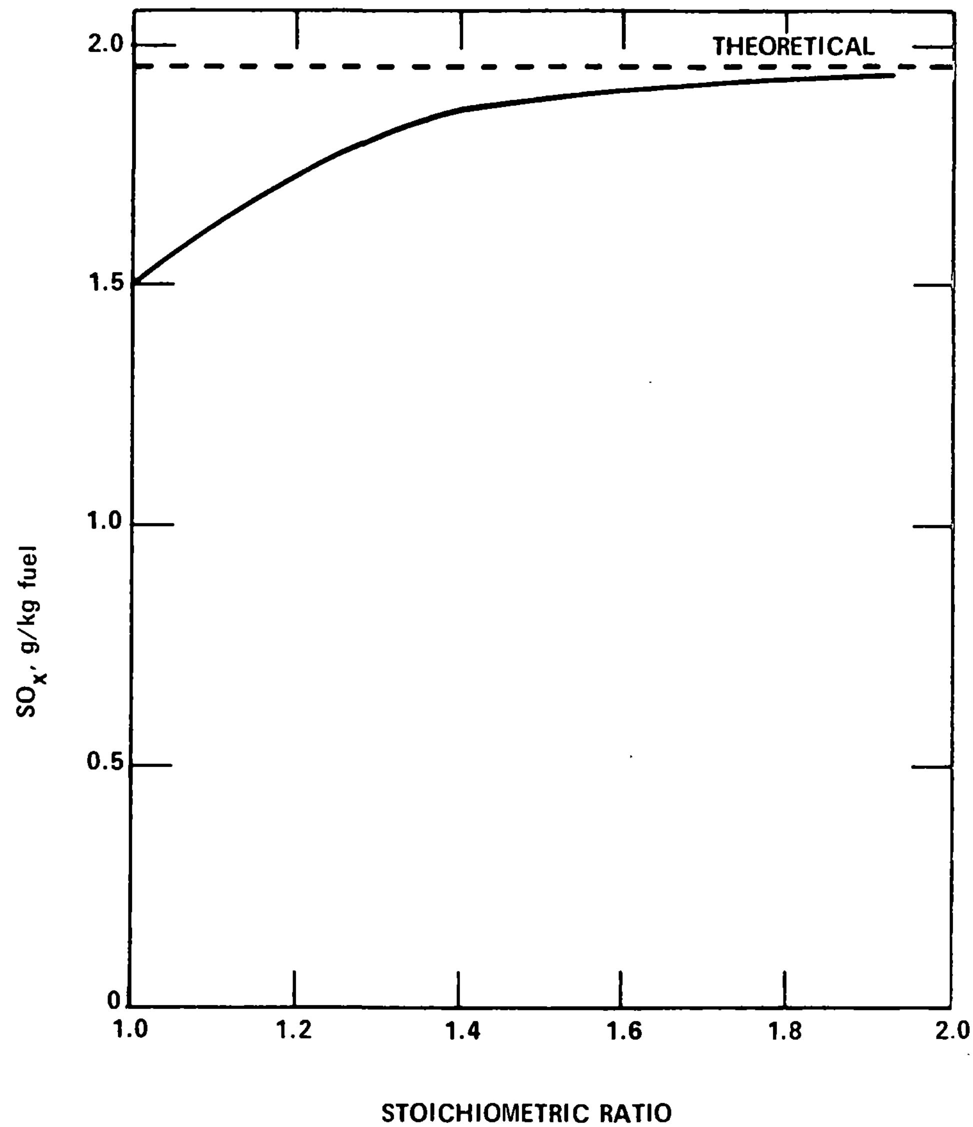


Figure 24. Sulfur oxides emissions versus stoichiometric ratio.

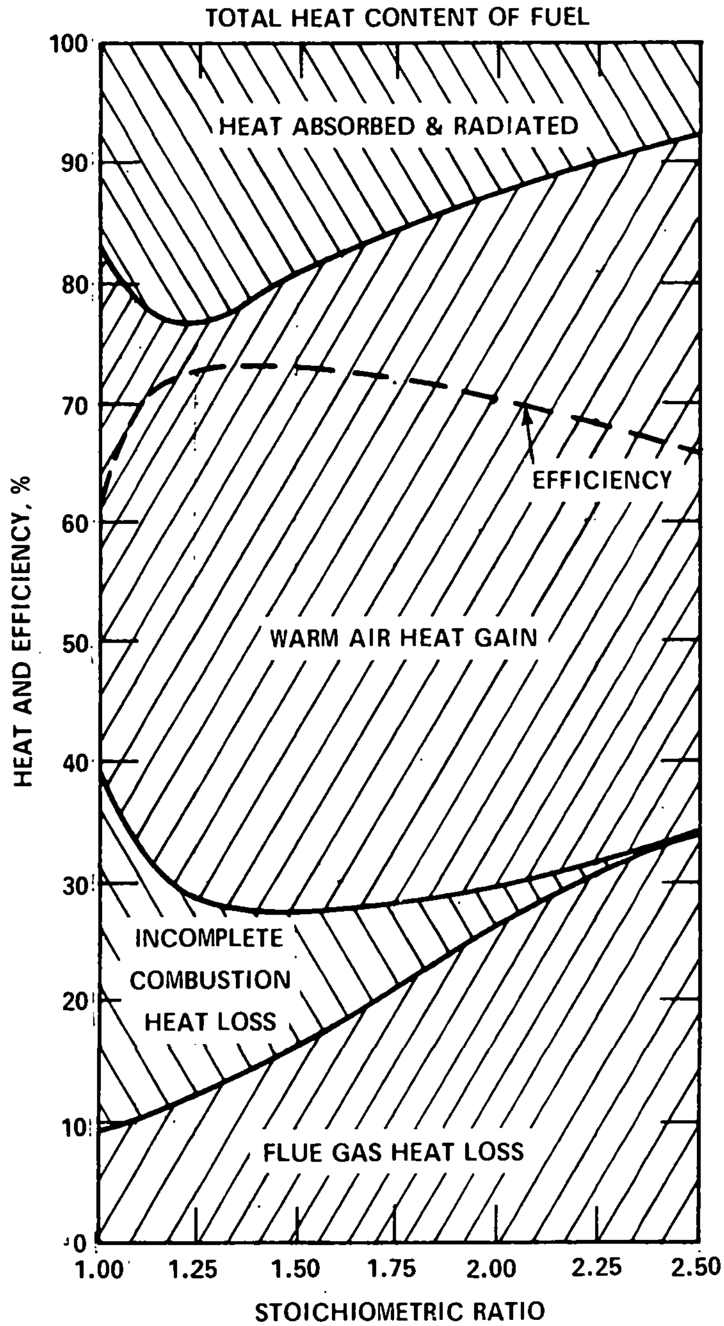


Figure 25. Experimental furnace heating efficiency.

lowest air/fuel ratio because the oxygen concentration is low and mixing is poor due to low turbulence. As the air/fuel ratio increases, the NO_x emissions increase until a peak is reached at an air/fuel ratio of 2.25. Beyond that point, lower temperatures and shorter residence times (because of the high air/fuel ratios) cause a decrease in NO_x emissions.

Note that the air/fuel ratio values obtained during this work are unique to the burner tested. However, this study did establish general trends which are applicable to most high-pressure atomizing-gun burners.

As a result of the work relating air pollutant emissions to air/fuel stoichiometry, it was evident that better combustion was needed. Emissions of smoke, particulates, CO, and HC were too high at air/fuel ratios below 1.6, but NO and SO_2 emissions were reduced. These results indicated that it was desirable to operate at a lower air setting to get higher furnace efficiency and lower NO and SO_2 emissions if combustible emissions could be reduced. Increased residence time and/or combustion modification were the most apparent methods to improve both combustion and furnace efficiency and to reduce NO and SO_2 emissions.

RESIDENCE TIME

This study was performed to determine the effects of residence time on air pollutant emissions[11]. The experimental furnace used in the stoichiometric studies was also used for these tests, except that the height of the combustion chamber was increased from 15 to 27 inches (a factor of 1.8), to allow a significant variation in combustion product residence time.

Residence times for the 27-inch and 15-inch combustion chambers, and a typical domestic furnace (Williamson Temp-O-Matic Lo Boy) are compared in Table 10. The residence times were calculated for each air/fuel ratio by dividing the volume of the combustion chamber by the flue gas flow rate at the average combustion chamber temperature.

Table 10. FURNACE RESIDENCE TIME COMPARISON

	Residence time, seconds		
Excess Air, %	Typical domestic Furnace combustion chamber	Experimental furnace (15-inch combustion chamber)	Experimental furnace (27-inch combustion chamber)
0	0.429	0.398	0.727
25	0.342	0.315	0.578
50	0.287	0.265	0.485
75	0.253	0.233	0.427
100	0.232	0.213	0.390
125	0.216	0.199	0.365
150	0.209	0.188	0.345

Theoretical values of CO_2 and O_2 (dry) in the flue gas were calculated based on the carbon/hydrogen ratio of the test fuel. These theoretical values appear in Figure 26 along with data taken for the studies with long and short residence times. As shown in Figure 26, actual CO_2-O_2 curves for the longer residence time conform much more closely to the theoretical curves than the curves for shorter residence times, reflecting the degree of incomplete combustion with shorter residence times.

Particulate emissions were reduced drastically by increased residence time as shown in the semi-log plot of Figure 27. The curve which describes the emissions at a longer residence time (dotted line) shifted down and to the left of the curve representing a short residence time (solid line). With a longer residence time the minimum is moved to a lower air/fuel ratio, and the quantity of emissions at the minimum point is reduced.

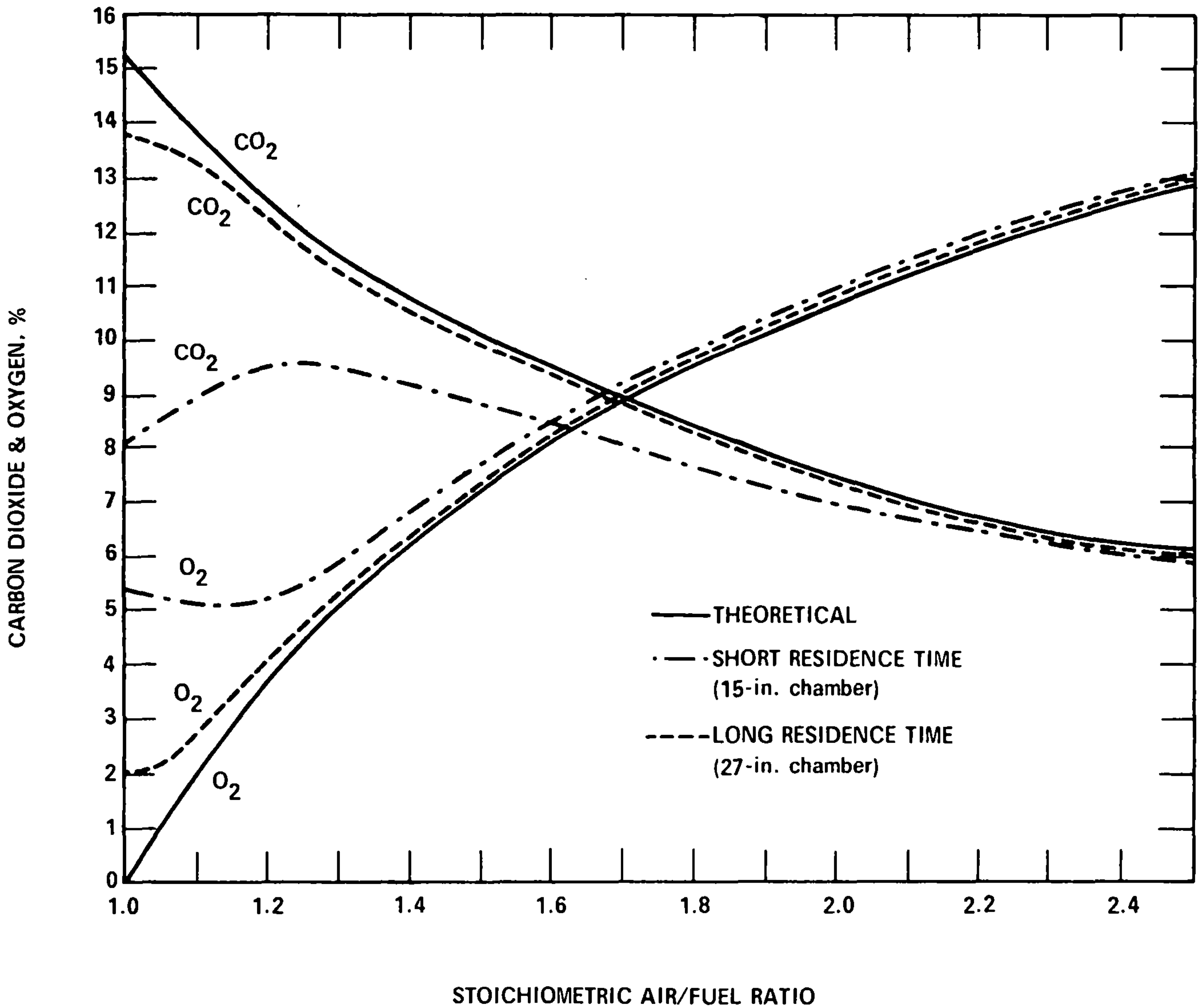


Figure 26. Effect of residence time on carbon dioxide and oxygen.

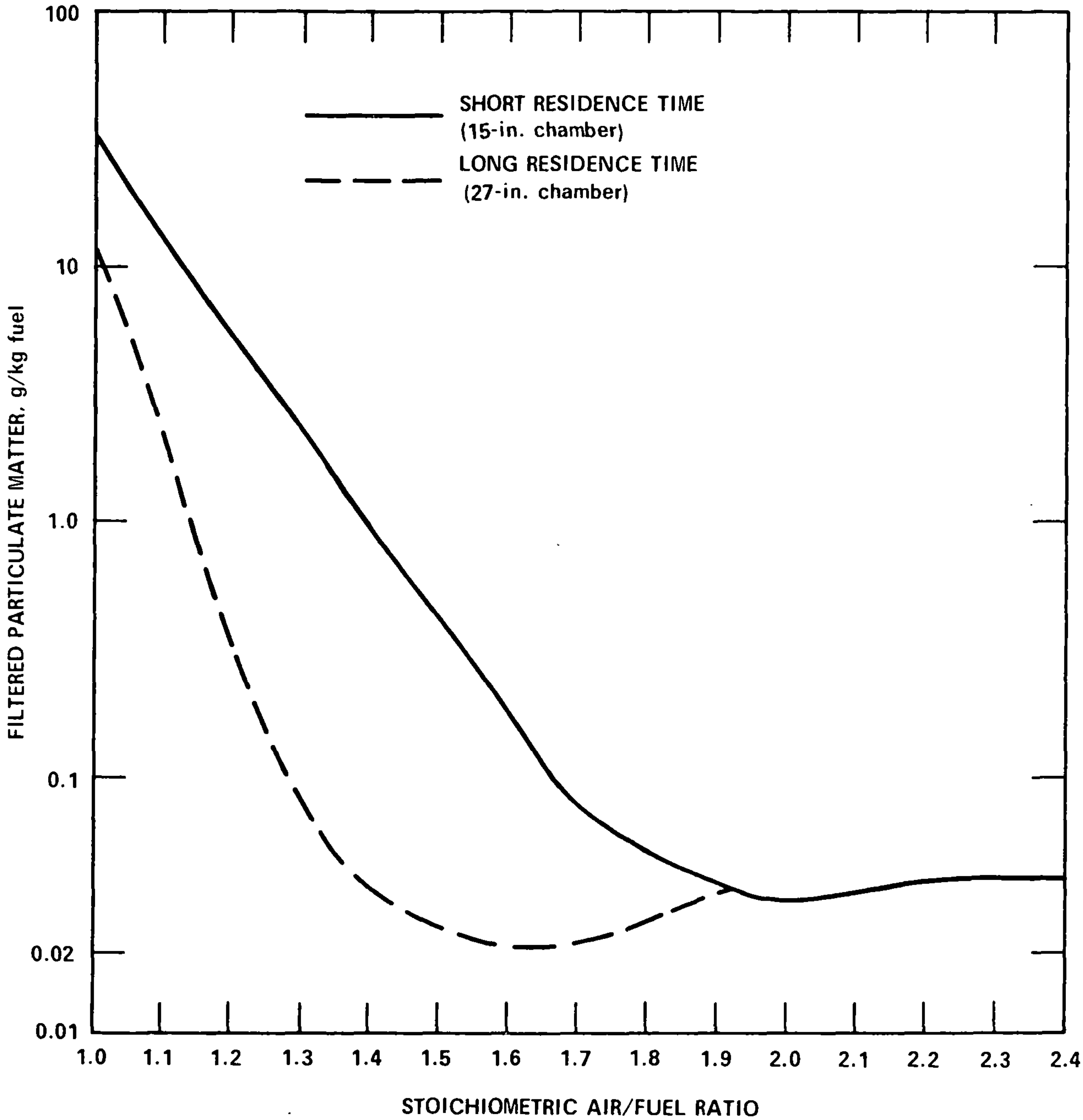


Figure 27. Effect of residence time on particulate emissions.

As expected, the smoke results shown in Figure 28 are similar to those for particulate weight. The minimum again occurred at a lower air/fuel ratio. Also shown in Figure 28 are data obtained in a concurrent project[12]. The smoke curve for the standard equipment furnace falls between the curves for the different residence times. (This standard equipment furnace was used as the basis for calculation of residence times in a typical domestic furnace as reported in Table 10.) It is clear that smoke was reduced significantly by longer residence time.

CO and gaseous HC data are shown in Figures 29 and 30, respectively. In both cases increased residence time shifted the minimum toward a lower air/fuel ratio. Also, the quantity of emissions at the minimum was reduced significantly.

NO emissions are plotted in Figure 31. (These values, reported as NO_x, include about 90 percent NO and 10 percent NO_2.) NO emissions from longer residence times were somewhat greater than those from tests at shorter residence times. At an air fuel ratio of 1.4 the increase was about 16 percent. However, NO_x emissions were 17 percent less for the longer residence time when compared to the NO_x emissions at the short residence time when the excess air in both cases was adjusted to give equivalent Bacharach smoke indices of 1, as is the practice of burner-furnace service men. (See Appendix A for explanation.)

Since NO levels are well below equilibrium, as shown in Figure 32, the formation reaction rate is controlling the NO quantity. This explains why an increase in residence time can be expected to result in an increase in NO emissions.

Emissions of SO_x were virtually unaffected by the change in residence time, as shown in Figure 33. This indicates that sulfur in the fuel oxidizes very rapidly.

Chapter 2 — BACKGROUND

For a number of years estimates of concentrations were calculated either from the equations of Sutton (1932) with the atmospheric dispersion parameters C_y, C_z, and n, or from the equations of Bosanquet (1936) with the dispersion parameters p and q.

Hay and Pasquill (1957) have presented experimental evidence that the vertical distribution of spreading particles from an elevated point is related to the standard deviation of the wind elevation angle, σ_E, at the point of release. Cramer (1957) derived a diffusion equation incorporating standard deviations of Gaussian distributions: σ_y for the distribution of material in the plume across wind in the horizontal, and σ_z for the vertical distribution of material in the plume. (See Appendix 2 for properties of Gaussian distributions.) These statistics were related to the standard deviations of azimuth angle, σ_A, and elevation angle, σ_E, calculated from wind measurements made with a bi-directional wind vane (bivane). Values for diffusion parameters based on field diffusion tests were suggested by Cramer, et al. (1958) (and also in Cramer 1959a and 1959b). Hay and Pasquill (1959) also presented a method for deriving the spread of pollutants from records of wind fluctuation. Pasquill (1961) has further proposed a method for estimating diffusion when such detailed wind data are not available. This method expresses the height and angular spread of a diffusing plume in terms of more commonly observed weather parameters. Suggested curves of height and angular spread as a function of distance downwind were given for several "stability" classes. Gifford (1961) converted Pasquill's values of angular spread and height into standard deviations of plume concentration distribution, σ_y and σ_z. Pasquill's method, with Gifford's conversion incorporated, is used in this workbook (see Chapter 3) for diffusion estimates.

Advantages of this system are that (1) only two dispersion parameters are required and (2) results of most diffusion experiments are now being reported in terms of the standard deviations of plume spread. More field dispersion experiments are being conducted and will be conducted under conditions of varying surface roughness and atmospheric stability. If the dispersion parameters from a specific experiment are considered to be more representative than those suggested in this workbook, the parameter values can be used with the equations given here.

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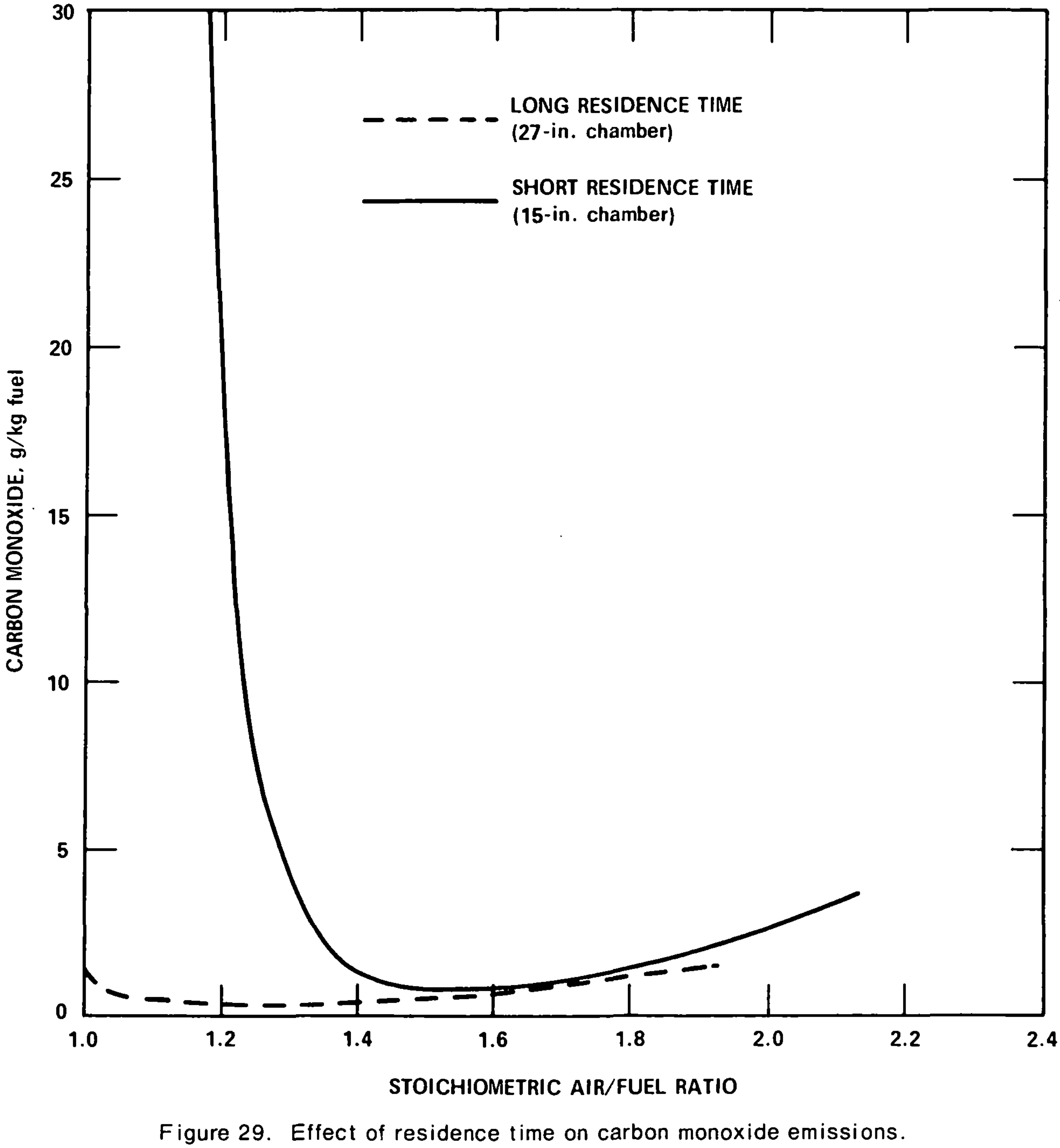

Figure 29. Effect of residence time on carbon monoxide emissions.

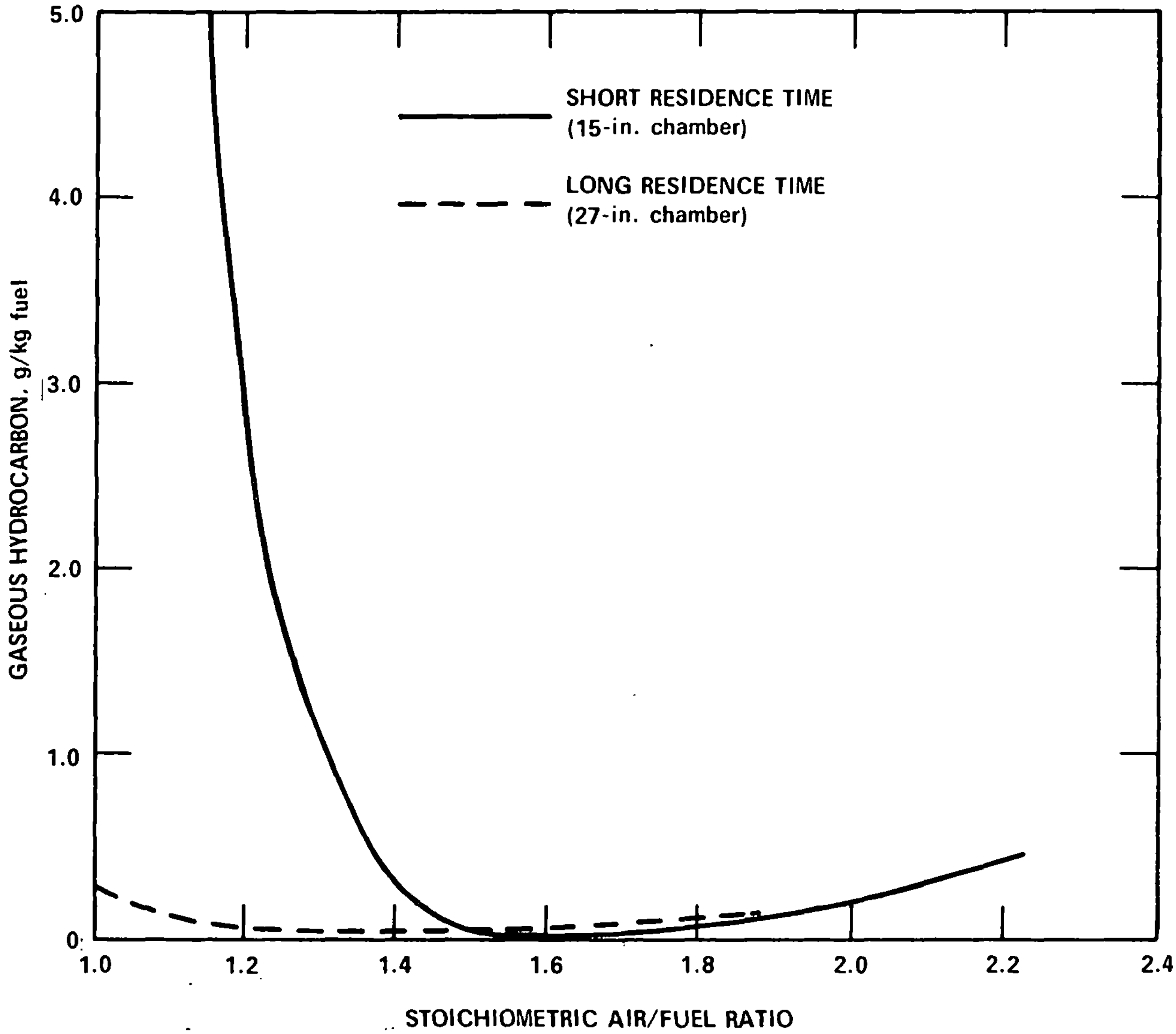

Figure 30. Effect of residence time on gaseous hydrocarbon emissions.

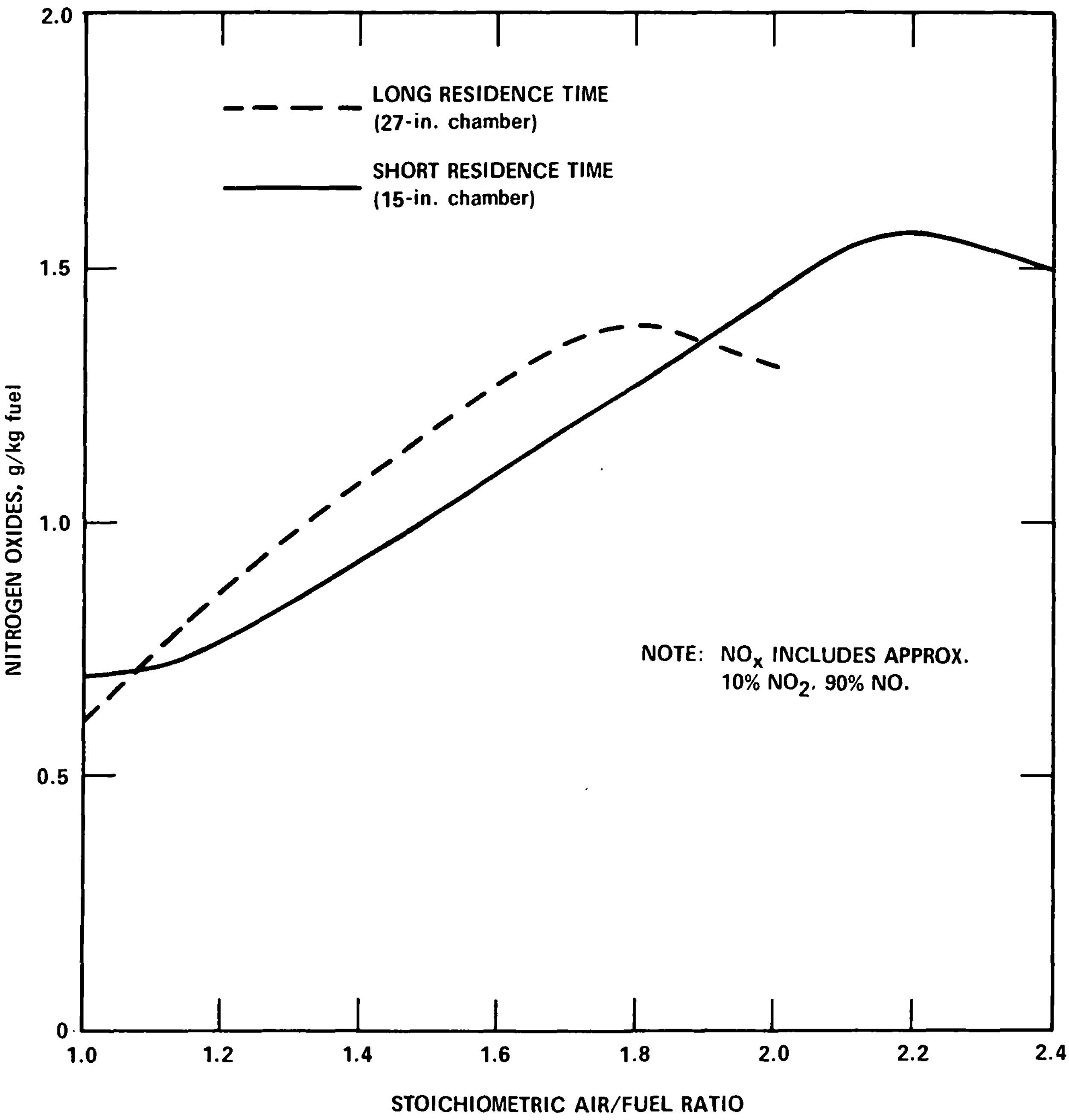

Figure 31. Effect of residence time on nitrogen oxides emissions.

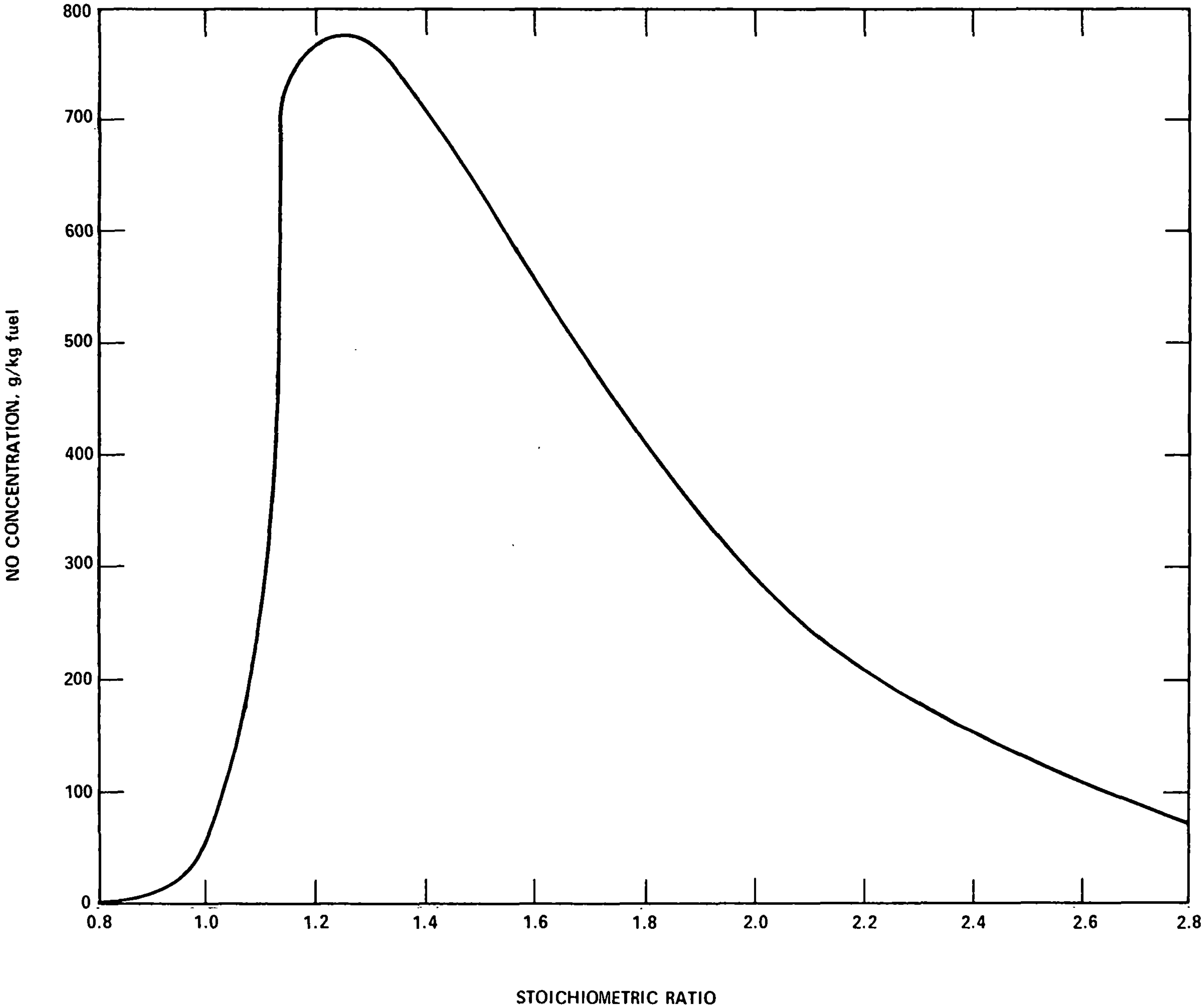

Figure 32. Nitric oxide equilibrium flame curve for No. 2 oil with 70° F air inlet temperature.

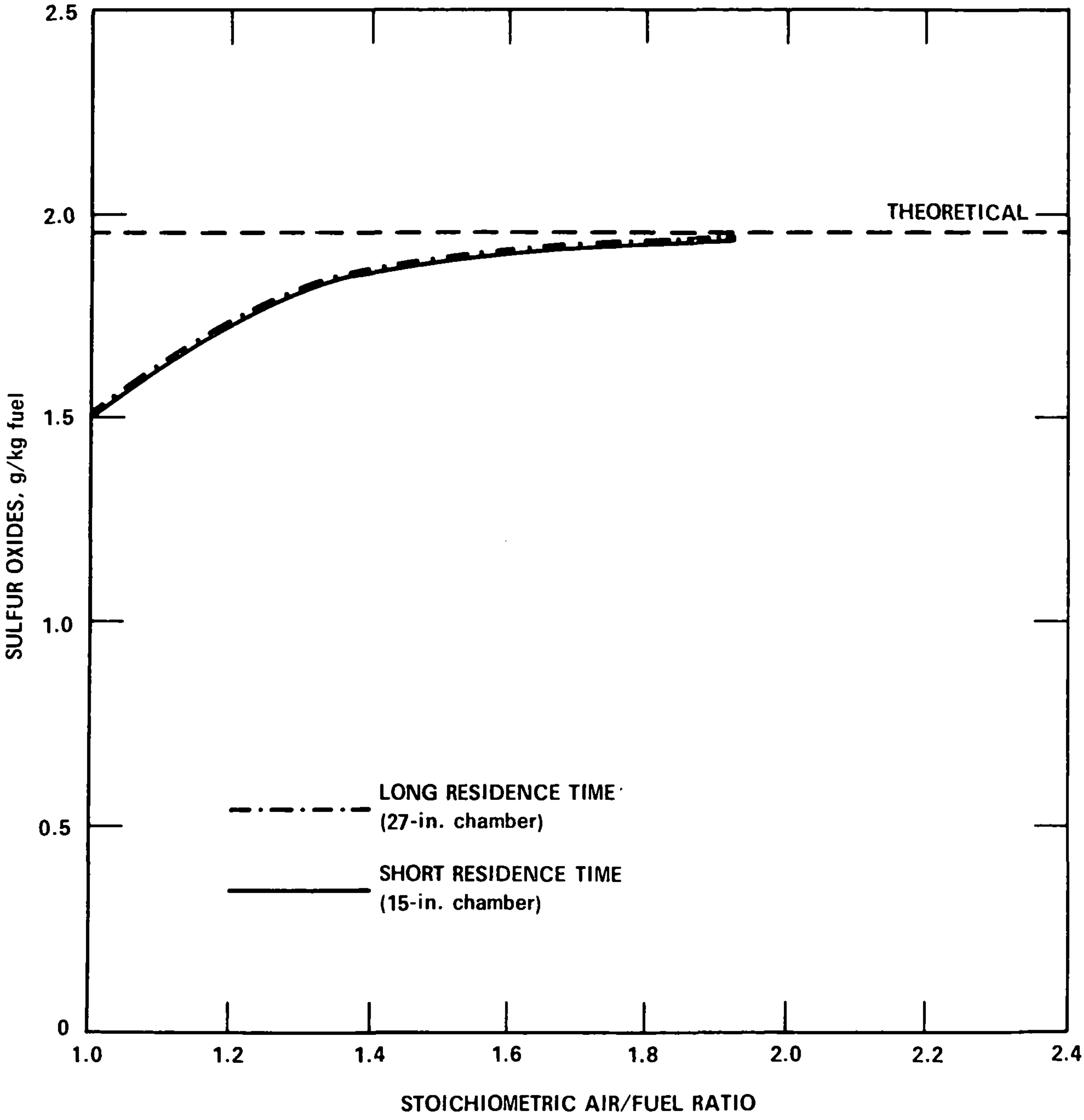

Figure 33. Effect of residence time on sulfur oxides emissions.

In general, the increase in residence time provided a noticeable decrease in total pollutant emissions and allowed the furnace to be operated thermally more efficiently; i.e., at a lower air/fuel ratio.

Although these studies show that residence time is an important factor in the control of air pollutant emissions, further work is needed to determine the extent to which residence time can be used to control emissions. An optimum residence time would allow enough time for approaching complete combustion (i.e., for minimizing CO, HC, and particulate emissions), and simultaneously be short enough to minimize NO_x formation.

COMBUSTION CHAMBER EFFECTS

Before studying combustion modification, it was decided to find the effects of combustion chamber configuration and material on air pollutant emissions. A refractory cylindrical chamber (fired into radially), a steel cylindrical chamber (fired into axially), and a refractory square chamber were tested under the same conditions. Combustion was poor in the steel chamber, presumably because it was non-refractory, not because of its shape. It was assumed that the non-refractory steel chamber would create a cold wall effect which would quench the flame before combustion was complete, thus producing excessive amounts of CO, HC, and smoke. In order to achieve acceptable combustion with the steel chamber, the burner had to be fired at a higher stoichiometric ratio, which reduces efficiency. Combustion in refractory-lined combustion chambers was good; there was very little difference in results with different chamber configurations. It is thus concluded that combustion chamber configuration has little effect on emissions if the chamber volume and dimensions are similar. If, however, the volume or dimensions are significantly different, chamber configuration can become very important with respect to the production of pollutant emissions[13]. It was also determined that the material used in the combustion chamber can have a great effect on emissions of CO, HC, smoke, and particulates. NO_x emissions were unaffected in all cases, indicating that most of this pollutant is formed early in the combustion process.

COMBUSTION IMPROVING DEVICES

Since the air/fuel stoichiometry and residence time studies indicated a need for improved burner performance, combustion modification was considered as a possible method of reducing air pollutant emissions. Five commercially available combustion-improving devices were tested to determine their effects on furnace efficiency as well as on emissions of smoke, CO, total gaseous HC, and NO_x. Each device was designed to improve the combustion of high-pressure gun-atomizing burners used in domestic oil-fired furnaces by improving the air/fuel mixture.

Plots comparing emissions for a range of air/fuel ratios are shown for average smoke, 10th minute smoke, CO, gaseous HC, and NO_x in Figures 34 through 38, respectively. Comparisons of efficiency are shown in Figure 39.

Compared with the standard burner, only the Union flame control device substantially reduced <u>average</u> smoke levels. The Gulf Econo-Jet reduced average smoke levels slightly with greater reduction at air/fuel ratios above 1.8. However, when the burners are compared at actual operating conditions, as shown in Table 4, only one burner tested had higher average smoke than the standard, and several burners significantly reduced the level of smoke emissions. For example, the Union device reduced smoke by almost 60 percent when compared at a No. 1 smoke level at "steady state" (hot running) conditions (see Appendix A).

The Union device reduced emissions of both CO and gaseous HC over most of the operating range of air/fuel ratio. At low air/fuel ratios all devices produced roughly the same levels of CO and HC, generally lower than those of the standard burner.

Even though the Monarch and Delavan devices slightly reduced NO_x emissions at air/fuel ratios above 1.45 and 1.75, respectively, only the Union device produced substantially less NO_x than the standard equipment, and then only at air/fuel ratios above 1.65. When the devices are compared at actual operating conditions (see Appendix C) all of them produce levels

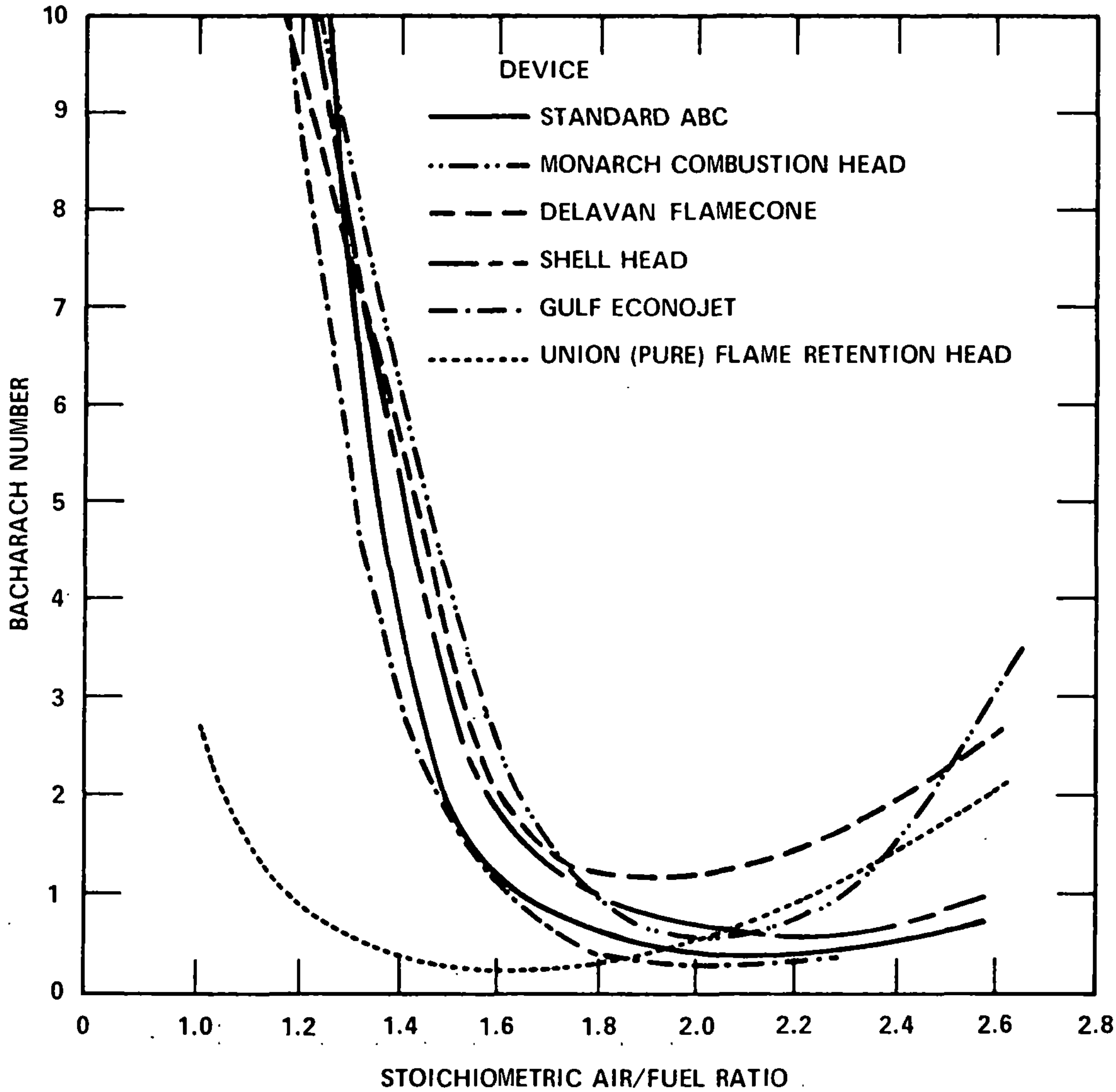

Figure 34. Average smoke emissions of combustion improving devices versus stoichiometric ratio.

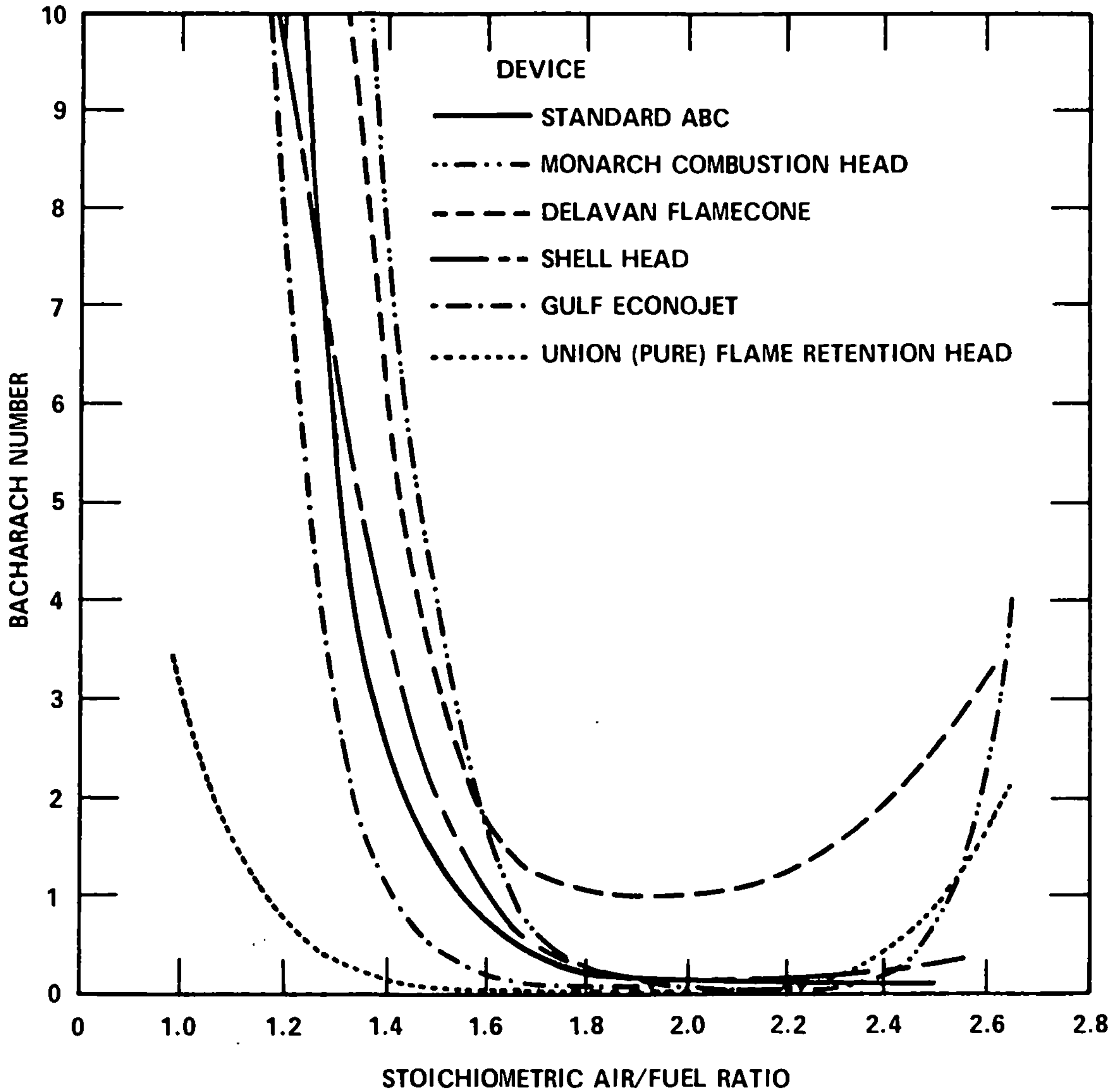

Figure 35. 10th-minute smoke emissions of combustion improving devices versus stoichiometric ratio.

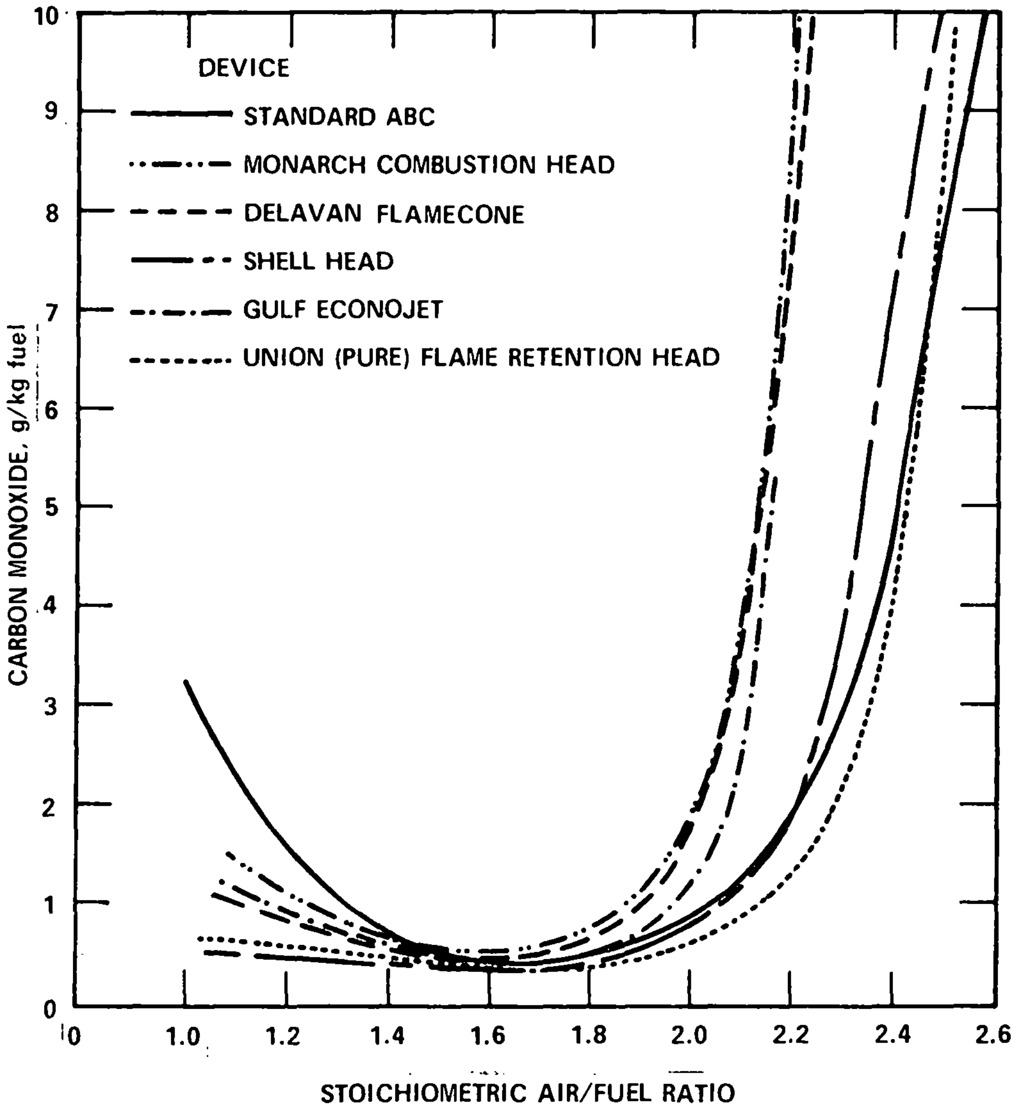

Figure 36. Carbon monoxide emissions of combustion improving devices versus stoichiometric ratio.

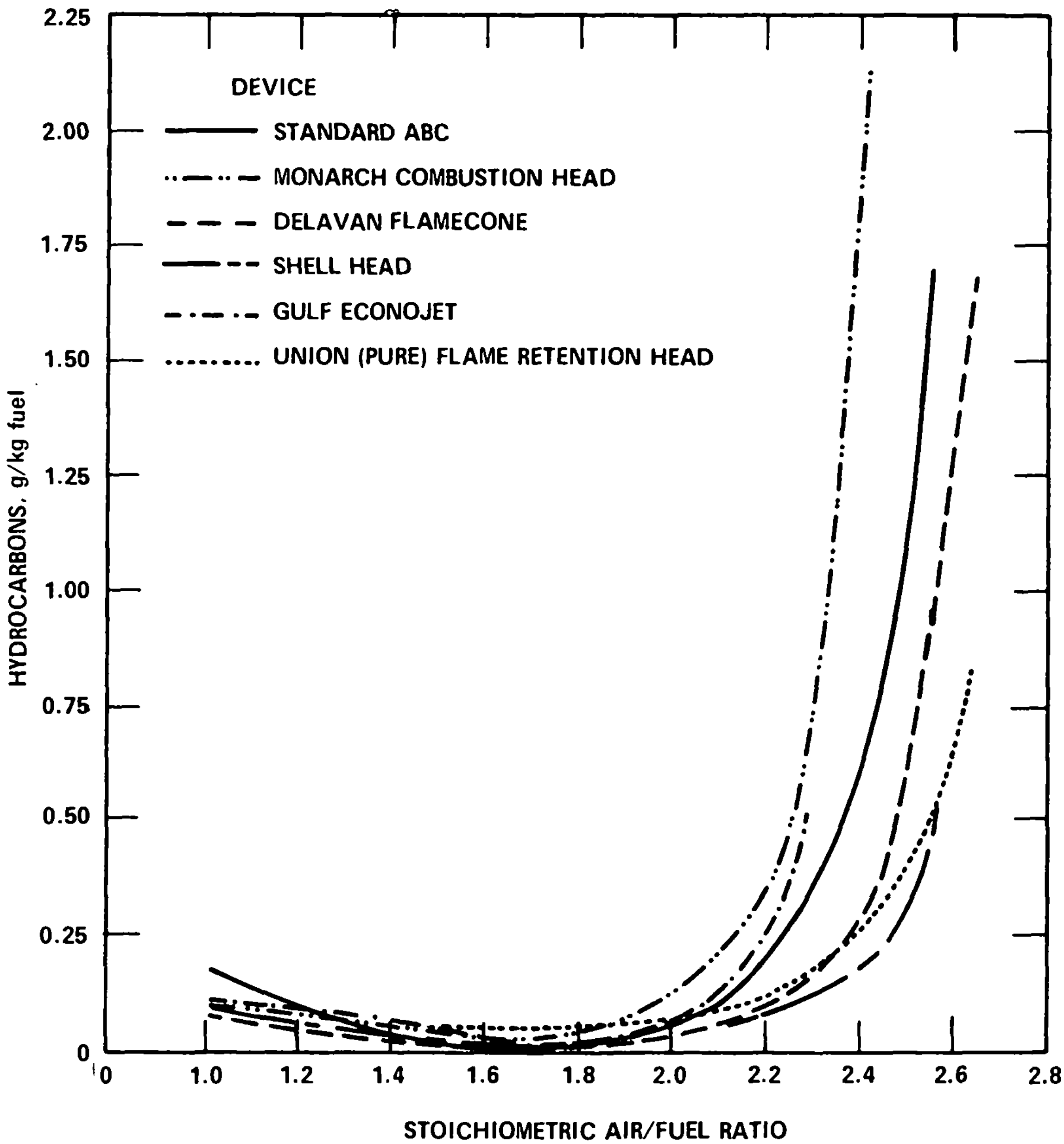

Figure 37. Gaseous hydrocarbon emissions of combustion improving devices versus stoichiometric ratio.

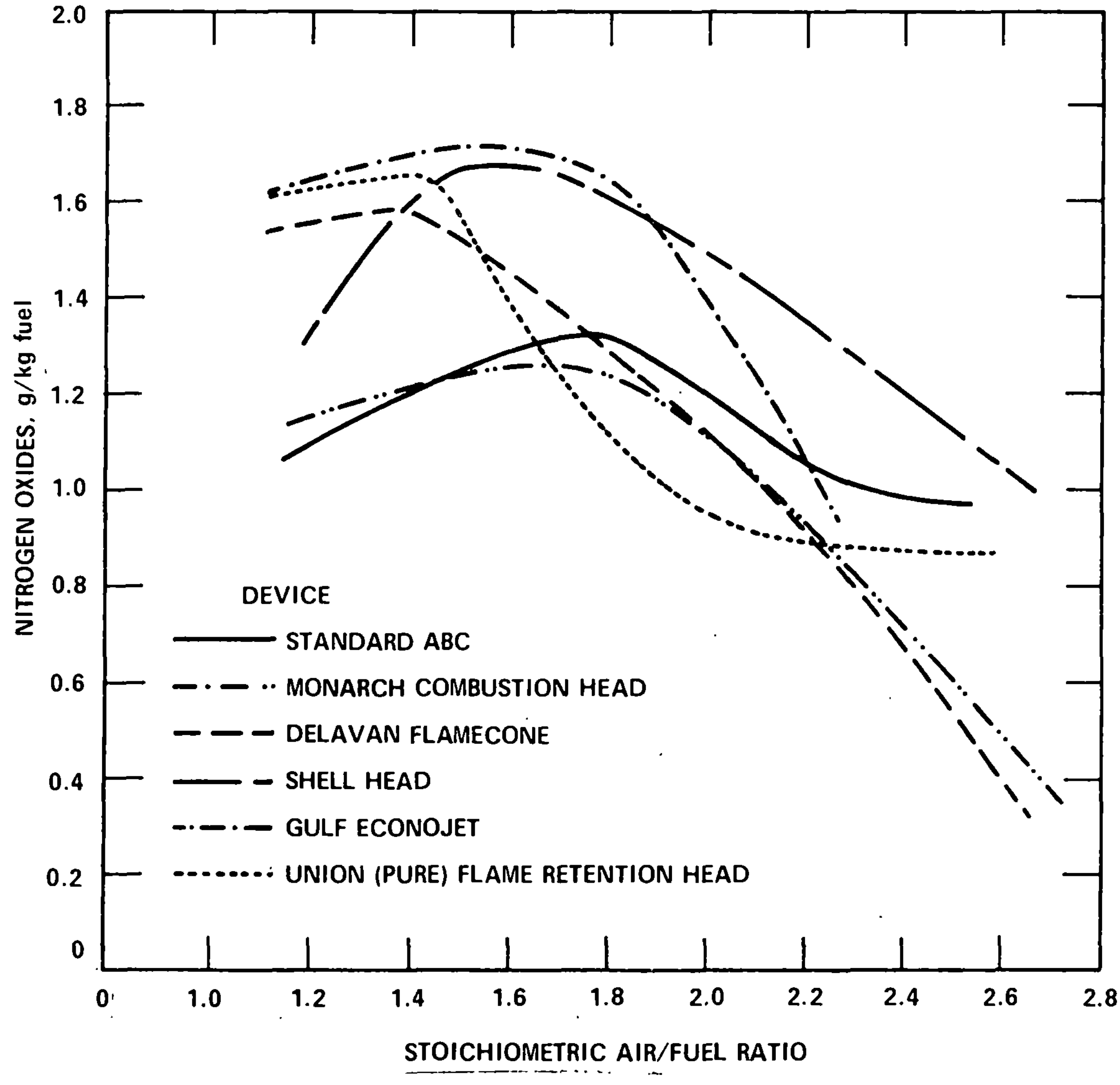

Figure 38. Nitrogen oxides emissions of combustion improving devices versus stoichiometric ratio.

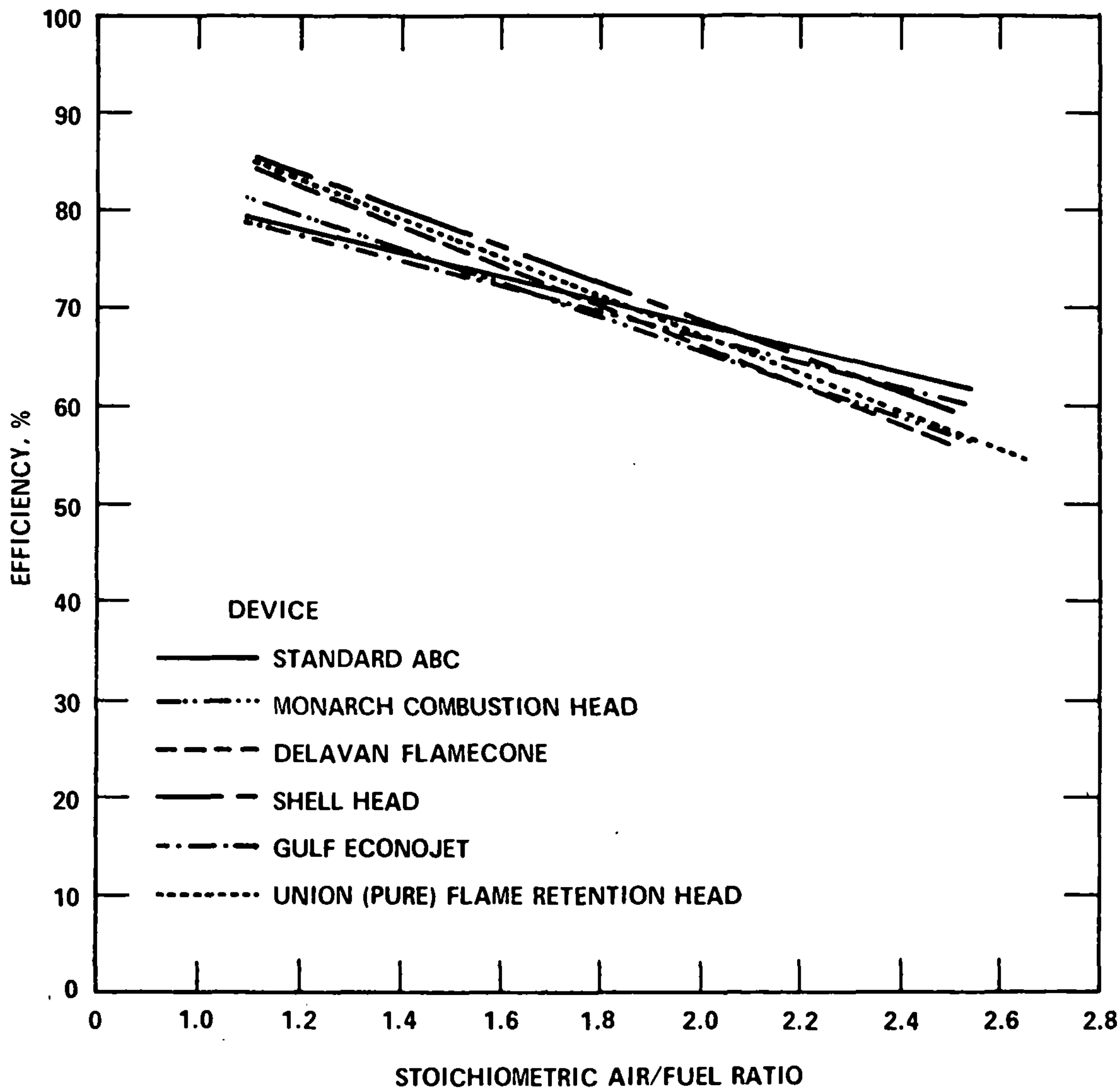

Figure 39. Overall heating efficiencies of combustion improving devices versus stoichiometric ratio.

of NO_x higher than those of the standard burner.

When compared with the standard burner, the Shell and Gulf devices had only slightly higher furnace efficiencies, whereas the Union device increased efficiency appreciably since it operates at a lower air/fuel ratio while producing a No. 1 smoke at "steady state" conditions.

During these tests, problems were encountered with defective burner equipment: various brands of nozzles showed non-uniform spray characteristics, one nozzle was defective; and in another case, other parts of the combustion improving devices were defective. After replacement or repair of the defective parts, the burners performed correctly, indicating that product consistency and quality control are critical in the manufacture of burner equipment, especially nozzles.

These tests indicated that only the Union flame control device substantially reduced smoke and increased efficiency when compared to the standard equipment (ABC Model 45 burner). None of the devices reduced NO_x when compared under actual operating conditions (see Appendix C). CO and gaseous HC emissions were about the same for all burners at low excess air levels.

Although these devices were designed to improve combustion in older inefficient furnaces (rather than in new, more efficient ones), one of the devices (the Union flame control device) reduced the smoke and increased the efficiency of a new, well-designed burner. This work indicates that certain combustion-improving devices offer potential for reducing levels of one or more pollutants and for improving combustion efficiency.

FLAME RETENTION BURNERS

The studies with combustion improving devices identified the Union flame control device, which utilizes flame retention, as being most effective of those tested in reducing pollutant emissions and increasing combustion efficiency. To verify these results and to further investigate flame retention, nine different burners, all featuring retention-type end cones, were tested: the ABC Mite, the Beckett Bantam, the standard burner (ABC Model 45) modified with the Union flame control device, the Sun-Ray, the White-Rogers, the Wayne, the Union, the U. S. Carlin, and the Esso Model 40.

The ABC Mite, Beckett Bantam, and Union device are shown in Figures 12 through 14, respectively. The ABC Mite differs from the others in that its blast tube diameter is much smaller. The Union device differs in that inlet air is controlled by sliding an air shield within the blast tube rather than by manipulating shutter vanes on the burner housing. The dimensions and operation of the Beckett Bantam, however, are the same as those of conventional burners. Each burner employs some form of shield, cone, or ring to which the flame "attaches" thus creating the flame retention effect.

The performance of the ABC Mite, the Beckett Bantam, and the standard with Union flame control device was superior (i.e., higher furnace efficiency, lower smoke, and no increase of CO and HC) to that of the standard and other burners featuring flame retention. Results of tests on the standard and superior performing burners are listed in Table 5 with the emissions of each.

The Union device had very high efficiency and low smoke emissions, but high NO_x emissions. High NO_x emissions would be expected from flame retention devices because of their more compact, intense flame resulting in higher flame temperatures. However, the ABC Mite had both low smoke and low NO_x emissions. The Mite's efficiency was higher than that of the standard but lower than that of the burner modified with the Union device. The reason for the ABC Mite's lower NO_x emissions is not known.

Table 5 shows that there is no difference between burners in CO or HC levels. All three flame retention burners and the standard produced 0.06 grams of HC and 0.5 grams of CO per kilogram of fuel burned. These levels are quite low compared to other sources (e.g., automobiles have HC and CO emissions of approximately 18 and 188 grams per kilogram of fuel, respectively).

These tests indicated that flame retention burners can be operated at low excess air levels without producing excessive smoke. This results in an increase in combustion efficiency and a corresponding reduction in total air pollutant emissions since less total fuel is required for a given heat load. The most important result of this work was that one burner (ABC Mite) was identified as reducing both smoke levels and NO_x. A study is now underway to define critical variables in burner design and maintenance which affect combustion efficiency and air pollution emissions. From this work a comprehensive manual will be written for distillate oil burner manufacturers and servicemen. This manual, which will describe the correct design, operation, and maintenance procedures to control air pollutant emissions while maintaining the highest combustion efficiency,is expected to be available by early 1974 (Contract No. 68-02-0017 with Rocketdyne).

CYCLIC-BASED EMISSIONS

The study of air/fuel stoichiometry effects on air pollutant emissions indicated that some pollutants have sizeable peaks during ignition and/or shutdown. In some cases these peaks account for most of the pollutant emissions. These findings were confirmed during subsequent studies[8,9].

CO and gaseous HC emissions both peak during ignition and after burner shutoff as shown in Figure 40. HC emissions return to near-zero after the initial peak and remain low until the burner goes off. Peaks are also responsible for much of the CO emissions. However, in this case the emissions tend to reach a measurable "equilibrium" value between peaks.

Both the smoke spots and particulate matter peak during ignition and taper off continuously for the remainder of the cycle. Figure 41 shows that by the end of the cycle very little smoke or particulate matter is emitted.

NO emissions do not peak like the other pollutants. Figure 42 shows that, after the initial jump, the emission level rises at a fairly steady rate. Although the NO emissions would eventually reach equilibrium and level off, the on-time of most domestic burners during a cycle is not long enough

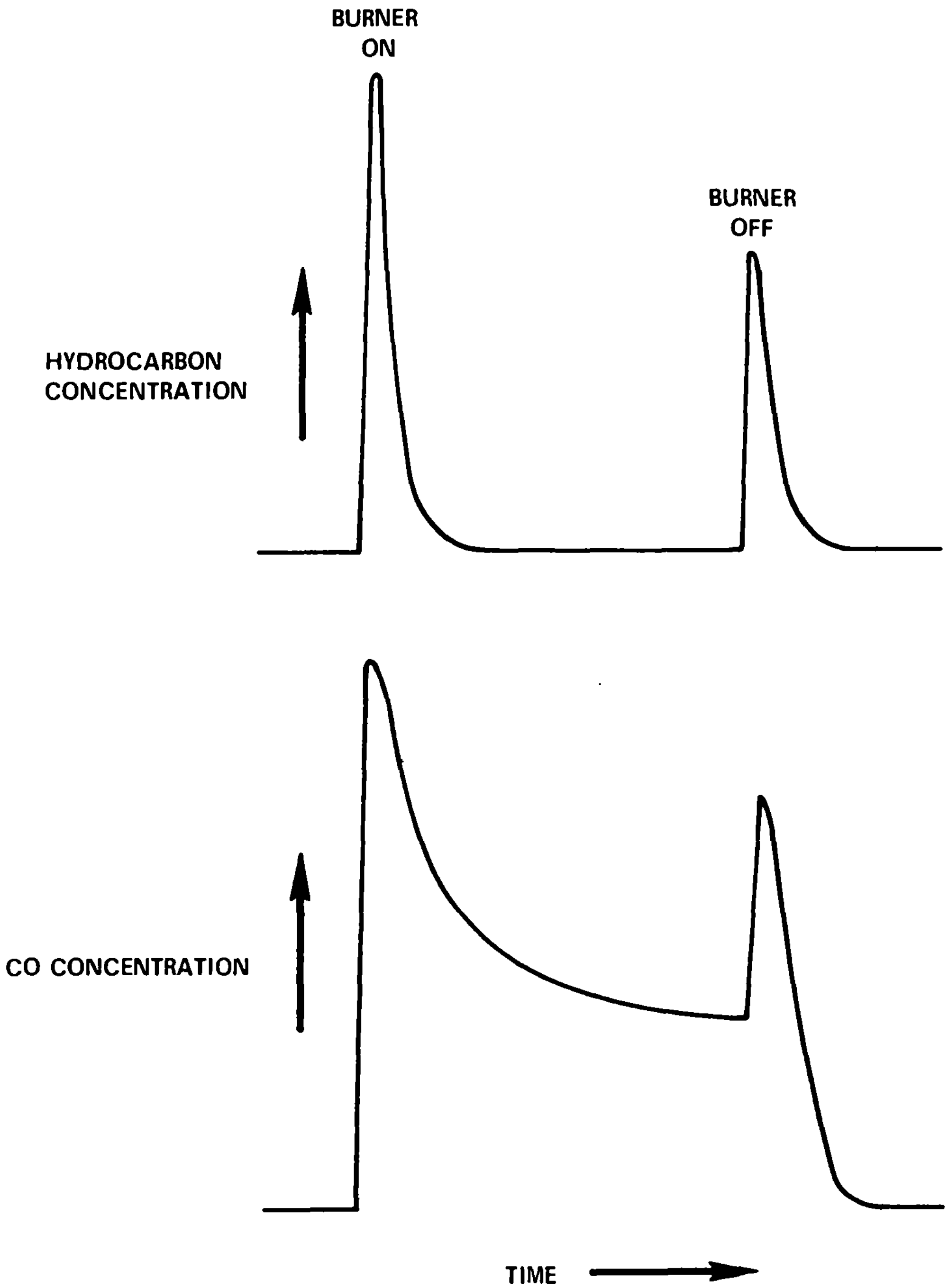

Figure 40. Hydrocarbon and carbon monoxide trends during cycle.

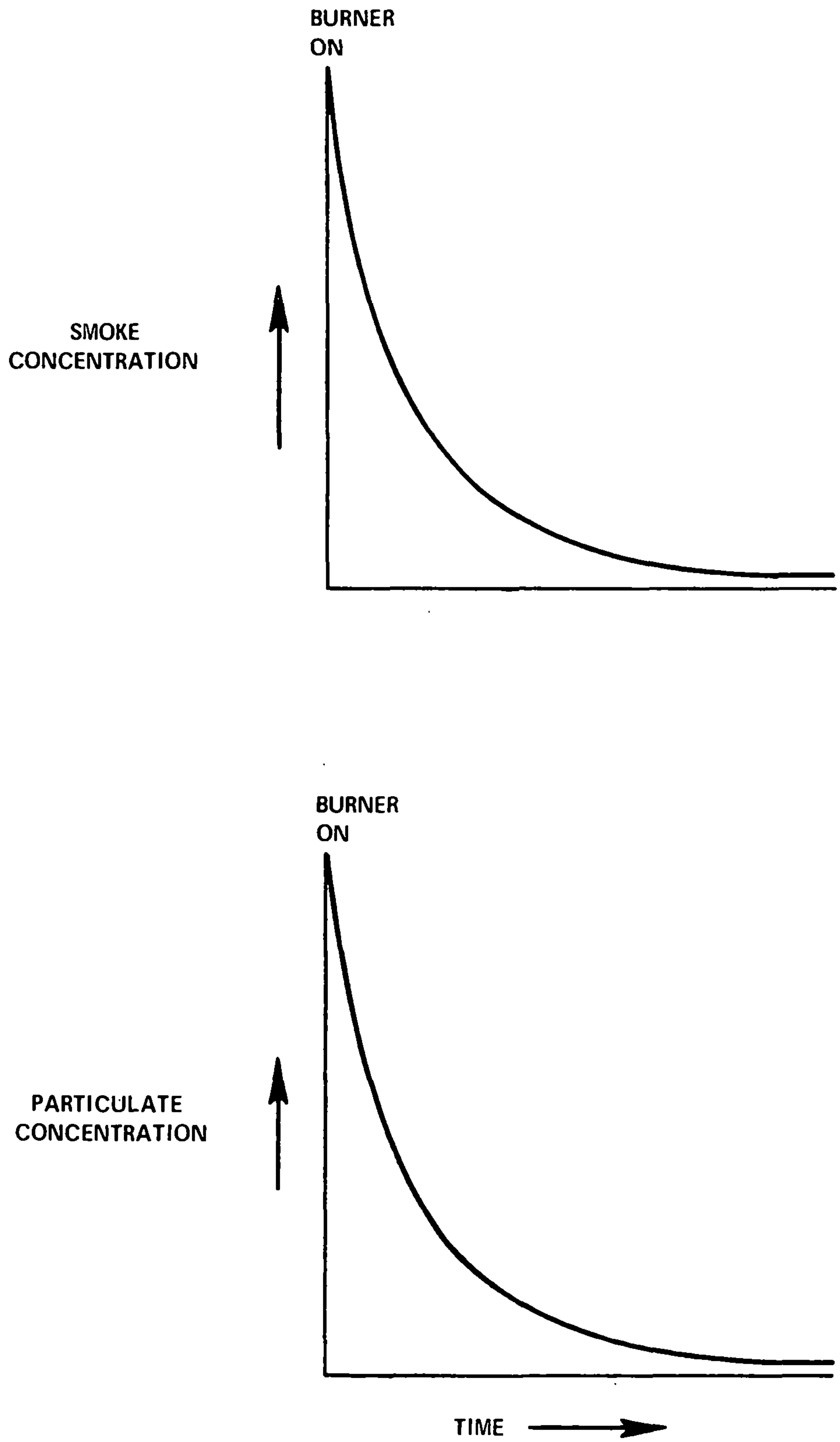

Figure 41. Smoke and particulate trends during cycle.

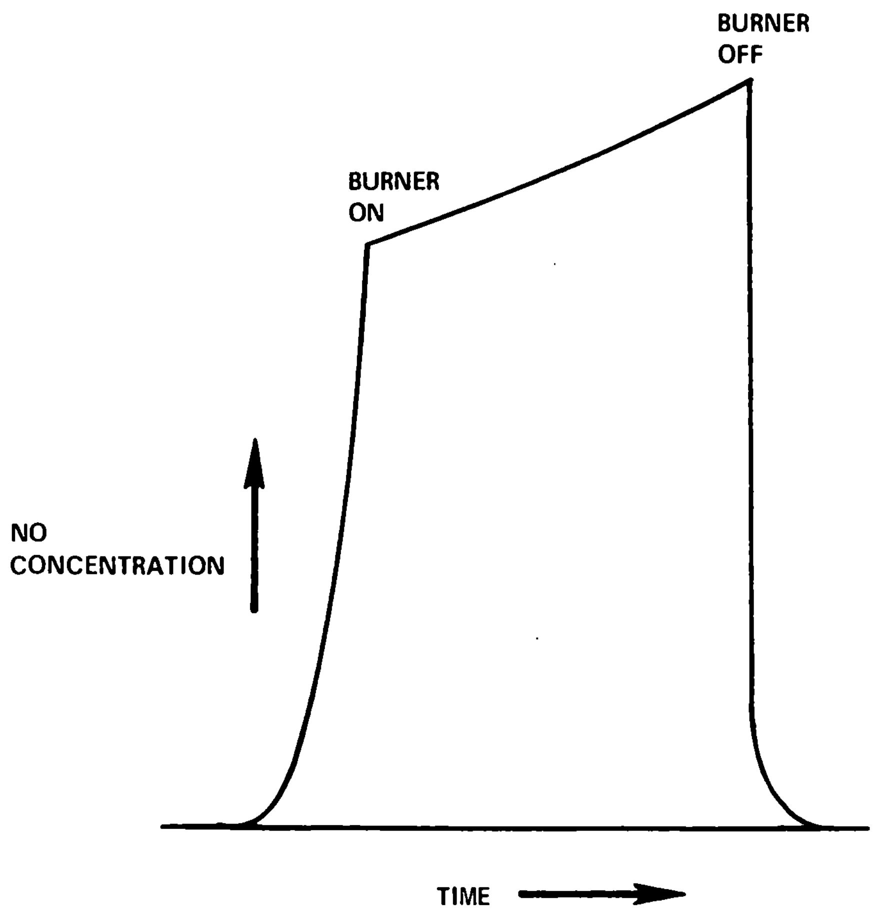

Figure 42. Nitric oxide trend during cycle.

for this to occur.

These peak emissions during ignition and/or shutdown are caused by variation in the combustion chamber temperature. At ignition, a cold refractory will not support complete combustion, thus producing peaks of CO, HC, and smoke. The source of post-burn emission is fuel leakage from the nozzle. The nozzle absorbs heat from the hot refractory and its temperature increases rapidly after the oil flow is shut off. The oil in the nozzle expands and flows from the nozzle. As the fuel drips into the hot combustion chamber it vaporizes and is partially oxidized, thus producing HC and CO.

The peak emissions during ignition could be eliminated or reduced by keeping the refractory warm during the burner-off period. The most apparent possibilities are pilot or modulating burners. However, a more sophisticated control system which cycles the burner more frequently, to maintain a hot refractory, is also a possible solution for ignition emissions. Post-burn emissions might be eliminated by: adding a solenoid cutoff valve in the fuel line, using a clutch to stop the fuel flow before the fan stops, or cooling the combustion chamber refractory rapidly after the burner is shut off.

It is important to recognize, however, that cyclic emissions mainly affect emissions of CO and HC both of which are very low for oil burners. Smoke and particulates can be reduced more effectively by means other than those mentioned above; e.g., the to-be-developed optimum distillate oil burner discussed earlier.

NATURAL GAS BURNERS

Both a Williamson Mono-Port and a Bryant Sectionalized gas burner were compared with oil burners. Each was rated at 100,000 Btu/hr, equivalent to that of the oil burners tested previously.

The tests showed that natural gas combustion with residential burners produce emission levels similar to those from distillate oil combustion. Results of these tests are shown in Figures 43 through 48.

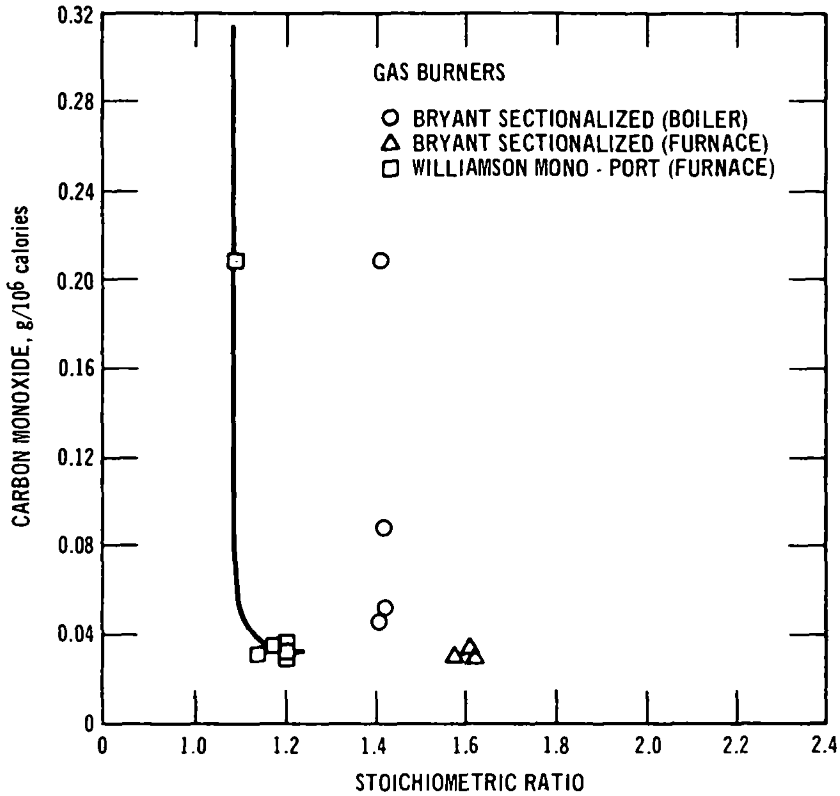

Figure 43. Carbon monoxide emissions for gas-fired units.

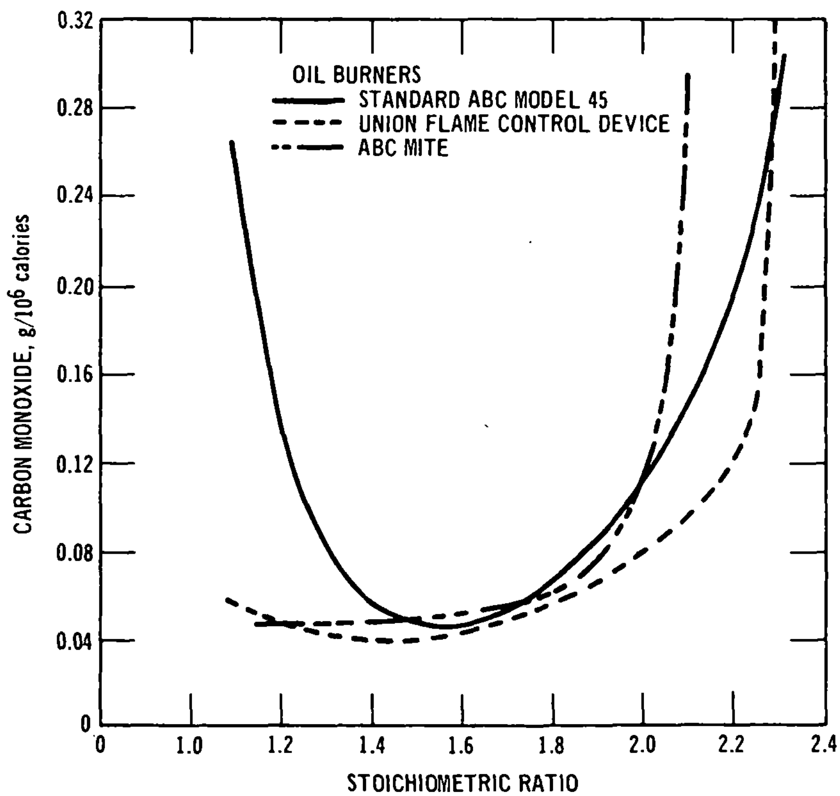

Figure 44. Carbon monoxide emissions for oil-fired units.

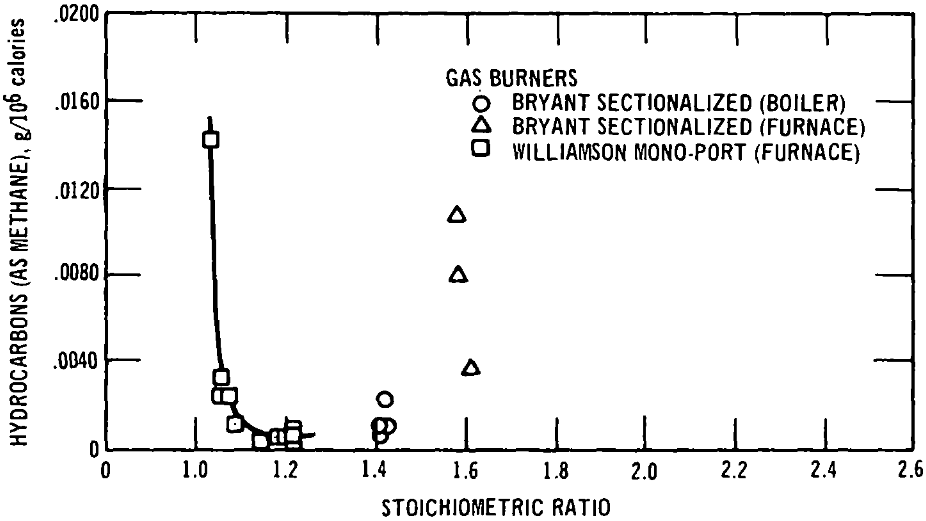

Figure 45. Hydrocarbon emissions for gas-fired units.

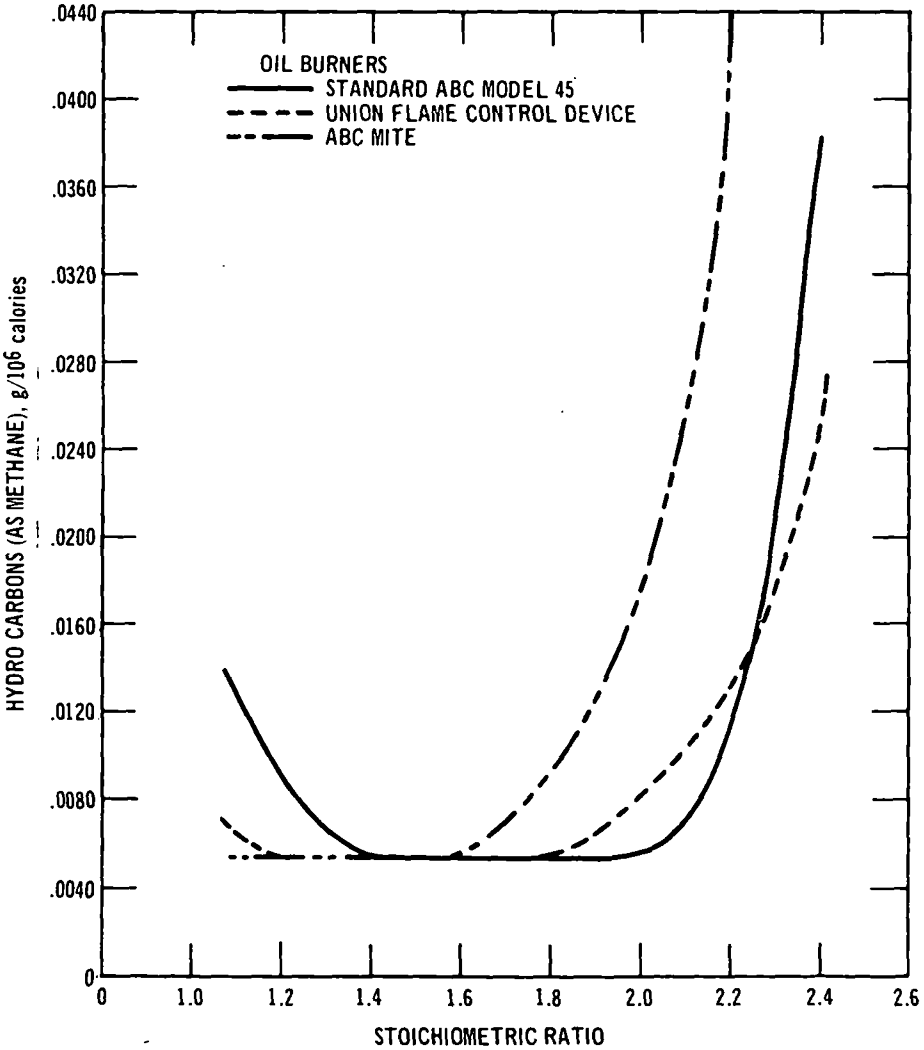

Figure 46. Hydrocarbon emissions for oil-fired units.

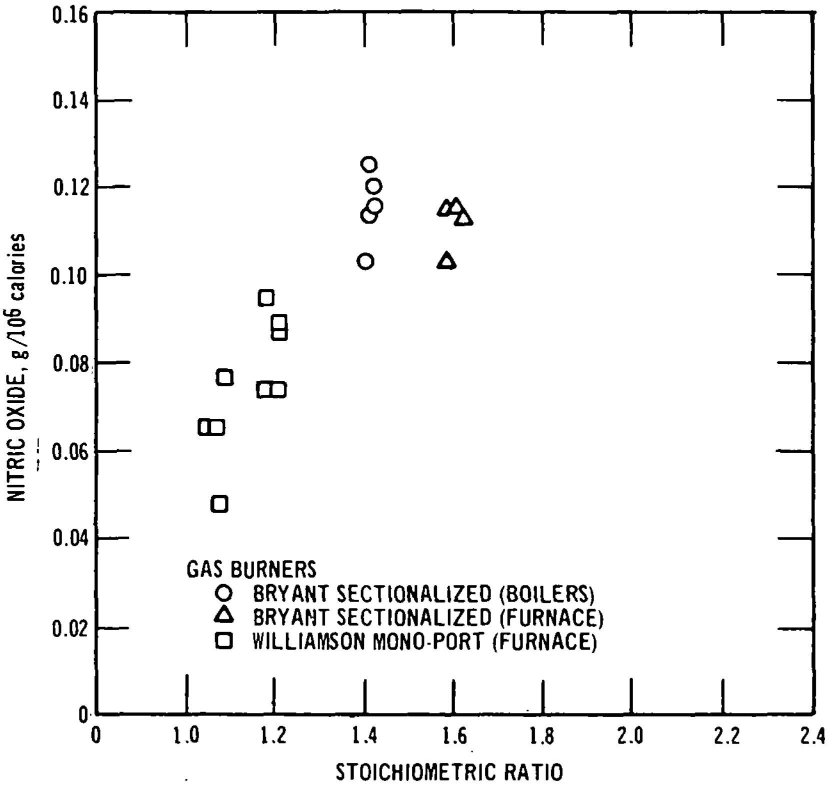

Figure 47. Nitric oxide emissions for gas-fired units.

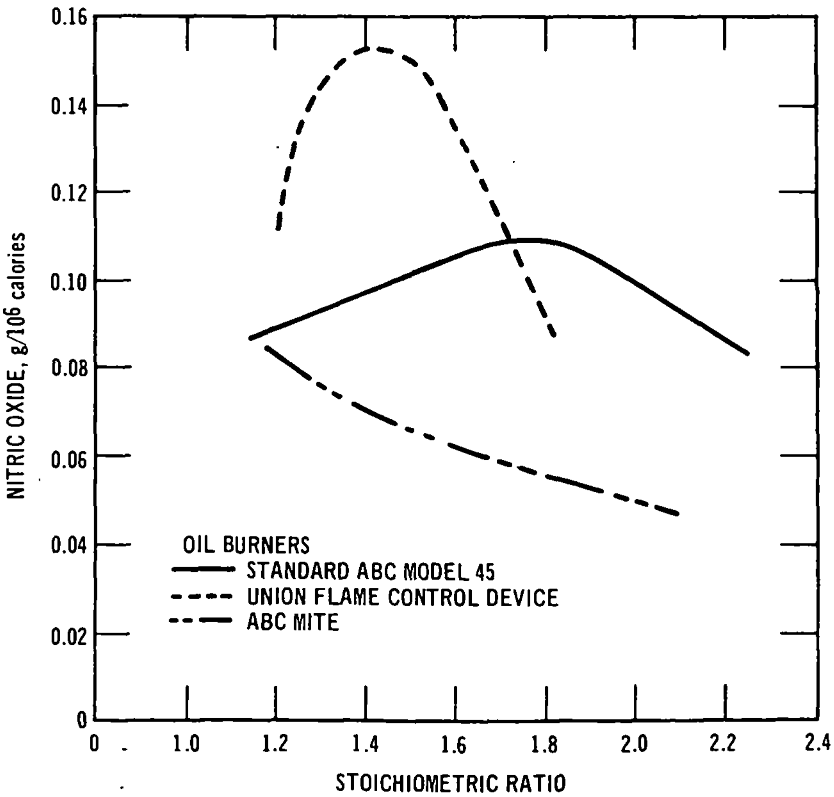

Figure 48. Nitric oxide emissions for oil-fired units.

NO_x emissions from the natural gas burners were about the same as those from most high-pressure atomizing-gun oil burners. The exceptions to this were the Williamson Mono-Port gas burner and the ABC Mite oil burner whose NO_x emissions were lower than emissions of the others tested.

Hydrocarbon emissions from the natural gas burners were generally slightly lower than those from oil burners. CO emissions were about the same with gas firing as with oil firing. Of course, smoke emissions from properly adjusted gas burners are negligible.

OTHER DISTILLATE OIL BURNERS

The domestic heater studies also included testing of experimental burners and commercially available burners other than the high-pressure atomizing-gun type. Two vaporizing burners were tested. One such burner was a vertical wall flame burner which vaporized fuel prior to combustion; the other was a blue flame burner which used a combination of low pressure atomization and vaporization. All other burners tested atomized the fuel and most of those were the low-pressure type. Several high-pressure atomization blue flame burners were tested; all but one utilized internal recirculation where the combustion products were recycled within the combustion chamber. (The exception incorporated external recirculation where the combustion products were taken from the combustion chamber and returned externally to the air inlet section.) Each of these burners is discussed in Appendix D; results of their tests are given in Appendix C.

Of the other oil burners tested, the Rocketdyne Una Spray burner shows some promise of commercial development. It has a unique method for atomizing the fuel. A thin film of oil flows over a small hollow glass sphere in which there is a very short narrow slit. Air, forced into the sphere at low pressure, atomizes the oil film as it emerges through the slit. The burner, more compact than other burners with the same rating, was designed for easy servicing. The efficiency of the prototype unit which was tested was high and smoke emissions were acceptable, but NO_x emissions were extremely high.

The blue flame burner also shows promise. It offers high efficiency, low smoke, and low NO_x emissions; however, thus far none have performed well during ignition. There are two main causes for poor combustion during ignition with blue flame burners: (1) most of these burners rely upon recirculation which is not established immediately; and (2) blue flame burners usually rely upon a hot surface surrounding the flame envelope, also not established immediately. Because most blue flame burners have either internal or external recirculation: smoke, NO_x, and noise level are reduced and the burner can be operated at low air/fuel ratios.

IGNITION SYSTEMS

Tests were made to determine the effect of ignition systems on pollutant emissions from domestic burners. Most ignition systems supply a high-energy arc to ignite the oil spray as it leaves the nozzle; ignition is usually on continuously during the burning cycle. Even though modern burners do not require a continuous ignition arc to stabilize the flame, most burners operate with the ignition on during the on-period. The main reason is that controls for turning the arc off after the flame is established add a few dollars to the cost of the burner.

It was found that NO was the only pollutant affected. Smoke, CO, HC, O_2, and CO_2 were not changed.

Three different ignition systems were tested as shown in Table 7. A Franceformer (Cat. LKJ) ignition system was tested with a Williamson (ABC Model 45) burner. First, the burner was run with the ignition on. It was then run at the same air/fuel ratio with the ignition disconnected after the flame was established. With the ignition off, there was a reduction in NO of 7 ppm (approximately 10 percent). This system was also tested with a Union (Pure) flame retention device: the average reduction during the first four runs without ignition was 7.8 ppm (about 7 percent); during the fifth experiment, the oil was turned off, thus no combustion. Therefore, any NO produced had to come from the electrical discharge of the ignition system. In these tests there was an average NO emission of 9.0 ppm.

The second ignition system tested was a Franceformer (Cat. 4LACYU-4) on a Beckett Bantam burner. The burner was first run with the ignition on.

Then, at the same air/fuel ratio, with the ignition turned off, NO was reduced by 9.0 ppm (about 10 percent).

The third unit tested was a Prestolite 0-120 ignition system, on an ABC Mite. This system showed no reduction in NO when the ignition was turned off. It is assumed that NO emissions were not affected by this ignition system because it had a lower power output than the others.

These tests indicated that ignition systems have no effect on smoke, CO, HC, O_2, or CO_2 emissions. Only NO emissions were affected, and even then the increase was relatively small.

NOZZLE EFFECTS

Because of problems encountered with nozzles during tests with combustion improving devices and since approximately 95 percent of the domestic oil burners in the U. S. are high-pressure atomizing-gun burners which use nozzles to atomize fuel oil, it was necessary to determine the effect of nozzles on air pollutant emissions. Four different brands of 80-degree, hollow-cone nozzles (Delavan, Monarch, Hago, and Steinen) rated at 0.75 gph were tested. Although all nozzles were new, each was examined microscopically before testing: all flaws were photographed. The tests were designed to determine if there was any difference in emission levels within a given type and brand of nozzle, and between different brands of nozzle to obtain minimum emission levels.

To obtain a random sample, two nozzles of each brand were bought from five different stores. The tests were made with a Williamson (ABC Model 45) burner at an air/fuel ratio of approximately 1.60. By operating at a constant air/fuel ratio the emissions of each nozzle can be directly compared. A statistical analysis of the data was performed upon completion of the tests. The results are given in Table 8.

The average fuel rate for all nozzles was 0.82 pounds/10 minutes (0.70 gph). The analysis showed that measurements of smoke, gaseous HC, NO, CO, CO_2, and efficiency were significantly different when comparing nozzles within a brand and when comparing different brands of nozzles. All tests were made at a confidence level of 95 percent. Since emissions vary significantly between nozzles, burners should always be readjusted when the nozzle is replaced.

The pre-test photomicrographs of all nozzle flaws qualitatively suggest a basis for the results that were obtained from the data. As shown in Table 8, emissions of 10th minute smoke, average smoke, and HC were lowest from Delavan; Monarch was second, followed by Hago. Steinen had the highest emission levels.

In the following discussion reference to smoothness and cleanliness is in relation to the nozzle distributor (or metering disk) and the nozzle tip around the orifice. These observations were made with a microscope, thus a surface which appears smooth without the aid of magnification may appear very rough under the microscope. The photomicrographs showed that Delavan nozzles were smoothest and were relatively clean. Monarch nozzles were rough but, although oily, were clean. Hago nozzles, more smooth than Monarch and less smooth than Delavan, were very dirty: there were many small particles, chips, and oil droplets on the nozzle surfaces. Steinen nozzles were rough and their surfaces were covered with many small particles, chips, and oil droplets. Because of the design of these tests it is not possible to recommend one brand of nozzle over another. Even though some nozzles had better performance than others, those with poorer performance may have been improved if the excess air had been adjusted. The following conclusions can be drawn, however:

1. There is a significant difference between nozzles of the same brand.
2. There is a significant difference between nozzles of different brands.
3. The furnace or boiler burner should always be readjusted when changing nozzles.

It would be beneficial if nozzle manufacturers would conform to standards strict enough to guarantee to the consumer that a nozzle with a given rating (flow rate, spray angle, and spray pattern) will not vary among brands or within the same brand over a period of time. A too-strict standard, however, would result in an unnecessary increase in nozzle price to the consumer.

EFFECT OF TIME ON TUNING

Tests were also made to determine the effect of time on burner performance; i.e., after a burner is adjusted, how rapidly its performance deteriorates. The same furnace was used for these tests as was used with the combustion improving and flame retention devices described previously. With each new nozzle tested, the burner was adjusted for a No. 1 tenth minute smoke spot. The burner was then cycled randomly to simulate the cycle of a furnace in a home. The test was duplicated to establish variability and reliability.

The results of the tests are presented in Figures 49 and 50. As shown in Figure 46 neither CO nor gaseous HC changed during the 10-week test period, and the change in NO was very small. However, the most dramatic change was with smoke, which changed from just below a No. 1 Bacharach number to near a Bacharach No. 6 in the 10-week period. As shown in Figure 50 the heating efficiency dropped from 78 percent to 68 percent during the same period.

This shows that air pollutant emissions, at least of smoke and particulate, can be significantly reduced and heating efficiency can be increased by adjusting the burner periodically. To determine whether the results of these tests were typical of results which would be obtained in actual practice, Battelle made follow-up measurements at 2-month intervals twice during the heating season as part of a field test program (Contract No. 68-02-0251).[14]

Of the four residential units on which follow-up measurements were made, the emissions of two remained essentially unchanged. On one unit CO_2 dropped by 8 percent and emissions of CO and HC increased, but not to significant levels. Smoke, particulate, CO, and HC increased on the fourth unit but the change was due to nozzle clogging which resulted from dirty fuel.

As a result of Battelle's field tests it is felt that the in-house results are not typical of most burners, but after tuning, the performance of some burners does deteriorate at a faster rate than the performance of most burners. To determine the seriousness of this problem further field tests are needed.

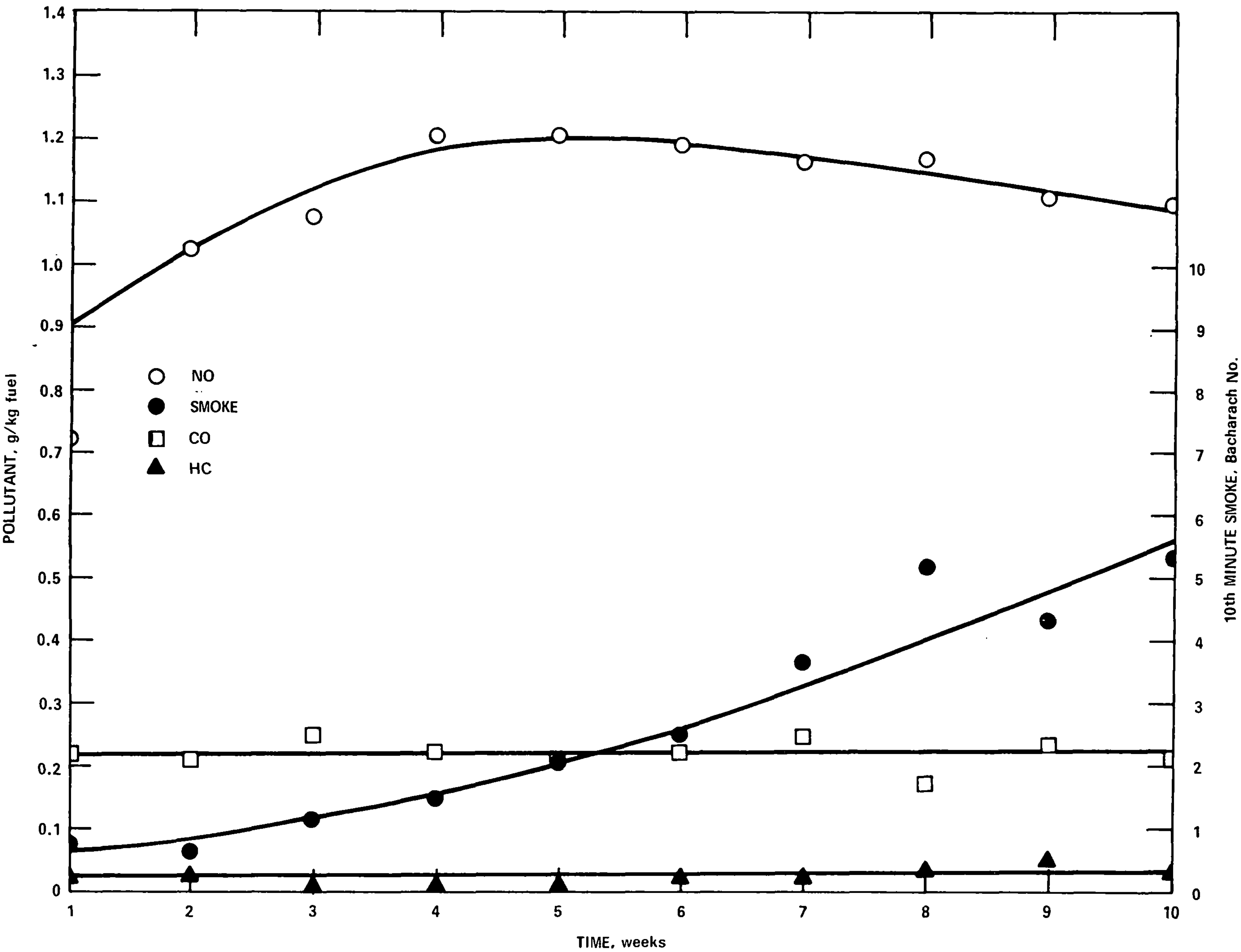

Figure 49. Change in pollutant emissions with time -- light-oil residential heater.

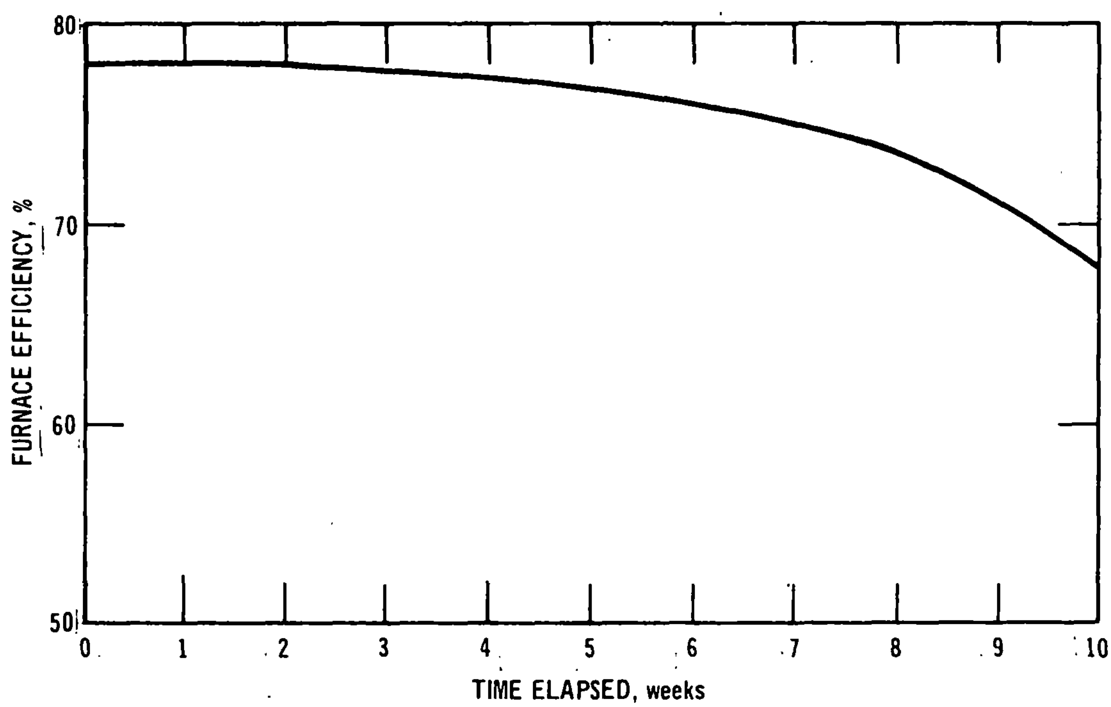

Figure 50. Deterioration of furnace efficiency with time.

BURNER MAINTENANCE

The importance of burner maintenance was shown in the field test study performed by Battelle.[14] It was found that tuning effectively reduces emissions of smoke and CO, but has little effect on the mean values of other pollutants. The most significant finding was that a major reduction in CO, gaseous HC, and particulate can be achieved by identifying and replacing or repairing units in bad condition. To exemplify this, some typical emission levels for the various types of residential equipment tested are shown in Table 11. The top line gives the average emissions for all units tested whereas the data from units in need of replacement have been excluded from the second line. By eliminating the three bad units the CO emissions were reduced from greater than 3.07 to 1.08 g/kg and the gaseous HC emissions were reduced from 0.79 to 0.10 g/kg, whereas NO_x remained essentially unchanged. Filterable particulate was reduced from 0.40 to 0.33 g/kg and total particulate was reduced from 1.24 to 0.83 g/kg. In other words, simply by eliminating equipment in need of replacement in the Battelle study, the following reductions could be achieved: CO by at least 65 percent (the exact percentage is not known since the instrumentation went off scale), gaseous HC by 87 percent, filterable particulate by 17 percent, and total particulate by 33 percent. Even these numbers are conservative since Battelle only included burners which were under a service contract. Therefore, instead of accounting for about 10 percent of the total burner population, burners in need of replacement probably account for 20 to 30 percent of the total population. This strongly indicates that emissions from residential sources could be reduced to an insignificant level simply by using proper maintenance procedures which would identify units in need of replacement and by providing proper tuning for the remainder.

Table 11. COMPARISON OF AVERAGE EMISSIONS FROM RESIDENTIAL OIL BURNERS[14]

				Emission factors, g/kg				
				Gaseous emissions			Particulate emissions (modified EPA procedure)	
Units	Condition	Number of units in sample	Bacharach smoke number at 5th minute point	CO	HC	NO_x	Filterable	Total
All units	As found	32	(a)	>3.07(b)	0.79	2.70	0.40	1.24
All units except those in need of replacement	As found	29	3.2	1.08	0.10	2.72	0.33	0.83
Percentage reduction when 3 bad units were eliminated				>65	87	-	17	33

(a) Oily smoke spots from the 3 units in need of replacement prevented obtaining a meaningful average.

(b) The analytical instrumentation went off scale at 3.07 g/kg.

PROCEDURES FOR REDUCING POLLUTANT EMISSIONS FROM CURRENT DISTILLATE-OIL-BURNING HEATERS

As part of one study[2], emission levels were calculated using fuel usage data for a typical Northeastern city. During the peak winter months domestic and commercial distillate-oil-fired units produced approximately 13 percent of the particulates emitted in that city. If all burners were operated at an air/fuel ratio resulting in a Bacharach smoke level of no greater than 1, the particulate produced from domestic and commercial heaters would be less than 1 percent of the total. Obviously, to account for 13 percent of the total particulates many burners being used must be worn out, poorly built, or maladjusted. Proper maintenance and quality control can reduce this type of pollutant emission. It is recommended that all burners, boilers, and furnaces be serviced by an authorized serviceman at least annually, normally just prior to the heating season.

All domestic burners can be operated at lower total emission levels with some sacrifice of efficiency, by operating the burner at a slightly higher than normal air/fuel ratio. As shown in Figure A-2 (Appendix A), the standard Williamson (ABC Model 45) burner would normally be operated at an air/fuel ratio of 1.53. If it were operated at a higher setting, 1.60 for example, emission levels of average smoke, CO, and HC would be lowered or remain constant. This higher setting will also allow for a small amount of drift after the burner is adjusted. If this burner were set at an air/fuel ratio of 1.53 and later drifted to a setting of 1.50, the smoke emissions would increase significantly, as shown in Figures A-2 and A-6.

As indicated in a related report[14] by Battelle, which was jointly sponsored by the Environmental Protection Agency and the American Petroleum Institute under Contract No. 68-02-0251, a serviceman should not increase the excess air level to unnecessarily high levels to reduce the smoke emissions. Besides reducing efficiency unnecessarily the CO and gaseous HC emissions can rise sharply at high air settings as shown in Figures A-3 and A-4. Since CO generally increases before gaseous HC as excess air is increased, a serviceman could be relatively certain that the gaseous HC emissions are low if the CO emissions are low. In order to measure CO emissions on a routine basis, an accurate, portable CO monitor must be developed.

Instrumentation for burner servicemen can be improved. If present instruments for measuring CO_2, stack temperature, draft, and smoke could be combined, the serviceman would be more likely to use the equipment. Better training is needed for the serviceman; not only in how to use the equipment properly, but in how to interpret the results. Better training will enable him to adjust heaters for maximum efficiency with minimum levels of air pollutant emissions.

In essence, the responsibility of reducing emissions from existing burners lies with the individual (homeowner and serviceman). He should utilize the methods described above and keep informed about future developments.

CONCLUSIONS AND RECOMMENDATIONS

Tests showed that low air/fuel ratios provide maximum efficiency, and that higher settings minimize emissions. Therefore, a compromise is necessary to obtain a setting which will provide an acceptable level for emissions without lowering the efficiency appreciably. The technique for finding this setting is discussed in Appendix A. The excess air should be set as low as possible without producing a smoke spot number greater than 1 under hot running conditions; i.e., after 10 minutes of operation. A refractory-lined combustion chamber, as opposed to a steel-lined chamber, will allow burner operation at a lower excess air level.

Combustion chamber configuaration effects and combustion improving devices (other than flame retention) were found to have little, if any, effect on pollutant emissions. The study also indicated that some ignition systems are capable of producing small amounts of NO_x; whereas others, with lower power, have no effect. It was also shown that nozzles can be responsible for unnecessary pollutant emissions. This can usually be corrected by adjusting the burner.

It was found that residence time and flame retention devices have the greatest effect on air pollutant emissions. A longer residence was shown to reduce emissions of smoke, particulate matter, CO, and HC. However, NO_x emissions may be increased slightly. One drawback to using a longer residence time for lowering pollutant emissions is that equipment manufacturers will have to make larger, bulkier furnaces or use lower fuel rates in present designs. Also, it may be that longer residence time would have a much smaller effect when more efficient burners with better performance are used.

Studies showed that most flame retention burners have better performance characteristics (higher efficiency with lower smoke and/or NO_x emissions) than those of a conventional high-pressure atomizing-gun burner. The ABC Mite was the only flame retention burner tested that reduced both smoke and NO_x emissions.

These studies indicate that several areas of further research are necessary. More work with the effects of residence time is needed to find the best residence time for low emissions with high efficiency. Also, more studies are needed for optimizing the burner design to improve fuel/air mixing. A contract has been awarded to the Rocketdyne Division of Rockwell International to design and develop an optimum distillate oil burner; i.e., a burner with high efficiency and low pollutant emissions. The results of this work will be available for oil burner manufacturers and servicemen early in 1974.

Field tests are needed for burners which were most promising in order to demonstrate long term effectiveness. As a result of an in-house study which indicated that burner performance can deteriorate significantly over a period of 10 weeks after tuning, Battelle performed a limited number of follow-up measurements during their field study[14]. Measurements were made at 2-month intervals twice during the heating season on four units. The tests indicated that some units are more prone to performance deterioration than others, but further tests are needed before precise conclusions can be made.

Research is also needed to find a method of controlling cyclic-based emissions. This could reduce pollutants such as smoke, particulates, HC, and CO. Reducing or eliminating the ignition and/or shutoff peaks could reduce pollutant emissions by 50 percent or more. The Rocketdyne work may result in a significant reduction in cyclic emissions. Cyclic emissions could also be reduced by utilizing modulation, or by using an undersized oil nozzle in a furnace or boiler, since the burner would have a longer on-time to meet a given heat load.

Tests in which natural gas was used as the fuel indicated that the level of air pollutant emissions from residential gas burners is about the same as that from equivalent-size oil burners. The exceptions to this were the Williamson Mono-Port gas burner and the ABC Mite oil burner whose NO_x emissions were lower than emissions of others tested.

It is also important to note that pollutant emissions from existing domestic heaters could be reduced significantly by proper maintenance, and by replacing poorly performing units as emphasized in the Battelle study[14].

This includes servicing by an authorized serviceman at least once each heating season, preferably at the beginning. The nozzle in an oil burner should be replaced each season and the burner should be readjusted by using proper equipment for measuring smoke and CO_2. The furnace air filters should be changed several times during the heating season to avoid appreciable reduction in furnace efficiency. Also, better instrumentation is needed for burner and furnace servicemen. As a followup, a program should be initiated for training servicemen to use the equipment properly. Organizations such as the American Boiler Manufacturers Association (ABMA), the American Petroleum Institute (API), the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), the Hydronics Institute, the National Oil Fuel Institute (NOFI), and the National Oil Jobbers Council (NOJC) could play important roles in such a program.

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APPENDIX A

BURNER ADJUSTMENT AND COMPARISON

To determine the operating and emission characteristics of the burners, emission measurements were made over a wide range of air settings. Typical results for tests of this type are shown in Figure A-1. Burner X appears to have lower emissions than burner Y. When comparing the two at one air/fuel ratio, that is true; however, when comparing them under actual operating conditions (i.e., at an air/fuel ratio where each operates efficiently with low smoke emissions) the burners may operate at different air/fuel ratios. In the case mentioned above, burner X may normally operate at an air/fuel ratio of 1.2 and burner Y at 1.6. The dotted lines show that burner Y actually produces lower emissions than burner X, on an actual operating basis.

For this reason a method was chosen which permitted the air/fuel ratio to be found at which each burner would operate normally. This setting was determined by using a technique employed by oil burner servicemen in adjusting furnaces. Since heating efficiency increases as the air/fuel ratio decreases, the air settings are usually set as low as possible without producing excessive smoke (>No. 1 smoke spot) at hot running conditions. Therefore, for purposes of comparison, the stoichiometric ratio was found for each burner at which a Bacharach No. 1 smoke spot was recorded at "steady state" conditions (after 10 minutes of operation). This procedure is illustrated in Figure A-2 for the Williamson (ABC Model 45) burner.

The various burners can be conveniently compared by reading the values of CO, HC, NO, average smoke spots, and efficiency at the

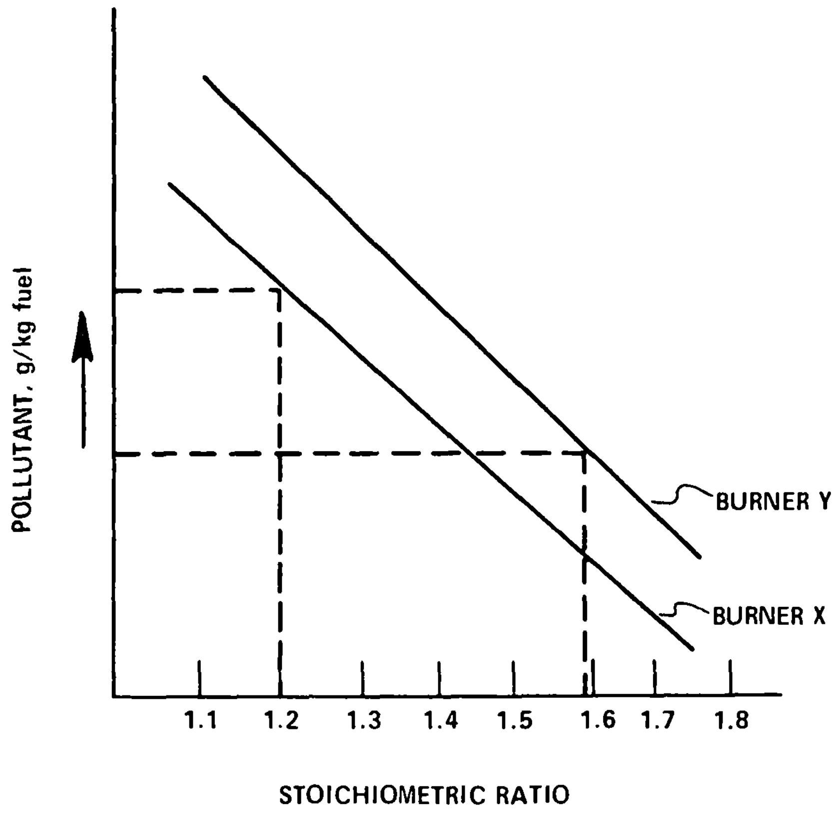

Figure A-1. Burner operating and emission characteristics.

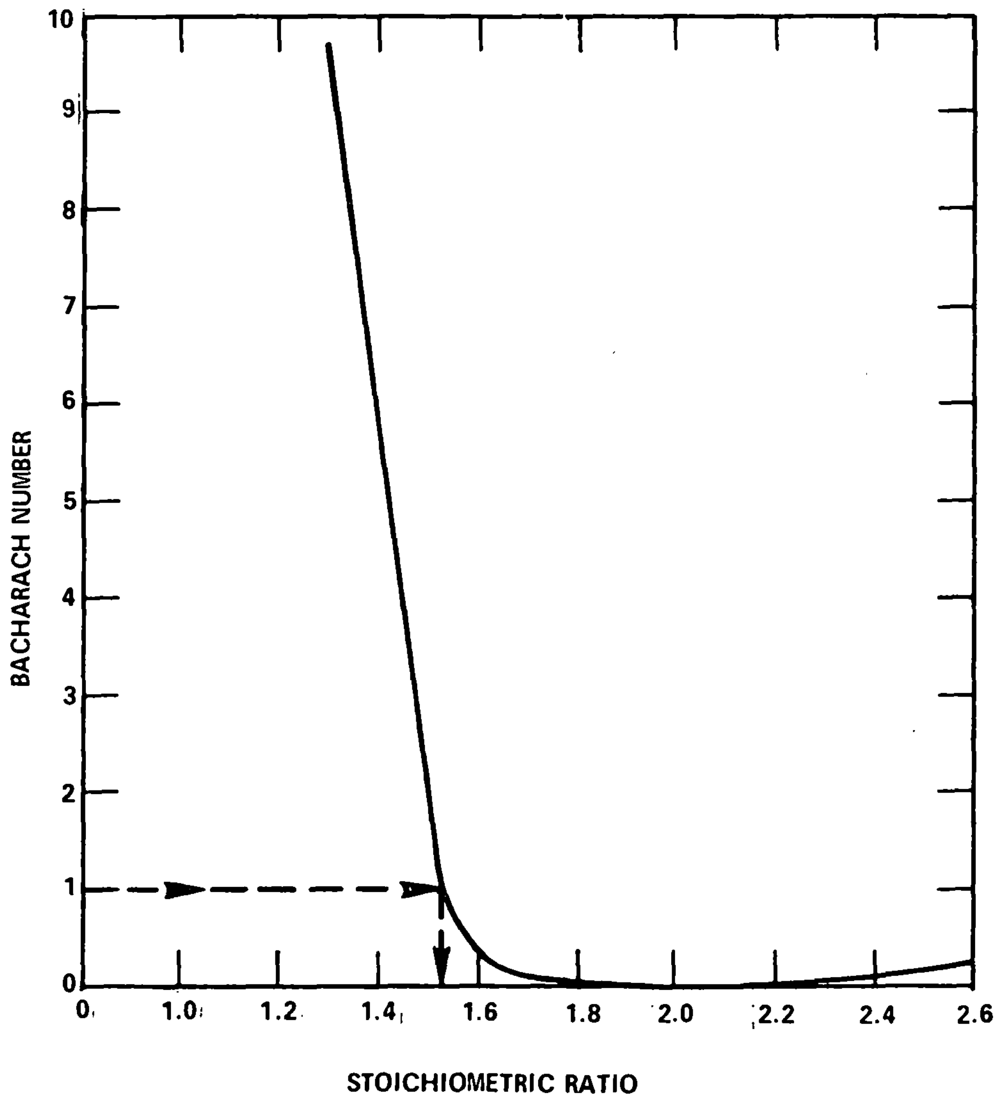

Figure A-2. Determination of stoichiometric ratio for No. 1 10th-minute smoke.

stoichiometric ratio at which a No. 1, 10th minute smoke spot was produced. Figures A-3 through A-7 show this procedure for the Williamson (ABC Model 45) burner.

Results of the emissions tests for all burners are in Appendix C. All burners tested or investigated are classified as high-pressure or low-pressure atomizing, air atomizing, blue flame, internal recirculating, or external recirculating. Those which utilized a combustion improving or flame retention device are indicated.

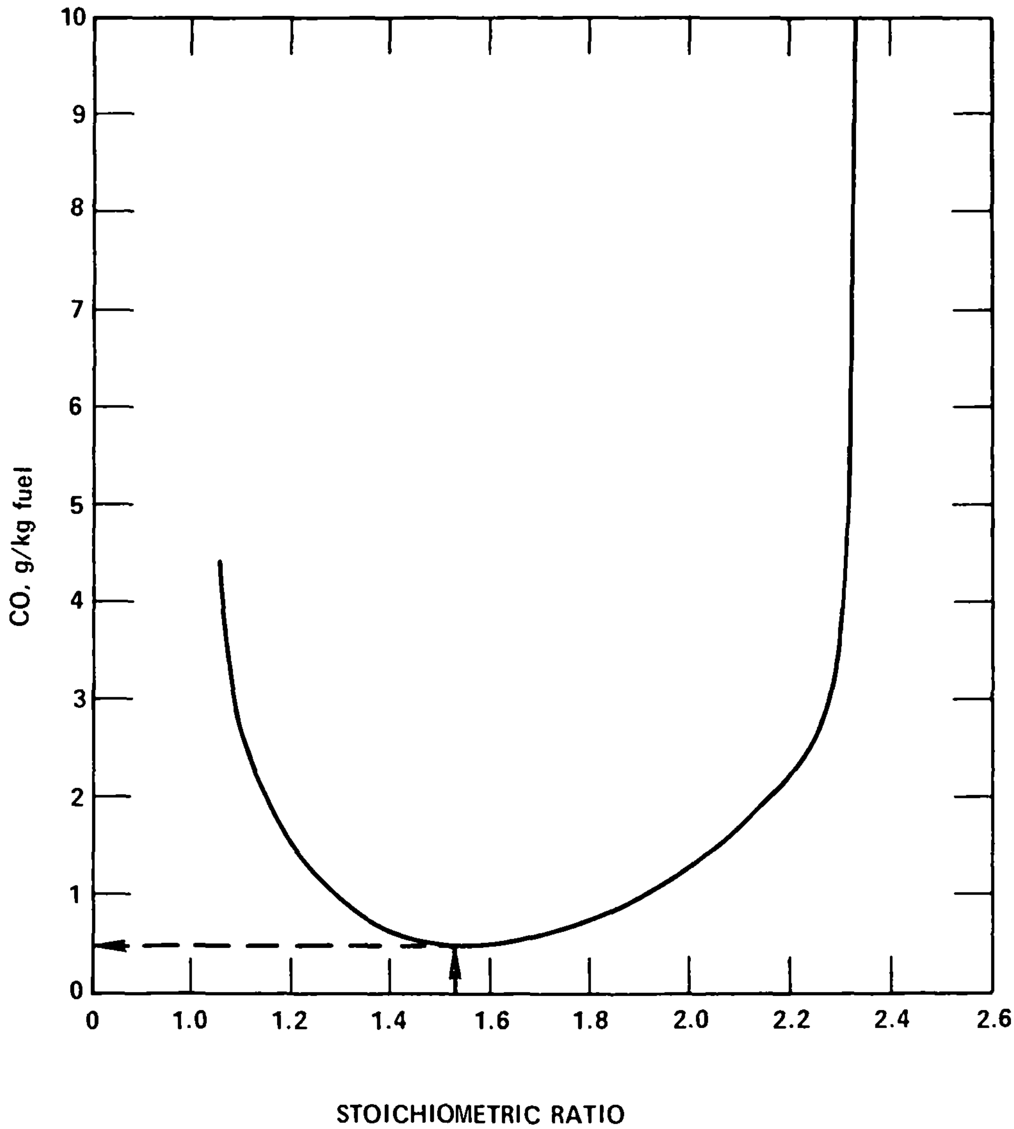

Figure A-3. Determination of carbon monoxide for normal operating conditions.

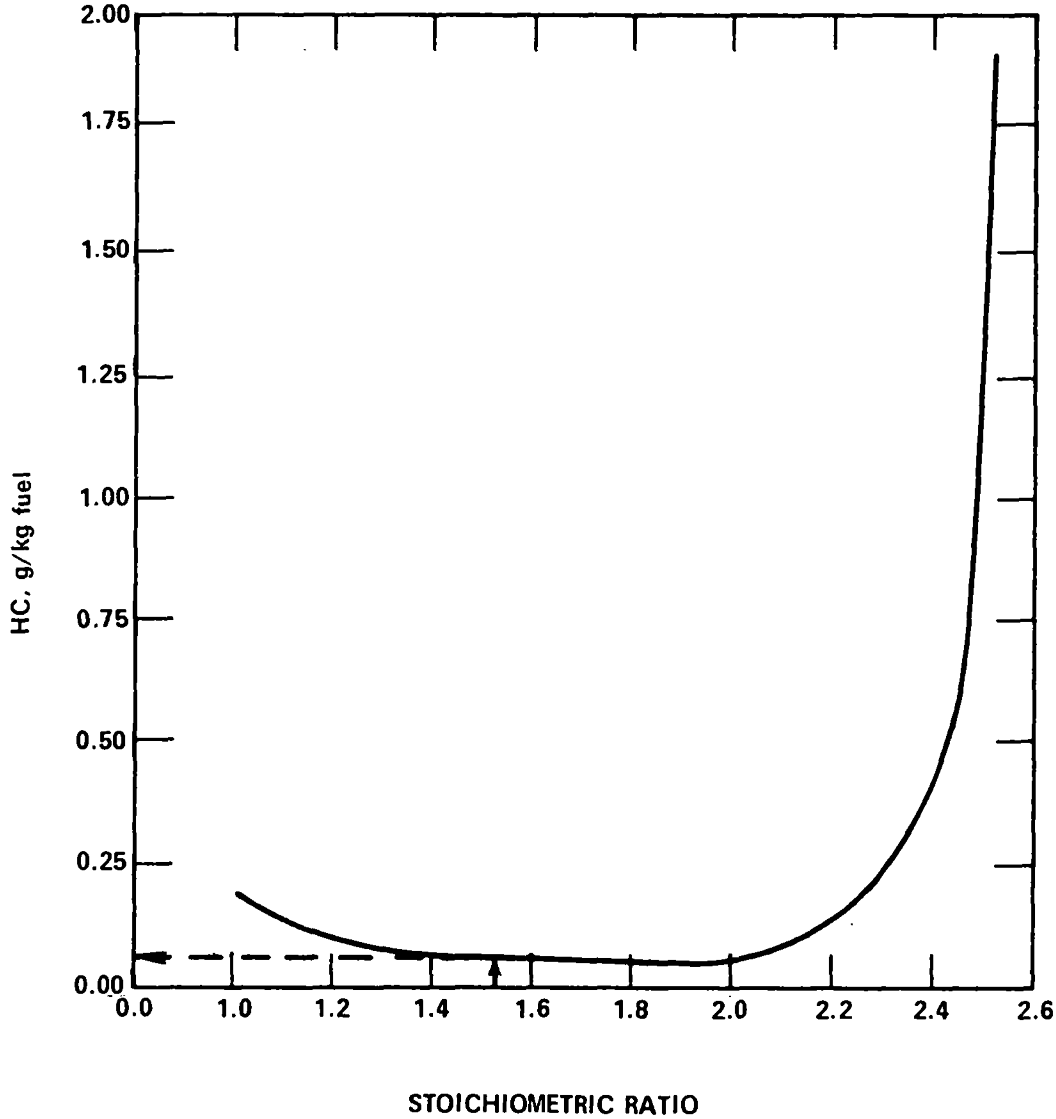

Figure A-4. Determination of hydrocarbons for normal operating conditions.

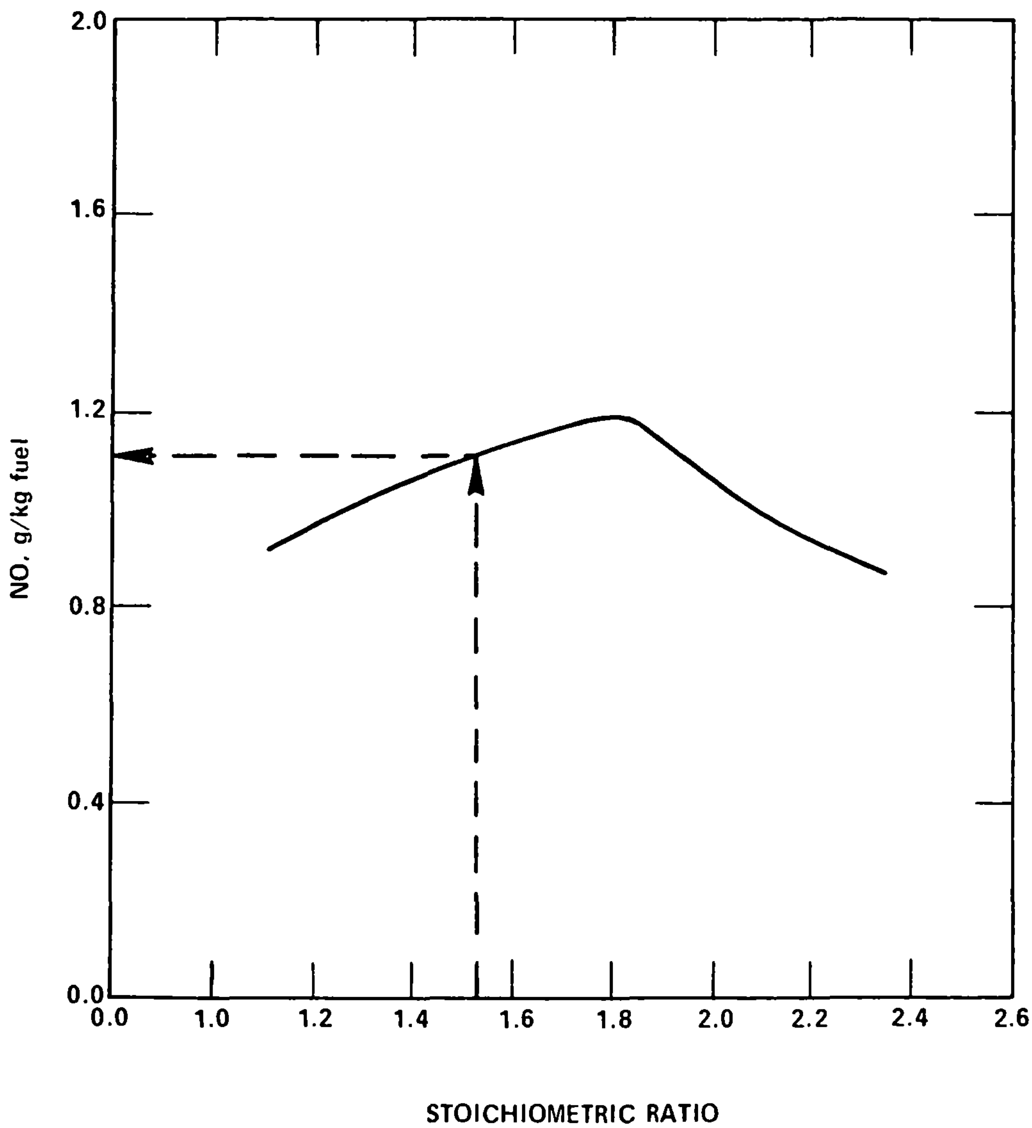

Figure A-5. Determination of nitric oxide for normal operating conditions.

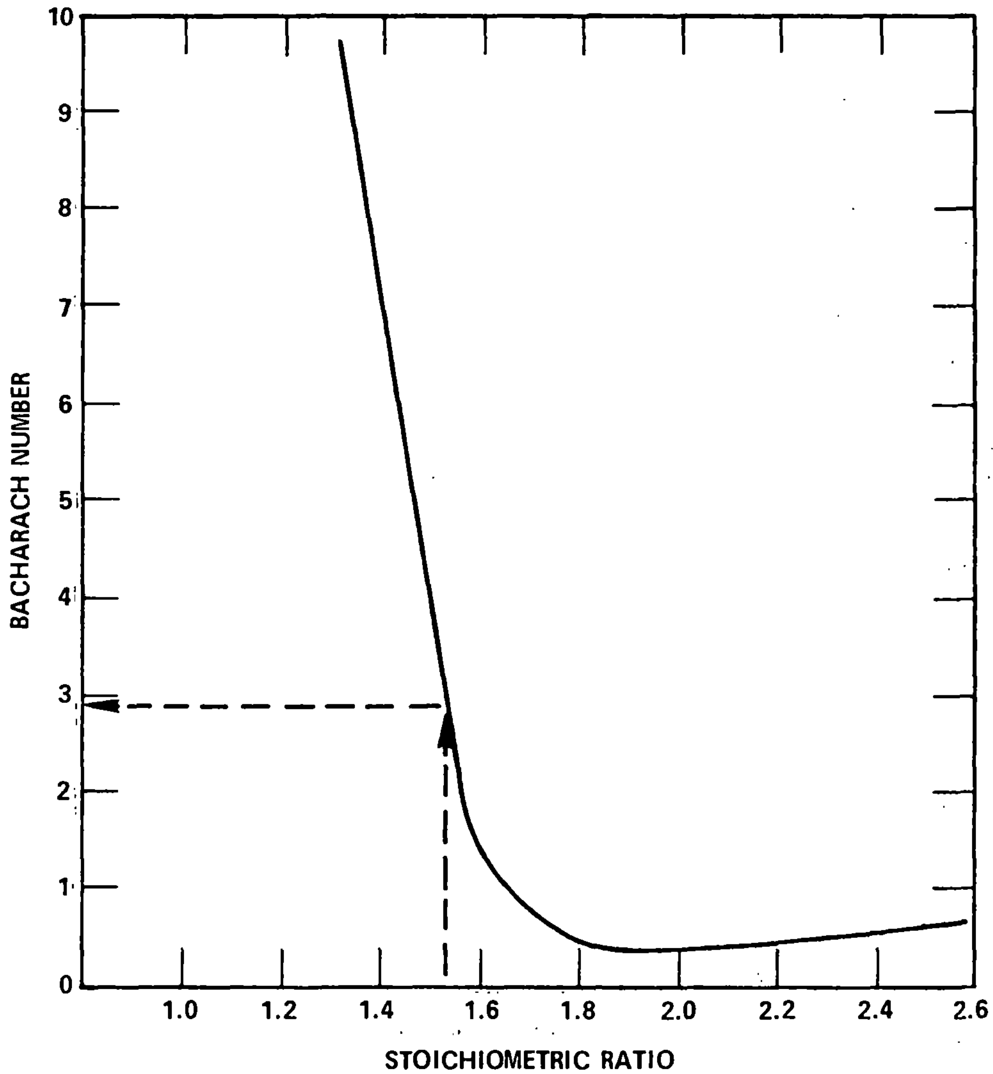

Figure A-6. Determination of average smoke for normal operating conditions.

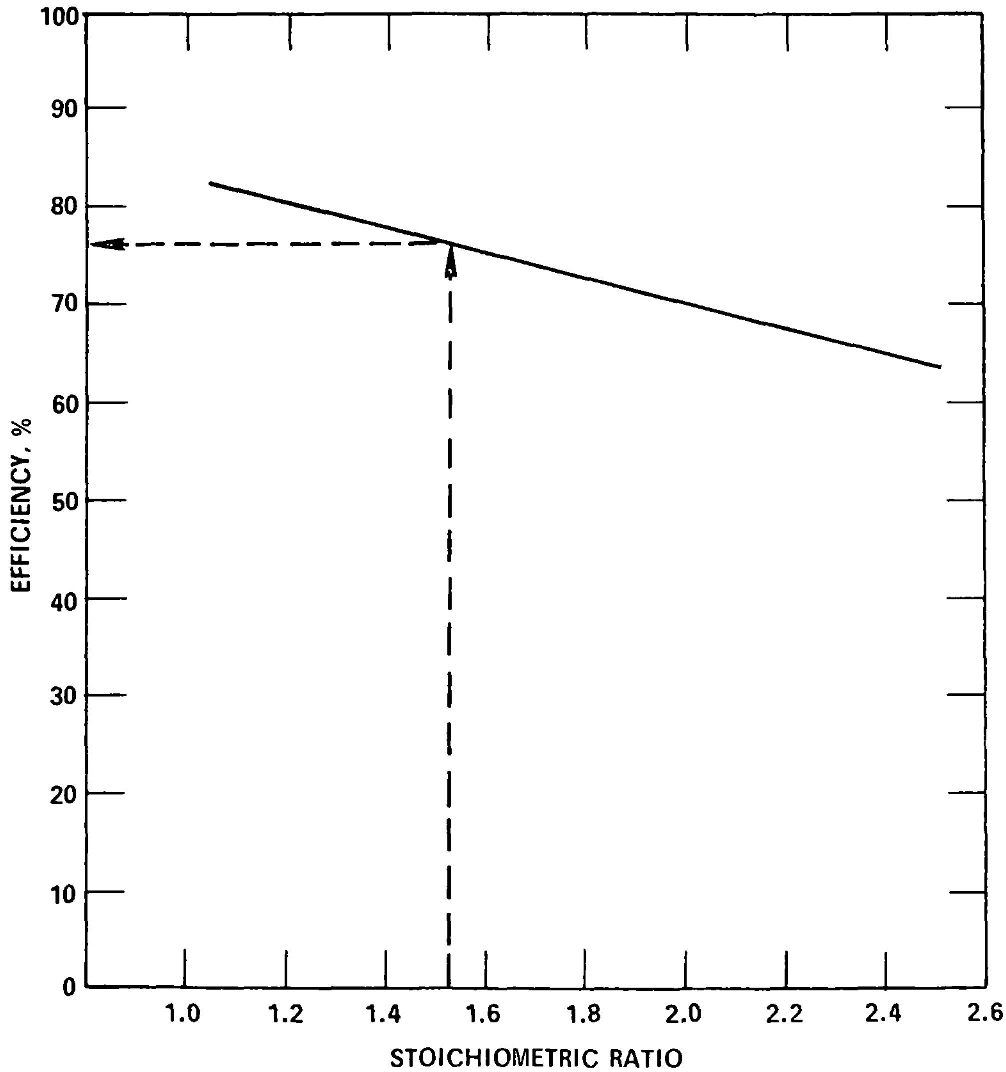

Figure A-7. Determination of efficiency for normal operating conditions.

FUEL ANALYSIS

Fuel:	Gulf Coast oil, refined at the Toledo Refinery
Description:	No. 2 distillate heating oil
Use:	Burner, boiler, and furnace studies
Location:	Combustion Research Section[a] Fairfax Laboratories 3914 Virginia Avenue Cincinnati, Ohio 45227

Viscosity, kinematic (D-445):	2.42 centistokes, 100°F
Gravity ° API:	36.4
Aniline point (D-611):	142.5°F
Total sulfur:	0.098 wt %
Ash % (D-482):	0.003 on 10% residuum
C/H ratio:	6.62
Heat of combustion (D-240):	18,443 Btu/lb

Distillation:

Initial, °F:	360
10%:	424
50%:	465
90%:	519
End point:	591

[a]Now: Combustion Research Section
Control Systems Laboratory
Environmental Protection Agency
Research Triangle Park, North Carolina 27711

APPENDIX B (CONTINUED)

Hydrocarbon analysis:

Paraffins, vol %:	38.4
Naphthenes, vol %:	35.3
Aromatics, vol %:	26.3
1-ring aromatics, vol %:	12.1
2-ring aromatics, vol %:	13.9
3-ring aromatics, vol %:	0.3
Olefins: vol %	<1.0

Appendix C

COMPARISON OF ALL OIL BURNERS TESTED

(These comparisons were made by determining the stoichiometric ratio for each burner--burning No. 2 oil--at a No. 1, 10th minute smoke spot on the Bacharach scale. See Appendix A, Burner Adjustment and Comparison, for more detail.)

The data included in this report is only representative of the burner models tested. Thus, the data is not necessarily representative of a manufacturer's entire model production.

Appendix C. COMPARISON OF ALL OIL BURNERS TESTED

Burner	Date(s) tested	Characteristics	Results							
			Efficiency %	10th min smoke	Avg smoke	NO, g/kg fuel	HC, g/kg fuel	CO, g/kg fuel	Stoich ratio	Air setting % CO_2
1. Standard burner										
Williamson (conventional ABC Model 45)	5-3-68 6-24-68 6-25-68	Conventional, high-press., atom.-gun	76.6	1.00	2.9	1.11	0.06	0.50	1.53	9.9
2. Combustion improving devices										
Delavan FlameCone[a]	12-16-68 12-17-68	High-press., atom.	70.5	1.00	1.3	1.30	0.03	0.6	1.80	8.2
Gulf Econo-Jet[a]	1-16-69 1-24-69 1-29-69	High-press., atom.	75.0	1.00	3.0	1.69	0.06	0.6	1.40	10.8
Monarch combustion head[a]	11-26-68 12-2-68	High-press., atom.	71.5	1.00	2.0	1.25	0.06	0.6	1.66	9.1
Shell combustion head[a]	2-13-69 2-14-69 2-17-69	High-press., atom.	76.0	1.00	2.0	1.68	0.06	0.3	1.60	9.4
Union (Pure) flame control device[a,b]	7/19-22/68	High-press., atom.	83.0	1.00	1.2	1.25	0.06	0.5	1.20	12.6
3. Flame retention devices										
ABC Mite (Model S)	3/10-11/69	High-press., atom.	79.5	1.00	2.0	0.77	0.06	0.5	1.38	10.9
Beckett Bantam (Model AF)	4-28-70 4-29-70 5/1-4/70	High-press., atom.	81.1	1.00	2.5	1.40	0.06	0.5	1.31	11.6

[a]Combustion-improving device installed on Williamson standard burner.

[b]Utilized flame retention

Appendix C. COMPARISON OF ALL OIL BURNERS TESTED (CONTINUED)

Burner	Date(s) tested	Characteristics	Results							
			Efficiency %	10th min smoke	Avg smoke	NO, g/kg fuel	HC, g/kg fuel	CO, g/kg fuel	Stoich ratio	Air setting % CO_2
3. Continued <u>Flame retention devices</u>										
Esso (Model 40)	11-16-70 12-3-70	High-press., atom.	80.2	1.00	2.6	1.76	0.02	0.28	1.44	10.7
Sun-Ray (Model DC-1)	3-5-69	High-press., atom.	73.0	1.00	1.1	1.16	0.06	0.6	1.63	9.3
Union burner (Model AFC)	2/17-19/71 2/23-24/71 3-9-71 3/18-19/71	High-press., atom.	80.0	1.00	3.5	1.00	0.08	0.25	1.16	13.5
U.S. Carlin (Model 150N-2R)	3-18-69 3-19-69	High-press., atom.	70.3	1.00[c]	2.2	1.48	0.08	1.0	1.86[c]	7.9
Wayne (Model ER)	6-9-69 6-10-69	High-press., atom.	75.0	1.00	1.7	1.14	0.04	0.5	1.42	10.7
Wayne (Model M-SR)	10-18-73	High-press., atom.	82.5	1.00	1.4	1.17	0.01	0.21	1.18	12.2
White-Rogers (Model FR-B)	5-26-69 5-27-69	High-press., atom.	78.0	1.00	2.1	1.45	0.02	0.4	1.48	10.2
4. <u>Miscellaneous devices</u>										
Cyril Meenan Combusto-Jet[b]	4-13-70 4-14-70	High-press., atom.	---	---	---	0.89	0.17	3.89	1.47	10.3
Stewart-Warner burner/boiler	1-29-70	High-press., atom.	No data	1.00	1.80	1.30	0.13	0.31	1.53	9.9

[b]Data incomplete: not comparable to other burners since 10th minute smoke is unknown.

[c]Extrapolated data.

Appendix C. COMPARISON OF ALL OIL BURNERS TESTED (CONTINUED)

Burner	Date(s) tested	Characteristics	Results							
			Efficiency %	10th min smoke	Avg smoke	NO, g/kg fuel	HC, g/kg fuel	CO, g/kg fuel	Stoich ratio	Air setting % CO_2
4. Continued Miscellaneous devices										
Stewart-Warner burner	6-18-70 7-11-70	Low-press., air-atom.	73.5	1.00	1.45	1.24	0.11	2.80	1.86	8.0
Master air-atomizing space heater[d]	10-8-69	Low-press., air-atom.	No data	<0.05	<0.10	1.3→ 1.1	0.1	0.6→ 0.5	1.45→ 1.8	10.4→ 8.2
Rockeydyne Una Spray[e]	6-9-70	Low-press., liquid-film, air-atom.	91.0	1.00	2.50	1.74	0.20	0.50	1.20	12.6
Torrid Heat Wall Flame burner/furnace	8-28-69	Rotary, verticle wall, flame	90.5	1.00	out of range of data	0.15[c]	0.0[c]	7.50[c]	1.11	13.7
Auburn blue flame	10-6-70 10-7-70	Blue flame, internal recirc	81.8	1.00	1.85	0.46	0.16	2.5	1.20	12.6
Bailey-OOHA blue flame[b]	9-2-70	Blue flame, external recirc	---	---	0.2	0.39	0.22	0.56	1.06	14.4
Bailey-OOHA blue flame[b]	2-6-73	Blue flame, external recirc	---	---	---	0.41	0.04	0.57	1.06	14.4
Blue-Jet blue flame	7-20-73	Blue flame, combination low-press. air atomizing and vaporization	83.8	0.0	---	1.20	0.25	2.01	1.25	11.8
Vapo-Product blue flame[b]	3-10-70	Blue flame, internal recirc	---	---	---	0.49	---	0.45	1.68	8.9

[b] Data incomplete; not comparable to other burners since 10th minute smoke is unknown.

[c] Extrapolated data.

[d] Space heater; not comparable to other burners.

[e] Efficiency not accurate; data from latest test 6/9/70.

APPENDIX D

OTHER DISTILLATE OIL BURNERS

Most of the burners discussed in this appendix were experimental or prototype designs. Therefore, future designs may have different performance characteristics and/or different emission levels.

Appendix D

OTHER DISTILLATE OIL BURNERS

1. Stewart-Warner Low-Pressure Burner

Tests showed that performance of this burner is inferior to that of high-pressure burners. The one advantage of the burner is that it does not require as much maintenance as a high-pressure unit.

2. Torrid Heat Wall Flame Burner and Furnace

Emission characteristics from this furnace were quite different from those of the high-pressure units. It had a very narrow range of excess air settings for good combustion and pollutant emissions were excessive at higher or lower settings.

3. Rocketdyne Una Spray Burner

This prototype burner has a unique air-atomizing system. The tests showed excellent combustion with low levels of emissions except for NO_x. Tests of a later model verified these results.

4. Blue Flame Burners

Of the blue flame burners tested only the Bailey-OOHA and the Blue-Jet performed satisfactorily. The others performed poorly during ignition, i.e. they had high smoke, CO, and HC emissions. The OOHA and Blue-Jet burners had higher CO and HC emissions during ignition than those of a conventional burner but they were much lower than those of the other blue flame burners tested. The main advantage of the blue flame burner is its low level of NO_x emissions. However, the NO_x emissions of the Blue-Jet burner were as high as those of a conventional burner, probably because the others utilized some form of recirculation of the combustion products and the Blue-Jet burner did not.

a. Auburn Blue Flame Burner

This burner is the Shell Ventres design which recirculates the flue gas through the flame. The burner performed erratically and had a very narrow operating range for good combustion. The one good feature of this burner was its low NO_x level of 25 ppm (about half the emission level of a high-pressure burner).

b. Vapo-Products Blue Flame Burner

This rather crude prototype burner, after a very noisy and smoky startup, burned quite well with an almost perfect blue flame. After ignition it produced zero smoke and only 30 ppm NO_x (at 3 percent O_2, dry basis). If the ignition problems can be corrected, the unit may be marketable.

c. Bailey-OOHA Blue Flame Burner

This blue flame burner was built to operate with a hot water generator. Initial tests were made in September 1970 at five excess air settings: three of the ignitions were very smoky. A complete set of data was not obtained because of some difficulties with the air pump. The low NO_x emissions of about 20 ppm were impressive.

In February 1973, tests were made on a new blue flame burner developed by Mr. Frank Bailey, research consultant of Operation Oil Heat Associates (OOHA). This burner design had corrected the problems of the earlier burner: NO_x levels were about 0.4 g/kg with accompanying low levels of CO and HC even at excess air levels as low as 5 percent. Since the new design is relatively simple, retrofit to many existing furnaces is possible and new units could easily be designed without adding significantly to costs. This burner has excellent potential for practical application.

d. Blue-Jet Blue Flame Burner

The Blue-Jet burner utilizes a combination of low pressure atomization and vaporization to prepare the fuel oil for combustion. During the ignition period (about 1 minute) the oil is atomized and ignites at an electrode located about midway from the nozzle and the burner grid. After the burner grid is sufficiently hot the ignition is switched off, and the flame jumps to the burner grid. Its appearance is then very similar to that of a natural gas burner. There is also a small flame inside the burner ahead of the grid which aids in vaporizing the fuel.

The performance of this burner was similar to that of a conventional burner, with one exception. The CO and gaseous hydrocarbon emissions had high peaks during the ignition period (2.16 g HC/kg and greater than 32 g CO/kg). The efficiency was about 84 percent, which is better than that of a conventional burner. NO_x emissions were about 1.2 g/kg which are similar to those of a conventional burner. Most blue flame burners have much lower NO_x levels but they usually utilize some form of combustion product recirculation and the Blue-Jet does not. This burner has excellent potential for practical application.

5. Master Air-Atomizing Space Heater

The burners from these units were tested: all produced relatively low emissions. However, they cannot be validly compared to other burners since the Master units can only be operated at one excess air setting.

6. Stewart-Warner Oil-Fired Boiler

A boiler was tested to determine if emission levels from boilers were significantly different from those of warm air furnaces. The tests showed no significant differences. Test results were confirmed by nearly identical data from the Stewart-Warner Laboratory in Lebanon, Indiana.

7. Cyril Meenan Combusto-Jet Burner

This prototype burner was a complete failure when tested the first time. It produced excessive amounts of NO_x (>150 ppm) and caught fire after 30 minutes of operation. The manufacturer returned with an improved design which operated satisfactorily but had no significant effect on emissions. This device may perform better in the larger range for which it was initially designed.

Appendix E. CONVERSION FACTORS

MULTIPLIERS TO CONVERT EMISSION FACTORS FROM g/kg TO OTHER UNITS FOR NO. 2 OIL[a]

To obtain emission factor in these units	Multiply emission factor in g/kg fuel by
Gaseous pollutants and particulate:	
kg/1000 liter fuel	0.862
$g/10^6$ calories input	0.092
lb/1000 lb fuel	1.000
lb/1000 gal	7.194
$lb/10^6$ BTU input	0.051
Gaseous pollutants[b]:	
ppm at 3% O_2, dry basis	$\frac{1770}{MW}$
ppm at 0% O_2, dry basis	$\frac{2065}{MW}$
ppm at 12% CO_2	$\frac{1597}{MW}$
Particulates:	
$lb/10^6$ scf flue gas at 3% O_2	4.58
$lb/10^6$ scf flue gas at 0% O_2	5.27
$lb/10^6$ scf flue gas at 12% CO_2	4.13

[a]Typical No. 2 fuel oil having 33 API gravity

[b]MW = molecular weight of pollutant

MULTIPLIER TO CONVERT EMISSION FACTORS REPORTED AS NO TO EMISSION FACTORS REPORTED AS NO_2

Emission factors for NO are often reported as NO_2 because a major portion of the nitrogen oxides is oxidized to NO_2 in the atmosphere. In this report, however, emission factors for NO are reported as NO. To convert emission factors reported as NO to NO_2 multiply by 1.53, which is the ratio of the molecular weights of NO_2 and NO.

Example: 1.11 g NO/kg fuel x 1.53 = 1.70 g NO_2/kg fuel.

MULTIPLIERS TO CONVERT FROM THE ENGLISH SYSTEM TO THE METRIC SYSTEM

To convert from	to	Multiply English units by
Btu/hr	cal/hr	251.98
Btu/lb	cal/g	0.56
^oF	^oC	5/9 (^{o}F-32)
ft/sec	m/sec	0.30
gph	liter/hr	3.79
in.	cm	2.54
lb/10 min	kg/10 min	0.45

BIBLIOGRAPHIC DATA SHEET	1. Report No. EPA-650/2-74-003	2.	3. Recipient's Accession No.
4. Title and Subtitle: A Study of Air Pollutant Emissions from Residential Heating Systems			5. Report Date: January 1974
			6.
7. Author(s): R. E. Hall, J. H. Wasser, and E. E. Berkau			8. Performing Organization Rept. No.
9. Performing Organization Name and Address: EPA, Office of Research and Development NERC-RTP, Control Systems Laboratory Research Triangle Park, NC 27711			10. Project/Task/Work Unit No. ROAP 21ADG-AO
			11. Contract/Grant No. In-House
12. Sponsoring Organization Name and Address: NA			13. Type of Report & Period Covered: Final
			14.

15. Supplementary Notes

16. Abstracts The report presents results of recent EPA research into the problem of air pollutant emissions from small-scale combustion systems. Major factors for controlling emission levels were found to be: excess air, residence time at high temperature, combustion air handling components of burners, and burner maintenance. Recommendations for minimizing emissions from new and existing equipment are given, based on the research results obtained. Data illustrating the effects of combustion parameter changes on emission levels are given both for experimental combustors and for residential heating equipment currently in use in the U.S. Future work, directed toward reduction of emissions, is also outlined.

17. Key Words and Document Analysis. 17a. Descriptors

- Air Pollution
- Combustion Control
- Gas Burners
- Oil Burners
- Combustion Products
- Nitrogen Oxides
- Sulfur Oxides
- Carbon Monoxide
- Hydrocarbons
- Smoke
- Maintenance
- Stoichiometry

17b. Identifiers/Open-Ended Terms

- Air Pollution Control
- Stationary Sources
- Residential Heating Equipment
- Particulates
- Residence Time

17c. COSATI Field/Group 13B, 21B

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
Unlimited	UNCLASSIFIED	123
	20. Security Class (This Page) UNCLASSIFIED	22. Price

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