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Project Summary

Combustion Modification Controls for Residential and Commercial Heating Systems

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This report provides an environmental assessment of combustion modification techniques for residential and commercial heating systems. The assessment evaluates NO_x reduction effectiveness, operational impact, thermal efficiency impact, control costs, and effects on pollutant emissions other than NO_x. Major equipment types and design trends are reviewed, although emissions and control data for commercial systems are very sparse. Natural gas and distillate oil are the principal fuels. NO_x, CO, and unburned hydrocarbons (and particulates for oil-firing) are the primary pollutants. High radiative heat transfer burners have been developed for gas-fired residential systems, lowering NO_x emissions by about 80 percent without increasing emissions of combustibles. For oil-fired residential systems, several new burner designs (including integrated burner/furnace systems) have been developed, lowering NO_x by 20 to 85 percent and generally decreasing CO, HC, and particulate emissions. Commercial application of these systems is very limited. No operational or maintenance problems are expected. Since the control techniques generally increase thermal efficiency, the additional initial investment cost will be offset by operational savings. Field test data from a commercially available oil-fired low-NO_x residential system suggest that the system poses less of a potential environmental hazard than a conventional unit.

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

Introduction

With the increasing extent of NO_x control application in the field, and expanded NO_x control development anticipated for the future, there is currently a need to ensure that: (1) the current and emerging control techniques are technically and environmentally sound and compatible with efficient and economical operation of systems to which they are applied, and (2) the scope and timing of new control development programs are adequate to allow stationary sources of NO_x to comply with potential air quality standards. With these needs as background, EPA's Industrial Environmental Research Laboratory, Research Triangle Park (IERL-RTP) initiated the "Environmental Assessment of Stationary Source NO_x Combustion Modification Technologies Program" (NO_x EA) in 1976. This program has two main objectives: (1) to identify the multimedia environmental impact of stationary combustion sources and NO_x combustion modification controls applied to these sources, and (2) to identify the most cost-effective, environmentally sound NO_x combustion modification controls for attaining and maintaining current and projected NO_2 air quality standards to the year 2000.

The NO_x EA's assessment activities have placed primary emphasis on: major stationary fuel combustion NO_x sources (utility boilers, industrial boilers, gas turbines, internal combustion engines, and commercial and residential heating systems); conventional gaseous, liquid, and solid fuels burned in these sources; and combustion modification control applicable to these sources with potential for implementation to the year 2000.

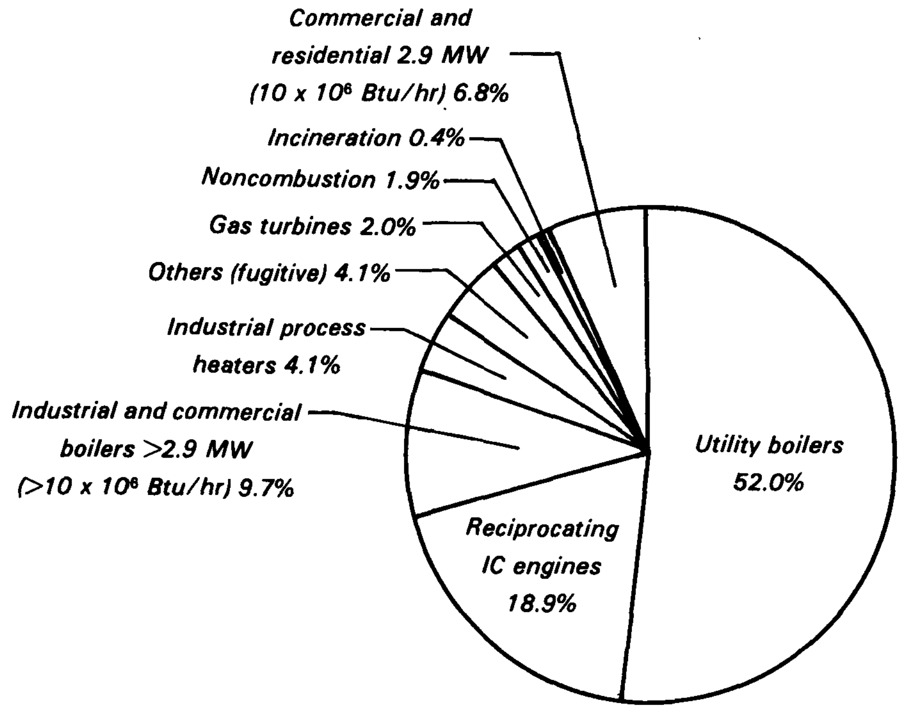
This report summarizes the environmental assessment of combustion modification controls for commercial and residential heating systems. It presents an outline of the environmental, economic, and operational impacts of applying combustion modification controls to this source category. Results of a field test program aimed at providing data to support the environmental and operational impact evaluation are also summarized.

Conclusions

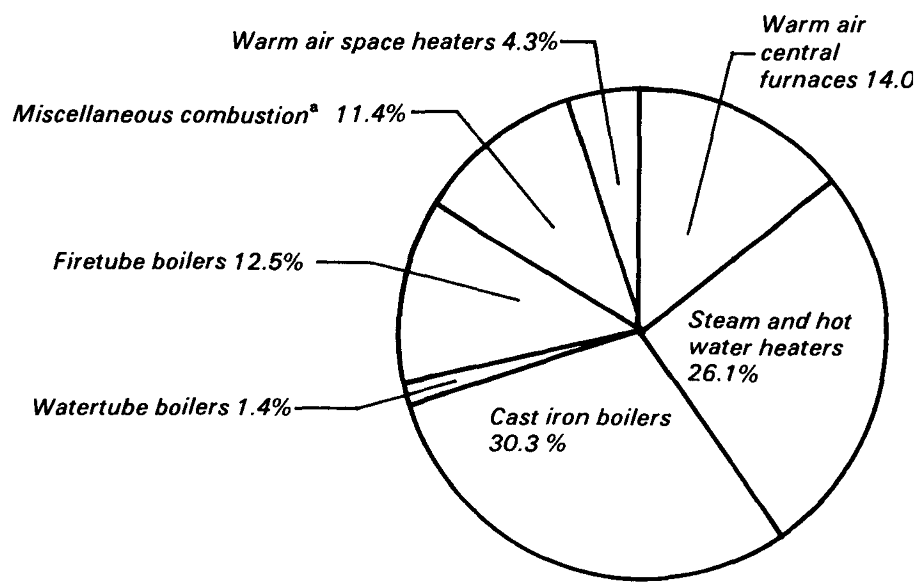
Source Characterization

Figure 1 shows that commercial and residential sources with a heat input capacity <2.9 MW (<10^7 Btu/hr) constitute the fourth largest NO_x emission category, contributing nearly 7 percent of the total NO_x from all stationary sources. Major fuel combustion sources in the residential and commercial category are central warm air furnaces, room or direct heaters, residential hot water heaters, and steam and hot water hydronic boilers used for space or water heating. Minor sources include stoves and fireplaces; these consume a relatively insignificant quantity of fuel compared to other space heating equipment. A breakdown of 1977 NO_x emissions from residential and commercial sources indicates that central warm air furnaces contributed 14 percent, steam and hot water heaters 26.1 percent, and warm air space heaters 4.3 percent of the total NO_x from the sources. A variety of factors, including continuing demand for new housing and fuel use trends, will tend to increase NO_x emissions from residential heating systems. Thus, given this trend and their potential for NO_x control, residential and commercial heating systems represent a priority source category for evaluation in the NO_x EA.

The primary fuels used for residential heating are natural gas and distillate



Total from all sources: 10.5 Tg/yr (11.6 x 10^6 ton/



Total from all sources with capacity less than 2.9 M
(10 x 10^6 Btu/hr): 0.709 Tg/yr (0.781 x 10^6 tons/yr)

[a]Includes cooling and air conditioning

***Figure 1.** Distribution of stationary man-made sources of NO_x emissions for the year 1977 (controlled NO_x levels.(Reference 1).*

›ils (No. 1 and 2 distillate). These fuels :ombined account for nearly 90 percent ›f all fuel burned for domestic heating. .iquefied petroleum gas (LPG-butane or ›ropane), coal, and wood are also used, ılthough in relatively small quantities. n 1976, LPG-fired equipment accounted or about 6 percent of domestic heating ·quipment, while coal- and wood-fired ınits accounted for only 2 percent. uilt-in, residential, electric heating ystems, including heat pumps, have ecome increasingly popular as omestic supply of clean fuels dwindles nd fuel costs increase. Electric heaters ı 1976 accounted for nearly 14 percent f residential heating equipment.

The primary fuels and equipment /pes used for domestic heating show ignificant regional variations. For xample, the Northeast depends priıarily on oil-fired steam or hot water nits, while in all other regions, naturalas-fired central warm air furnaces are sed primarily for domestic space eating.

Combustion equipment designs for ıost residential heating systems are uite similar. For natural-gas-fired quipment, the single-port upshot or ıe tubular multiport burners are the ıost common. Natural-gas-fired warm ir furnaces, room heaters, or hot water eaters generally use a pilot flame to ɟnite the burner automatically. ·istillate-oil-fired residential heating ystems generally use high-pressure tomizing gun burners. Nearly all new il-fired burners use the flame retention urner head which promotes more fficient combustion.

Commercial heating systems can be ivided into three general categories: varm air unit heaters or space heaters, varm air furnaces or duct heaters, and ıot water or steam systems. The ombustion systems for commercial varm air units (or space heaters) and uct heaters are generally similar to esidential systems, although there are ı few unique commercial gas-fired esigns. Warm air units and duct ıeaters are either direct or indirect ired. Direct fired heaters use only clean aseous fuels, exhausting the combusion products directly into the heated ›pace. Indirect fired heaters use either as or oil and are vented to the outdoors. 'hese units, except for their larger :apacity, are generally similar to esidential central warm air furnaces.

Hot water and steam systems in the :ommercial size capacity, here defined n the range of 0.12 - 2.9 MW [(0.4 - 10) x 10^6 Btu/hr] heat input capacity, include cast iron hydronic boilers, and small firetube and watertube boilers used in both the commercial and industrial sectors. Cast iron hydronic boilers are also used in residential applications. These units, common in the Northeast and Northcentral regions of the U.S., are primarily either gas- or distillate-oil-fired. Firetube and small watertube boilers used to heat large commercial plants and buildings are similar to the smaller industrial boilers used to generate process steam. These boilers are generally fired with gas, oil, or (less frequently) stoker coal, and account for about 25 percent of the installed capacity of steam and hot water boilers with heat input capacity less than 2.9 MW (10 x 10^6 Btu/hr).

Source Emissions

Because natural gas and distillate oil are the principal fuels used in residential and commercial heating systems, air pollutant emissions represent the primary waste stream of environmental concern. Coal- and wood-fired furnaces and stoves, however, also produce ash solid waste streams. Although increasing in popularity due to the scarcity and high cost of other fuels and electricity, residential wood- and coal-fired systems still account for only 2 percent of all domestic heaters. Thus, nationally, solid waste streams from residential heating pose an insignificant environmental concern. Commercial coal-fired watertube and firetube stokers are also the source of solid waste streams. These units, which account for about 15 percent of the firetube and watertube population, could increase in popularity with economic and political incentives for increased use of domestic coal.

Flue gas emissions from natural-gas-fired residential and commercial combustion sources include primarily NO_x, CO, and unburned hydrocarbons (HC). When fuel oil or coal is burned, smoke, particulate, and SO_2 are also emitted. The levels of NO_x, CO, and HC from oil and coal combustion are usually higher than those from gas combustion. Figure 2 shows the general trends of steady-state smoke and gaseous emissions from oil-fired residential heaters as a function of combustion air settings. Commercial boilers show similar trends. For both equipment types, the operating setting corresponding to lowest emissions of CO, HC, and smoke coincides with high NO_x levels. As the excess air is reduced from the theoretical setting, concentrations of CO, HC, and smoke increase because of lack of oxygen in the flame and reduced turbulent mixing which leads to incomplete combustion. At very high excess air levels, these emissions can also increase due to the excessive combustion air which cools the flame, also resulting in incomplete combustion.

A major factor contributing to high combustible emissions, particularly in residential burners, is the transient operating mode. The on/off cycle is a dominant characteristic of warm air furnaces, and is quite important as a cause of increased emissions. Figure 3 shows qualitative emission traces from an oil burner during a typical cycle. CO and HC emissions peak at ignition and shutoff. HC concentration drops to insignificant levels between the peaks, while CO emissions tend to flatten out at a measurable level. Particulate emissions continuously taper off after the ignition-induced peak, whereas NO emissions first rise rapidly for a short period and then continue to rise at a more moderate rate as the combustion chamber temperature increases. These transient emissions are caused mainly by variations in combustion chamber temperature. At ignition, a cold refractory will not assist complete combustion; therefore, peaks of CO, HC, and smoke can occur. In addition to the cold refractory, wear and tear on the oil pump causes poor shutoff performance and (thus) high smoke and combustible emissions.

In general, except for SO_2 emissions which depend entirely on the sulfur content of the fuel, all other criteria pollutant emissions are primarily a function of burner nozzle type, combustion chamber shape and material, and operating practice.

Table 1 summarizes 1977 emissions for stationary combustion sources with heat input less than 2.9 MW (10 x 10^6 Btu/hr). These sources include primarily residential and commercial heating systems, as well as small industrial boilers. Residential and commercial heating systems contribute 56 and 28 percent, respectively, of the total NO_x from these sources. These emissions are seasonal; nearly all the total annual output occurs in the winter months, during which the impact of residential and commercial heating on ground level ambient NO_2 concentration in urban areas can be significant.

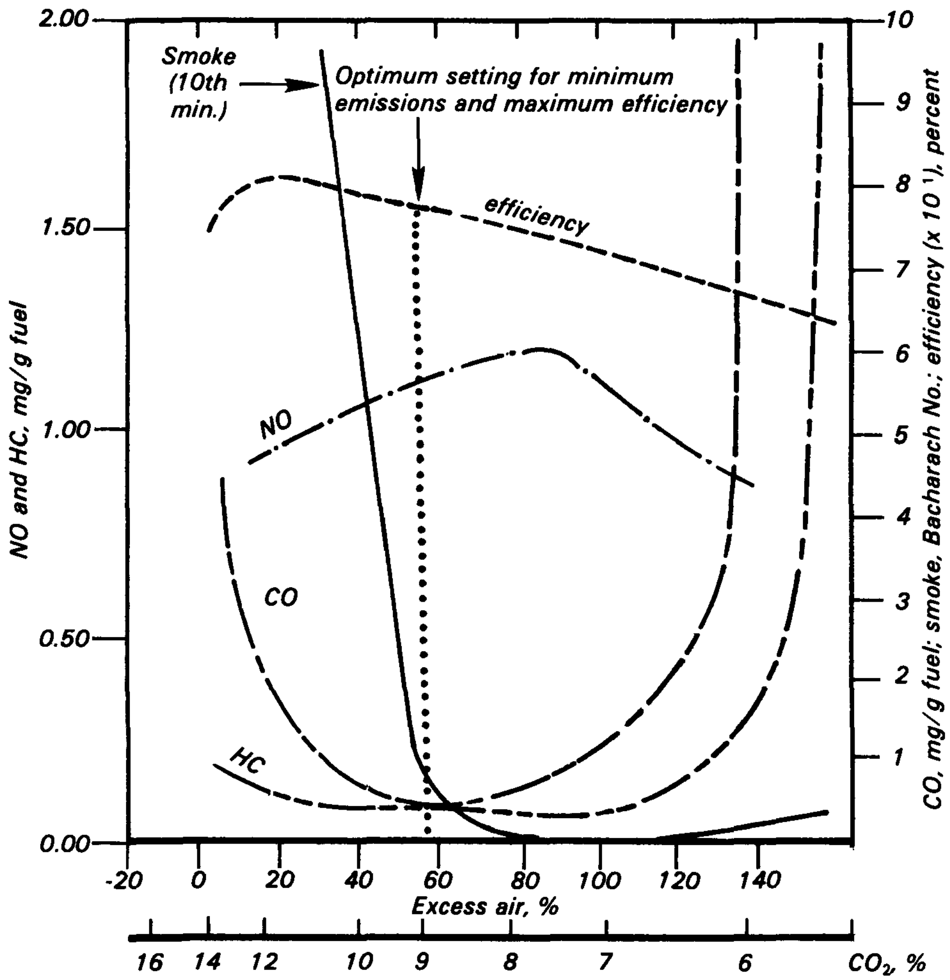


Figure 2. General trend of smoke, gaseous emissions, and efficiency versus stoichiometric ratio for a residential oil burner.

Control Alternatives

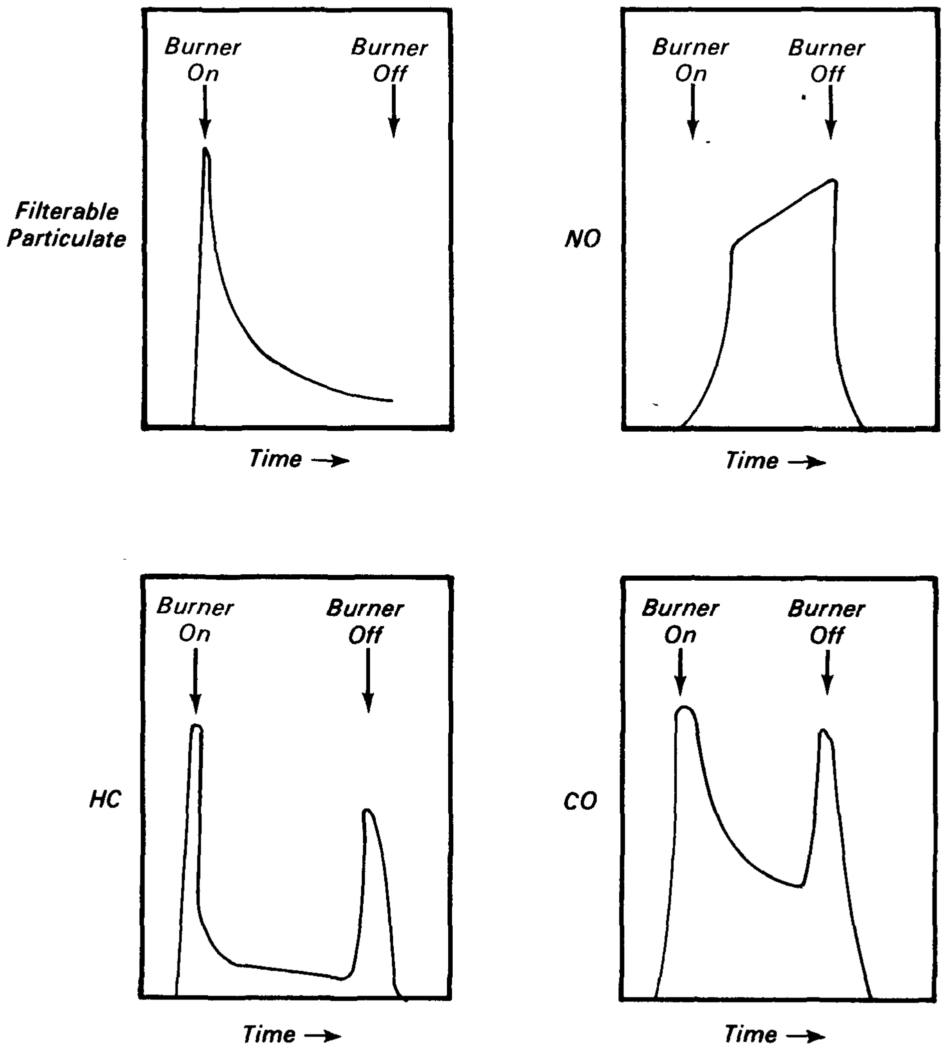
In general, very little emission control technology for gas- and oil-fired residential and commercial systems has been implemented in the field. Most emission control work for residential heaters has centered on tuning and maintenance of exisitng equipment or installation of new more efficient equipment for reduced fuel consumption and minimum visible emissions. Tuning usually reduces CO, HC, and particulates (smoke), without much effect on NO_x emissions. New furnace concepts utilize advanced burner designs which allow efficient operation at low excess air. Some of these burners are also capable of low NO_x emissions.

NO_x emission control techniques under development for residential and commercial equipment are typically adapted to the specific fuel and burner type. Because NO_x emissions from either gas or distillate oil combustion are primarily thermal NO_x, control techniques are aimed at controlling temperature or oxygen availability in the high temperature flame region. Tables 2 and 3 summarize NO_x control alternatives for residential heaters firing natural gas and distillate oil, respectively. These controls have been developed primarily for warm air furnaces; however, the advanced burners and combustor redesign technology presented in these tables could possibly be applied to other domestic heating equipment and some larger commercial installations.

For residential gas-fired heaters, the American Gas Association Laboratories (AGAL) has developed radiant screens and secondary air baffles capable of average NO_x reductions of 58 and percent, respectively. However, th controls may find little applicat because of installation and performa problems subsequently identified by Gas Appliance Manufacturers Asso tion (GAMA). Two advanced NO_x con alternatives are the Bratko Surf Combustor and the Amana Heat Tra fer Module (HTM). In these conce radiation from the combustion z maintains a lower temperature in combustion products and thus lo NO_x production while maintaining g efficiency and low CO levels. N emissions from both the Bratko Amana burners are about 80 perc below levels of conventional warm furnaces. Unlike the Bratko, the Am unit is commercially available, and cost to the consumer is generally $1 to $300 above that of a conventio furnace.

The modulating furnace syst produces a cooler flame by altering burner firing rate to respond to heating load instead of cycling on and NO_x reductions of about 40 perc have been reported. AGAL is curre investigating pulse combustion residential heating using a condens exhaust gas system, with prelimin NO_x emissions reported as 19 to ng/J. Commercialization of the pu combustor residential heating syste expected to begin in 1981. Cataly promoting combustion of fuel at l temperature offer potential for very l NO_x emissions while maintaining g combustion efficiency. Research gro and trade organizations are inve gating the commercial feasibility catalytic combustion for residen warm air and hot water syste burning natural gas. Performance a emission data for these systems h not yet been published; however, N emissions are expected to be very l

Residential oil-fired heaters a forced draft fired and therefore m readily modified for reduced emissi and increased efficiencies than natu draft gas-fired heaters. Early w focused on the development of flame retention oil burner. The burners produce lower CO, HC, a smoke emissions and operate at lov excess air levels than previous conv tional oil burners. In some designs, flame retention devices also lower N emissions by 20 to 40 percent. Furth more, they stay tuned longer and th maintain low combustible emissi



igure 3. Characteristic emissions of oil burners during one complete cycle.

evels. These units are now the primary esidential oil burners sold.

As part of its combustion research program, EPA has supported low-NO_x ıigh efficiency residential burner evelopment since 1971. Under one program, Rocketdyne developed a controlled-mixing burner head for etrofit and new applications on domestic heaters. It was estimated that widespread application of the relatively nexpensive burner head would be effective in reducing NO_x by 20 percent and increase efficiency by 5 percent on he average for each retrofitted furnace. Recently the burner was integrated with an "optimum"* low emission, high efficiency warm air furnace. NO_x emissions have been reduced by 65 to 70 percent, and steady state efficiencies have been increased by as much as 10 percent over those of conventional designs. The EPA program emphasized the necessity to match the firebox, burner, and heat exchanger design to achieve low NO_x emissions while also maintaining low levels of CO, HC, and smoke.

*Terminology used by Rocketdyne to characterize he final design capable of achieving program goals

Both the Blueray "blue flame" and the M.A.N. burners use aerodynamic flue gas recirculation to achieve a blue flame with distillate fuel oil. These burners thus achieve reduced flame temperature, reduced oxygen concentrations in the near-burner zone, and rapid vaporization of the fuel prior to ignition. These conditions result in low NO_x emissions on the order of 15 to 40 ppm corrected at zero percent excess air, representing NO_x reductions of 50 to 80 percent. Theoretically, these burners could be scaled up to larger commercial sizes. The Blueray furnace system is currently the only commercially available low NO_x system in the U.S. for oil-fired residential use. The M.A.N. burner, developed in West Germany, is marketed in parts of Europe and Canada.

Techniques aimed at reducing seasonal pollutant emissions from residential heating systems are also effective in delivering improved fuel economy and generally reduced equipment use. Replacement of wornout furnaces, tuning, and changes in thermostat anticipator settings are the most effective emission reduction techniques, with overall combustible emission reductions ranging from 16 to 65 percent for CO, 3 to 87 percent for HC, 59 percent for smoke, and 17 to 33 percent for particulates. Installation of delayed action solenoid valves and reduced firing capacity through minor modification or installation of a new flame retention burner are effective in reducing excessive smoke emissions during furnace start-up and shutdown. Reported average smoke reductions range from 24 to 82 percent. In general, all these techniques result in fuel savings, sometimes as high as 39 percent, in addition to lowering combustible emissions.

Application of control technology to commercial heating equipment is very limited. Theoretically, the flame quenching and surface combustion concepts investigated for gas-fired residential equipment could also apply to commercial heaters burning natural gas. Similarly, low-NO_x burner designs for distillate oil firing or optimum air/fuel mixing concepts could possibly be scaled up to the larger commercial equipment.

NO_x control technology from gas- and oil-fired industrial boilers include low-NO_x burners, staged combustion, flue gas recirculation, load reduction, and low excess air operation. These techniques could possibly apply to commercial size boilers of similar design. Low-NO_x burners are the most attractive control alternative for this boiler size. Some U.S. companies are currently working on new burner designs, primarily for oil-fired boilers. Most of these efforts, however, have been

Table 1. *Estimated 1977 Air Pollutant Emissions from Stationary Fuel Combustion Sources with Heat Capacity Less t 2.9 MW (10 x 10^6 Btu/hr)*

Sector	Equipment	Fuel	Total Capacity, MW (10^6 Btu/hr)	Fuel[a] Consumption EJ (Quads)	Air Pollutant Emissions Gg (10^3 tons)				
					NO_x	CO	HC	Particulates	SO
Residential	Warm air central furnaces	Natural gas	—	1.876 (1.979)	65.7 (72.5)	19.0 (20.9)	6.40 (7.10)	7.50 (8.27)	0.4 (0.5
		Distillate oil	—	1.354 (1.428)	33.8 (37.3)	33.8 (37.3)	6.40 (7.06)	10.3 (11.4)	14 (16
	Warm air space heaters	Natural gas	—	0.57 (0.60)	19.9 (21.9)	5.7 (6.3)	1.94 (2.14)	2.30 (2.54)	0.1 (0.1
		Distillate oil	—	0.42 (0.44)	10.5 (11.6)	10.5 (11.6)	1.97 (2.17)	3.20 (3.53)	45. (50.
Residential and Commercial	Miscellaneous combustion	Natural gas	—	1.524 (1.608)	53.3 (58.8)	15.2 (16.8)	5.20 (5.73)	6.10 (6.73)	0.4 (0.4
		Distillate oil	—	0.926 (0.977)	27.4 (30.2)	27.4 (30.2)	5.15 (5.68)	8.33 (9.19)	118 (130
	Steam and hot water heaters	Natural gas	—	2.1 (2 2)	82.8 (91.3)	17.8 (19.6)	4.76 (5.25)	16.6 (18.3)	0.6 0.6
		Distillate oil	—	1.4 (1.5)	77.9 (85.9)	41.7 (46.0)	13.4 (14.8)	10.6 (11.7)	150 (165
		Residual oil	—	0.11 (0.12)	17.5 (19.3)	1.64 (1.81)	2.74 (3.02)	9.09 (10.0)	52. (58.
		Coal	—	0.043 (0.045)	7.1 (7.8)	7.53 (8.30)	2.12 (2.34)	150.2 (165.6)	30. (33.
Commercial and Industrial	Cast iron boilers	Natural gas	143,520 (489,495)	1.8 (1.9)	91.7 (101.1)	35.3 (38.9)	4.06 (4.48)	6.88 (7.59)	0.5 (0.5
		Distillate oil	33,730 (115,041)	0.35 (0.37)	23.7 (26.1)	0.56 (0.61)	3.34 (3.68)	4.18 (4.61)	37. (41
		Residual oil	53,790 (183,456)	0.47 (0.50)	84.6 (93.3)	0.66 (0.73)	11.8 (13.8)	13.2 (14.6)	225 (248
		Coal	31,590 (107,742)	0.097 (1.0)	14.6 (16.1)	21.3 (23.5)	5.53 (6.10)	314.3 (346.6)	110 (122
	Watertube boilers	Natural gas	5,770 (19,679)	0.053 (0.056)	3.16 (3.5)	1.06 (1.17)	0.18 (0.20)	0.05 (0.05)	0.0 (0.0
		Distillate oil	4,490 (15,313)	0.021 (0.023)	1.18 (1.3)	0.06 (0.07)	0.01 (0.01)	0.18 (0.20)	3.2 (3.6
		Residual oil	5,240 (17,872)	0.015 (0.016)	2.38 (2.6)	0.02 (0.02)	0.07 (0.08)	0.42 (0.46)	6.7 (7.3
		Coal	1,900 (6,480)	0.012 (0.013)	3.0 (3.3)	0.91 (1.00)	0.19 (0.21)	23.5 (25.9)	16. (17.
	Firetube boilers	Natural gas	79,090 (269,748)	1.358 (1.433)	31.0 (34.2)	15.2 (16.8)	1.75 (1.93)	3.02 (3.33)	0.2 (0.2
		Distillate oil	31,530 (107,538)	0.37 (0.39)	12.8 (14.1)	0.34 (0.38)	2.05 (2.26)	2.57 (2.83)	18. (20.
		Residual oil	48,200 (164,393)	0.354 (0.374)	30.7 (33.9)	0.29 (0.32)	5.12 (5.65)	5.73 (6.32)	92 (101
		Coal	14,420 (49,181)	0.11 (0.116)	14.1 (15.6)	5.40 (5.95)	3.40 (3.75)	130.0 (143.4)	91 (101
Total	All equipment	All fuels	—	15.22 (16.97)	708.8 (781.6)	261.4 (288.3)	87.6 (96.6)	728.3 (803.1)	1,14 (1,26

[a]EJ = 10^{18} Joules = 0.948 Quads = 0.948 x 10^{15} Btu

oriented toward industrial (2.9 to 73.3 MW heat input) size boilers.

Cost of Control

Table 4 summarizes estimated costs for the most effective NO_x control alternatives for residential heating systems. As indicated, retrofit of the controlled mixing burner head for residential oil-fired warm air furnaces is the most cost-effective alternative to achieve a NO_x emissions level of about 45 ng/J of useful heat. Cost-effect ness of other alternatives for oil-f warm air furnaces is generally c parable, falling in the $1 to $4 n range. Similarly, for gas-fired warm furnaces, both the Amana HTM furn

Table 2. *Performance Summary of Low-NO_x Control Equipment for Natural Gas-Fired Residential Heaters*

Control	Average Operating Excess Air, percent	Cyclic Pollutant Emissions, ng/J heat input NO_x[a]	CO	UHC[b]	Steady State Efficiency, percent	Cycle Efficiency, percent	1978 Installed Control Cost	Comments
Baseline	40-120	28-45	8.6-25	3.3-33	70	60-65	($500-$800)[c]	Costs include installation
Radiant screens	40-120	15-18	6.4	NA	75	70	NA	Emissions of CO and HC can increase significantly if screen is not placed properly or deforms
Secondary air baffles	60-80	22	14	NA	NA	NA	NA	Requires careful installation. Best suited for single-port upshot burners
Bratko Surface combustion burner	10	7.5	5.5-9.6	NA	NA	NA	$100-$200	Not commercially available. Still under development
Amana (HTM)	NA	7.7	26	NA	85	80	$100-$300 over conventional furnace	Commercially available design. Spark ignited, thus requires no pilot
Modulating furnace	NA	25	NA	NA	75	70	$50-$250 over conventional furnace	Furnace is essentially derated. Thus it requires longer operation to deliver a given heat load
Pulse Combustor	NA	10-20	NA	NA	95	95	$300-$600	Currently being investigated by AGAL. Efficiencies correspond to condensing systems.
Catalytic Combustor	NA	<5	NA	NA	90	85	$100-$250	Still at the R&D stage. Efficiencies correspond to condensing systems.

[a]Sum of NO + NO_2 reported as NO_2
[b]Unburned hydrocarbons calculated as methane (CH_4)
[c]Typical costs of uncontrolled unit
NA = not available

Table 3. *Performance Summary of Low-NO_x Control Equipment for Distillate-Oil-Fired Residential Heaters*

Control	Average Excess Air, percent	Cyclic Pollutant Emissions, ng/J heat input NO_x[a]	CO	UHC[b]	Smoke Number	Particulate	Steady State Efficiency, percent	Cycle Efficiency, percent	1978 Installed Control Cost	Comments
Baseline	50-85	37-85	15-30	3.0-9.0	3.2	7 6-30	75	65-70	($650-$1000)[c]	Range in NO_x emissions is for residential systems not equipped with flame retention burners. Emissions for other pollutants are averages
Flame Retention Burner Head	20-40	26-88	11-22	0.2-1 8	2.0	NA	80-83 also depends on heat exchanger	NA	$52	If a new burner is needed as well as a burner head, the total cost would be $385.
Controlled Mixing Burner Head by EPA/ Rocketdyne	10-50	34	13	0.7-1.0	0.5-0 9	NA	80 also depends on heat exchanger	NA	$43	Cost of mass produced burner head only about $1.50. Combustible emissions are relatively low because hot firebox was used.
Integrated Furnace System by EPA/ Rocketdyne	20-30	19	20	1.2	0 32	NA	84	74	$250 over conventional furnace	Uses optimized burner head. For new furnace installation only. Combustible emissions are higher than with burner head because of quenching in an air cooled firebox. Recent cost estimate.
Blueray "blue flame" Burner/Furnace System	20	10	4.5-7.5	1.5-2 5	zero	NA	84	74	$100 over conventional furnace	New installation only. Furnace is commercially available. Recent cost estimate.
M A.N Burner	10-15	10-25	30	NA	1.0	NA	85	NA	NA	Both for retrofit or new installations. Not yet commercially available in U.S Commercialization expected in 1982.

[a]Sum of NO and NO_2 reported as NO_2
[b]Unburned hydrocarbons calculated as methane (CH_4)
[c]Typical costs of uncontrolled unit

Table 4. *Cost Impact of NO_x Control Alternatives*

Control	Fuel	Achievable NO_x Level, ng/J useful heat	1978 Incremental Investment Cost	Cost Effectiveness, \$/ng/J[a]	Payback Period Base on Annual Fuel Bill of \$500, years
Amana (HTM) Furnace	Natural Gas	12 (390 ng/m³ fuel)	\$100-\$300 over cost of conventional furnace	1.7-5 2	1-3
Modulating Furnace	Natural Gas	35 (920 ng/m³ fuel)	\$50-\$250 over cost of conventional furnace	1 4-7.0	1-3.8
Surface Combustion Burner (Infrared Bratko)	Natural Gas	12 (390 ng/m³ fuel)	\$100-\$200 over cost of conventional furnace/heater	1.7-3.4	3.5-8.0
Pulse Combustion Burner[b]	Natural Gas	21 (683 ng/m³ fuel)	\$300-\$600 over cost of conventional furnace/heater	6.1-12.2	1.7-3.5
Catalytic Combustion Burner[b]	Natural Gas	Estimated 5 (163 ng/m³ fuel)	\$150-\$250 over cost of conventional furnace/heater	2.3-3.9	1 4-2.3
Flame Retention Burner Head	Distillate Oil	50 (1.8 g/kg fuel)	\$52—retrofit including installation	2 6	Less than 1
Flame Retention Burner	Distillate Oil	50 (1.8 g/kg fuel)	\$385—retrofit of reduced capacity burner	12.8	3.5
EPA/Rocketdyne Burner Head	Distillate Oil	45 (1.6 g/kg fuel)	\$43—retrofit including installation	1.3	Less than 1
EPA/Rocketdyne Furnace	Distillate Oil	29 (0.7 g/kg fuel)	\$250 over cost of conventional furnace	4.2	2.5
Blueray Furnace	Distillate Oil	20 (0 7 g/kg fuel)	\$100 over cost of conventional furnace	1.7	1

[a]Based on uncontrolled NO_x emissions of 70 ng/J heat output for natural-gas-fired heaters and 80 ng/J heat output for distillate-oil-fired heaters Cost effectiveness is based on the differential investment cost of the control.
[b]Based on installation of a condensing system where seasonal efficiencies can be as high as 95 percent.

and the modulating furnace are comparably cost-effective, in the \$1 to \$7 ng/J range. Surface combustor, pulse combustor, and catalytic burner for gas-fired units and the Rocketdyne developed techniques for oil-fired units are not commercially available. The payback periods listed in the table, are estimates based on the time required to recover the money spent for the initial investment of installing NO_x control equipment. Since all these control alternatives increase thermal efficiency, and thus fuel savings, the initial investment cost is often recouped in 1 year or less.

Incremental Emissions Due to Controls

To assess the effects of a low-NO_x burner/furnace design on the incremental emissions of pollutant species other than NO_x from a residential heating unit, an oil-fired Blueray low-NO_x, high-efficiency home furnace was field tested. The unit was in a Medford, LI, NY, residence and had been in service about 1 year. The model tested fired distillate fuel oil at 0.63 mg/s (0.6 gal./hr) and had a rated heat input of 24.6k J/s (84,000 Btu/hr). The program involved testing in two modes of operation: continuous and cyclic (10 minutes on and 10 minutes off). The cyclic mode is more representative of typical operation. Sampling and analysis of the flue gas stream, using slightly modified Environmental Assessment Level 1 procedures, were performed (Reference 2). Detailed test results are reported in Volume II of the full report summarized here.

Table 5 shows average flue gas composition data for the two tests. In the cycling test, there were peaks in the CO and HC emissions at the start and end of each period of operation. This initial peak is included in the average concentration noted. Start-up peak emissions averaged 2000 ppm for CO and 400 ppm for HC. The NO_x levels started at zero and, toward the end of the firing cycle, reached 16 ppm which was the average value for the continuous firing test. Average NO_x emissions were also very low in both cyclic and continuous operation. Particulate emissions were very low and did not vary from continuous to cyclic operation. Organic emissions increased substantially for cyclic operation. Liquid column chromatographic, infrared, and low resolution mass spectrometric analyses of the samples showed that, for both cyclic and continuous operation, the samples contained primarily aliphatic hydrocarbons, with some aromatics and carboxylic acids.

Table 6 summarizes flue gas emission data, including those for trace elemen

Table 5. *Flue Gas Composition: Blueray Unit*

Component	Cyclic	Continuous
NO_x ng/J as NO_2	6.6	10
ppm, dry	11	16
SO_2, ng/J	35.5	26.9
SO_3, ng/J	1.0	0.2
UHC, ng/J as CH_4	5.0	0
ppm, dry	23	0
CO, ppm dry	160	25
CO_2, % dry	12.9	13.1
O_2, % dry	4.0	3.8
Particulate, ng/J	1.30	1.32
Total $(>C_7)$ Organics, µg/m³	2 63x10⁴	1,300

Table 6. Flue Gas Composition (μg/dscm): Residential Warm air Furnaces

Element	Blueray Cyclic	Blueray Continuous	Average Conventional Cyclic
NO_x	5.4×10^3	7.7×10^3	4.2×10^4[a]
SO_2	2.7×10^4	2.1×10^4	8.2×10^4[a]
SO_3	770	150	4.5×10^3
CO	4.5×10^4	6.9×10^3	1.2×10^4[a]
Antimony	<0.46	<0.38	4.4
Arsenic	<0.54	<0.46	1.2
Barium	<11	<8.5	12
Beryllium	<0.014	<0.012	—
Bismuth	<0.62	<0.62	—
Boron	<10	<3.0	—
Cadmium	<1.1	<1.7	8.5
Chromium	<5.5	<85	22
Cobalt	<5.7	<6.8	—
Copper	11	15	120
Iron	46	420	11
Lead	<21	<21	32
Manganese	<2.5	<12	—
Mercury	<3.0	<4.2	0.92
Molybdenum	<3.5	<11	—
Nickel	<11	<68	220
Selenium	<1.8	<2.3	—
Tellurium	<0.77	<0.69	—
Thallium	<41	<37	—
Tin	<0.92	<0.69	—
Titanium	<1.0	<2.5	—
Vanadium	<1.1	<0.62	2.2
Zinc	<2.8	<3.2	85
Organics ($>C_7$)	6.0×10^3	290	2.4×10^3

[a]*Calculated from emission factors in "Compilation of Air Pollutant Emission Factors," EPA report AP-42*

species. For comparison, average Level 1 emission data from several conventional oil-fired furnaces recently tested are also shown (Reference 3). To facilitate direct comparisons, all concentration data in the table are shown as $\mu g/m^3$, adjusted to an end of flue pipe O_2 content of 17 percent, the average value found in the Reference 3 tests.

Environmental Impact Evaluation

The data summarized in Table 6 were evaluated by a Source Analysis Model (SAM), specifically SAM/IA (Reference 4), to give a quantified measure of the potential hazard posed by emissions from a residential warm air furnace, and to assess how a low-NO_x design affects the potential hazard.

SAM/IA was developed for use in Environmental Assessment projects to provide estimates of the potential hazard associated with some discharge streams. The basic index of potential hazard defined by SAM/IA is Discharge Severity (DS). The DS for a given species is defined as the ratio of that species' discharge stream concentration to the species' Discharge Multimedia Environmental Goal (DMEG). DMEGs, defined in the Environmental Assessment program for a large number of species, represent the maximum pollutant concentration desirable in a discharge stream to preclude adverse effects on human health or ecological systems.

Table 7 presents human-health-based DS values, calculated from the data in Table 6, for species where DS exceeded unity for any data set evaluated. The DS values for NO_x, SO_2, and CO for the conventional furnace were calculated using AP-42 emission factors: these species were not directly measured in the conventional furnace test program.

The table indicates that, for both types of units, Cr and Ni emissions appear to present the greatest potential environmental hazard; in all cases, their DS is a sizable fraction of total stream DS. However, measured levels of these metals may be an artifact of the stream sampling methodology. The flue gas sampling trains in both the conventional furnace test program and the NO_x EA contained many stainless steel components. Thus, some of the reported Cr and Ni could have come from the sampling train itself, rather than being a significant component of the flue gas.

For both units, SO_2 emissions were flagged and emissions of certain organic categories had DS values greater than 1. For the conventional units, amines were flagged as being of potential concern; for the Blueray unit, carboxylic acids would be of potential concern under cyclic operation. The DS for NO_x exceeds 1 for conventional units, but is less than 1 for the low-NO_x Blueray unit under both continuous and cyclic operations.

In summary, flue gas stream Total Discharge Severity (TDS) for typical conventional units appears to fall between the TDS for the low-NO_x unit under cyclic (normal) operation and that for the low-NO_x unit under continuous operation. If Cr and Ni are removed from the TDS calculations, adjusted TDS's of 22, 6.2, and 9.3 result for the conventional, Blueray continuous, and Blueray cyclic data, respectively. Thus, if measured Cr and Ni indeed come from the sampling train, then the low-NO_x unit's TDS under both cyclic and continuous operation is lower than that of the conventional units. This suggests that using the Blueray design to control NO_x from oil-fired heating units is environmentally sound.

Recommendations

The Environmental Assessment of combustion modification controls for residential and commercial heating units was often frustrated by the lack of good quality data in several areas. Thus, recommendations from the study focus on extending the data base necessary for evaluating the effects of these controls on heating system operation, costs of operation, and emissions.

With respect to emission data from residential space heating equipment, a substantial amount of information has been gathered. Numerous control alternatives for NO_x and combustible pollutants have been investigated. Some low-NO_x and high efficiency furnace designs are commercially available, while other equally effective designs are either at final demonstration stages or await commercialization.

Table 7. *Flue Gas Discharge Severity: Oil-Fired Residential Warm Air Furnaces*

		Discharge Severity		
Component	*MEG Category*	*Conventional Cyclic*	*Blueray Continuous*	*Blueray Cyclic*
Cr	*68*	*22*	*85*	*5.5*
Ni	*76*	*15*	*4.5*	*0.73*
Alkylhalides	*2*	*13*	—	—
SO_2	*53*	*6.3*[a]	*1.6*	*2.1*
NO_x	*47*	*4.7*[a]	*0.86*	*0.60*
SO_3	*53*	*4.5*	*0.15*	*0.77*
Amines	*10*	*1.6*	—	—
Carboxylic acids	*8*	—	*0.20*	*2.3*
CO	*42*	*0.30*[a]	*0.17*	*1.1*
Total stream		*59.0*	*95.7*	*15.5*

[a] *Not measured; DS based on AP-42 emission factor s.*

Performance test data on these improved designs are being gathered in EPA sponsored field and laboratory programs. These and other test programs will aid in further documenting the performance and reliability of these advanced controls and quantifying their impact on other pollutant emissions.

Cost data on NO_x control alternatives for residential heating systems are generally sparse and imprecise. This lack of definitive cost data prevented a detailed economic impact assessment of widespread implementation of control alternatives. As advanced controls become available, future studies should quantify the cost impact of NO_xcontrol implementation to achieve specific levels of control.

Information on NO_x control alternatives for commercial size steam and hot water boilers burning gas or oil is also scarce While it can be speculated that some boiler designs lend themselves to NO_x control techniques developed for industrial size boilers, little experimental data exist to confirm this. Low-NO_x burner technology for heat input capacities in the size range of 0.1 to 2.9 MW (0.4 to 10 x 10^6 Btu/hr) shows promise based on advanced burner technology developed for both residential units on the small side and industrial units on the larger side, but definitive demonstration is needed.

NO_x control alternatives for solid-fuel-fired residential and commercial equipment have also seen very limited study. Past and on-going test programs have mainly dealt with quantifying the pollutant levels and identifying equipment operating parameters and fuel characteristics which have some impact on these levels. Primary pollutants of interest for this category of equipment have been particulate and smoke emissions as well as levels of unburned HC, toxic elements, and polycyclic organic matter (POM). The simplicity of the solid-fuel-fired equipment, whether coal- or wood-fired, often does not permit extensive modification of existing equipment or operating procedures reduce NO_x levels. Investigative effor in this area should continue to determir potential NO_x control technology appl cable to new unit design, while st concentrating on reducing the impact other criteria and noncriteria pollutai emissions.

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