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Particulate and Gaseous Emissions from Natural Gas Furnaces and Water Heaters

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Reference 9

Jean L. Muhlbaier
General Motors Research Laboratories
Warren, Michigan

Three furnaces and one hot water heater were tested for particulate and gaseous emissions. The effects of fuel, stoichiometry, operating conditions, and appliance type on emission levels were studied. The filterable particulate levels from a properly operating furnace were very low. However, condensable particulate emissions were considerably greater, approximately the same as predicted by EPA estimates of furnace particulate emissions. Carbon emissions comprised about 12% of filterable particulate emissions. However, when operated highly fuel-rich, copious amounts of elemental carbon particles were emitted with a mass median diameter of less than 0.4 μm. Gaseous emissions were dependent on cycling of the furnace and stoichiometry.

An estimate was made of the daily furnace emissions compared to daily emissions from a 1980 catalyst-equipped automobile. While gaseous emissions were less than the corresponding vehicle emissions, the particle emissions from the furnace were three times greater than particle emissions from a 1980 vehicle.

Natural gas heating has been largely overlooked as an emission source, partly due to the clean-burning characteristics of methane and partly due to the small size of each source. However, several factors make residential furnace emissions worth studying. For example, in 1975, there were 42 million residential consumers of natural gas in the U.S.,[1] accounting for 58% of residential fuel consumption.[2] In addition to the large number of sources, emissions are released near the ground which tends to maximize the impact. Finally, since there are no restraints on residential furnace emissions, some homes will undoubtedly be heavy polluters due to poorly maintained and/or poorly adjusted furnaces.

According to the *Compilation of Air Pollutant Emission Factors* (AP-42),[3] the particulate emissions from natural gas usage in homes are 2.2–6.4 ng/J, and 8.4 ng/J from liquefied petroleum gas (LPG). To place these numbers in perspective, one can assume the average residence has a 106 × 10^6 J/h (100 000 Btu) furnace. In one hour of use, approximately 0.4 g of particles would be emitted. This is comparable to the amount of particulate material emitted from an automobile using unleaded gasoline in a distance of 10 mi.[4]

Unfortunately, the above emission estimate is based on very few measurements. The LPG particulate emission estimate is actually based on no data, but was extrapolated from the methane results. The most extensive study since AP-42 has been done by Kalika, *et al.*[5] who made 200 emissions tests at 100 residences with gas furnaces and found an average filterable particulate emission of 0.33 ng/J. This is far below the AP-42 estimate of 2-6 ng/J. The total particulate (filtered plus condensed) was measured in a few tests and was found to vary from 9-55 ng/J. This study suggests that nearly all of the material passes through the hot filter and condenses upon cooling. It is unclear if the particulate emission estimates suggested by AP-42 refer to filterable or total particulate. Another study of six gas-fired residential furnaces was made for EPA[2] in 1979 in which an average of 1 ng/J of filterable particulate was measured. Cycling the furnace on and off appeared to have no effect on the organic emissions although other studies have found just the reverse.[6]

From the existing data, there remain several unanswered questions. For example, the source emission compilation, AP-42, appears to overestimate the quantity of filterable emissions, and the importance of the condensable material is unclear. Emissions from LPG have never been measured although LPG accounts for about 10% of residential gas usage.[2] In various studies, particulate emissions have been analyzed for trace metals and specific organic compounds, but the contribution of elemental carbon, sulfate, and nitrate to the total mass has not been determined. Finally, the effect of the air/fuel ratio and the effect of furnace cycling has not been clearly established.

The present study centered on total particulate emissions although gaseous emissions were also measured. Emissions were collected from appliances installed in the laboratory to study the effect of fuel, stoichiometry, cycling, and appliance type. Residential measurements were also made to determine if the laboratory results were realistic.

Experimental Methods

Laboratory Tests

A Lennox 116 × 10^6 J/h (110 000 Btu) furnace and a KGA 150-L, 42 × 10^6 J/h (40 000 Btu) hot water heater were used to study emissions from gas appliances. The furnace contained four parallel ribbon jets, each with an air shutter for controlling air to the flame. Since a natural gas supply was not available, cylinders of 93% methane were used. This corresponds to the composition of natural gas in the Detroit area, which is 93% methane and has a gross heating value of 3.7 × 10^7 J/m^3.[7] Liquid propane with a heating value of 9.4 × 10^7 J/m^3 was also used as a fuel. The fuel was passed through a dry gas meter to monitor usage, which was approximately 0.046 m^3/min of methane and 0.019 m^3/min of propane. The hot water heater could only be run on methane and no regulation of air to the flame was possible. The fuel usage for the hot water heater was 0.017 m^3/min methane. The sampling system is shown in Figure 1. The exhaust gases were drawn through a 20-cm diameter flow tube to a floor exhaust. The air flow was controlled by the floor exhaust rate rather than by natural draft. The particle collection devices were mounted at the far downstream end of the flow tube. There were three particle collection devices, a 47-mm filter, a 142-mm filter, and an 8-stage Andersen impactor. Gelman A-E glass fiber filters were used for mass measurement of particles. Each collection device was equipped with a rotameter and a mercury manometer to monitor the air flow and pressure drop across the filter. The temperature at the sampling point was about 90°C. The filters were not heated, but quickly reached the temperature of the exhaust gas. During some tests, the filtered air was drawn through two water-filled impingers which collected condensable material.

The air velocity through the tube was measured to determine the fraction of exhaust air sampled. The flow changed according to the load on the exhaust system. The air flow was monitored by measuring the CO_2 concentration at the sampling point. From the volume of fuel burned, the expected emission rate of CO_2 was calculated. Carbon dioxide was the only major carbon combustion product with CO present only as a trace constituent. From the CO_2 concentration in the tube, the dilution could be calculated to arrive at a flow rate. The volume flow through the tube varied from 2–6 m^3/min. The air flow found in residential chimneys averaged about 4 m^3/min. The air velocity through the sampling probes was two to four times the velocity of the exhaust gas. A high sampling rate was considered necessary due to the low emissions. This super-isokinetic condition is not expected to compromise the results since the particles are submicron and are expected to follow the air stream.

Gas concentrations were measured above the flame before dilution occurred as well as at the point where the particles were sampled. Carbon dioxide and carbon monoxide were measured routinely and a few measurements of hydrocarbons and nitrogen oxides were also made.

Residential Sampling

Furnace emissions were measured at two homes to determine if the laboratory measurements were representative of residential operation. The furnaces tested were a Luxaire 174 × 10^6 J/h (165 000 Btu) furnace with six ribbon jets and a 132 × 10^6 J/h (125 000 Btu) BDP furnace with four slotted jets. Samples were drawn through a probe inserted in the flue pipe connecting the furnace and the chimney. The gaseous sample passed through a heated 47-mm filter to a dry gas meter and finally to a CO_2 analyzer.

Furnace emissions were also measured at the chimney exit at both houses. An aluminum chimney extension with a 3-in. port was placed on the chimney. Sampling was done using source-sampling equipment complying with EPA Method 5 procedures. The sample was drawn through a ½ in. diameter nozzle through a heated probe and filter which removed particulates and finally through two water-filled impingers which removed condensable material. Sampling was done at the chimney center rather than traversing the 'stack' as specified by EPA Method 5. Since flow measurements were based on the CO_2 concentration, a sample traverse was unnecessary. The temperature in the chimney was about 71°C for the smaller furnace and 90°C for the larger furnace.

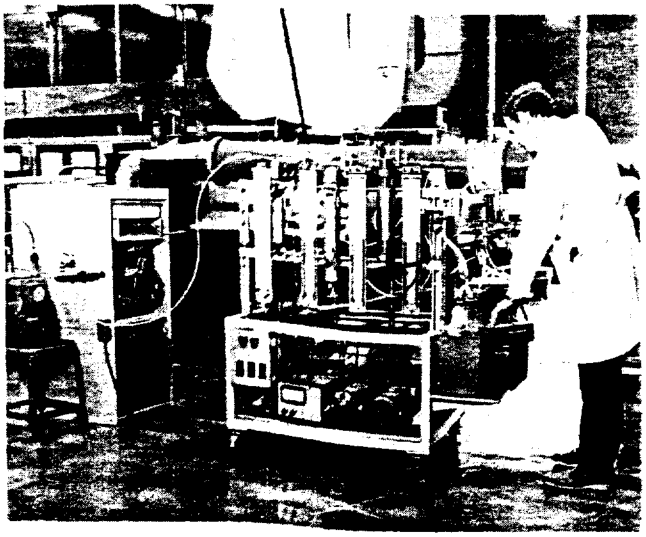

Figure 1. The furnace and sampling system used for laboratory emission testing.

Analytical Procedures

Particle Size Analysis. An 8-stage Andersen cascade impactor was used for particle size experiments. Uncoated glass fiber filters were used for the impaction surfaces and back-up filter. The large quantity of water generated (approximately 4 × 10^5 g of water/g of particles) made particle size measurements difficult. For this reason, cascade impactor measurements were only made with the furnace running fuel-rich when particle concentrations were much higher.

Carbon Analysis. Most filters were analyzed for both organic and elemental carbon by the method of Cadle, *et al.*[8] Samples were collected for carbon analysis on 47-mm quartz fiber filters which were preheated overnight at 500°C. The analysis consisted of heating a 1-cm^2 filter section to 650°C in helium. Organics were volatilized and catalytically oxidized to CO_2. During the second stage of the analysis, air entered the system and the elemental carbon was oxidized to CO_2. The CO_2 concentration from the two stages can be related to the organic and elemental carbon concentrations, respectively. A problem inherent in this technique is that the organic carbon may char and be measured as elemental carbon. Therefore, the carbon numbers presented in this paper represent 'apparent organic' and 'apparent elemental' carbon.

Extractables and Benzo(a)pyrene. The analysis for benzo(*a*)pyrene (B*a*P) has been described previously.[9] A glass fiber filter was extracted in benzene-ethanol and taken to dryness to determine the extractable fraction. The extract was re-extracted in hexane-methylene, dried, and dissolved in acetonitrile. An aliquot was injected into a liquid chromatograph with a Zorbax ODS column and the B*a*P fluorescence measured.

Nitrate and Sulfate. A few filter and impinger samples were analyzed for nitrate and sulfate. Impinger samples were analyzed directly. Glass fiber filters were extracted ultrasonically in 10 mL of deionized water. Nitrate and sulfate concentrations were determined using ion chromatography as described by Small, *et al.*[10]

Results

Filterable Mass Emissions

A summary of the filterable mass emission results is given in Table I. The emission rate as a function of fuel, stoichiometry, cycling, and appliance type will be discussed. The laboratory results and residential sampling results were very similar so all results will be considered together.

Table I. Average filterable mass emissions from gas appliances.

Appliance[a]	Fuel[b]	Flame color	Operation	No. tests	Filterable mass (ng/J)
1	LPG	blue	continuous	8	0.31
1	LPG	blue	cyclic	3	0.17
1	LPG	yellow	continuous	2	0.37
1	LPG	yellow	cyclic	3	0.22
1	LPG	luminous	continuous	5	10
1	LPG	luminous	cyclic	1	5.1
1	methane	blue	continuous	2	0.11
1	methane	yellow	continuous	2	0.054
1	methane	luminous	continuous	2	3.2
2	methane	blue	continuous	3	0.09
2	methane	blue	cyclic	1	0.25
3	NG	blue	continuous	3	0.06
3	NG	luminous	continuous	1	0.35
4	NG	blue	continuous	1	0.085
4	NG	luminous	continuous	1	4.0

[a] 1. 116 × 10⁶ J/h furnace with four ribbon jets (laboratory).
2. 150-L 42 × 10⁶ J/h hot water heater (laboratory).
3. 174 × 10⁶ J/h furnace with six ribbon jets (residence).
4. 132 × 10⁶ J/h furnace with four slotted jets (residence).

[b] LPG — liquid propane gas.
NG — natural gas.

Fuel. Three types of fuel were used: bottled methane (93% methane) and liquid propane (LPG) were used in the lab, and natural gas (93% methane) was in use at the residences. There is no reason to expect different emissions from bottled methane and natural gas, so they will be considered a single category. However, higher emissions are found from LPG in all tests. The average emission from a properly adjusted methane flame (blue or yellow flame) is 0.092 ± 0.062 ng/J (12 tests). The average emission from a properly adjusted LPG flame is 0.28 ± 0.16 ng/J (16 tests). The LPG emission rate is about three times higher than the average methane emission rate. A similar result can be seen when the appliance runs highly fuel rich (luminous flame). The mean emissions are 2.7 ± 1.8 ng/J (4 tests) for methane and 9.2 ± 3.5 ng/J (6 tests) for LPG. Again, approximately three times higher emissions come from LPG combustion.

According to emission estimates from AP-42, residential furnaces will emit 2–6 ng/J when fueled by methane and 8 ng/J when fueled by LPG. Although it is unclear, AP-42 seems to be referring to filterable particulate. The emissions of filterable particulate found here are considerably lower than AP-42 estimates. The only tests which approach the AP-42 estimate are those made with a highly luminous flame, but this is hardly normal operating procedure. However, these results are similar to the Kalika study[5] in which filterable emissions were measured to be about 0.3 ng/J.

Stoichiometry. A properly adjusted gas appliance has a blue flame. By adjusting the air shutter on each gas jet, the flame color could be varied from very blue to a highly luminous white flame. Tests were run in three different air shutter configurations, resulting in a blue flame (open shutter), a yellow flame (partially closed shutter), and a luminous white flame (closed shutter). The results using these three configurations are shown in Table II and are grouped according to fuel type.

Table II. The effect of stoichiometry on filterable emissions.

Flame color	LPG (ng/J)	Methane (ng/J)
Blue	0.28 ± 0.18 (11)[a]	0.10 ± 0.07 (10)
Yellow	0.28 ± 0.11 (5)	0.05 ± 0.01 (2)
Luminous	9.2 ± 3.5 (6)	2.7 ± 1.8 (4)

[a] For this and future tables, the emissions will be listed as a mean value ± a standard deviation. The number of tests is in parentheses.

There is no indication that a blue flame emits less material than a yellow flame. However, when the flame shutter is completely closed, the particulate emissions increase by a factor of 30.

Operation. The furnaces were operated in a cyclic and a continuous mode. A continuous test consisted of igniting the furnace, running for 1–2 hours, and turning the furnace off. During a cyclic test, the furnace was turned on and off several times during air sampling. The furnace cycles were 3 min on/3 min off, 5 on/5 off, or 10 on/5 off. These tests were run to determine whether large amounts of particulate matter are emitted during ignition or shut down. The results are shown in Table III for operations with a blue or yellow flame. Fuels used were LPG for the furnace tests and methane for the hot water heater tests. Obviously, there is no indication of increased emissions during cyclic operation of the furnace. This was surprising since the filters were visibly darker after a cyclic run compared to a continuous run, but the mass was seemingly unaffected. There may be a burst of carbon soot during ignition that colors the filter but does not noticeably affect the mass. There is a suggestion of increased emissions during cyclic operation of the hot water heater although only one cyclic test was made.

Table III. Effect on operation on filterable emissions.

	Continuous (ng/J)	Cyclic (ng/J)
Furnace	0.33 ± 0.19 (10)	0.20 ± 0.04 (6)
Hot water heater	0.088 ± 0.53 (3)	0.25 (1)

Appliance Type. Three types of furnaces were tested, two gas furnaces with ribbon burners and a gas furnace with a slotted burner, and one hot water heater. The average emissions for each appliance operating under normal conditions on methane are shown in Table IV.

Table IV. Effect of appliance type on filterable emissions.

	(ng/J)
Furnace 1—ribbon	0.079 ± 0.030 (4)
Furnace 2—ribbon	0.063 ± 0.050 (3)
Furnace 3—slotted	0.086 (1)
Hot water heater	0.088 ± 0.053 (3)

The emission levels from the four appliances are quite similar. All of the appliances were new except Furnace 2, which was 6 years old. Neither appliance type nor age appeared to have an effect on emissions.

Size Spectrum of Particulate Emissions. The small mass emission rates combined with the huge quantities of water present made size distribution measurements difficult. A few cascade impactor measurements were made with the furnace operating highly fuel-rich. The results of two tests are shown in Figure 2. Obviously, nearly all the mass is on the backup filter, indicating a mass median diameter of less than 0.4 μm. There is no significant size difference between emissions from LPG and methane.

Carbon Content of Filterable Particulate. Eighteen filters were analyzed for organic and elemental carbon. The results are shown in Table V. During normal operation with a blue flame, most of the carbon is organic. During fuel-rich operation, nearly all of the mass can be accounted for with elemental carbon. Two samples were collected at the chimney exit where the exhaust gas was considerably cooler (90°C compared to 170°C). These two samples showed a much higher organic carbon content, indicating that some volatile compounds may have condensed after cooling.

As mentioned earlier, the filters taken during a cyclic run were darker than those taken during a continuous run. The three continuous tests had a mean elemental carbon content of 1%, while the three cyclic tests had a mean elemental carbon content of 10%. Apparently there is a burst of carbon soot during ignition, but it still comprises a small portion of the total weight.

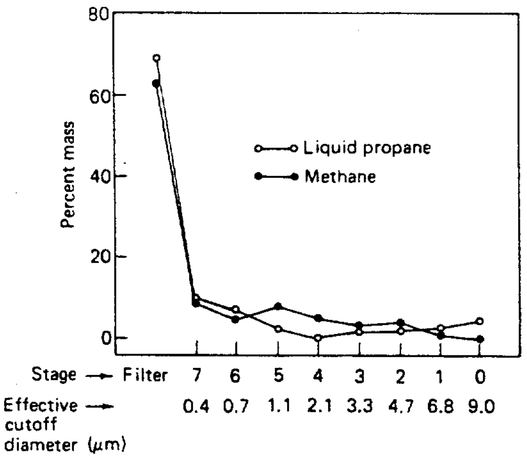

Figure 2. Particle size distribution from furnace during fuel-rich condition.

The only other carbon measurements that have been made were done by Hansen, *et al.*[11] They proposed total C emission factors of 0.003–0.007 ng C/J for commercial use of natural gas and 0.2–2.5 ng C/J for domestic use of natural gas. This was based on an analysis of particulate collected on a hot filter. Emission values from this work for domestic use are much lower, approximately 0.001–0.06 ng/J for a properly regulated flame and 0.3–12 ng/J from a very fuel-rich situation.

Table V. Carbon content of furnace particulate.

	% Organic C		% Elemental C	
	Avg.	Range	Avg.	Range
Blue flame	8 (10)	0–27	4 (10)	0–21
Blue flame, chimney	40 (1)		8 (1)	
Luminous flame	5 (6)	0–8	89 (6)	20–110
Luminous flame, chimney	33 (1)		46 (1)	

% Extractable and Benzo(a)pyrene. The extractable fraction and BaP levels were determined on seven filter samples. The extractable fraction varied from 0–4%. This is consistent with the organic carbon composition of less than 10%. Of the three samples collected for BaP analysis when operating with a blue flame, only one had a measurable concentration of 3.9 ppm. Samples collected during very fuel-rich conditions had BaP levels of 15, 19, and 32 ppm (LPG) and 160 ppm (methane). This is equivalent to 0.14–0.67 pg/J under rich conditions.

Sulfate and Nitrate. Since carbon accounted for such a small fraction of the emission mass, four filters and two background filters were analyzed for sulfate and nitrate. The average nitrate emission was 0.018 ± 0.0009 ng/J, comprising about 12% of the total mass. The average sulfate emission was 0.06 ± 0.10 ng/J, comprising 43% of the total mass. Therefore, more than half of the particulate collected is nitrate or sulfate. This accounts for about 2% of the S added to the propane and 0.02% of the NO_x emissions.

During two of the tests, a second filter holder was placed behind the first. The nitrate and sulfate levels were as high on the second filter. This indicates that the particles are forming as the gas cools or that artifact formation is taking place on the filter. Based on studies by others, it is quite conceivable that *all* of this sulfate and nitrate is due to artifact formation on the glass fiber filter.[12,13]

Condensable Particulate

Twelve tests were run to assess the importance of condensable material. Two water-filled impingers beyond the filter were used to collect the condensables. Several background samples were also run. Results of the tests are shown in Table VI. Background values were subtracted from all test values. The appliances and fuels are the same as shown in Table I.

Based on this data set, there is no obvious difference in condensable emissions with different fuels, flame chemistry, or furnace operation. Despite there being a large range of values and a significant background level, it is still obvious that the condensable material far outweighs the filterable material collected under normal operation. If the condensable particulate is taken into account, the emission level of 2–8 ng/J cited by AP-42 seems quite appropriate.

Since sulfate and nitrate were such large contributors to the filterable particles, four impinger collections were also analyzed for these species. The average NO_3^- condensable emission was 1.1 ± 0.2 ng/J which accounted for 30% of the mass. The $SO_4^=$ emission was 1.7 ± 0.2 ng/J which accounted for 40% of the mass. As with the filters, the majority of the particulate collected in the impingers was $SO_4^=$ or NO_3^-.

The backup impinger had 80% as much $SO_4^=$ and 60% as much NO_3^- as the first impinger. It becomes difficult to determine how much of these species are actually particles and how much are artifacts formed in the impingers. It is unlikely that SO_2 will oxidize to $SO_4^=$ by bubbling through deionized water since some type of catalytic agent is necessary for SO_2 conversion. However, based on the sulfur content of the propane (1.1 ng S/J), about 50% of the fuel sulfur is collected as $SO_4^=$. It seems surprising that half of the sulfur would be emitted as SO_3 and half as SO_2. No explanation is available for the apparent high $SO_4^=$ formation. On the other hand, only 1–2% of the NO emissions were collected as nitrate, which corresponds more closely to other source measurements.

The problem of artifact formation will not be resolved here. However, it is obvious that major portions of the collected particles are sulfate and nitrate. There is a strong probability that the variability in others' results comes from two problems: (1) the proportion of material collected on a hot filter com-

Table VI. Condensable furnace emissions.

Appliance	Fuel	Flame	Operation	No. tests	Avg. (ng/J)	Range (ng/J)
1	LPG	blue	continuous	5	1.8	0.76–3.1
1	LPG	blue	cyclic	3	2.8	0.48–6.4
1	LPG	luminous	continuous	2	4.2	1.7 –6.7
1	LPG	luminous	cyclic	1	3.8	
4	NG	blue	continuous	1	4.2	
4	NG	blue	cyclic	1	5.6	
4	NG	luminous	continuous	1	3.9	

Table VII. Variations in furnace gaseous emissions with stoichiometry.

	Blue flame	Yellow flame	Luminous flame
HC (ppm)	<2	<2	<2
CO (ppm)	13	13	25
CO_2 (%)	1.5	1.5	1.5
NO (ppm)	57	13	10

pared to that which condenses downstream and (2) the degree of artifact formation taking place. These problems can become a dominating influence when studying a source such as a gas furnace which has extremely low particle emissions.

Gaseous Emissions

Carbon dioxide and carbon monoxide were measured during every laboratory test, and hydrocarbons and nitrogen oxides were measured intermittently. The variation of gas concentrations as a function of stoichiometry are shown in Table VII, with LPG as the fuel. Hydrocarbons were always below the detection limit. Carbon dioxide concentration is only a function of the fuel consumption, not the air-to-fuel ratio. Carbon monoxide concentrations were enhanced slightly under fuel-rich conditions, but not sufficiently to show up as a decrease in CO_2. Nitrogen oxide was highest with the fuel-lean flame, as expected, since this is the hottest flame.

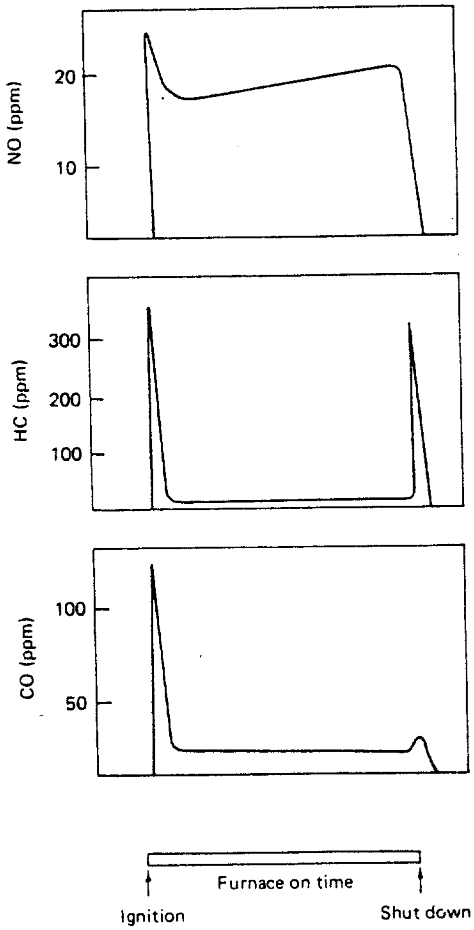

Figure 3. Effect of cycling on gaseous emissions.

There is difficulty involved in determining mass emission rates of gases because the gases, unlike the particles, are highly influenced by the on and off cycling of the furnace. The approximate change in the gas concentrations with cycling are shown in Figure 3. Nitrogen oxide showed a small initial spike and a gradual increase as the temperature rose. Hydrocarbons and carbon monoxide show large concentration spikes during ignition and shutdown. This is especially important for the hydrocarbon emission rate since the intermediate concentration approaches zero.

The mass emission rates found in this study and three other studies are shown in Table VIII.[3,5,6] Nitrogen oxides are reported as nitric oxide which is the predominant species at the source. Hydrocarbons are reported as methane. The CO and NO_x values found in this study are slightly higher than the other three studies. Another study by the Gas Association found NO emission levels of 35 ng/J after sampling many furnaces, in excellent agreement with this study.[14] The hydrocarbon emission rate in this study is based on a concentration of 100 ppm for 30 sec of cycling and less than 1 ppm for 10 min of continuous operation. The hydrocarbon values from the literature show the widest variation, most likely due to the cycling fluctuations.

Table VIII. Comparison of gaseous emission rates from this study and three other studies (ng/J).

	This study	Hall, *et al.*[6a]	Kalika, *et al.*[5b]	AP-42[3b]
CO	35	12	26	8.6
NO	37	25	32	22
HC (CH_4)	~5	0.8	34	3

[a] These numbers were converted from g/10^6 cal.

[b] These numbers were converted from lb/10^6 ft^3; NO_x which was reported as NO_2, is reported here as NO.

Discussion

Filterable particulate emissions from gas appliances are extremely low, approximately 0.09 ng/J from natural gas combustion and 0.28 ng/J from propane combustion. About 60% of the filtered particulate is nitrate or sulfate, which may be artifacts formed on the filter. Elemental carbon (4% of the particulate) and organic carbon (8%) make up some of the remainder. The remaining material may be largely water. The higher emissions from propane may simply be due to the higher level of sulfur odorant added to the propane rather than to the natural gas (0.17 ng/J sulfur in natural gas and 1.1 ng/J sulfur in propane).

Table IX. A comparison of daily emissions from furnaces and automobiles.

	Emission factors		Daily emission rates	
	furnace ng/J	auto g/mi	furnace g/day	auto g/day
Total particles	4	0.040[a]	3.5	1.1
CO	30	7[b]	26	190
NO	36	2[b]	31	54
HC	5	0.41[b]	4	11

[a] Ref. 4.

[b] 1980 emission requirements.

Stoichiometry appears to have little effect until the air shutter is completely closed and the flame becomes luminous. At that point, high elemental carbon emissions (2.7 ng/J natural gas and 9.2 ng/J propane) and benzo(*a*)pyrene levels, which are usually negligible, also become significant. The emitted particles are very small, with a mass median diameter of less than 0.4 μm.

Condensable particulate emissions are approximately 4 ng/J, a value which overwhelms filterable emissions and is more in line with the AP-42 emission estimate. Approximately 70% of this material is nitrate or sulfate. There is not enough information available to conclude if there is artifact formation occurring.

Gaseous emissions show large variations, both as a function of flame condition and furnace operation. In particular, carbon monoxide and hydrocarbons show large spikes during ignition and shutdown. The gaseous emission levels found here are similiar to those found in other studies.

One way to place these numbers in perspective is to compare daily furnace emissions to daily automobile emissions for a single household. The annual U.S. residential natural gas usage is about 1.4×10^{11} m^3 spread over 42×10^6 users.[1] This is approximately 3300 m^3 or 1.3×10^{11} J/user/yr. If there are 150 heating days in a year, the daily usage is 8.7×10^8 J. The average family car is driven 10 000 mi/yr or 27 mi/day. The emissions factors and the daily emissions rates are shown in Table IX. In a given day, particulate emissions from a furnace are significantly higher than from an automobile. Surprisingly, furnace gaseous emissions are a significant fraction of automotive emissions. For example, the daily NO emissions from a furnace are 57% of the daily emissions from an automobile. Of course, on an annual basis furnace emissions become a smaller fraction since furnace use is seasonal. But, in winter when air stagnation is common, residential gas usage may contribute to the pollution burden of many local areas.

Acknowledgments

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Dr. Muhlbaier is Senior Research Scientist, Environmental Science Department, General Motors Research Laboratories, Warren, MI 48090

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[illegible] Hildemann, [illegible]
SPRCP, December 1981

- Furnaces:

Application

1 [illegible] (110,000 Btu/hr) furnace [illegible] ribbon [illegible]
3 [illegible] 165,000 Btu/hr furnace [illegible] 3 ribbon [illegible]
4 F[illegible] 80,000 Btu/hr furnace [illegible]

- Fuel
  [illegible]
  [illegible]
  [illegible] different
  [illegible] wetted [illegible]
  natural gas [illegible] must be
  [illegible] single category"

- "proposed [illegible]" [illegible]
  [illegible]

- "[illegible]" conditions [illegible]

- [illegible] [illegible]
  - Luminaire [illegible] [illegible] overhead [illegible]
    [illegible] [illegible]

- [illegible] PM Emission
  - From Table IV: Average [illegible] emission under normal operating conditions

Furnace 1: [illegible] × [illegible] × [illegible] = [illegible]

Furnace 2: [illegible] × [illegible] = .15 [illegible]

Furnace 3: [illegible] × [illegible] = [illegible]

- Condensable PM emission: [illegible] Table V.

Furnace [illegible]: [illegible] = [illegible] × [illegible] = [illegible]

[illegible] the [illegible] Furnace [illegible]
[illegible] Table VIII,
[illegible] Summary - Avg [illegible] Do [illegible]

CO: [illegible] * $\frac{lb/10^6 Btu}{[illegible]}$ * [illegible] $\frac{Btu}{hr}$ = 85 $\frac{lb}{hr}$

NO: [illegible] * $\frac{lb/10^6 Btu}{[illegible]}$ * [illegible] $\frac{Btu}{hr}$ = [illegible] $\frac{lb}{hr}$ NO

as NO_2 [illegible] * $\frac{46}{30}$ = 35[illegible] $\frac{lb}{hr}$ NO_2

THC = [illegible] = 12 $\frac{lb}{hr}$ THC

CO_2: [illegible] * [illegible] * [illegible] = [illegible]

= 115.9 $\frac{lb}{10^6 Btu}$ * [illegible] $\frac{Btu}{hr}$ = [illegible],800 $\frac{lb}{hr}$ CO_2

SOURCE CATEGORY: Natural Gas

EXCLUSION CRITERIA CHECKLIST

REFERENCE Particulate and Gaseous Emissions From Natural Gas Furnace and Water Heaters JAPCA, December 1981 by J.L. Muhlbaier

CRITERIA	YES	NO
1. Test series averages are reported in units that can be converted to the selected reporting units?	✓	
2. Test series represent compatible test methods?	✓	
3. In tests in which emission control devices were used, the control devices are fully specified?	✓	
4. Is it clear whether or not the emissions were controlled (or not controlled)?	✓	

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Date 5/27/92

INDICATE WHETHER ANSWER IS YES OR NO WITH AN "X" IN APPROPRIATE BOX.

IF ALL ANSWERS ARE "YES" PROCEED TO **METHODOLOGY/DETAIL CRITERIA CHECKLIST.**

SOURCE CATEGORY N6

METHODOLOGY/DETAIL CRITERIA CHECKLIST

REFERENCE Evaluation of Gaseous Emissions...

CRITERIA	YES	NO	COMMENTS
1. Is the manner in which the source was operated well documented in the report?	✓		
Was the source operating within typical parameters during the test?	✓		
2. Did sampling procedures deviate from standard methods?		✓	
If so, were the deviations well documented?			
Were the deviations appropriate?			
Comment on how any alterations in sampling procedure may have influenced the results.			
3. Were there wide variations in the results?	✓		Only results for blue and yellow flame considered as "normal conditions"
If yes, can the variations be adequately explained by information in the report?			
If the variations are not well explained, should the data be considered of poor quality?			
4. Do the test reports contain the raw data sheets?		✓	
Are the nomenclature and equations used equivalent to those specified by the EPA?	✓		
Comment on the consistency and completeness of the results.	✓		Results are consistent and complete except for raw data sheets

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INDICATE YES OR NO WITH AN "X" IN THE APPROPRIATE BOX. FILL IN COMMENTS.

IF, BASED ON ABOVE ANSWERS, THE SOURCE REPORT PROVIDES ADEQUATE DETAIL AND DEMONSTRATES SOUND METHODOLOGY, PROCEED TO RATING THE DATA IN THE RATING CRITERIA CHECKLIST.

SOURCE CATEGORY Nat Gas

RATING CRITERIA CHECKLIST

Reference Particulate and Carbon Emissions from Natural Gas Furnaces and Water Heaters

	RATING CRITERIA	YES	NO
A	Tests performed by a sound methodology and reported in enough detail for adequate validation?		✓
B	Tests were performed by a generally sound methodology, but not enough detail for adequate validation?	✓	
C	Were tests based on untested or new methodology that lacks significant amount of background data?		✓
D	Were tests based on generally unacceptable methods, but may provide order-of-magnitude values for the source?		✓

COMMENTS

Overall rating of B applied to all data due to lack of raw data sheets and other validation information

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Date 5/91

BASED ON ANSWERS AND COMMENTS ABOVE, ASSIGN A RANK TO THIS LITERATURE SOURCE:

B

RANK ASSIGNED TO EMISSION SOURCE DATA

PM, CO, CO2, NO, HC