#5071

BASELINE CHARACTERIZATION OF COMBUSTION PRODUCTS AT THE GRI CONVENTIONAL RESEARCH HOUSE

FINAL REPORT

(October 1987 - May 1988)

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16. Abstract (Limit: 200 words)

The Gas Research Institute has arranged to conduct a series of experiments in an unoccupied research house to evaluate indoor air quality in relation to various space-conditioning systems and control strategies. Baseline trace combustion product characterization experiments were completed, and a detailed analysis of experiment results was performed. Results of the baseline characterization and unvented space heater experiments were compared with previously acquired data at other houses. Results show a low NO_2 decay constant and a moderate infiltration rate. A blower door test and perfluorcarbon tracer gas experiments were also performed. Results of these experiments confirm an average to low infiltraton rate for this house and are consistent with results obtained by the SF_6 tracer decay method. Range hood experiments show effective capture of range emissions but poor capture of oven emissions, due to the location of the oven away from the range and hood. The emission rates of combustion products from the range, oven, and fan forced unvented space heater were determineded using a probe test and a hood test. Emission rates for appliances were within the expected range based on published results.

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Research Summary

Title	Baseline Characterization of Combustion Products at the GRI Conventional Research House.
Contractor	Chamberlain GARD GRI Contract Number: 5087-254-1507
Principal Investigator	N. P. Leslie
Report Period	October 1987 - May 1988 Final Report
Objective	To characterize the indoor air quality in the Conventional Research House located in Chicago, Illinois.
Technical Perspective	Indoor air quality continues to be an important issue to the gas industry, the general public, and the scientific and regulatory communities. A reliable and current information base is needed, characterizing the residential environment, rates of significant indoor emission of combustion products from gas appliances and other sources, and the ultimate fate of these emissions. Evaluation of contaminant levels and their distribution in relation to various space-conditioning systems and control strategies as well as emission mitigation techniques will provide valuable information.
Results	Baseline contaminant level characterization tests were completed, and a detailed analysis of test results was performed. Results of the baseline characterization and unvented space heater tests were compared with previously acquired data at other houses. Results show a low NO_2 decay constant and a moderate infiltration rate. A blower door test and perfluorcarbon tracer gas tests were also performed. Results of these tests confirm an average to low infiltraton rate for this house and are consistent with results obtained by the SF_6 tracer decay method. Range hood tests show effective capture of range emissions but poor capture of oven emissions, due to the location of the oven away from the range and hood. The emission rates of combustion products from the range, oven, and fan forced unvented space heater were tested using a probe test and a hood test. Emission rates for appliances were within the expected range based on published results.

Technical Approach

The Test Plan identifies tests and protocol for performing each test. Levels of NO_2 and CO in the house were measured during central heating system operation. Special emission tests were performed on UVGSH's and the range and oven. Levels of radon were measured during each test. Vertical distribution of NO_2 was measured using Palmes Tubes. Long term infiltration rates were measured using perfluorocarbon tracers. Emissions from the range and oven were characterized using hood tests. Range, oven, and space heater emissions were measured by an independent laboratory.

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Section 1
INTRODUCTION

The objective of the Gas Research Institute (GRI) indoor air quality and safety program is to identify and assess risks and resolve potential environmental, safety, and health issues related to gas use in the residential and commercial market sectors, with emphasis on indoor air quality in homes. As a first step, a reliable and current information base is needed to characterize the residential environment, including rates of significant indoor combustion product emissions from gas appliances and other sources, and the ultimate fate of these emissions (such as dilution, or adsorption by materials). Relevant performance goals which emphasize indoor air quality in homes include:

- o Characterize (and place into proper perspective with other emission sources) emissions from gas appliances that may affect indoor air quality,
- o Characterize factors other than emission strength (such as dwelling unit characteristics, occupant lifestyle, and equipment usage patterns) that could impact indoor air quality,
- o Assess the risk of using unvented gas appliances compared to alternative equipment, integrating information on emissions, exposure, and health effects, and
- o Develop cost-effective control strategies or other mitigation measures, if needed, for maintaining indoor air quality at acceptable levels.

This program focuses on the Conventional Research House, an unoccupied single story residence of conventional construction with zone control of space conditioning. Selected indoor air quality experiments were conducted to develop information on combustion products, their distribution within the house, and the effectiveness of various mitigation techniques. This project parallels work being done for GRI in the Contemporary Research Houses in Gaithersburg, Maryland, permitting equivalent measurements in both types of houses.

During the period between October 1987 and May 1988 a series of experiments was conducted at the Conventional Research House to characterize indoor combustion products. Each experiment was performed in accordance with protocols specifying systems and appliances to be operated, length of operation, status of interior doors, and technician activities. Experiments included baseline characterization and special tests of the gas range and oven and unvented gas-fired space heaters (UVGSH).

These experiments were designed to examine the critical factors that impact residential air quality, with emphasis on nitrogen dioxide (NO_2) and carbon monoxide (CO). A total of 16 different experiments were performed during the months of October 1987 through May 1988.

Section 2 of this report describes the Conventional Research House and experimental setup along with a description of each experiment. Section 3 summarizes the results of each test. Section 4 presents conclusions and recommendations stemming from the work.

Section 2
TECHNICAL APPROACH

2.1 House Description

The Conventional Research House, located on the northwest side of Chicago, Illinois, is typical of a large segment of existing houses in the East-North-Central region of the United States. Constructed in 1957, the research house is a one-story, detached, single-family dwelling with full basement, 3 bedrooms, and a floor area of 1,150 square feet per floor including hallways. It has half brick veneer and half wood frame, cedar siding, R-12 ceiling insulation, insulated painted plaster walls, weatherstripped wood windows with aluminum storms and screens, weatherstripped wood doors with storm doors, and a 2-car detached garage with a small office. An insulated, sealed wall was constructed between the west basement and the furnace room to provide a controlled third zone for zoning tests. The basement floor and exterior walls are uninsulated concrete. All rooms except hallways and furnace room have supply registers, and all rooms except hallways, furnace room and baths have ducted return registers.

For the purposes of testing zoned heating and cooling systems, the house was divided into four zones:

- First floor living room area,
- First floor bedroom area,
- Basement living area, and
- Basement furnace room (uncontrolled).

Combustion product levels were monitored in these four locations plus the kitchen and outdoors to identify local combustion product levels associated with gas appliance use.

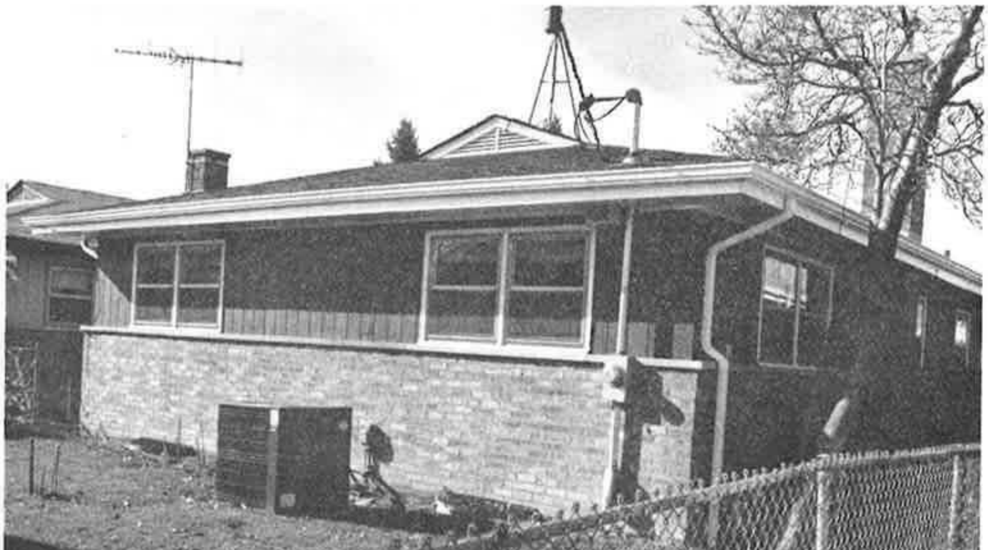
A data acquisition system (DAS) was designed and installed at the research house in accordance with the Research House Utilization Plan[1]. The DAS continuously monitors over 150 parameters using PC-based software. The detached office contains the data acquisition system computer and gas monitoring equipment. A heated underground pipe from the house to the office serves as the conduit for wiring and gas sample tubing. Table 2.1 summarizes the characteristics of the Conventional Research House. Photographs of the house appear in Figure 2.1. The floor plans of the house, including locations of gas appliances, space conditioning equipment and IAQ monitoring locations, are shown in Figure 2.2. Appendix D contains photographs of the house, DAS, and test apparatus.

TABLE 2.1

CONVENTIONAL RESEARCH HOUSE CHARACTERISTICS

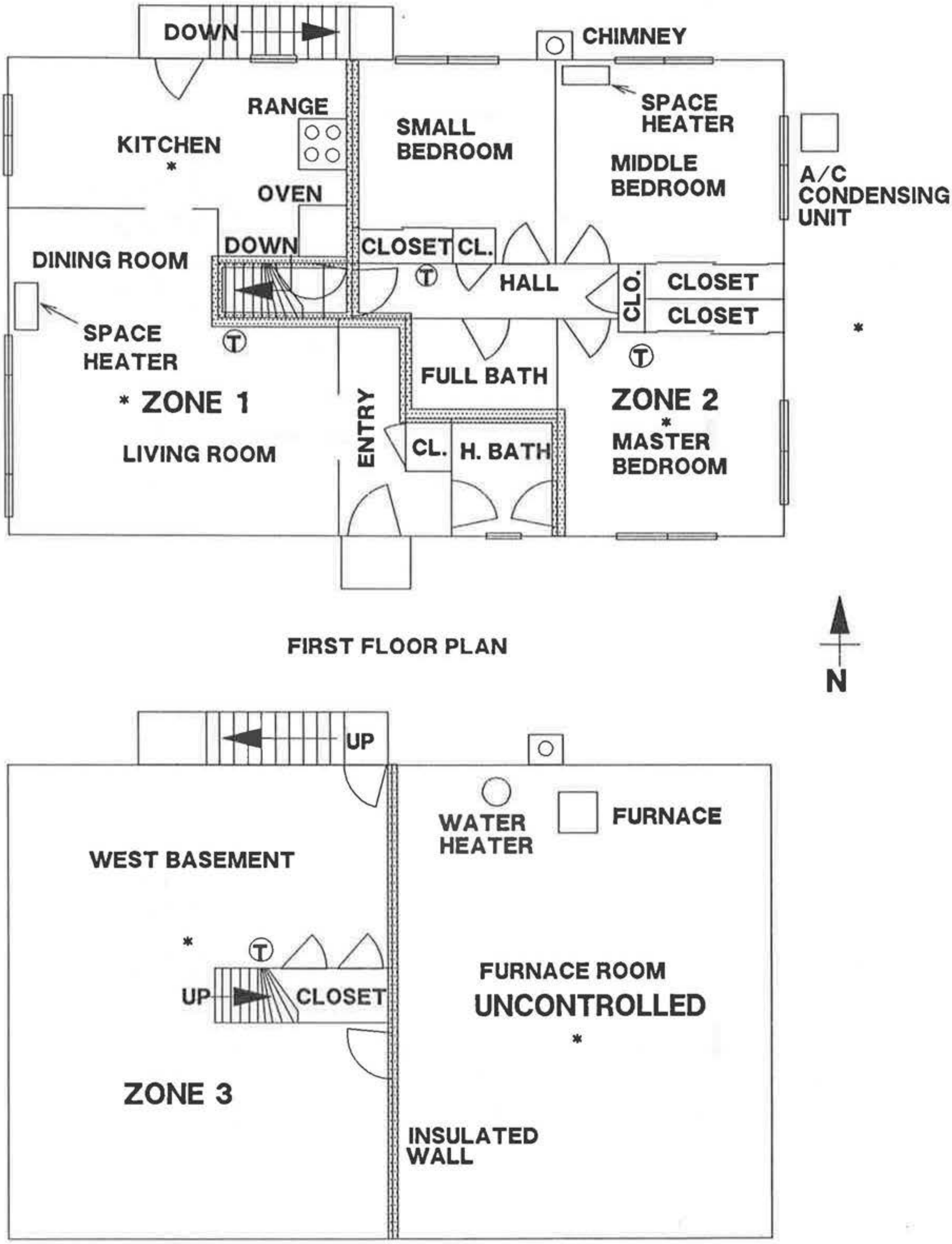
Location	Chicago, Illinois	
Year Constructed	1957	
Style	One-Story with Full Basement 3 Bedrooms, 1-1/2 Bath 2-Car Detached Garage with Office	
Floor Area	1,150 ft^2 per Floor	
	Living Room	592 ft^2
	Bedroom	558 ft^2
	West Basement	575 ft^2
	Furnace Room	575 ft^2
Construction	Half Brick Veneer, Half Cedar Frame R-12 Ceiling and Wall Insulation Painted Plaster Walls Wood Double-Hung Windows, Wood Doors Weatherstripped Storm Windows and Doors Uninsulated Concrete Basement	
Space Conditioning	Gas Forced Air HeatPipe Furnace 1,050 cfm Air Flow Rate 73,500 Btu/h Input, 82% Efficiency 2-Speed Compressor with A-Coil 30,000/22,000 Btu/h Output, SEER 12.45	
Zone Volumes (Excluding/Including Closets, Cabinets, Furnishings and Appliances)		
	Living Room	4,160/4,375 ft^3
	Bedroom	3,688/4,126 ft^3
	West Basement	4,092/4,120 ft^3
	Furnace Room	4,114/4,120 ft^3
	Total House	16,054/16,741 ft^3

VIEW LOOKING EAST



VIEW LOOKING WEST

FIGURE 2.1 CONVENTIONAL RESEARCH HOUSE



* IAQ CONTINUOUS MONITORING LOCATION

BASEMENT FLOOR PLAN

FIGURE 2.2 CONVENTIONAL RESEARCH HOUSE FLOOR PLANS

2.2 Indoor Air Quality Monitoring Plan

To ensure the highest level of comparability of the IAQ measurements conducted at the Contemporary and Conventional Research Houses, an Indoor Air Quality Monitoring Plan, Appendix C of this report, was prepared for GARD by GEOMET Technologies, Inc., the Contemporary Research House contractor. The Plan, based on GEOMET's experience and previous testing at its research houses, specifies the experiments which were performed and the general procedures which were followed in the conduct of those experiments. The Plan includes:

- Measurement locations, parameters, and frequencies,
- Equipment specifications,
- Experiment plan for baseline measurements,
- Plans for specialized experiments, and
- Quality assurance procedures.

In accordance with the Plan, parameters were monitored continuously for the outdoor environment, indoor/outdoor exchange, indoor environment, combustion products, gas usage, and appliance status. Air quality monitoring stations for the DAS were located in the living room, kitchen, master bedroom, basement living area, furnace room, and outdoors. Palmes Tubes were placed in each room during special tests to measure integrated NO_2 concentrations over an extended period (e.g., 4 days). Radon was measured using charcoal canisters, and perfluorocarbon tracer gas measurements were taken to determine the long term infiltration rate and interzonal air flows. Table 2.2 identifies the major measurement parameters and techniques used during the experiments.

Measurements for outdoor and indoor environments (except gaseous combustion products) were scanned every 5 seconds and hourly averages were recorded. Gaseous combustion products in each of the 6 sampling locations were recorded every 15 minutes. Natural gas consumption was recorded hourly using the DAS and validated with manual readings at the beginning and end of special tests.

Indoor/outdoor air exchange was measured by the SF_6 tracer dilution method, in accordance with the American Society for Testing and Materials (ASTM) Method E741-80. GARD developed an automated injection system which was programmed to release SF_6 into each room of the house manually prior to starting special tests and when the remaining concentration in the living room zone fell to a specified level. SF_6 was measured at each of the indoor zones plus outdoors once every hour.

TABLE 2.2

MEASUREMENT PARAMETERS AND TECHNIQUES

Parameter	Technique
Outdoor Environment	
Temperature	Thermistor
Relative Humidity	Thin Film Capacitance
Windspeed/Direction	Anemometer/Vane
Solar Radiation	Pyranometer
Barometric Pressure	Piezoresistive Sensor
Indoor/Outdoor Air Exchange	
Whole House Infiltration Using SF_6 Decay	Gas Chromatography Electron Capture Detection
Interzonal Air Flows	Perfluorocarbon Tracers
Indoor Environment	
Temperature	Thermistor
Relative Humidity	Thin Film Capacitance
Gases	
Carbon Dioxide (CO_2)	Nondispersive Infrared (NDIR)
Carbon Monoxide (CO)	NDIR
Nitrogen Dioxide (NO_2)	Palmes Tubes
Nitrogen Oxides (NO,NO_x)	Chemiluminescence
Radon	Charcoal Canisters
Energy	
Natural Gas Consumption	Dry Gas Meter
Status	
HVAC System	Relay Closure
UVGSH, Appliances	Manual Record

2.3 Description of Experiments

The experiments performed during the 1987-1988 heating season were designed to characterize the baseline conditions in the research house and to characterize the emission rates of UVGSH's and gas appliances. Information was also obtained on combustion product decay rates and vertical and zonal distribution of combustion products throughout the house. Five types of experiments were conducted:

- o Baseline Heating,
- o Unvented Space Heaters in Living Room,
- o Range and Oven Operation,
- o Source Emissions from Range and Oven, and
- o Source Emissions from Fan Forced Convective UVGSH.

Table 2.3 shows the schedule of experiments and dates. The following paragraphs further describe each experiment.

2.3.1 Baseline Central Heat

The modulating furnace (Figure 2.3) in modulating central heat mode was used as the baseline heating system during 3 one-week tests (2/26/88-3/3/88 and 3/14/88-3/28/88). Modulating the furnace increased run time during mild weather compared to cycling at full firing rate. The purpose of this test was to characterize the baseline combustion product levels during central heat operation. PFT measurements were conducted with 2 types of PFT sources (Type 1 on the first floor, Type 2 in the basement) during routine operation of the central forced air heating system (2/24/88-2/28/88). Doors between rooms on the first floor were open. Closet doors and the 2 doors between the first floor and the basement were closed. Radon levels were measured in three separate tests, one set of measurements each week (2/29/88-3/3/88; 3/14/88-3/17/88; and 3/21/88-3/24/88). One set of Palmes tubes was used to monitor average NO_2 levels in each zone (2/27/88-3/3/88).

2.3.2 Appliance Simulation During Baseline Central Heat

Appliance simulation was performed 2 days during each week of baseline central heating to study the effect of appliance operation on combustion product levels. Appliance operating conditions and settings followed the test protocol contained in the Indoor Air Quality Monitoring Plan. The right front range burner operated at high setting between 8:15 and 8:45 a.m., with an

TABLE 2.3

SCHEDULE OF EXPERIMENTS BY DATE

Experiment	Days During 1988
Baseline Characterization	
Baseline Central Heat	2/27, 2/28, 3/1, 3/15-3/20, 3/22-3/24
Appliance Simulation During Baseline Central Heat	2/29, 3/2, 3/14, 3/21
Unvented Space Heaters in Living Room	
Blue Flame Convective Heater	3/4-3/6
Radiant Tile Heater	3/6-3/9
Fan Forced Convective Heater	3/9-3/11
Range and Oven Operation	
Without Range Hood Operation	5/11-5/15
With Range Hood Operation	5/19, 5/20, 5/23, 5/24, 5/27
Source Emissions	
Range and Oven	10/87
Unvented Space Heaters	5/86, 6/88

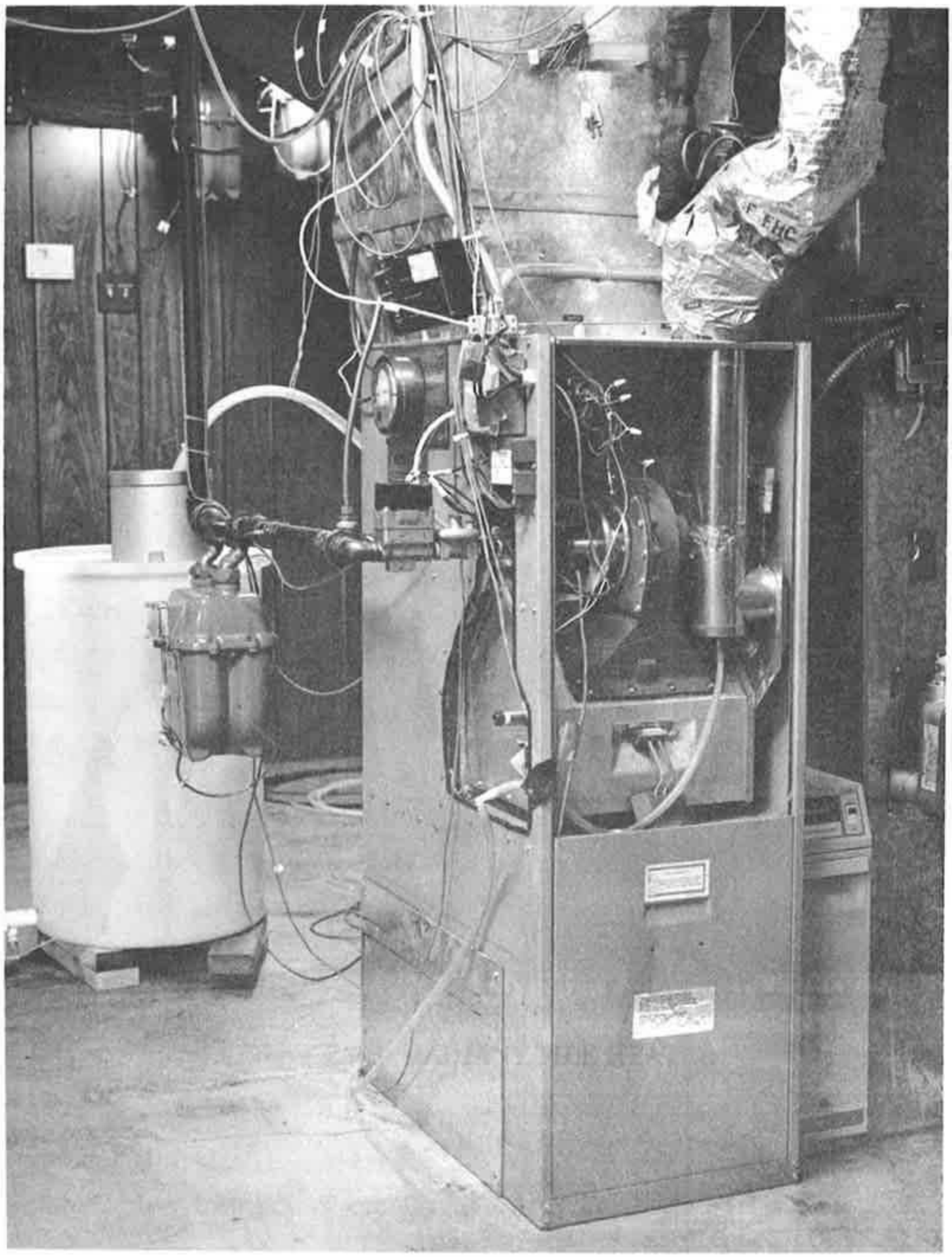


FIGURE 2.3 MODULATING HEATPIPE FURNACE

ANSI-certified combustion utensil used for the pan load. The oven operated at 350°F for 1 hour between 4 and 5 p.m., with a ceramic pot used for the load. The impact of gas water heater and gas dryer usage on combustion product levels during appliance simulation days was also evaluated.

2.3.3 Unvented Gas Space Heaters in Living Room

Combustion product levels associated with unvented space heater operation were examined in an experiment involving sequential operation of 3 different space heaters in the same location in the living room. The following three types of space heaters were used:

- o 10,000 Btu/h blue flame convective heater (3/4/88-3/6/88),
- o 15,000 Btu/h (max.) radiant tile heater (3/6/88-3/9/88), and
- o 14,000 Btu/h (max.) fan forced convective heater (3/9/88-3/11/88).

All 3 heaters are equipped with oxygen depletion sensors (ODS). The heaters used during these experiments were the same heaters used in previous experiments at the Contemporary Research House. The emission rates of the blue flame convective heater and the radiant heater had been previously characterized by the Institute of Gas Technology (see report in Appendix B). The emission rate of the fan-forced convective heater was characterized as a part of this project.

The blue flame convective heater, Sears Model 155.853100 (Figure 2.4), has a ribbon-type burner with a characteristic blue flame combustion. Heat transfer to the space is through free convection out the top of the heater. A manually operated piezoelectric spark igniter ignites the pilot gas which allows main flame through a thermosensor. The heater does not have a thermostat and requires no electricity for operation.

The radiant tile heater, Empire/Corcho Model R15 NAT (Figure 2.5), transfers a significant portion of the heat by infrared radiation. Combustion takes place on the surface of a ceramic tile, which is heated by convection. As the tile becomes hot, it emits infrared radiation. The heater has 3 heat settings: 5,000 Btu/h, 10,000 Btu/h, and 15,000 Btu/h. Ignition and operation are the same as the blue flame convective heater.

The fan forced convective heater, Osaka Gas Model 44-740 Fan Heater 4000 (Figure 2.6), is a blue flame convective heater which uses a fan to improve combustion characteristics and to reduce the discharge temperature to a lower level. A portion of the fan suction draws air through the heat exchanger. The combustion products are mixed with dilution air to reduce the blower discharge temperature to 175°F. The heater has high voltage spark ignition and thermosensor. A 5-stage thermostat controls the firing rate and blower speed. Quick connect gas fittings allow easy

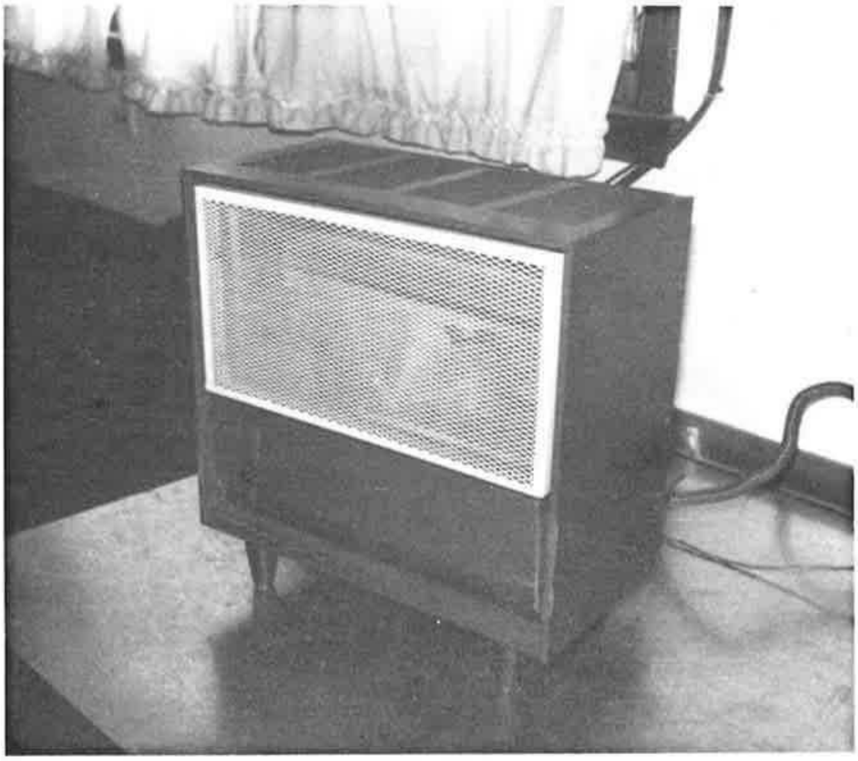


FIGURE 2.4 BLUE FLAME CONVECTIVE HEATER

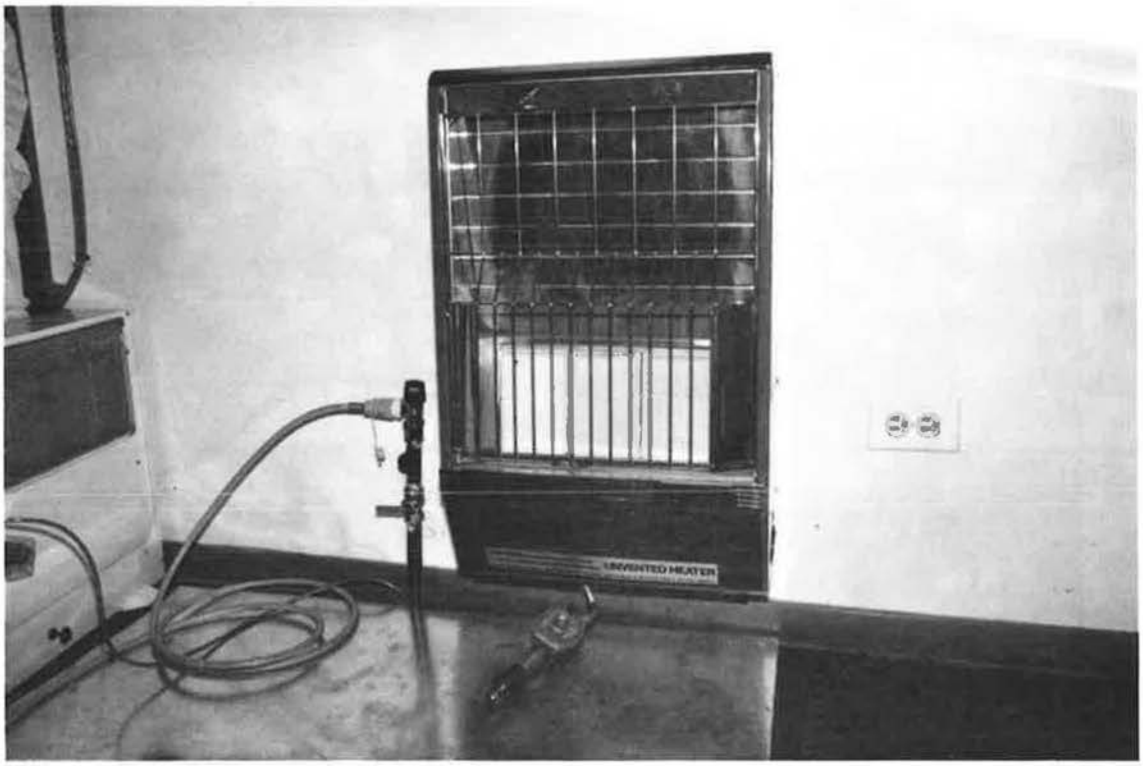


FIGURE 2.5 RADIANT TILE HEATER

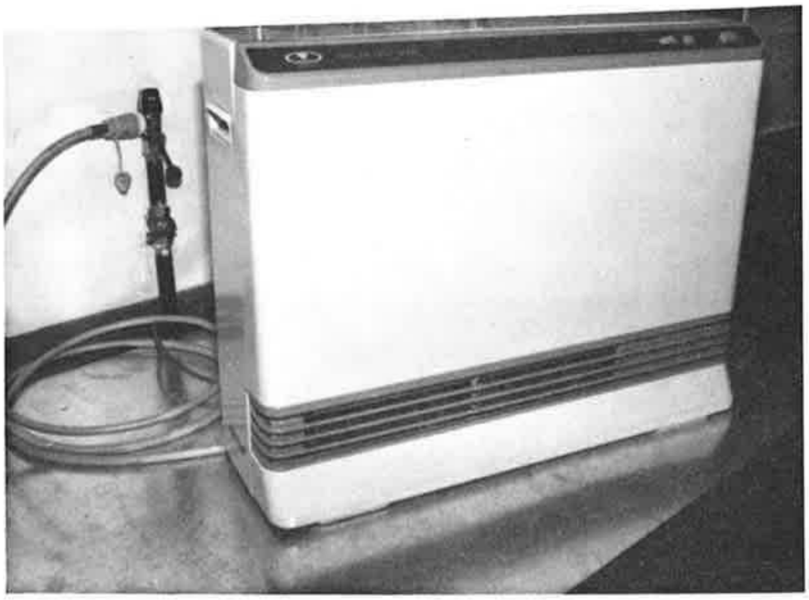


FIGURE 2.6 FAN-FORCED CONVECTIVE HEATER

removal for relocation. The heater requires manual start and does not shut off, but modulates to the lowest heat output as return temperature deviates from setpoint.

The objective of the UVGSH experiment was to compare NO_2, CO, and CO_2 concentrations and decay rates when each UVGSH operated at full firing rate during an 8 hour period as the only source of heat in the house. For comparison, the heaters were operated under the same conditions and in the same location in the living room. During these tests the house was treated as a single-story house with the basement isolated from the upstairs and all interior doors on the first floor open. All windows and exterior doors were closed throughout the experiment. The distribution of NO_2 during operation of the UVGSH's was characterized by the use of vertical arrays of Palmes tubes in all rooms of the house and outdoors. Palmes tubes were present only during operation of the blue flame convective heater and the radiant tile heater (3/4/88-3/9/88). This period provided a consistent set of operating conditions and the opportunity for measurement of detectable levels of NO_2 in different rooms at different heights. Interzonal air flows were characterized during the same period. Radon canisters were deployed for 2 three-day periods (3/4/88-3/7/88; and 3/7/88-3/10/88).

2.3.4 Range and Oven Operation Without Range Hood

Baseline characterizations of the impact of range and oven operation on combustion product levels were conducted over a 5 day period by operating the right front burner, the oven, and a combination of the burner and oven, without range hood operation. Settings and schedules were specified in the IAQ Monitoring Plan. Palmes tubes were deployed throughout the 5 day period to characterize the average NO_2 distribution in the house (5/11/88-5/16/88). PFT measurements were performed over a 4-day period to determine the air exchange rates and the interzonal airflows in the house (5/11/88-5/15/88). Radon canisters were present for a 3-day period during this test (5/11/88-5/14/88).

2.3.5 Range and Oven Operation with Range Hood

The effect of range hood operation on combustion product levels was examined in a series of experiments similar to the baseline range and oven characterizations. During these experiments, the range hood exhaust fan was operated on high speed, with the same protocol for range and oven operation as the baseline characterizations. The objective of these experiments was to examine the effectiveness of the range hood in removing CO and NO_2 emissions from the range and oven. Radon canisters were deployed for a 3-day period (5/19/88-5/22/88) during these experiments.

2.3.6 Source Emissions from Range and Oven

During a 5 day period in October 1987, emission rates for NO, NO_x, NO_2, CO, CO_2 and unburned hydrocarbons (UBH) were determined by direct flue product measurements performed by the Institute of Gas Technology (IGT) on the range-top and oven burners. Standard measurement procedures previously used in other gas range studies were adopted for this test series. Appendix A contains the results of these measurements.

2.3.7 Source Emissions from Fan Forced Convective UVGSH

Source emissions from the blue flame convective heater and the ceramic tile radiant heater were measured by IGT in 1986[2]. Continuous monitoring analyzers and a sampling hood were used by IGT to determine emission factors. IGT performed a similar measurement of the fan forced convective heater at IGT's laboratory during June 1988 to determine source emissions of CO, NO, NO_x, and NO_2. The sampling hood was modified to properly measure the emissions and a more sensitive CO analyzer was required due to the dilution effect of the fan. Appendix B reports the results of these emissions measurements.

2.4 Quality Assurance

Quality assurance (QA) objectives for this program were defined in the IAQ Monitoring Plan. To ensure that the program QA objectives were met, a series of quality control (QC) procedures were implemented in accordance with the Plan, including:

- Operational checks,
- Performance checks,
- Multipoint calibrations, and
- Precision checks.

Routine QC procedures included daily checks of sampling system airflows and appropriateness of data, and weekly multipoint calibrations with standard gas concentrations. Strip chart recorders provided backup for the DAS and were useful for range verification checks. Thermistors, humidity sensors and meteorological instruments were compared with NBS-traceable devices before and after the test period.

Section 3
RESULTS

Baseline characterization of combustion products in the Conventional Research House focused primarily on 2 combustion products: NO_2 and CO. Detailed information was gathered on these combustion products for each experiment. In addition, longer term average concentrations of radon and NO_2 were determined. The results of baseline experiments discussed below include:

- o Pollutant levels during baseline operation,
- o Comparison of UVGSH's under similar operating conditions,
- o Spatial variations in indoor NO_2 concentrations, and
- o Effect of range hood operation on pollutant levels.

Table 3.1 summarizes outdoor air temperatures, air infiltration rates, and hourly gas consumption rates during each of these experiments. Table 3.2 lists peak pollutant levels measured during each of the 7 experiments.

3.1 Combustion Product Levels During Baseline Operation

The baseline characterization included 3 modes of operation: central heat without appliance simulation; central heat with appliance simulation; and no heat and no appliance simulation. The first identifies the combustion product levels associated with pilot lights and furnace operation. The second experiment examines the impact of range, oven, and water heater operation. The third experiment shows the impact of pilot lights alone.

TABLE 3.1

OUTDOOR TEMPERATURES, AIR INFILTRATION RATES, AND FUEL CONSUMPTION RATES FOR EACH EXPERIMENT

Experiment	Range of Outdoor Temperatures (°F)	Average Infiltration Rate (ACH)	Gas Consumption Rate (Btu/h)
Baseline Furnace Operation			
Central Furnace	18 to 68	0.36	80,900
Appliance Simulation	20 to 50	0.23	80,900
UVGSH in Living Room			
Convective Heater	22 to 47	0.24	11,100
Radiant Heater	27 to 56	0.22	15,500
Fan Forced Heater	27 to 59	0.21	14,000
Range and Oven Operation			
Without Range Hood	41 to 80	0.13	
With Range Hood	43 to 83	0.19	
Appliance Gas Consumption			
Range RF Burner (High)			10,000
Oven (Peak Input)			20,300
Oven (at 350°F)			9,300
Range and Oven Pilot Lights (3)			500
Water Heater			28,200
Water Heater Pilot Light			800

TABLE 3.2

PEAK COMBUSTION PRODUCT CONCENTRATIONS

Experiment	Living Room		Master Bedroom		West Basement		Outdoor Air	
	CO (ppm)	NO_2 (ppb)	CO (ppm)	NO_2 (ppb)	CO (ppm)	NO_2 (ppb)	CO (ppm)	NO_2 (ppb)
<u>Baseline</u>								
Central Furnace	3.5	63	3.5	60	4.1	45	5.2	56
Appliance Simulation	8.7	175	3.3	175	3.1	62	2.8	60
<u>UVGSH in Living Room</u>								
Convective Heater	5.1	942	5.0	1,005	4.7	35	5.2	78
Radiant Heater	17.1	584	17.7	623	4.0	32	5.5	63
Fan Forced Heater	4.2	186	4.1	187	3.8	26	5.8	59
<u>Range and Oven Operation</u>								
Without Hood	10.8	403	10.5	404	2.8	29	4.3	79
With Hood	4.5	220	4.4	191	1.3	24	1.8	97

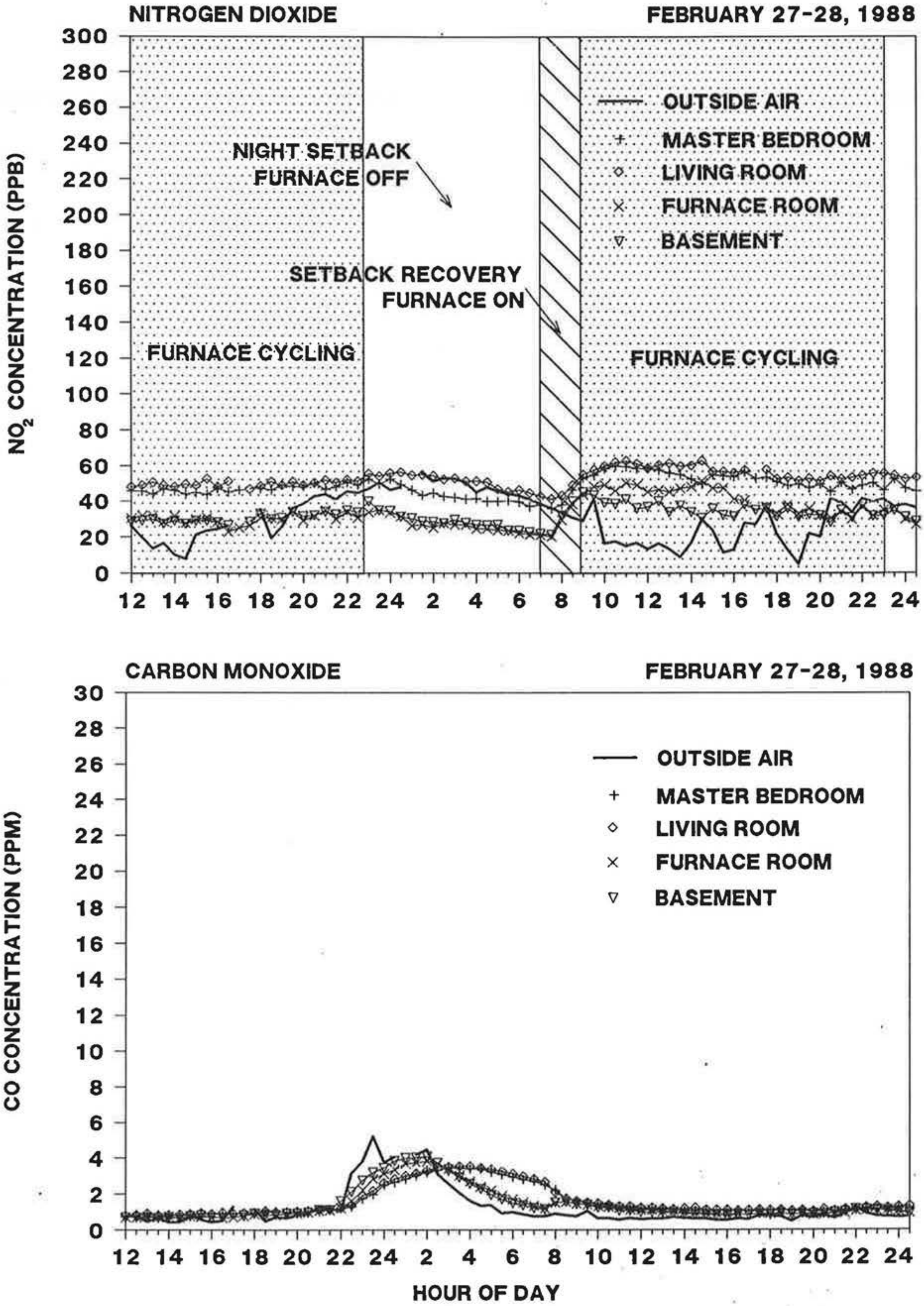


FIGURE 3.1 NO_2 AND CO LEVELS DURING BASELINE FURNACE OPERATION

3.1.1 Baseline Furnace Operation Without Appliance Simulation

Figure 3.1 shows typical NO_2 and CO concentrations in different locations of the house along with coincident outdoor concentrations during operation of the central furnace. The setback recovery hour was 7 a.m., at which time the furnace ran continuously at maximum output for nearly 2 hours. After the setback recovery period, the furnace cycled to maintain comfort conditions until 11 p.m. The furnace remained off for the setback period from 11 p.m. until 7 a.m.

NO_2 concentrations were low throughout the house, but were usually higher on the first floor than in the basement or outdoors. NO_2 concentrations increased somewhat when the furnace started in the morning. Furnace room concentration showed the greatest increase, but all levels were within the range of indoor concentrations observed when the heating system was not operating. Basement and furnace room concentrations were lower than first floor concentrations when the furnace was off during setback and during evening hours when the furnace operated less frequently to maintain comfort conditions. Changes in outdoor NO_2 concentration did not significantly impact indoor concentrations. The effect of pilot light operation on first floor NO_2 concentrations was most evident during setback hours, when the first floor concentration was 20 to 30 ppb higher than in the basement.

CO concentrations were also low. However, changes in outdoor CO concentration did affect indoor concentrations, both in the basement and on the first floor. Differences in response between the basement and first floor to the increased outdoor concentration may be due to the infiltration flow path and interzonal flow from the basement and the first floor. Almost no difference in concentrations between the basement and first floor was observed, and indoor CO concentrations were only slightly higher than outdoor concentration (except during the period of increased CO level outdoors).

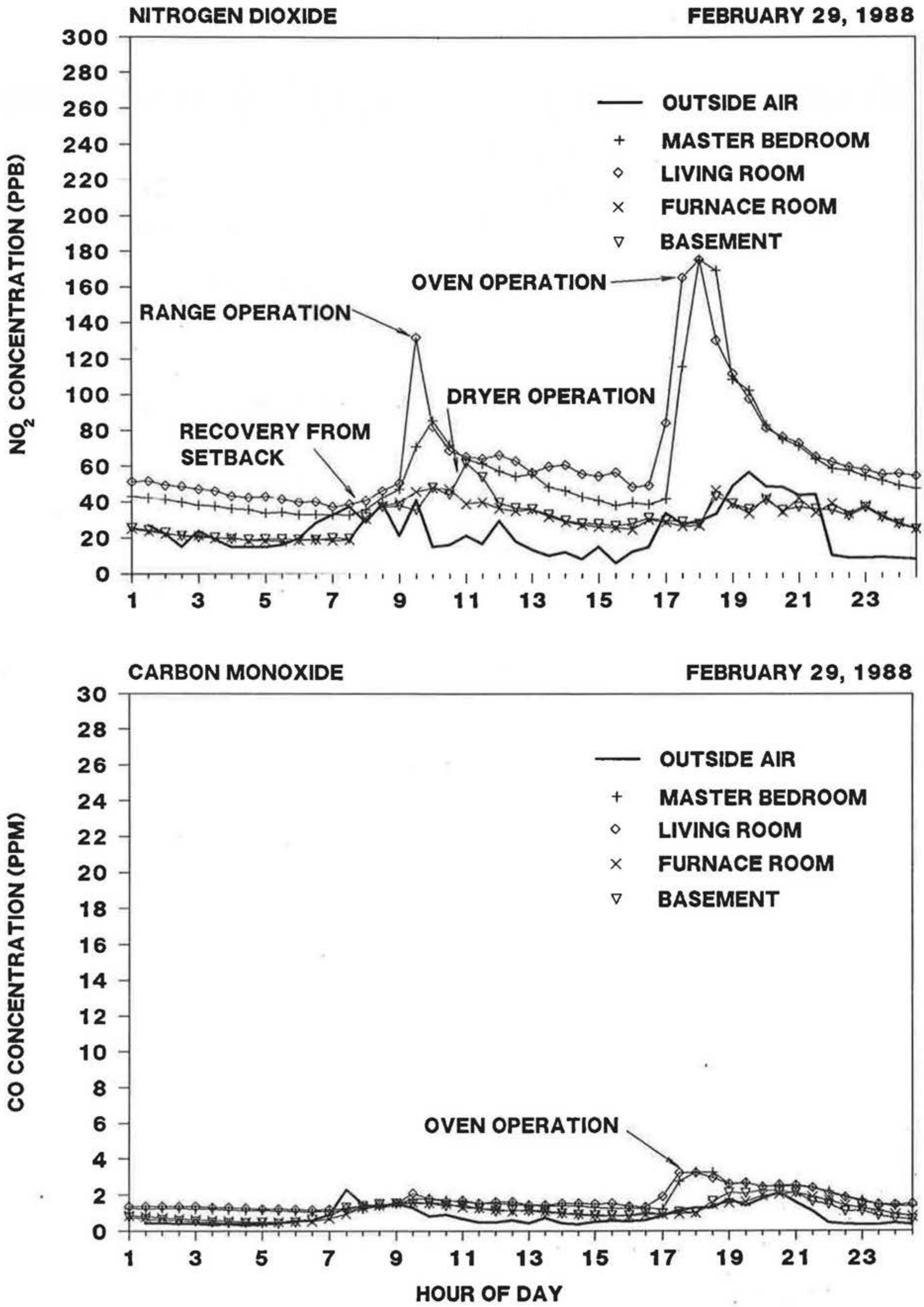


FIGURE 3.2 NO_2 AND CO LEVELS DURING BASELINE APPLIANCE SIMULATION

3.1.2 Baseline Furnace Operation With Appliance Simulation

Figure 3.2 shows concentrations of NO_2 and CO for a typical appliance simulation day during the heating season, with heating supplied by the central furnace through a duct distribution system. During this experiment, doors between the first floor and basement were closed; all other doors were open. The effect of setback recovery and appliance simulation on zonal pollutant concentrations was most pronounced for NO_2. During the setback period until 7 a.m., the furnace was off, and pollutant levels in the basement zones matched outdoor air concentrations. Pollutant levels in the living room zone were the highest due to emissions from the range and oven pilot lights. Nearly uniform mixing of pollutants throughout the house occurred during the setback recovery period between 7 a.m. and 9 a.m. The furnace ran continuously during this period. Range burner operation (8:15 a.m. to 8:45 a.m.) and oven operation (4 p.m. to 5 p.m.) affected first floor concentrations more than basement or furnace room concentrations, even though the furnace was cycling periodically throughout the day after the setback recovery period. Gas dryer operation (10 a.m. to 10:40 a.m.) increased the NO_2 level in the basement at 11 a.m., but it did not affect the furnace room concentration. With the furnace cycling, the equilibrium concentration in the two basement zones remained between the first floor and outdoor concentrations. The impact of oven operation on basement concentrations was reduced because the furnace only operated briefly during the hours between 5 p.m. and 8 p.m. Specific results of appliance simulation experiments include:

- o Mixing of pollutants throughout the house occurred when the furnace operated continuously for extended periods (e.g., setback recovery).
- o Basement concentrations during furnace cycling periods were between outdoor and first floor concentrations, indicating incomplete mixing.
- o Basement concentrations when the furnace was off for extended periods (e.g., setback) tracked outdoor concentrations with some lagging, indicating little interzonal flow from the first floor.
- o Bedroom concentrations (away from source emissions from pilot lights) during setback were somewhat lower than living room concentrations, indicating partial mixing on the first floor.
- o Living room and bedroom concentrations increased during operation of gas appliances, but basement concentrations remained low, indicating little interzonal flow from the first floor to the basement.
- o Pilot light emissions from the domestic hot water heater in the furnace room did not contribute to basement pollutant levels.

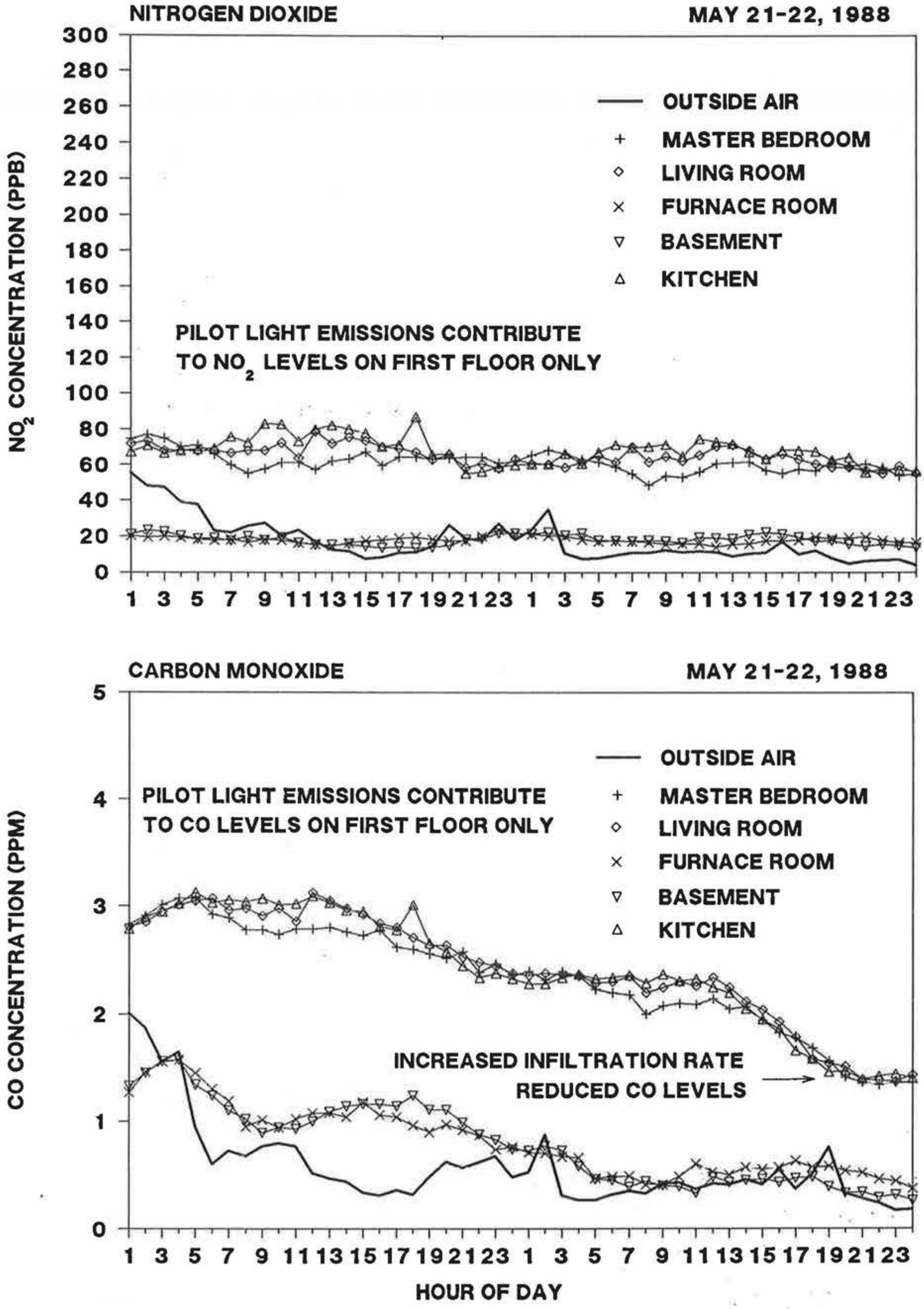


FIGURE 3.3 NO_2 AND CO LEVELS WITH HEATING SYSTEM OFF

3.1.3 Heating System Off

The house had four pilot lights which were lighted continuously, two for the range and one each for the oven and water heater. Pilot lights on the first floor consumed 0.45 cubic feet (CF) of gas per hour, while the water heater pilot light consumed 0.8 CF per hour. Figure 3.3 shows the effect of these pilot lights on indoor pollutant levels. Pilot lights increased the first floor NO_2 concentration by approximately 45 to 55 ppb compared to the basement and outdoors. CO concentrations increased by 1 to 2 ppm depending on the infiltration rate. Water heater pilot light emissions did not increase furnace room concentrations, but were most likely vented outdoors through the heater vent. Emission sources on the first floor did not increase basement pollutant concentrations.

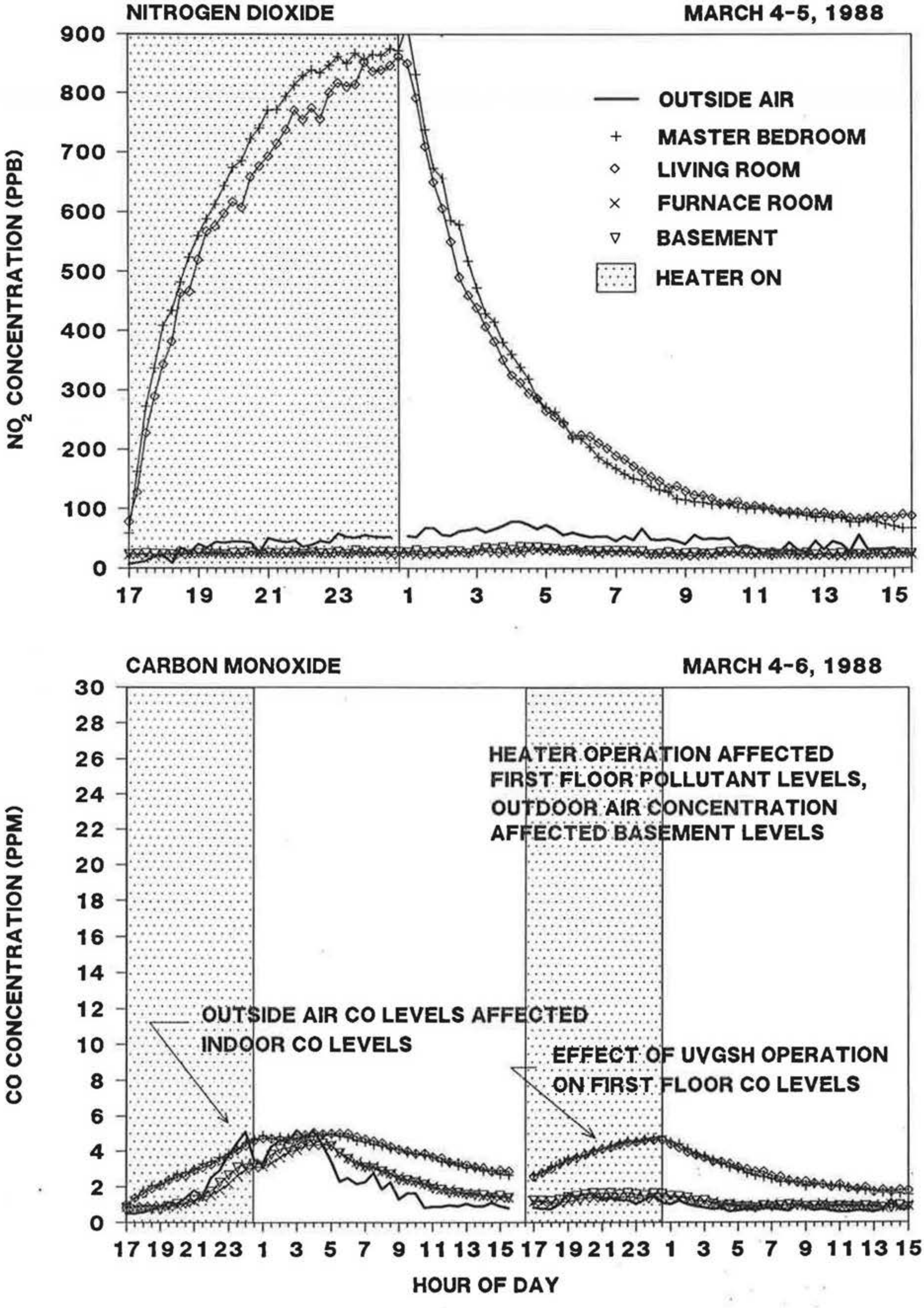


FIGURE 3.4 NO_2 AND CO LEVELS DURING BLUE FLAME CONVECTIVE UVGSH OPERATION

3.2 Comparison of UVGSH's Under Similar Operating Conditions

Three types of UVGSH were located in the living room and run at full output for a period of 8 hours each to compare indoor NO_2 and CO concentrations during and after heater operation. Combustion product concentrations in the living room, master bedroom, basement, furnace room, and outdoor air were measured for a blue flame convective heater, a ceramic tile radiant heater, and a fan forced convective heater.

3.2.1 Blue Flame Convective UVGSH

Figure 3.4 shows NO_2 and CO levels during and after operation of the blue flame convective UVGSH. NO_2 levels on the first floor increased rapidly after heater startup to a peak concentration of approximately 900 ppb just prior to heater shutoff. Once the heater was shut off, first floor NO_2 levels decayed exponentially to near baseline concentrations within 12 hours after the heater was shut off. Coincident basement concentrations remained at or below outdoor levels throughout the experiment.

The 8 hour operating period was selected to allow first floor concentrations to reach equilibrium conditions prior to shutting off the heater. The equilibrium period was verified in a subsequent experiment in which the heater was operated continuously for a period of 15 hours. During that experiment, first floor NO_2 concentrations remained stable near 800 ppb after 7 hours of operation. The lower peak concentration observed in that case was a result of first floor pilot lights being shut off during the experiment and a higher infiltration rate.

NO_2 concentrations observed during this experiment confirmed results of heater emissions tests contained in Appendix B. The blue flame convective heater, which had a 33 percent lower gas input rate than the other 2 heaters, generated substantially higher NO_2 emissions. The measured NO_2 emission factor was 0.0244 $lbs/10^6$ Btu versus 0.0122 $lbs/10^6$ Btu for the radiant heater and 0.00275 $lbs/10^6$ Btu for the fan-forced convective heater.

Heater operation increased CO levels on the first floor to a peak level of approximately 5 ppm. During the first day of the experiment (March 4-5), fluctuations in the outdoor CO level influenced indoor CO concentrations. During the replicate day of the experiment (March 5-6), the outdoor concentration remained very stable, and the effect of heater operation on indoor CO concentrations could be observed. The NO_2 concentration profile during the replicate day was nearly identical to the profile shown in Figure 3.4.

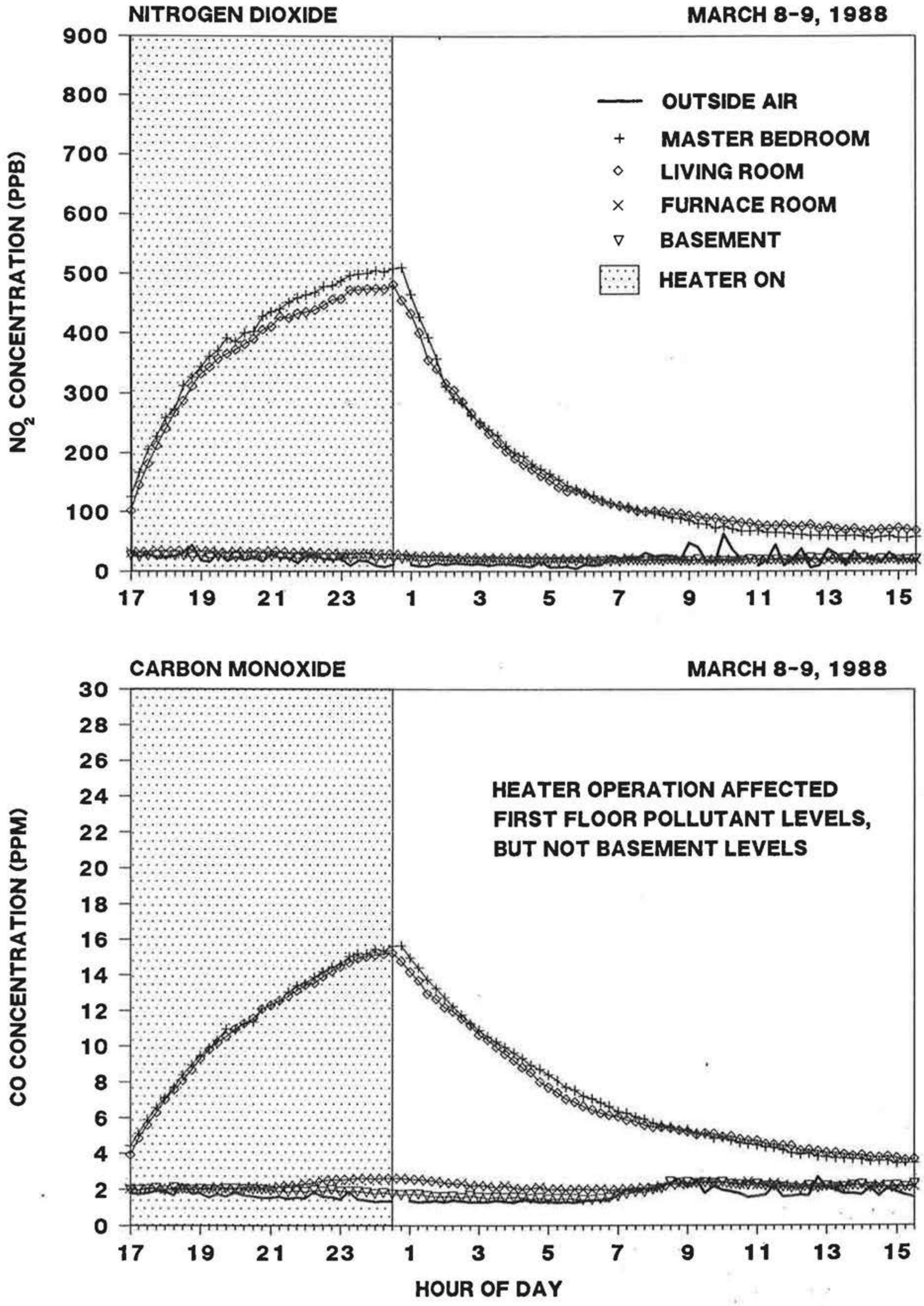


FIGURE 3.5 NO_2 AND CO LEVELS DURING RADIANT UVGSH OPERATION

3.2.2 Radiant UVGSH

Figure 3.5 shows NO_2 and CO levels during and after operation of the radiant UVGSH. The shapes of the combustion product concentration profiles for the radiant heater were similar to the blue flame convective heater, except the peak concentrations differed. The peak NO_2 concentration was 500 ppb, approximately half the peak of the blue flame convective heater. However, the decay period to near baseline concentrations subsequent to heater shutoff was reduced only slightly to 11 hours.

The peak CO concentration during the radiant heater experiment was 16 ppm, which was much higher than for either convective heater. Decay to baseline CO levels following heater shutoff required almost 16 hours.

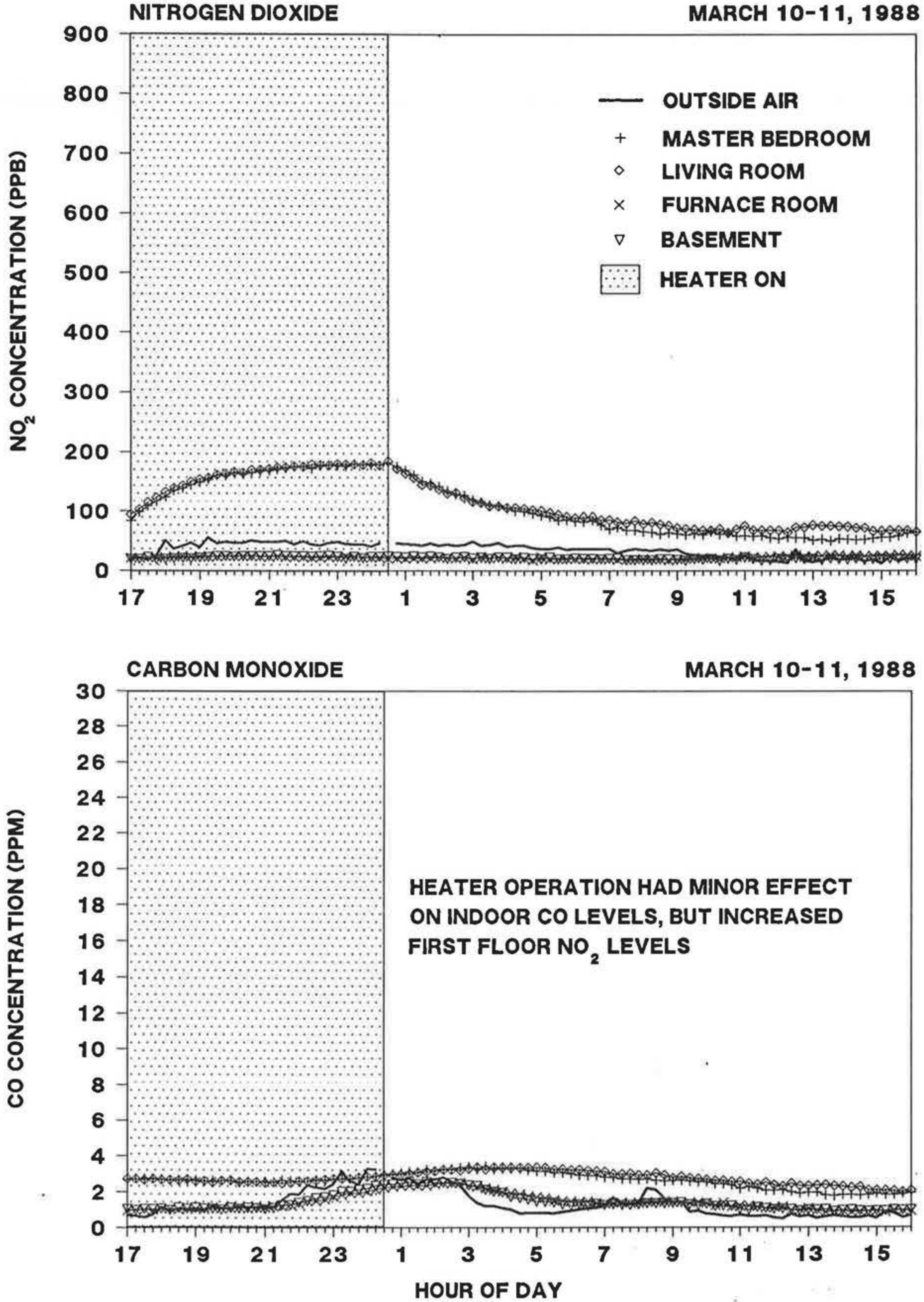


FIGURE 3.6 NO_2 AND CO LEVELS DURING FAN FORCED CONVECTIVE UVGSH OPERATION

3.2.3 Fan-Forced Convective UVGSH

Figure 3.6 shows NO_2 and CO levels during and after operation of the fan-forced convective UVGSH. The shapes of the combustion product concentration profiles for the fan-forced heater differed from the other two heaters, especially for CO. The peak concentration of NO_2 on the first floor was about 200 ppb, and equilibrium conditions during heater operation occurred within 4 hours after the heater was started. The decay period to baseline NO_2 concentrations occurred within 7 hours following heater shutoff.

Heater operation had little effect on CO concentrations. First floor CO concentrations did not rise during heater operation until fluctuations in outdoor CO levels during the experiment influenced indoor levels. The slight decay observed following heater shutoff was a lagged response to the reduction in outdoor CO concentration.

3.2.4 Comparison with Contemporary Research House

Table 3.3 compares peak living room combustion product concentrations at the Conventional Research House and the Contemporary Research House during UVGSH experiments. The peak NO_2 concentration of 942 ppb in the Conventional Research House during the blue flame convective heater experiment was almost five times higher than the peak concentration of the same heater using a similar protocol at the Contemporary Research House[3]. The next highest NO_2 concentrations occurred with the radiant heater, with a peak concentration of 584 ppb. This heater had a peak of 110 ppb at the Contemporary Research House. The fan forced convective heater had the lowest concentrations at 186 ppb, compared with 50 ppb at the Contemporary Research House.

The highest CO concentrations observed during the UVGSH experiments at both houses occurred with the radiant heater, with a peak concentration of 17 ppm after 8 hours of operation at the Conventional Research House. This compares with a peak of 11 ppm after 3 hours operation at the Contemporary Research House. Peaks for the other 2 heaters were 5 and 4 ppm which were similar to concentrations at the Contemporary Research House.

TABLE 3.3
COMPARISON OF PEAK COMBUSTION PRODUCT LEVELS AT THE CONVENTIONAL RESEARCH HOUSE AND THE CONTEMPORARY RESEARCH HOUSE

Experiment/ Combustion Product	Conventional Research House	Contemporary Research House
Convective Heater		
NO_2 (ppb)	942	200
CO (ppm)	5	5
Radiant Heater		
NO_2 (ppb)	584	110
CO (ppm)	17	11
Fan Forced Heater		
NO_2 (ppb)	186	50
CO (ppm)	4	3

3.3 Spatial Variations

3.3.1 Interzonal Flow of Combustion Products

The indoor air quality experiments performed using a central furnace and unvented space heaters provided a good understanding of the distribution of combustion products in the house and the impact of central furnace operation, zonal barriers, and space heater operation on interzonal air and combustion product flows. Analysis of hourly data on NO_2, CO, and SF_6 during particular experiments was useful in characterizing interzonal combustion product flows.

As illustrated previously in Figure 3.2, mixing of combustion products throughout the house occurred when the furnace operated continuously for extended periods (e.g., setback recovery). Basement concentrations during furnace cycling periods were between outdoor and first floor concentrations, indicating incomplete mixing. Basement concentrations when the furnace was off for extended periods (e.g., setback) tracked outdoor concentrations with some lagging, indicating little flow from the first floor to the basement. Bedroom concentrations (away from source emissions from pilot lights) during setback were somewhat lower than living room concentrations, indicating partial mixing on the first floor. Living room and bedroom concentrations increased during operation of gas appliances, but basement concentrations remained low, indicating little interzonal flow from the first floor to the basement.

Combustion products did not migrate from the first floor to the basement during the UVGSH experiments (as illustrated previously in Figures 3.4 through 3.6). The doors between the first floor and basement were closed and interzonal air and combustion product flow appeared to be from the basement to the first floor. To examine this issue, a series of experiments were conducted in which SF_6 was injected only into one zone at a time. During these experiments, the central furnace did not operate, and all doors between the living room area, bedroom area, west basement, and furnace room were closed. Zonal SF_6 concentrations observed during decay periods following injections provided insight into the direction of interzonal flows. It was determined that most outside air flowed into the basement and furnace room. Interzonal flow occurred from the west basement into the living room zone and to a lesser extent into the bedroom zone. When the furnace room door was closed, almost no flow was observed from either half of the basement to the other half. Outdoor air entering the furnace room exited primarily through interior stacks and the water heater vent and did not flow into first floor rooms. No detectable flow was observed from the first floor to the basement. Almost no flow occurred from the bedroom to the living room area when the zone doors were closed, but some interzonal flow occurred from the living room to the bedrooms.

TABLE 3.4
SPATIAL VARIATION IN NO_2 CONCENTRATIONS MEASURED BY PALMES TUBES

a. UVGSH Experiment

Height above Floor (cm)	Average NO_2 (ppb) in Room			
	Living Room	Master Bedroom	Basement	Outdoors
15	307	295	24	
60	307	296	22	
110	303	311	22	
160	295	335	22	
213	317	341	21	
Average	306	316	22	39
Continuous Analyzer	307	316	22	33
Stratification (15 to 213 cm)	10	46	-3	

b. Range and Oven Experiments

Height above Floor (cm)	Average NO_2 (ppb) in Room			
	Living Room	Kitchen	Master Bedroom	Basement
15	153	153	131	20
60	154	157	146	20
110	156	145	149	19
160	154	179	152	18
213	166	186	158	19
Average	157	164	147	19
Continuous Analyzer	139	135	138	19
Stratification (15 to 213 cm)	13	33	27	-1

3.3.2 NO_2 Concentrations Using Palmes Tubes

During the UVGSH experiments and range hood experiments, arrays of Palmes Tubes were deployed in each room to measure vertical stratification of NO_2 and long term (4 day) average concentration throughout the house. Tubes in each room were placed at heights of 15, 60, 110, 160, and 213 cm (6, 24, 43, 63, and 84 inches) above the floor. Palmes Tubes were also placed in each zone during the baseline furnace operation. Table 3.4 summarizes results of the measurements in the living room, master bedroom, and basement for each experiment. Results for the kitchen are also included for the range experiments.

Palmes Tubes in the UVGSH experiments were present for 5 days during experiments of the blue flame convective and radiant heaters. Tubes were removed prior to starting the fan forced convective heater experiment. Results show little stratification except in the bedroom, which showed a 46 ppb change from lowest to highest point. The large difference in concentrations between the first floor and basement is also verified. Measured combustion product concentrations using Palmes Tubes agreed well with the averages of continuous analyzer readings during the same period.

During the range and oven experiments, the Palmes Tubes were present for the 5 days of the experiments without range hood operation. The first floor rooms showed small vertical stratification between lowest and highest points, but almost no stratification between the 110 cm station and the highest point except in the kitchen.

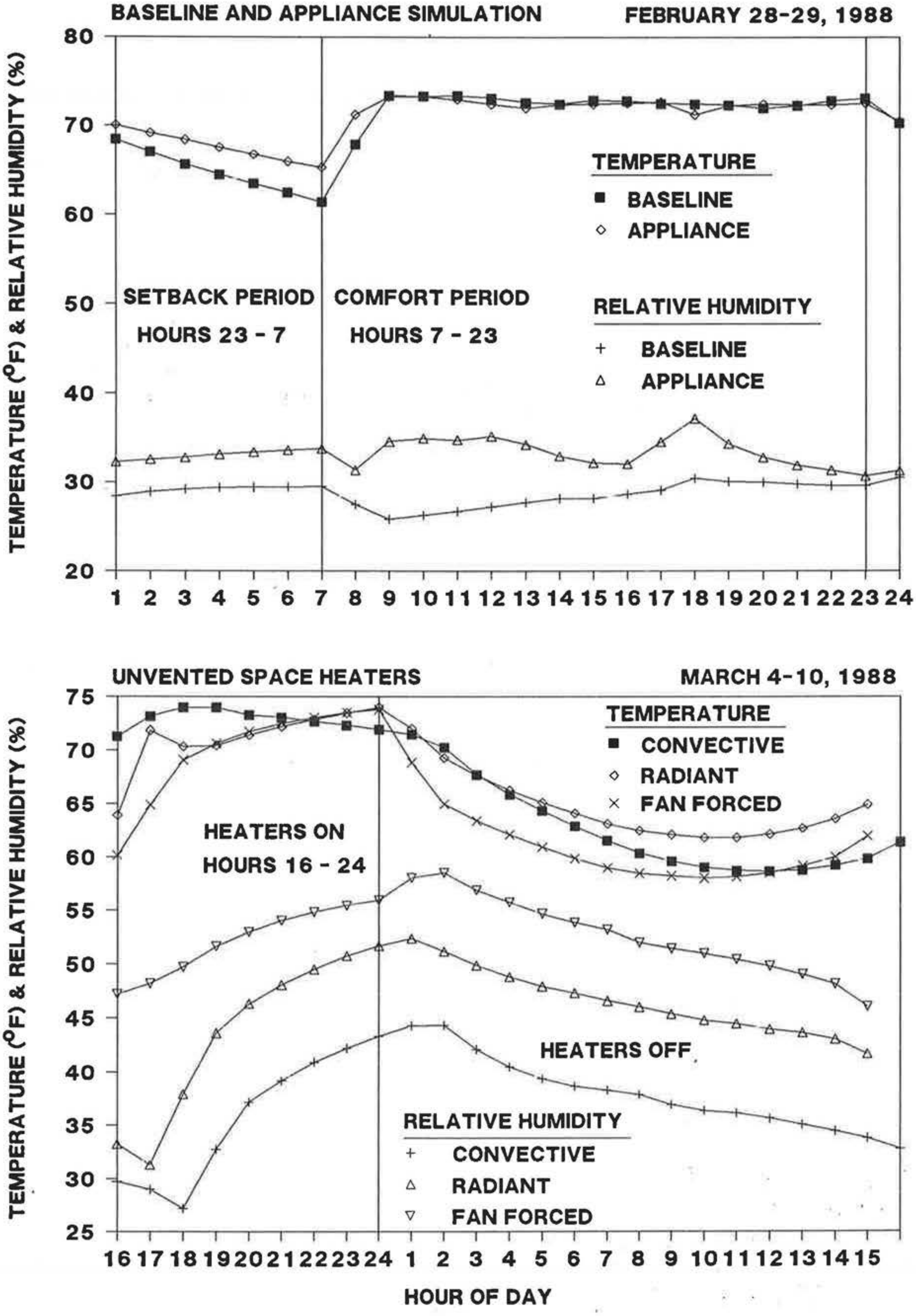


FIGURE 3.7 LIVING ROOM CONDITIONS DURING BASELINE AND UVGSH TESTS

3.3.3 Indoor Temperatures and Relative Humidity

Figure 3.7 shows the living room conditions during a typical day of baseline central heating and appliance simulation experiments and during each of the 3 "UVGSH in living room" experiments. Temperatures during baseline experiments dropped during setback hours and recovered within 2 hours to comfort conditions. Relative humidity increased during baseline appliance simulation days in response to shower, range, oven, and dishwasher operation. In each UVGSH experiment, the living room temperature at 110 cm was relatively stable after an initial warmup period of 2 hours. Temperatures decayed more quickly after heaters were shut off than under central heat at the same outdoor air temperatures due to colder conditions in the basement and away from the living room throughout the experiments. As shown in Table 3.5, room temperatures before and after heater operation for UVGSH experiments were fairly uniform on each floor, but the basement temperatures were much colder than first floor temperatures. As expected, the relative humidity increased significantly when using the space heaters. Increases were a function of heater capacity and relative humidity at the start of the experiment.

TABLE 3.5
ROOM TEMPERATURES BEFORE AND AFTER UVGSH EXPERIMENTS

Room	Blue Flame Convective Heater Before (°F)	Blue Flame Convective Heater After (°F)	Radiant Heater Before (°F)	Radiant Heater After (°F)	Fan Forced Convective Heater Before (°F)	Fan Forced Convective Heater After (°F)
Living Room	73	71	64	75	64	76
Kitchen	72	70	64	72	64	73
SE Bedroom	70	69	64	70	62	68
NE Bedroom	69	68	63	69	60	67
NC Bedroom	70	68	64	70	61	67
Hallway	69	69	64	71	62	71
Full Bath	70	69	64	70	61	68
Half Bath	70	69	65	70	61	68
W Basement	62	57	57	57	56	56
Furnace Room	65	60	59	59	56	57
Outside Air	35	26	50	44	46	33

3.4 Effect of Range Hood Operation on Combustion Product Levels

Three experiments were conducted with and without range exhaust hood operation to examine the impact of range and oven operation on indoor combustion product concentrations and to evaluate the effectiveness of the hood in removing combustion products at the source. The ducted range hood vents through the roof to outdoors. The oven is mounted separately from the range and is not directly under the hood. Table 3.6 lists total hourly gas consumption for the range and oven and peak combustion product levels during hours of appliance operation.

The experiments conducted with and without hood operation comprised morning experiments conducted from 9 a.m. to 10 a.m. and afternoon experiments conducted from 4 p.m. to 5 p.m., including:

Day	Morning	Afternoon
1	Range	Oven
2	Range	Range and Oven
3	Range and Oven	Range and Oven

TABLE 3.6

HOURLY GAS CONSUMPTION DURING RANGE AND OVEN EXPERIMENTS

Date	Appliance Operated (9-10 am)	Gas CF (9-10 am)	Peak NO_2 (ppb)	Peak CO (ppm)	Appliance Operated (4-5 pm)	Gas CF (4-5 pm)	Peak NO_2 (ppb)	Peak CO (ppm)
Without Hood								
5/13/88	Range	9.1	185	3.0	Oven	9.4	173	5.0
5/14/88	Range	7.7	174	3.0	Range/Oven	18.1	392	7.3
5/15/88	Range/Oven	17.8	389	8.4	Range/Oven	17.8	403	10.8
With Hood								
5/23/88	Range	9.6	69	1.5	Oven	9.3	171	3.3
5/24/88	Range	9.4	66	1.0	Range/Oven	18.4	149	2.8
5/27/88	Range/Oven	15.5	206	4.5	Range/Oven	18.6	220	4.5

Figures 3.8 and 3.9 show the NO_2 and CO concentrations respectively for experiments without and with hood operation. Results of these experiments show that the range hood was effective in removing range emissions, but was less effective in capturing oven emissions. As seen in the photograph of the kitchen in Appendix D, the hood is located directly above the range, but the wall-mounted built-in oven is 3 feet to the right of the range and hood. The vent to the room is at approximately 5 feet above the floor, making effective capture by a remote hood difficult. Peak NO_2 concentrations without hood operation varied proportionally with total gas consumption during the hour and were similar for range and oven emissions. On the other hand, peak CO concentrations were higher during oven operation, even though the total hourly gas consumption was nearly the same as the range consumption.

The peak range and oven NO_2 concentrations observed during the morning range, afternoon oven experiment (May 13, 1988) were consistent with range and oven source emissions data obtained in October 1987 for these appliances (see Appendix A Tables 1 and 2). The range and oven NO_2 emission rates were 0.0208 and 0.0167 Lb/10^6 Btu respectively, while the peak ambient NO_2 concentrations were 185 and 173 ppb.

The peak range and oven CO concentrations observed during the same experiment were also reasonably consistent with range and oven source emissions data. CO source emission data for the right front burner shows a similar emission rate per BTU as the oven at 350°F (0.0533 and 0.0560 Lb/10^6 Btu respectively). The observed peak CO concentrations (3 and 5 ppm) seem to indicate a somewhat higher emission rate from the oven than from the range burner. The difference could be due to incomplete mixing, since the observed peak was an ambient peak in the living room while the emission characterization was an hourly average in the flue of the appliance. It is also possible that the emission characterization results may have underreported the oven CO emission rate. The oven emission rate on the Broil setting rose above the maximum range of the analyzer and the characterization was stopped after only 12 minutes of broil operation. If a similar but shorter duration range limit problem occurred when the burner cycled on during the 350°F setting characterization, it may have gone undetected when calculating the average emission factor for the hour.

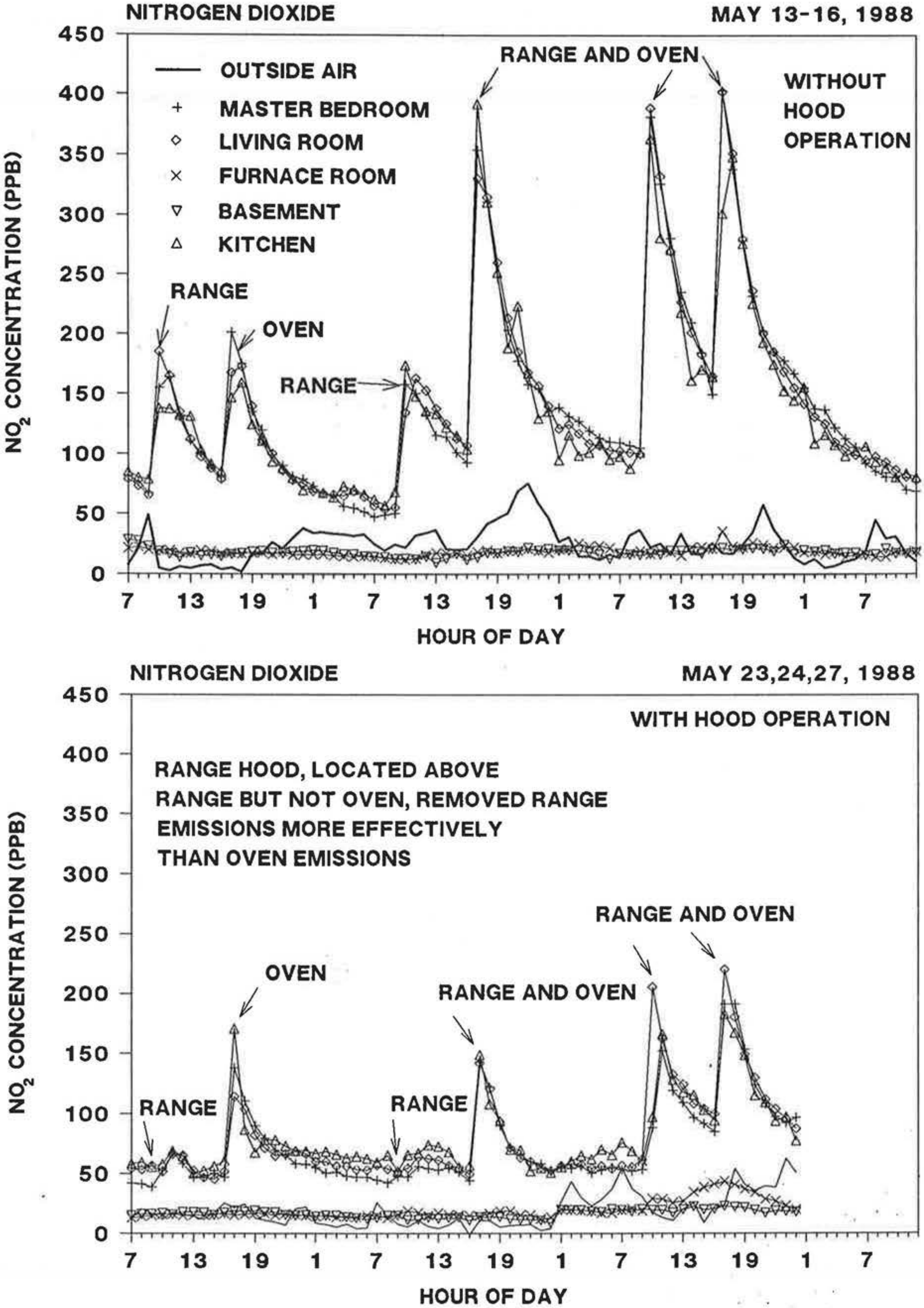


FIGURE 3.8 COMPARISON OF NO_2 LEVELS DURING RANGE AND OVEN TESTS

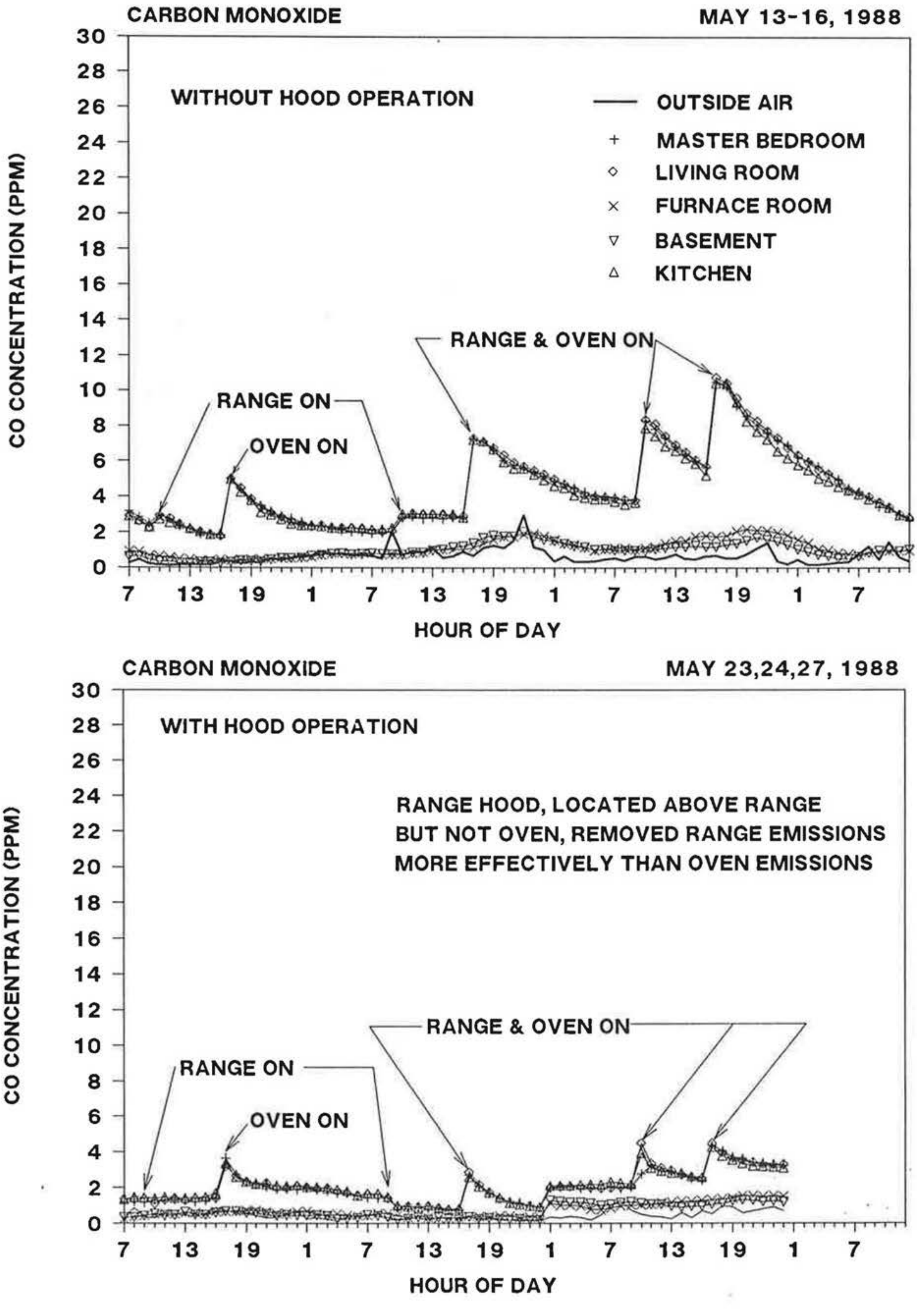


FIGURE 3.9 COMPARISON OF CO LEVELS DURING RANGE AND OVEN TESTS

3.5 Radon Levels

Average radon levels on the first floor and basement were measured using charcoal canisters several times throughout the experiment period. Each measurement lasted 4 days. Table 3.7 lists results of these experiments. Results show low levels of radon throughout the house. Radon levels in the basement did not increase with furnace operation. The maximum radon level detected was 1.4 PicoCuries per liter (pCi/L).

TABLE 3.7
RADON CONCENTRATIONS

Experiment	Radon Concentration (pCi/L) First Floor	Basement	Furnace Room
Summer 1987	1.1	1.3	-
Furnace	0.5	0.9	<0.4
UVGSH in LR	<0.4	1.0	<0.4
Zoned UVGSH	0.4	1.0	0.7
Range W/O Hood	1.0	1.2	0.9
Range With Hood	0.4	1.4	1.1

3.6 Estimation of Combustion Product Decay Rates

Collection of detailed data on combustion product concentrations during UVGSH operation in the living room enabled estimation of combustion product decay rates using a one compartment model. The two types of combustion products examined in the UVGSH experiments require different decay models. NO_2 is a reactive gas whose decay depends not only on the outdoor air infiltration rate but also chemical reaction. The model therefore must account not only for the air exchange rate, but the decay rate caused by other indoor removal mechanisms. CO is not reactive and its decay rate is dependent on air exchange rates only.

3.6.1 One Compartment Model

A single-equation one compartment mass balance model can be used to estimate combustion product decay rates, as long as reasonably uniform mixing occurs within the compartment[3,5]. For the UVGSH experiments, the first floor was considered to be the single compartment. The mathematical expression for the change in average indoor combustion product concentration in a single compartment is:

$$dC/dt = (a\,C_o) + ((S\,Q)/V) - (a+k)\,C \qquad (1)$$

where:

C	=	indoor combustion product concentration (10^{-6}g/m^3)
C_o	=	outdoor combustion product concentration (10^{-6}g/m^3)
Q	=	fuel input rate for the appliance (Btu/h)
a	=	air exchange rate (1/hr.)
S	=	indoor emission rate for an unvented gas appliance (10^{-6}g/Btu)
V	=	indoor volume (m^3, and)
k	=	rate constant for indoor combustion product removal (1/hr.)

The solution to the above equation for the change in C with time (t), holding all other factors constant with respect to time and with boundary values C(0) at t=0, is as follows:

$$C(t) = ((a\,C_o + (S\,Q)/V)/(a + k))\,[1 - e^{-(a + k)t}] + C(0)\,e^{-(a + k)t} \qquad (2)$$

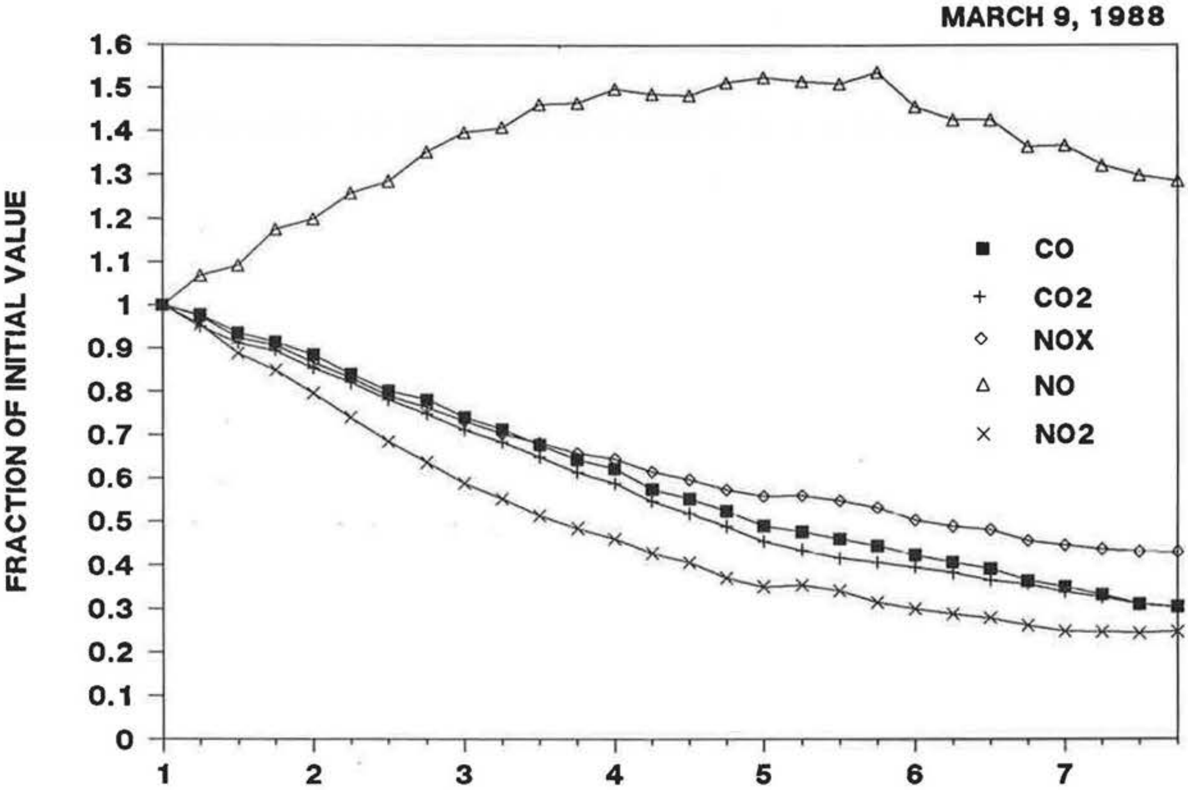
For S = 0,

$$C(t) = (a\,C_o/(a + k))\,[1 - e^{-(a + k)t}] + C(0)\,e^{-(a + k)t} \qquad (3)$$

For S and k = 0,

$$C(t) = C_o + (C(0) - C_o)\,e^{-a\,t} \qquad (4)$$

These equations were used to estimate the air exchange rate (a) and the indoor combustion product removal rate constant (k) during the operation of the blue flame convective and radiant heaters.



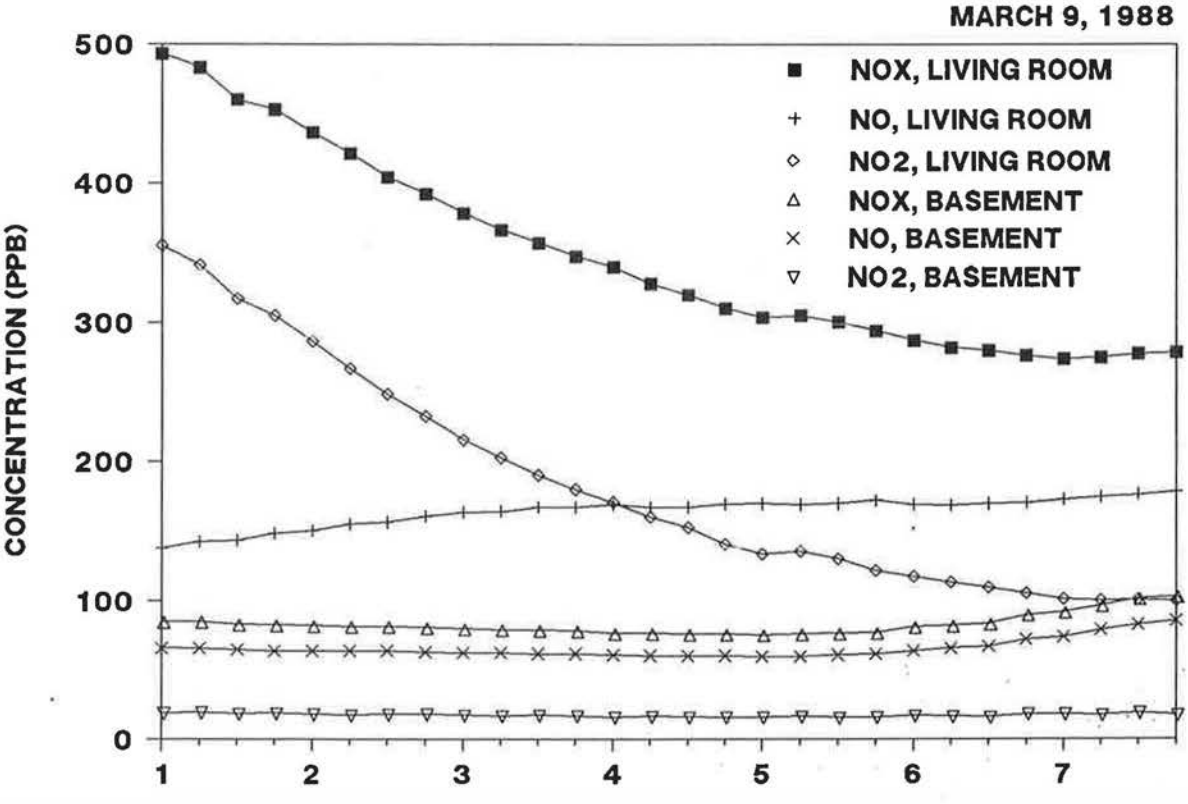


FIGURE 3.10 COMPARISON OF COMBUSTION PRODUCT DECAY RATES FOR RADIANT HEATER

3.6.2 Air Infiltration Rate

The one compartment model can be used to estimate infiltration rate with a tracer gas which does not have indoor removal or indoor sources. In this case, Equation (4) can be solved for the hourly infiltration rate (a) as follows:

$$a = (\ln[(C(0)-C_O)/C(t)-C_O)]) / (t - t_0) \quad (5)$$

Equation (5) can be used with gases such as CO_2 during the decay period following appliance operation to determine the air exchange rate with all sources, including other compartments (e.g., the basement), as long as the indoor concentrations are sufficiently higher than background concentrations.

SF_6 is another generally accepted tracer gas used to measure infiltration rates. SF_6 is used at the Conventional Research House to measure whole house infiltration rates through periodic injection and decay. Because only trace amounts of SF_6 occur naturally, equation (5) is further simplified to:

$$a = [\ln(C(0)/C(1))] / (t_1 - t_0) \quad (6)$$

However, for the estimation of combustion product decay rates during the UVGSH experiments, the whole house infiltration rate using SF_6 as the tracer gas was inappropriate. Since interzonal air flow occurred between the basement and the first floor, the background concentration C_O of SF_6 was neither zero nor constant over the period of interest. The basement infiltration rate was significantly higher than the first floor, and thus the basement SF_6 concentration changed rapidly. As this changing concentration entered the first floor through interzonal air flow, it influenced the first floor concentration differently depending on the concentrations in each zone. For the UVGSH experiments, the appropriate method of SF_6 injection and decay would be to inject only into the first floor, which was not done during these experiments.

To determine the indoor removal rate (k), it was necessary to estimate the air exchange rate (a) in the first floor. Since SF_6 was not available, combustion products generated during heater operation were used. Figure 3.10 compares the decay rates in the living room zone of CO, CO_2, NO, NO_2, and NO_x after operation of the radiant heater. Also shown in this figure are the oxides of nitrogen concentrations in the living room and basement zones. CO and CO_2 decay rates agreed quite closely during the first 4 hours of decay. The low level of NO at the start of the decay period coupled with conversion of NO_2 to NO resulted in an increase in NO concentration over time and a more rapid decay rate for NO_2. Using Equation (4) for the CO_2 decay rate during this period, the average air exchange rate (a) in the living room was calculated at 0.19 /hr. Calculated air exchange rates during the other blue flame convective and radiant UVGSH decay periods appear in Table 3.8.

3.6.3 NO_2 Decay Rate

The NO_2 decay rate following heater operation was calculated using measured indoor and outdoor NO_2 concentrations for the blue flame convective and radiant heaters. With measurements of the NO_2 concentration and air exchange rate, it is normally possible to determine the decay rate during the period following appliance operation because the source emission rate is zero at this time. However, the Conventional Research House had a second source of emissions - the pilot lights on the oven and range - which continued to provide source emissions throughout the decay period. These emissions result in a "steady-state" indoor concentration (C_{ss}) that would prevail if only the range pilot lights were in operation. C_{ss} represents the term (a C_O + (S Q)/V)/(a + k) in Equation (2). Substituting C_{ss} into equation (2), the indoor removal rate (k) can be calculated as follows:

$$k = \ln [(C(0)-C_{ss})/(C(t)-C_{ss})] / (t - t_0) - a \qquad (7)$$

C_{ss} can be estimated from the data following the decay period and during periods of no furnace or appliance operation. Table 3.8 includes average values for the indoor removal rate (k) in the living room during UVGSH experiments estimated using Equation (7) and a C_{ss} of 65 ppb for NO_2. The average indoor removal rate during these experiments was 0.17 /hr.

3.6.4 Comparison with Contemporary Research House

Baseline characterization experiments similar to those conducted at the Conventional Research House were performed at the Contemporary Research House, permitting a comparison of results between houses. Differences between the houses include wall and ceiling materials, surface treatments, and floor coverings. The Contemporary Research Houses have plasterboard walls and ceilings with one coat of contractor-applied latex paint. The Conventional Research House has plaster walls and ceilings with rock lath and at least two coats of oil-based paint. The NO_2 removal rate for plasterboard with one coat of paint is 2.6 /hr.; the rate for unpainted plasterboard is greater than 8.3 /hr.[4] The removal rate for oil-base painted plaster walls is considerably lower, but requires measurement to determine the exact removal rate.

TABLE 3.8
NO_2 DECAY RATES AND AIR EXCHANGE RATES FOLLOWING UVGSH OPERATION IN THE CONVENTIONAL RESEARCH HOUSE

Location/ Date	Types of UVGSH	Estimated Decay Rate, 1/h: NO_2 Indoor Removal Rate (k)	Estimated Decay Rate, 1/h: Air Exchange Rate (a)
Conventional Research House			
March 5, 1988	Convective	0.14	0.22
March 6, 1988	Convective	0.15	0.21
March 7, 1988	Radiant	0.21	0.15
March 8, 1988	Radiant	0.15	0.19
March 9, 1988	Radiant	0.21	0.19
Average		0.17	0.19
Contemporary Research House			
December 9, 1987	Convective	0.64	0.19
December 11, 1987	Radiant	1.10	0.22

Carpeting at the Conventional Research House is limited to the living room. The Contemporary Research Houses are fully carpeted, except in the kitchen, bathroom, and basement. Carpeting in both houses is man-made fiber, with a removal rate of approximately 2 /hr.[4] Other furnishings are similar between the houses, except that the Contemporary Research Houses have bedspreads on each bed.

Based on results of similar UVGSH experiments, NO_2 decay rates were significantly different for the two houses. For example, as shown in Table 3.8, the air infiltration rate at the Contemporary Research House during its radiant heater experiment was 0.22 ACH. This rate was close to the air exchange rate of 0.19 estimated for the Conventional Research House. However, the NO_2 decay rate (k) was 1.1 /hr, which was substantially higher than the value of 0.17 for the Conventional Research House. While lower decay rates were reported for the Contemporary Research House after longer periods of operation (e.g., 20 hours), the two houses behaved in a significantly different way with respect to indoor NO_2 removal rates.

TABLE 3.9

ESTIMATED EMISSION RATES FOR CONVECTIVE AND RADIANT UVGSHs

Basis for Estimate	Estimated Emission Rate, 10^{-6}g/Btu Convective (UVGSH)	Radiant (UVGSH)
Conventional Research House		
- Range Pilots ON	13.4	5.2
- Range Pilots Off	11.4	---
Contemporary Research House		
- Upstairs Operation	5.4	3.2
- Downstairs Operation	---	4.8
IGT Hood Test at Contemporary Research House	11.1	5.5
Previous IGT Hood Test	11.4	3.0
IGT Chamber Test	8.9	3.6
LBL Chamber Test	---	5.5

TABLE 3.10

ESTIMATED STEADY-STATE NO_2 CONCENTRATIONS

	Estimated Value			
	Convective UVGSH		Radiant UVGSH	
Parameter	Convent. Res. House	Contemp. Res. House	Convent. Res. House	Contemp. Res. House
Emission Rate (10^{-6}g/Btu)	11.4	5.4	5.2	3.2
Fuel Input Rate (Btu/h)	11,639	11,639	16,274	16,274
Indoor Volume (m^3)	240	205	240	205
Air Infiltration Rate (1/h)	0.2	0.2	0.2	0.2
Indoor NO_2 Removal Rate (1/h)	0.2	0.7	0.2	0.7
Indoor NO_2 Concentration (ppb)	735	181	469	150

The estimated decay and infiltration rates were also used together with measured indoor and outdoor NO_2 concentrations during the periods of UVGSH operation to compare estimates of emission rates for each heater. These estimates are compared with those from the Contemporary Research Houses and those from prior hood/chamber tests by IGT (Appendix B) and LBL[2] in Table 3.9. The estimates from the Conventional Research House were higher than those from Contemporary Research House and were more consistent with previous hood/chamber tests. The heater emissions during tests at Contemporary Research House were not confined to the upstairs volume because of an open stairwell connecting the upper and lower levels of the house. In the Conventional Research House, the door at the top of the stairs to the basement was kept closed during UVGSH operation. When the radiant UVGSH was operated downstairs at the Contemporary Research House and average concentrations throughout the house were considered, the estimated emission rate (4.8×10^{-6}g/Btu) agreed more closely with that from the Conventional Research House (5.2×10^{-6}g/Btu).

The emission rates from Table 3.9, together with data from previous UVGSH experiments at the Contemporary Research Houses, were used to estimate steady-state NO_2 concentrations for the two houses. The predicted indoor NO_2 Concentration (ppb) for continuous UVGSH operation is calculated from the data in Table 3.10 as follows:

$$\text{Predicted } NO_2 \text{ (ppb)} = \frac{\text{Emission Rate} \times \text{Fuel Rate} \times 0.532 \text{ ppb per } 10^{-6}\text{g/m}^3}{\text{Indoor Volume} \times (\text{Air Infiltration Rate} + NO_2 \text{ Decay Rate})}$$

The inputs and steady-state estimates are provided in Table 3.10. These estimates ignore the relatively smaller contributions of outdoor concentrations (10 to 20 ppb) and range pilots (45 to 55 ppb for the Conventional Research House). As shown in the table, the predicted steady-state concentrations are three to four times higher in the Conventional Research House compared to the Contemporary Research House. The predicted values for the Conventional Research House are somewhat lower than the maximum observed NO_2 concentrations during the UVGSH experiments (possibly due to pilot light emissions). The predicted concentrations in the Contemporary Research House are somewhat higher than the observed maximum concentrations.

Section 4
CONCLUSIONS AND RECOMMENDATIONS

Activity during the first year of IAQ experiments at the GRI Conventional Research House focused on purchasing and installing instrumentation, revising and debugging the data acquisition system, and characterizing the baseline levels of CO, NO_2 and radon during the heating season. In addition, significant work was undertaken in measuring the combustion product levels associated with unvented space heaters. Results of this work have established the baseline combustion product levels, emissions, and decay rates when using unvented space heaters as the only source of heat. These results form a good basis for providing additional understanding of emissions and mitigation techniques. Results of IAQ experiments include:

- Central furnace operation did not increase combustion product levels in the house, except for a slight rise during recovery from setback.

- Appliance simulation increased combustion product levels during and following range and oven operation, but only on the first floor.

- Pilot lights in the kitchen increased NO_2 and CO levels by 45 ppb and 2 ppm respectively over basement and outdoor levels. The water heater pilot light did not contribute significantly to indoor concentrations.

- The blue flame convective heater had the highest NO_2 emissions of the 3 types of UVGSH tested. The ceramic tile radiant heater had the highest CO levels as well as high NO_2 levels. The fan-forced convective heater had appreciably lower NO_2 emissions and very low CO emissions.

- Vertical stratification of NO_2 during UVGSH experiments was low, but higher in the bedrooms than in the living room (where the heaters were located). NO_2 levels in the basement did not rise above outdoor levels.

- Special infiltration experiments identified interzonal air and combustion product flow patterns to be from the west basement to the first floor, but not reverse. The furnace room did not interact appreciably with the other three zones.

- The range hood was effective in removing range emissions because the range was directly below the hood. However, it was less effective in removing oven emissions because the oven was not directly under the hood.

- Radon levels throughout the house were less than 1.4 pCi/L. Furnace operation did not affect radon levels, which were somewhat lower in winter than in summer.

- o Air infiltration and NO_2 indoor removal rates were estimated using a one compartment model for the first floor. The air exchange rate was estimated at 0.19 /hr. The NO_2 removal rate was calculated at 0.17 /hr.

- o Indoor NO_2 removal rates at the Conventional Research House were significantly lower than at the Contemporary Research Houses. Wall and ceiling construction and surface treatment characteristics and amount of floor area carpeted may have contributed to the difference.

Planned experiments during the next year focus on 5 areas:

- o Baseline characterization during the cooling season,
- o Supplemental experiments using unvented space heaters,
- o Acid aerosol emissions experiments,
- o Spark ignition range and oven experiments, and
- o Monitoring during prototype HVAC equipment tests.

These experiments will provide information on the effectiveness of various source removal and mitigation techniques such as activated charcoal and advanced hood designs. Further measurements during operation of the fan-forced convective UVGSH during cold weather will examine humidity and emission levels for this system. Acid measurements will be conducted to characterize the levels of airborne acids during and following operation of gas appliances.

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APPENDIX A

SOURCE EMISSIONS FROM RANGE AND OVEN

EMISSION RATES FROM THE GRI RESEARCH HOUSE GAS RANGE

Emission rates for nitrogen dioxide (NO_2) nitric oxide (NO), total nitrogen oxides (NO_x), carbon monoxide (CO) and unburned hydrocarbons (UBH) were determined from primary data obtained from 31 tests performed on the range-top and oven burners of the cooking appliance located in the GRI research house.

Range and Oven Burners

The range, manufactured by Modern Maid, contained four identical, stamped aluminum, top burner units, and was integrally mounted into the countertop of the kitchen. A standing pilot was used to ignite the burners, and a vented hood was located above the range.

A Universal bake/broil oven unit was mounted separately from the range-top burners. The unit was equipped with a single burner for both bake and broil modes and a standing pilot for ignition.

Test Procedures

Standard test procedures previously used by IGT in other gas range studies[1-3] were adopted for this test series.

For the range-top burner tests, the procedure consisted of placing an American National Standards Institute (ANSI Z21.1.1.1-1967)[4] cooking pot and a quartz dome collection hood above each burner. A single port sample tube was positioned in the middle of the dome outlet to obtain a sample for analysis. Operation of the burner for 10 to 15 minutes was usually required to obtain steady instrument readings. Three levels of gas input were employed in the tests, namely at full input, one-half input and at an input representative of a "simmer" condition.

For the bake/broil burner tests, a multi-port single tube[4] was placed in the flue outlet to obtain a representative sample for analysis. The unit was operated under no-load conditions.

All tests in this series were performed from cold start. For the range tests, the ANSI pot was cooled, filled with water and reset before each test run. Instrumentation was provided to measure NO_x, NO, NO_2, CO, UBH and carbon dioxide (CO_2). The instruments were calibrated in the morning and at midday to ensure zero or minimal instrument drift during testing.

Test Results

A total of 31 runs were made and are summarized below:

12 range-top burner tests at high input (~ 9500 Btu/h), 3 tests on each of the 4 burners.

8 range-top burner tests at moderate input (~ 4500 Btu/h), 2 tests on each of the 4 burners.

8 range-top burner tests at low input (~ 1400 Btu/h), 2 tests on each of the 4 burners.

2 oven burner tests, thermostat set at 375°F, to simulate "bake" condition.

1 broil burner test (suspended after 12 minutes because of excessive CO emissions).

The test results are presented as an average value for each burner in Table 1 (on an air-free concentration basis) and in Table 2 as an emission rate (in $lbs/10^6$ Btu). The standard deviations, the measure of repeatability of the test procedure, are also shown. The observable trends for each constituent, NO_2, NO, NO_x, CO and UBH are summarized as follows:

NO_2

- At each level of input, there are no statistical differences in the NO_2 emission rates between range-top burners. Furthermore, reducing input from high to moderate levels had little if any effect on NO_2 emission rates. Finally, reducing input to low levels resulted in a significant increase of about 50% in the emission rate, compared to higher input level concentrations.

- In summary, the average NO_2 emission rate (all burners) at high and moderate range-top burner input levels was found to be about 0.0203 ± 0.0003 $lbs/10^6$ Btu. At low input, the emission rate increased to 0.0320 ± 0.0006 $lbs/10^6$ Btu. Repeatability was found to be very good.

NO

- At each level of input, the emission rate tended to be the same between burners, but exhibited a greater variability than did the NO_2 emission rate. As input was reduced, NO emission rates decreased.

- In summary, as range-top burner inputs were reduced from high to moderate to low levels the average emission rate (all burners) steadily decreased from 0.0441 ± 0.0009 to 0.033 ± 0.001 and finally to 0.0104 ± 0.0009 $lbs/10^6$ Btu respectively.

Table 1. EMISSION RATES FROM TEST RANGE, AIR FREE BASIS

Burner and Setting*		No. of Tests	Input, Btu/h	NO_2 Ave.	NO_2 S.D.	NO Ave.	NO S.D.	NO_x Ave.	NO_x S.D.	CO Ave.	CO S.D.	UBH Ave.	UBH S.D.
				Air Free, ppm									
Range LF	H	3	9330	20.7	1.0	66.7	0.9	87.4	1.3	40.8	4.4	<3.1	--
	M	2	4520	20.3	0.4	56.1	5.1	76.4	5.5	32.7	0.2	5.0	0.1
	L	2	1350	31.9	0.1	16.9	1.6	48.8	1.5	333.0	22.3	335.6	87.7
Range RF	H	3	9650	20.9	0.7	62.7	1.3	83.6	1.4	87.8	8.7	<3.1	--
	M	2	5120	18.6	0.7	49.1	4.0	67.7	3.3	36.6	1.6	10.7	6.7
	L	2	1470	31.2	1.1	16.2	2.0	47.3	0.9	376.6	17.8	548.2	45.2
Range LR	H	3	9580	20.7	0.2	73.0	0.8	93.7	0.8	87.9	3.2	<3.0	--
	M	2	4060	21.2	1.5	45.2	0.9	66.4	2.4	64.3	3.5	29.4	4.3
	L	2	1290	33.7	0.9	13.5	1.3	47.1	0.4	462.0	1.1	361.9	6.8
Range RR	H	3	9240	20.5	1.4	68.9	2.4	89.4	3.8	18.0	4.2	<3.2	--
	M	2	4820	19.7	1.0	49.9	0.3	69.7	0.8	29.2	1.6	8.0	2.8
	L	2	1480	30.5	1.0	17.4	5.2	47.9	6.2	368.0	69.7	444.9	5.6
Oven Bake		2	7620	16.7	0.1	70.8	0.1	87.5	0.1	92.2	2.9	6.0	2.0
Oven Broil**		1	23890	36.6	--	118.3	--	154.8	--	1532.3	--	737.0	--

* L = Left, R = Right, F = Front, R = Rear, H = High, M = Moderate, L = Low.
** Oven broil test suspended after 12 minutes because of excessive CO emissions.

Table 2. EMISSION RATES FROM TEST RANGE, LBS EMITTED/10^6 BTU INPUT

Burner and Setting*		No. of Tests	Input, Btu/h	NO_2		NO		NO_x (as NO_2)		CO		UBH (as CH_4)	
				Ave.	S.D.	Ave.	S.D.	Ave.	S.D.	Ave.	S.D.	Ave.	S.D.
				lbs/10^6 Btu									
Range LF	H	3	9330	0.0207	0.0010	0.0434	0.0006	0.0872	0.0013	0.0248	0.0027	<0.001	--
	M	2	4520	0.0203	0.0004	0.0365	0.0033	0.0762	0.0055	0.0198	0.0001	0.0017	0.0002
	L	2	1350	0.0318	0.0001	0.0110	0.0010	0.0486	0.0015	0.202	0.014	0.116	0.030
Range RF	H	3	9650	0.0208	0.0007	0.0408	0.0008	0.0834	0.0014	0.0533	0.0053	<0.001	--
	M	2	5120	0.0185	0.0007	0.0319	0.0026	0.0675	0.0033	0.0222	0.0010	0.0037	0.0023
	L	2	1470	0.0311	0.0010	0.0105	0.0012	0.0472	0.0009	0.228	0.011	0.190	0.016
Range LR	H	3	9580	0.0207	0.0002	0.0474	0.0005	0.0934	0.0008	0.0534	0.0019	<0.001	--
	M	2	4060	0.0212	0.0015	0.0294	0.0006	0.0662	0.0024	0.0390	0.0021	0.0102	0.0015
	L	2	1290	0.0335	0.0008	0.0088	0.0008	0.0470	0.0004	0.280	0.001	0.154	0.002
Range RR	H	3	9240	0.0204	0.0014	0.0448	0.0016	0.0891	0.0038	0.0109	0.0025	<0.001	--
	M	2	4820	0.0197	0.0010	0.0325	0.0002	0.0694	0.0008	0.0177	0.0009	0.0028	0.0010
	L	2	1480	0.0304	0.0010	0.0113	0.0034	0.0478	0.0062	0.223	0.042	0.125	0.002
Oven Bake		2	7620	0.0166	0.0001	0.0461	0.0001	0.0872	0.0001	0.0560	0.0018	0.0021	0.0001
Oven Broil**		1	23890	0.0365	--	0.0769	--	0.154	--	0.930	--	0.256	--

* L = Left, R = Right, F = Front, R = Rear, H = High, M = Moderate, L = Low

** Oven broil test suspended after 12 minutes because of excessive CO emissions.

NO_x

- Total NO_x behaviour was similar to that obtained for NO.

- At high input the emission rate was 0.088 ± 0.001 lbs/10^6 Btu, decreasing to 0.070 ± 0.002 lbs/10^6 Btu at moderate input, and finally to 0.048 ± 0.001 lbs/10^6 Btu at low input.

CO

- CO emission factors exhibited a greater degree of variability than found for nitrogen oxides. For example, at high input, the right-front and left rear burners exhibited much higher emission rates than found for the other two burners. Past test results have shown considerable scatter in CO emissions.[3] The scatter is likely due to the unique way each burner flame impinges the grate and pot, which in turn quenches the CO to CO_2 reaction. Note that CO emission rates are much more consistent at low and moderate inputs, where less potential flame impingement may occur.

- At high input, CO emission rates were 0.036 ± 0.006 lbs/10^6 Btu and depended on burner location. As input was reduced to moderate levels, CO emissions were generally reduced to 0.025 ± 0.003 lbs/10^6 Btu. At low input levels, CO emission rates increased to 0.234 ± 0.015 lbs/10^6 Btu.

UBH

- Unburned hydrocarbon emissions were found to be mainly dependent on input and to a lesser extent on burner position.

- At high input levels, UBH emission rates were virtually zero, increasing to 0.005 ± 0.001 lbs/10^6 Btu at moderate input, and to 0.147 ± 0.014 lbs/10^6 Btu at low input.

Comparison to Literature Data

In addition to presenting the standard deviation, to indicate the repeatability of the test procedure, another measure of determining the validity of the test results is to compare them to available literature data.[3] The variation in historical results is presented to indicate the expected range of emission rates. Table 3 presents a comparison of the current results to literature data and shows that the research house range and oven burner emission rates fall within the bounds of the literature data.

Table 3. COMPARISON OF MEASURED EMISSION FACTOR TO LITERATURE DATA

Constituent	Emission Factor: Variation in Research House Data	Emission Factor: Variation in Literature[3] Data
	lbs/10^6 Btu	lbs/10^6 Btu
Range-Top Burners*		
NO_2	0.0204-0.0207	0.017-0.042
NO	0.0408-0.0474	0.033-0.057
NO_x (as NO_2)	0.0834-0.0934	0.067-0.114
CO	0.0109-0.0534	0.027-0.210
Oven		
NO_2	0.0166	0.010-0.032
NO	0.0461	0.036-0.069
NO_x	0.0872	0.081-0.106
CO	0.0560	0.016-0.129

* At high input of about 10,000 Btu/h.

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3. Cole, J. T. and Zawacki, T. S., "Emissions from Residential Gas-Fired Appliances," Topical Report GRI-84/0164, February 1985.

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APPENDIX B

SOURCE EMISSIONS FROM UNVENTED SPACE HEATERS

EMISSION RATES FROM THE UNVENTED SPACE HEATER

Emission rates for nitrogen dioxide (NO_2), nitric oxide (NO), total nitrogen oxides (NO_x), carbon monoxide (CO), and unburned hydrocarbons (UBH) were determined from primary data obtained in 27 tests performed with an unvented space heater supplied by GARD Division of Chamberlain Manufacturing Corporation.

Space Heater Characteristics

The unvented space heater used in the test program was an Osaka Gas Model 44-740 fan heater 4000. The unit was equipped with a specially designed, low-emitting modulating burner and an induced draft fan to supply combustion air and to circulate room air through the heater. The heater has a rated gas input of about 1500 to 4000 cal/h (5,120 to 13,640 Btu/h). The unit was capable of operating at 6 distinct input levels, within the stated range. Input was thermostatically controlled and input level could be observed by a panel of 6 lights located on the top front of the unit. Six lights on indicated full input while one light on indicated the lowest input possible. Overall heater dimensions were 22 in. wide X 17 in. high X 7 in. deep. Supply and circulating air entered the top rear of the unit (6.5 in. X 16 in. open area) and exited at the bottom front (2.5 in. X 15.5 in. open area).

Test Procedures and Instrumentation

Two types of tests, probe and hood,[1] were conducted to determine the validity of using the "hood" method for determining emissions from heaters equipped with powered burners and air circulating fans. The probe and hood test methodologies were appropriately modified to accommodate the presence of the air blower.

The hood method was modified by placing baffles around the heater such as to deflect the air stream exiting the heater upwards through the chimney section of the hood, as shown in Figure 1. Several shakedown tests were performed to determine proper positioning of the heater and baffles beneath the hood. The results of the tests indicate that:

- The heater should be positioned relative to the hood as per original hood method protocol.

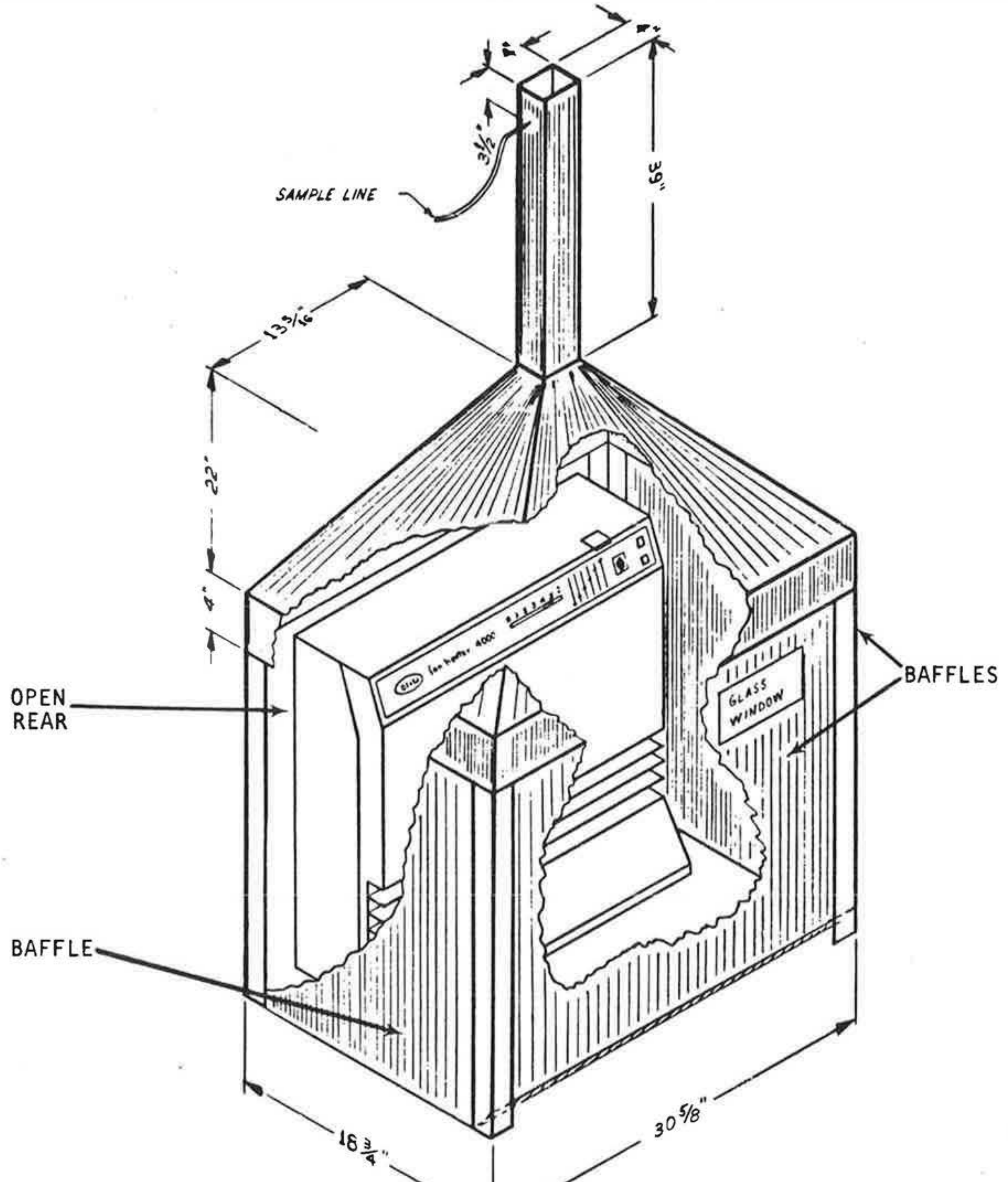


Figure 1. STANDARD HOOD MODIFICATION

- Three baffles should surround the heater to maximize the amount of heater-circulating air driven up the chimney and minimize the amount of room dilution air mixed with the circulating air (Figure 1).

The probe method was modified by placing an extended duct on the exit opening of the heater to provide for complete mixing of combustion products with the circulating air and uniform air distribution before sampling (Figure 2). A five-port glass sampling probe was placed at the centerline of exit of the extended duct.

The instruments used to perform the tests are described as follows:

- NO_x — TECO Model 12A chemiluminescence analyzer
- CO_2 — Beckman Model 864 NDIR analyzer
- CO — Horiba Model 300E APMA NDIR trace CO monitor
- UBH — Beckman Model 400 flame ionization detector
- Gas Flow — Tylan Model FM362 mass flow meter and Rockwell Instruments R-200 positive displacement gas meter with temperature compensation.

Preliminary tests were also performed to determine whether combustion products were escaping at locations other than the circulating air duct exit, as for example, through cracks in the heater case. This was done by placing the sampling probe at locations leaks were likely to occur and noting the sample CO_2 concentration. An increase in background CO_2 concentration would indicate a leak. No leaks were found and the only source of emissions entering the room is the heater circulating air exit.

Experimental Results

Gas Input Levels

Gas input was monitored by continually recording the output of the mass flow meter as a function of time and space heater setting. Desired gas input rate levels (for 3 and 4 lights being on) were obtained by manipulating the thermostat switch until a stable level was observed. Typical tracings of gas input are shown in Figure 3 and discussed as follows:

- Upon ignition from cold start, gas input rises to above 14,000 Btu/h. At the highest input, gas flow slowly decreases as operating time increases. A steady input of about 14,000 Btu/h is reached after 15 to 20 minutes of operation (Figure 3A). No discernable difference was observed between inputs with the 5 or 6 panel indication steps, with lights on.

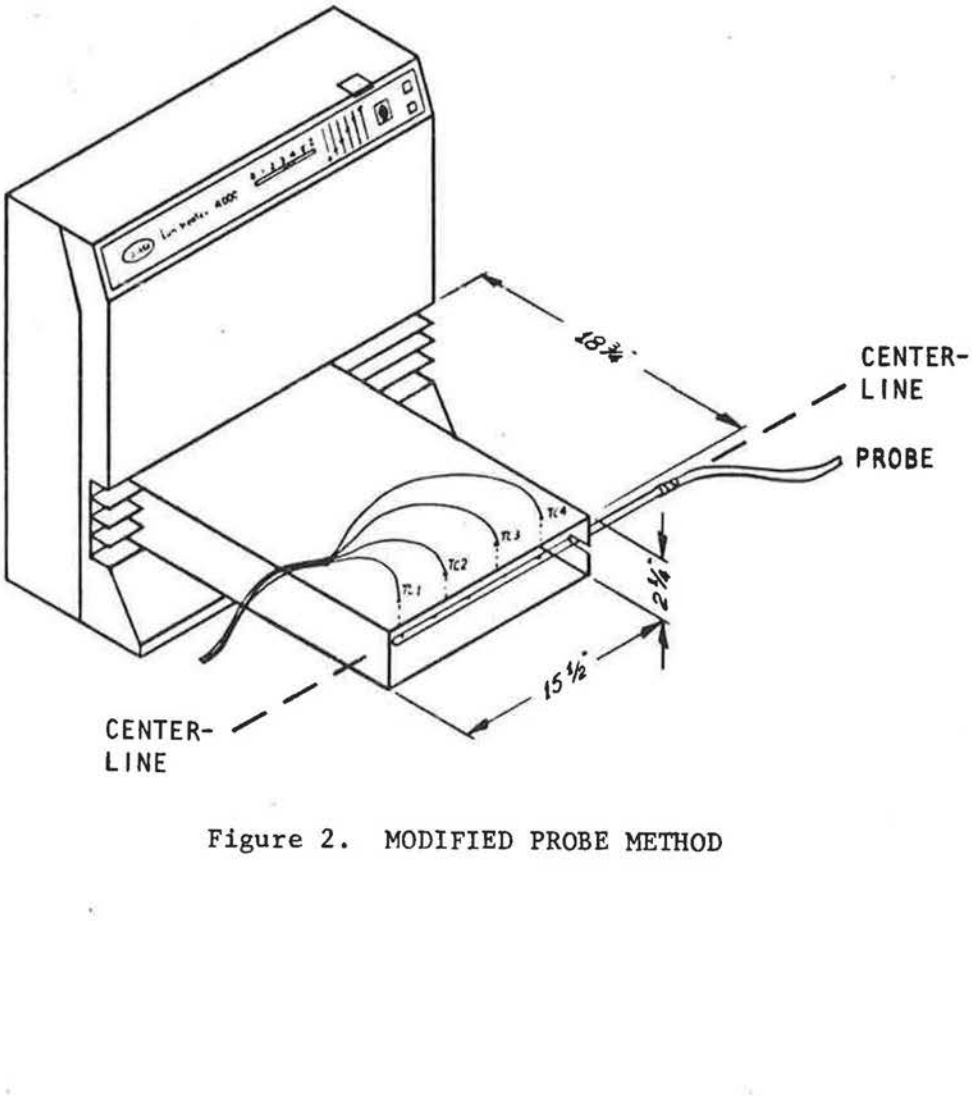
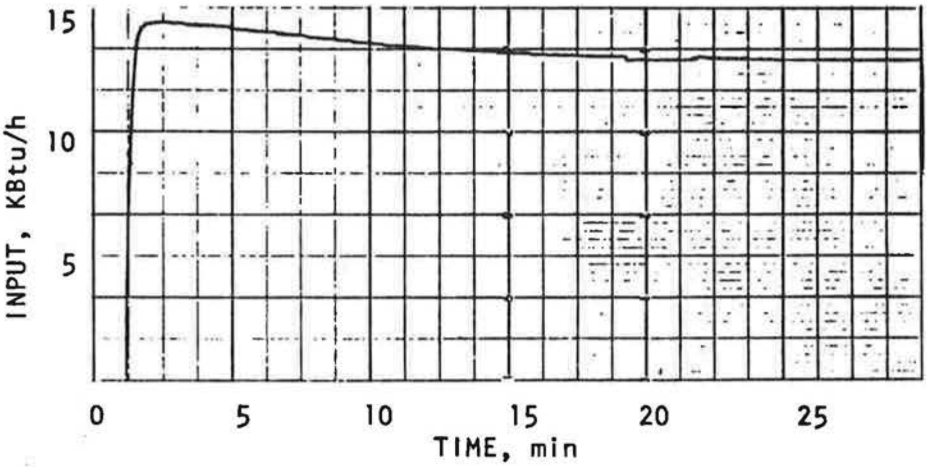
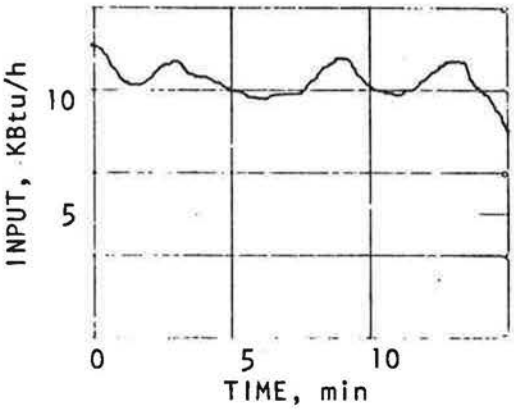


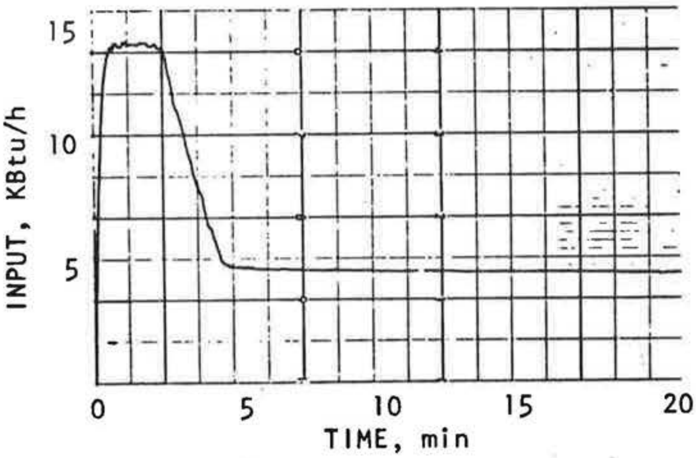
Figure 2. MODIFIED PROBE METHOD



A. GAS INPUT, 5 OR 6 LIGHTS ON



B. GAS INPUT, 4 LIGHTS ON



C. GAS INPUT, 1 LIGHT ON

Figure 3. GAS INPUT LEVELS

- Low input was obtained by switching the thermostat to its lowest setting (1 light). The tracing in Figure 3C shows that the heater takes about 2 minutes to traverse from the highest to lowest input. The low input gas rate is very stable at about 5000 Btu/h. No discernable difference could be observed between inputs with the 1 and 2 panel indication steps with lights on.

- Mid-input levels were reached by manipulating the thermostat switch such as to maintain the same number of lights on during the test period. A typical trace obtained with 4 lights on is shown in Figure 3B. Input was found to vary significantly with time, 8,000 to 12,000 Btu/h, even though 4 lights were always on. After careful examination of gas-line pressure and metering devices, it was concluded that the variations in gas input rate are due to the space heater control mechanism.

- In summary, gas input rates could be stabilized at inputs corresponding to 1 and 2 lights (5,000 Btu/h), 3 lights (8,000 Btu/h), 4 lights (11,000 Btu/h), and 5 and 6 lights (14,000 Btu/h). Inputs at the two mid-level ranges (3 and 4 lights) exhibited significant excursions during testing.

Air Flow Rate and Temperature

Two important heater characteristics, circulating air temperature rise and flow rate, were determined from primary data obtained during testing by the "probe" method. Outlet average circulating air temperature was obtained by measuring (and averaging) temperatures at four evenly spaced locations at the centerline of the extended duct outlet (Figure 2). Circulating air flow rate was estimated by two methods (carbon balance and heat gain) assuming 88% of the energy contained in the fuel was transferred to the circulating air for the heat gain method. The remaining 12% consists of 9% latent heat and about 3% case losses.

The results are shown in Table 1 and are summarized as follows:

- Air temperature rise of about 70°F was measured at the lowest input investigated (4,940 Btu/h) and steadily increased to about 106°F as gas input rate was increased to 14,100 Btu/h.

- Good agreement (within 8%) was obtained between the two methods used to estimate air flow rate. Air flow increased from about 60 CF/min at low gas input rate to over 100 CF/min at the highest input tested. At mid-input levels of 8,840 to 11,360 Btu/h, air flow remained fairly constant at about 90 CF/min.

Emission Rates

The test results are presented as an average value for each gas input level tested, on an air-free basis and as an emission rate (in lbs/10^9 Btu). Results with the hood method are shown in Table 2 and with the probe method,

Table 1. SPACE HEATER CHARACTERISTICS

Burner Setting*	Burner Gas Input, Btu/h	Circulating Air Temperature Rise, °F	Circulating Air Flow Rate, By ΔT Rise, CF/min	Circulating Air Flow Rate, By CO_2 Balance, CF/min
5 and 6	14,100	106	108	100
4	11,360	99	93	87
3	8,840	83	86	89
1 and 2	4,940	70	60	59

* - Number of lights.

Table 2. EMISSION RATES FROM TEST HEATER HOOD METHOD

AIR FREE BASIS

Burner Setting	Burner Input Btu/h	No. of Tests	NO_2 Ave.	NO_2 S.D.	NO Ave.	NO S.D.	NO_x Ave.	NO_x S.D.	CO Ave.	CO S.D.	UBH Ave.	UBH S.D.
			ppm Air Free									
5 and 6	13,890	4	2.62	0.10	3.57	0.07	6.19	0.11	2.6	1.5	0.0	0.0
4	11,190	4	2.43	0.18	2.47	0.16	4.91	0.28	4.9	1.1	0.69	0.29
3	8,160	4	2.07	0.08	1.32	0.16	3.39	0.17	7.8	2.0	7.7	3.9
1 and 2	5,190	4	2.22	0.10	0.22	0.02	2.43	0.10	46.2	2.9	20.0	2.5

LBS EMITTED/10^9 Btu INPUT

Burner Setting	Burner Input Btu/h	No. of Tests	NO_2 Ave.	NO_2 S.D.	NO Ave.	NO S.D.	NO_x* Ave.	NO_x* S.D.	CO Ave.	CO S.D.	UBH** Ave.	UBH** S.D.
			lbs/10^9 Btu									
5 and 6	13,890	4	2.75	0.10	2.44	0.05	6.49	0.12	1.7	1.0	0.0	0.0
4	11,190	4	2.55	0.19	1.69	0.11	5.15	0.29	3.1	0.7	0.25	0.11
3	8,160	4	2.17	0.08	0.90	0.11	3.56	0.18	5.0	1.3	2.8	1.4
1 and 2	5,190	4	2.33	0.10	0.15	0.01	2.55	0.10	29.5	1.9	7.3	0.9

S.D. - Standard Deviation

* - NO_x as NO_2

** - UBH as CH_4

in Table 3. The standard deviation of the mean value, the measure of the repeatability of the test procedure, is also shown.

The observed trends for each constituent; NO_2, NO, NO_x, CO, and UBH, obtained from the hood tests, are summarized as follows:

$\underline{NO_2}$

- Reducing input from 14,000 to 5,000 Btu/h had only a marginal effect on NO_2 emission rates, about a 15% decrease in the NO_2 emission rate, from 2.62 to 2.22 $lb/10^9$ Btu.

<u>NO</u>

- Reducing input resulted in a significant and systematic reduction in NO emission rates.
- In summary, the NO emission rate decreased from 3.57 $lb/10^9$ Btu, at 13,890 Btu/h, to only 0.22 $lb/10^9$ Btu, at about 5,000 Btu/h.

$\underline{NO_x}$

- Because of the drastic reduction in NO emissions as input was reduced, NO_x emissions followed a similar trend
- In summary, the NO_x emission rate decreased from 6.19 lbs (as NO_2)/10^9 Btu to 2.55 lbs (as NO_2)/10^9 Btu, as the input was systematically reduced from 13,890 to 4,190 Btu/h.
- At full input, total NO_x (on a volumetric basis) consisted of about 50% NO and 50% NO_2. But as input was reduced, the percentage of NO_x as NO_2 increased reaching over 90%, at the lowest input tested.

<u>CO</u>

- CO emissions increased as gas input rate was decreased.
- In summary, the CO emission rate slowly increased from 1.7 $lb/10^9$ Btu to 5.0 $lb/10^9$ Btu, as the input was reduced from 13,890 to 8,160 Btu/h. A dramatic increase to 29.5 $lb/10^9$ Btu was noted, as the input was lowered to 5,190 Btu/h.

<u>UBH</u>

- UBH emissions exhibited similar trends to those shown by CO — emission rates increased as input was decreased.
- In summary, virtually no UBH emissions were detected at the full input of 13,890 Btu/h. The UBH emission rate increased from 0.69 lbs (as CH_4)/10^9 Btu to 20.0 lbs (as CH_4)/10^9 Btu, as input was decreased from 11,190 to 5,190 Btu/h

Table 3. EMISSION RATES FROM TEST HEATER PROBE METHOD

AIR FREE BASIS

Burner Setting	Burner Input Btu/h	No. of Tests	NO_2 Ave.	NO_2 S.D.	NO Ave.	NO S.D.	NO_x Ave.	NO_x S.D.	CO Ave.	CO S.D.	UBH Ave.	UBH S.D.
			ppm Air Free									
5 and 6	14,100	4	2.87	0.29	4.48	0.28	7.35	0.35	4.5	2.5	0.0	0.0
4	11,360	1	2.12	NA	3.18	NA	5.30	NA	9.4	NA	0.0	NA
3	8,840	2	2.32	0.08	2.51	0.86	4.83	1.11	2.4	0.4	0.4	0.6
1 and 2	4,940	4	1.95	0.22	0.43	0.06	2.39	0.55	50.7	3.0	14.3	2.8

LBS EMITTED/10^9 Btu INPUT

Burner Setting	Burner Input Btu/h	No. of Tests	NO_2 Ave.	NO_2 S.D.	NO Ave.	NO S.D.	NO_x* Ave.	NO_x* S.D.	CO Ave.	CO S.D.	UBH** Ave.	UBH** S.D.
			lbs/10^9 Btu									
5 and 6	14,100	4	3.01	0.30	3.06	0.19	7.71	0.37	2.9	1.6	0.0	0.0
4	11,360	1	2.23	NA	2.17	NA	5.56	NA	6.0	NA	0.0	NA
3	8,840	2	2.43	0.08	1.72	0.59	5.07	1.16	1.5	0.3	0.1	0.2
1 and 2	4,940	4	2.05	0.23	0.29	0.04	2.51	0.58	32.4	1.9	5.2	1.0

S.D. - Standard Deviation

NA - Not Applicable

* - NO_x as NO_2

** - UBH as CH_4

Comparison of the results obtained by the hood (Table 2) and probe (Table 3) test methods indicate that the probe results exhibit the same trends shown by the hood results. Specific observations are summarized as follows:

- There are no significant differences between average NO_2 emission rates determined by the hood and probe method at the 95% confidence level.

- NO emissions obtained by the probe method were generally higher by 0.2 to 0.95 ppm, air free basis, but these differences were not significant at the 95% confidence level.

- There are no significant differences between average CO and UHB emission rates obtained by the two test methods. However, CO emission rates exhibited greater variability from run to run, than NO_2 or NO, as indicated by the high CO standard deviation.

Conclusions

The major conclusion reached as a result of this study is that the hood and probe test methods can be modified such that emission rates can be accurately determined from heating appliances equipped with power burners and air circulating fans.

Literature Cited

1. Zawacki, T.S., Cole, J.T., Jasionowski, W.J. and Macriss, R.A., "Measurement of Emission Rates From Gas-Fired Space Heaters," Report GRI-86/0245, Institute of Gas Technology, Chicago, IL, October 1986.

Energy Development Center

May 29, 1986

Mr. Roy Fortman
GEOMET Technologies, Inc.
20251 Century Blvd.
Germantown, Maryland 20874

Re: Emission Factor Tests at Gaithersburg's Test Site

Dear Roy:

Enclosed herewith is one copy of the data collected at the Test House in Gaithersburg, Maryland on April 30 and May 1, 1986. The CO_2, CO, NO and NO_x concentrations from a probe near the top of the hood were determined by non-dispersive infrared gas analyzers and a chemiluminescent gas analyzer. The CO_2 values listed on the data sheets are % deflection readings and not concentrations. Also, enclosed is a photocopy of CO_2 analyzer's calibration data sheet. The values for CO, NO and NO_x are in parts per million.

The enclosed Table 1 presents a summary of emission factors for the two unvented space heaters; namely, Sears Model No. 155. 853100 (S) Empire/Corcho Model R15 NAT (E/C). The emission factor calculations are based on the data at the 30 minute burn time and the information supplied by Dan Cade with regards to the heating value of the cylinder gas used in these tests. The values reported correspond to the steady-state emission rates and not to any transient conditions.

The test results in Table 1 show that the emission factors, determined for the Sears Unit (blue-flame burner heater with no suspended tiles) at the Gaithersburg site, compare well with previous data developed at IGT with the same heater last year.

The test results in Table 1 also show that the emission factors determined for the Empire/Corcho Unit (Infrared) at the Gaithersburg site for CO compare well with previous IGT data. The emission values for NO_2 and NO_x are, however, about double the previous measurements (0.012 lbs/10^6 Btu), but still within the values typical of infrared tile burners. Don Cade advised me that there were some problems with the controls of this unit, during its use at the Gaithersburg site. Any changes in the controls could, probably, explain these differences.

Please call me, Bob Macriss or Tom Zawacki, if you have any questions or comments regarding the data.

Yours truly,

Walt Jasionowski

Walt Jasionowski
Senior Engineer
Energy Utilization Research
(312) 890-6433

WJJ/pp
Enclosure

cc: Dr. I. Billick, GRI
R. A. Macriss
T. S. Zawacki

INSTITUTE OF GAS TECHNOLOGY

Table 1. EMISSION FACTORS, LBS/10^6 BTU

Run No.	CO	NO	NO_x	NO_2
S-1	0.0290	0.0393	0.0840	0.0237
S-2*	0.00725	0.0419	0.0845	0.0203
S-3	0.0329	0.0435	0.0938	0.0271
S-4	0.0305	0.0372	0.0835	0.0264
Average	0.0308 ± 0.0011	0.0405 ± 0.0014	0.0865 ± 0.0025	0.0244 ± 0.0015
Previous	0.02595 ± 0.00085	0.0372 ± 0.0001	0.0823 ± 0.0001	0.02525 ± 0.00015
E/C-1	0.154	0.000353	0.0129	0.0124
E/C-2	0.154	0.000335	0.0134	0.0131
E/C-3	0.145	0.000413	0.0117	0.0111
Average	0.1510 ± 0.0030	0.000367 ± 0.000024	0.01267 ± 0.00050	0.01220 ± 0.00059
Previous	0.1635 ± 0.0010	0.000012 ± 0.000039	0.006577 ± 0.000096	0.006560 ± 0.000085

* Run S-2 CO results are questionable. Power lawn mower fumes were getting into background analysis.

Osaka Gas Company, Ltd   2-17-87

Classification	Combustion system	Surface combustion system (ceramic burner)			
	Heat release system	Forced convention system			
Overall dimension (mm)		Height: 440, Width: 560 Depth: 170 (Leg; 220)			
Weight (kg)		14			
Gas consumption (kcal/h)	Gas type	6C	13A	6A	LP
	Max. combustion	4.000	4.000	4.000	0.33 kg/h
	Min. combustion	1.500	1.500	1.500	0.13 kg/h
Power source		Single phase, 100 V, 60 Hz			
Power consumption (W)	Max.	45			
	Min.	34			
Room temperature adjustment		Electronic thermostat			
Wind direction		Downward below the main body			
Air volume control		Automatic control by main burner thermocouple output			
Operation system		Quick operation by push-button system			
Ignition system		Continuous spark ignition			
Safety device		.Non-combustion prevention devices (thermocouple) .Extinguished fire sensor (thermocouples) .Overheat prevention device (temperature fuse, high limit switch) .Safety device for power interruption (safety valve type) .Overcurrent prevention device (current fuse) .Gas shut-off device (operated by a mercury switch when gas heater falls down)			
Noise		42 dB (A)			
Displays		Combustion indicator lamp (large LED)			
		Power monitor lamp (6 LEDs)			

Section 7.0

QUALITY ASSURANCE AND QUALITY CONTROL

This section includes general guidelines for the development of a QA program and QC procedures for the IAQ monitoring program for the conventional research house. It does not, however, contain specific QC procedures.

The QA program consists of detailed and specific procedures that delineate how data of known and accepted quality are produced. QC is the routine application of procedures for obtaining the standards of performance in the QA plan.

7.1 QUALITY ASSURANCE PROJECT PLANS

A QA project plan should be prepared to address the objectives of this project. The following elements should be considered for inclusion in the plan:

- Project organization and responsibility
- QA objectives for measurement data in terms of precision, accuracy, completeness, representativeness, and comparability
- Sampling procedures
- Sampling custody
- Calibration procedures and frequency
- Analytical procedures
- Data reduction, validation, and reporting
- Internal QC checks and frequency

- Performance and system audits and frequency
- Preventive maintenance procedures and schedules
- Specific routine procedures to be used to assess data precision, accuracy, and completeness of specific measurement parameters involved
- Corrective action
- QA reports to management.

Guidelines for preparing project QA plans have been prepared by the U.S. Environmental Protection Agency in the "OTS Guidance Document for the Preparation of Quality Assurance Project Plans," dated October 1, 1987.

7.2 QC PROCEDURES

To ensure that QA objectives are met, a series of QC procedures should be implemented on a routine basis. QC procedures include the following:

- Operational checks
- Performance checks
- Multipoint calibrations
- Precision checks.

7.2.1 Operational Checks

Operational checks should be performed each weekday to evaluate the reasonableness of the output of the measurement device under the measurement conditions at the time. Examples of daily onsite operational checks include the following:

- Pollutant analyzers--appropriate background concentrations, appropriate response to sources
- SF_6 analyzer--appropriate response to injection, appropriate decay rates
- Thermistors--appropriate readings, similarities between rooms of same zone.

7.2.2 Performance Checks

Performance checks are checks on measurement results compared with primary or secondary reference standards (e.g., comparison of thermistor measurements and an National Bureau of Standards (NBS)-traceable mercury-in-glass thermometer). Examples of performance checks to be implemented for this project are presented in Table 12. Recommended frequencies for performance checks are also included in the table. In some situations, such as after installation of new measurement devices or repair of a measurement device, the frequency of performance checks should be increased until adequate performance has been verified.

7.2.3 Multipoint Calibrations

Multipoint calibrations are performed to relate the measurement device output to known input values over the measurement range of the device. The required frequency of multipoint calibrations is generally a function of instrument performance as it relates to drift of the instrument response to a fixed input over time. For relatively stable

Table 12. Performance Checks for Measurement Parameters at the Test Residences

Parameter	Performance Check	Recommended Frequency
Temperature*	Comparison with NBS-traceable measurement device	Monthly
Relative humidity	Psychrometer comparison (ASTM E337-84)**	Monthly
Tracer gas	Zero and span check	Weekly
Pollutants	Zero and span check	Weekly
Windspeed	Anemometer comparison	Monthly
Wind direction	Compass comparison	Monthly
Barometric pressure	Weather Service comparison	Monthly
Precipitation	Rain gauge comparison	Semiannually
Gas volume	Total of submeters compared with house meter	Weekly

* Thermistor or thermocouples; indoor or outdoor.

** American Society for Testing and Materials Standard Test Method.

instruments such as thermistors or thermocouples, infrequent multipoint calibrations accompanied by periodic performance checks will be adequate. For less stable devices such as tracer gas and pollutant analyzers, more frequent calibrations will be required.

Recommended frequencies for multipoint calibrations are presented in Table 13 for the major measurement parameters at the research house. As indicated in the table, for a number of measurement devices, multipoint calibrations will consist of colocating NBS-traceable measurement devices to record outputs under a range of measurement conditions. Multipoint calibrations will be performed using standard procedures available in the technical literature and in the American Society for Testing and Materials Annual Book of ASTM Standards.

7.2.4 <u>Precision Checks</u>

Precision checks consist of temporary colocation of identical measurement devices at measurement sites in the test residences. Precision checks should be performed annually by colocating approximately 10 percent of each type of measurement device (e.g., thermistors, humidity sensors). For some parameters (e.g., precipitation, air infiltration, and solar radiation), colocating instruments is not possible. In cases where precision checks are logistically unfeasible, repeatability of the measurement device will be assessed during multipoint calibrations, performance checks, or external audits.

Table 13. Requirements for Multipoint Calibrations at the Research House

Parameter	Calibration Procedures	Recommended Frequency
Temperature*	Water bath (4-point)	Semiannually**
Relative humidity	Saturated salt solutions (ASTM E104-85)	Semiannually**
Tracer gas	Multipoint (5-point) span gases	Biweekly
Pollutants (continuous monitors)	Multipoint (5-point) span gases	Biweekly
Windspeed	Colocated anenometer***	Annually
Wind direction	Compass***	Annually
Barometric pressure	Colocated NBS-traceable barometer***	Annually
Precipitation	Colocated rain gauge	Annually
Gas volume	Colocated measurement device	Annually

* Thermistor or thermocouples; indoor or outdoor (except soil).

** Preferred times are prior to and following the heating season.

*** Over range of measurement conditions.

7.3 PERFORMANCE AND SYSTEM AUDITS

7.3.1 Internal Audits

Internal audits should be conducted routinely by the project QA officer to assess performance of the total measurement system. Internal audits consist of review of data files; documentation forms; test site operation records; maintenance logs; and, as required, onsite inspection and review of the facilities, instrumentation, recordkeeping, and operational procedures at the research house as they relate to quality control for the measurement program.

7.3.2 External Audits

An external performance audit should be conducted annually by a qualified independent audit organization. This external performance audit shall provide an assessment of key components of the measurement system where appropriate by (1) challenging continuous analyzers with known inputs, (2) colocating audit measurement devices, (3) verifying system specifications, (4) applying control and/or split samples, and (5) making independent observations. The auditing organization shall provide a prompt report of audit procedures and results.

7.4 PREVENTIVE MAINTENANCE

To ensure that downtime is minimized, a rigorous program of preventive maintenance should be implemented at the research house. Nearly all of the instrumentation used at the house is commercially supplied; maintenance schedules should be developed on the basis of manufacturers' recommendations. Proper recordkeeping is required to ensure that maintenance procedures are applied on a routine basis. Control charts should be implemented where applicable to identify changes or trends in instrument response.

7.5 CORRECTIVE ACTIONS

While the measurement program is under way, the QA program must be continually sensitive to emerging problems that affect data quality. Corrective actions may be initiated as a result of daily operational checks, performance checks, or audits.

Responsibilities for corrective measures are distributed among all staff members on the project. All staff members must be cognizant of procedures for (1) problem detection, (2) problem analysis, (3) corrective actions, (4) verification, and (5) reporting and recordkeeping.

7.6 DOCUMENTATION

To ensure that QC procedures are followed, a rigorous program of documentation should be instituted. Documentation should include research house laboratory log books, daily status checklists, instrumentation daily checklists, calibration forms, and documentation of experimental test conditions and procedures.

APPENDIX A

OCCUPANT SIMULATION PROTOCOL FOR THE GRI
SPACE-CONDITIONING PROGRAM

OCCUPANT SIMULATION PROTOCOL--APPLIANCE OPERATING CONDITIONS AND SETTINGS

Appliance/Activity	Parameter	Condition/Setpoint
Hot water heater	Temperature setpoint	130 °F
Shower	Water temperature	105 °F
Clothes washer	Water temperature--wash	Warm*
	--rinse	Cold
	Water level	High
	Cycle setting	Regular/heavy
	Load**	Towels
Clothes dryer	Cycle setting	Timed-regular/heavy
	Load	Towels (same)
Dishwasher	Cycle	Normal with heated dry
	Load	Four each--plates, cups, glasses, silverware settings
Range burner	Burner	Right front
	Burner setting	High
	Pan	ANSI pot
	Pan load	78-oz (2.3 L) H_2O
Range oven	Setting	350 °F
	Oven load--pot	Ceramic pot
	--content	15-oz (0.4 L) H_2O
Refrigerator	Refrigerator load***	4 gal H_2O
	Freezer load***	2 gal H_2O two trays of ice cubes

* Exact temperature dependent on the washer.

** Washer should be approximately half filled with dry towels. Record dry towel weight once.

*** One gallon of water in refrigerator and two trays of ice cubes to be changed each Tuesday at 1000 with door opening totaling 30 s.

OCCUPANT SIMULATION PROTOCOL
SCHEDULE OF ACTIVITIES

Occupant Heat Simulation (7 Days Per Week)

Room	Watts	Time Period
MBR	150	0800-0830
K/DR	350	0830-0900
DN	200	0900-1100
LR	100	1100-1200
K/DR	200	1200-1230
LR	200	1430-1600
K/DR	200	1600-1700
K/DR	350	1700-1800
LR	200	1800-2200
CBR	100	1900-2200
MBR	150	2200-0800
CBR	75	2200-0800

Occupant Moisture Simulation (7 Days Per Week)

Room	g/h	Time Period
LR	270	0800-1300
LR	270	1500-2200
MBR	270	1600-0840

OCCUPANT SIMULATION SCHEDULE*

	Appliance Use	Lighting (7 days/wk)	Occupant Heat (7 days/wk) (Room-Watts)	Occupant Moisture (g/h) (7 days/wk)
			From 2200	From 2200 270
0700			MBR-150 CBR-75	270
0800	Shower Range burner	CBR MBR Bath K DR	MBR-150 K/DR-350	450
0900	Clothes washer			270
1000	Shower Clothes dryer	DN (Basement)	DN-200	270
1100			LR-100	270
1200			K/DR-200	0
1300				0
1400				0
1500			LR-200	270
1600	Oven (350 °F)		K/DR-200	540
1700	Dishwasher	K DR	K/DR-350	540
1800			LR-200	540
1900	TV-CBR	LR		540
2000		CBR	CBR-100	540
2100	TV-LR	MBR		540
2200			MBR-150 CBR-75	270
2300			To 0800	270 To 0800

* MBR--Master Bedroom, LR--Living Room, DR--Dining Room, CBR--Child's Bedroom, K--Kitchen, DN--Downstairs.

OCCUPANT SIMULATION PROTOCOL--SCHEDULE OF ACTIVITIES

Appliance Use

Activity	Time Period
Shower	0800-0820
Range Burner (high)	0815-0845
Clothes Washer	0900-0930 (one cycle)
Shower	1000-1010
Clothes Dryer	1000-1040
Oven (350 °F)	1600-1700
Dishwasher	1700-1730 (one cycle)

Appliance Use (7 Days Per Week)

Activity	Time Period
TV--Child's Bedroom*	1900-2100
TV--Living Room	2000-2200

* Simulated with 150-W light bulb in thermal simulator.

Lighting (7 Days Per Week)

Activity	Time Period
Master Bedroom (MBR)* Child's Bedroom (CBR)* Master Bathroom (Bath)*	0800-0830
Kitchen (K)* Dining Room (DR)**	0830-0900
Downstairs (DN)**	0900-1100
Kitchen	1630-1800
Dining Room Living Room	1800-2200
Child's Bedroom	1900-2200
Master Bedroom	2000-2300

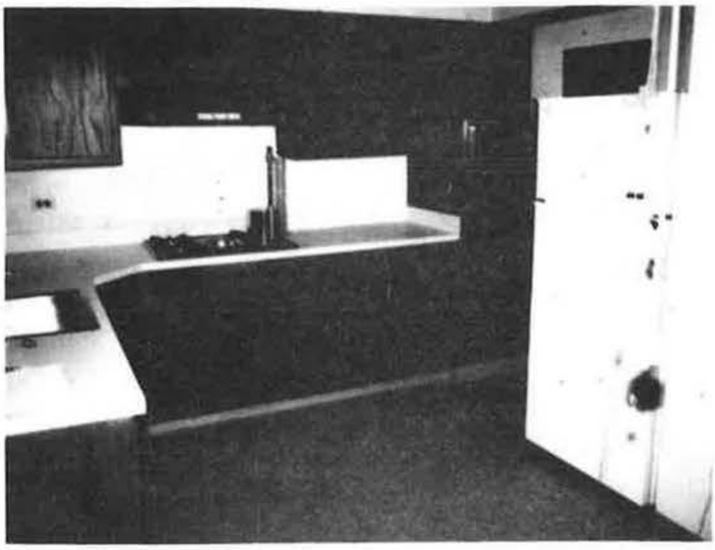
* 100 W.
** 200 W.

APPENDIX D

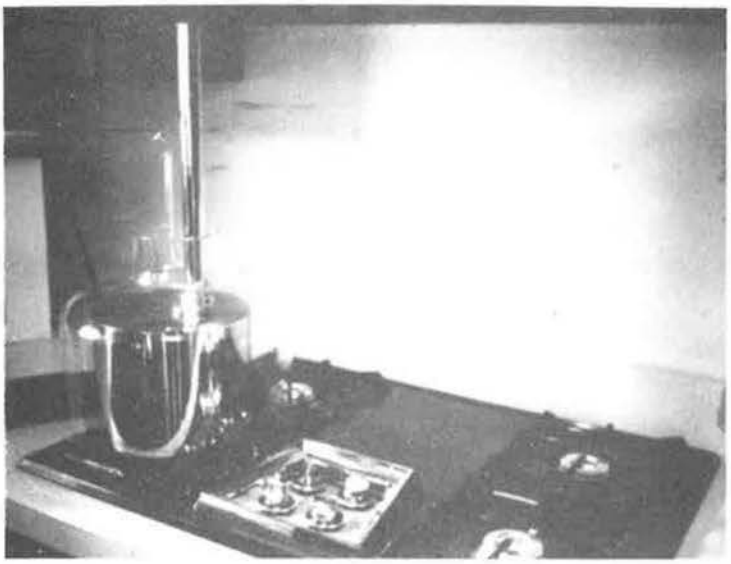
CONVENTIONAL RESEARCH HOUSE PHOTOGRAPHS

GAS ANALYZING EQUIPMENT IN OFFICE

LIVING ROOM ZONE STATION



KITCHEN, SHOWING RANGE AND SEPARATE OVEN



RANGE WITH COMBUSTION UTENSIL

GAS ANALYZING EQUIPMENT IN KITCHEN

Osaka Gas Co, Ltd - NO_2 data (2-17-87)

Gas Component (vol%)

	13A-1	6C-1	6A
CH_4	85		
H_2		57.5	
n-C_3H_8	15	12.5	
N_2		30	
n-C_4H_{10}			22
air			78

Unit: p.p.m.

Gas type	Test gas	Combustion	Compensated NO_2	Compensated Nox
6C	6C-1	Max.	2.4	3.8
		Min.	1.3	1.5
13A	13A-1	Max.	4.6	9.3
		Min.	2.1	3.1
6A	6A	Max.	4.0	9.9
		Min.	1.8	2.7
LP	Butane	Max.	7.6	10.0
		Min.	2.7	3.5

APPENDIX C

CONVENTIONAL RESEARCH HOUSE INDOOR AIR QUALITY MONITORING PLAN

GEOMET TECHNOLOGIES, INC.

20251 CENTURY BOULEVARD • GERMANTOWN, MARYLAND 20874 • 301/428-9898

Section 1.0

INTRODUCTION

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LIST OF FIGURES

LIST OF TABLES

GEOMET Report Number IE-1844

March 15, 1988

CONVENTIONAL RESEARCH HOUSE INDOOR AIR QUALITY MONITORING PLAN

FINAL REPORT

prepared for

Neil Leslie
GARD Chamberlain
7449 North Natchez Avenue
Niles, Illinois 60648

Under

Purchase Order Number H33091

by

GEOMET Technologies, Inc.
20251 Century Boulevard
Germantown, Maryland 20874-1192

Section 2.0

MEASUREMENT LOCATIONS, PARAMETERS, AND FREQUENCY

Section 1.0

INTRODUCTION

1.1 BACKGROUND

GARD is initiating a research program on indoor air quality (IAQ) in the conventional research house located in Chicago, Illinois. This work is being conducted for the Environment and Safety Research Department of the Gas Research Institute (GRI). The indoor air quality program will parallel other work being conducted under contract with the Building Systems Research group of GRI. Under the latter contract, GARD is testing space-conditioning systems in the research houses. This work involves testing of both conventional and prototypical heating and cooling plants and delivery systems.

The GARD IAQ program will examine indoor air quality issues under baseline conditions during Phase I of the program. In future work, IAQ will be examined as an adjunct to tests of advanced heating, ventilating, and air conditioning (HVAC) systems and in special experiments.

GEOMET is also under contract with the Building Systems Research Group of GRI to perform testing of space-conditioning systems at its two contemporary research houses. As part of this work, GEOMET prepared a Research House Utilization Plan (GEOMET Report Number IE-1872). This document provides specifications for measurement parameters, monitoring locations, monitoring instrumentation, operational considerations, site operations, protocols, data processing, and quality assurance (QA) and quality control (QC). Use of the document by all three research house contractors (GARD, GEOMET, and the National Association of Home Builders) ensures uniformity of measurements at the three research house locations and enhances comparability of the data collected.

GEOMET has also been under contract with GRI's Environment and Safety Department. For the past 3 years, GEOMET has conducted a major IAQ research effort at the GEOMET research houses. Experiments and measurement protocols have been designed to systematically evaluate, quantify, and classify the critical factors that impact residential air quality, with primary emphasis on nitrogen dioxide (NO_2) and carbon monoxide (CO). This work has resulted in a substantial data base on IAQ in the contemporary research houses.

To ensure the highest level of comparability of the IAQ measurements conducted at the contemporary and conventional research houses, a monitoring test plan should be used at the conventional houses that parallels the test plan used at the contemporary houses. This document, based on GEOMET's experience and previous testing at its research houses, has been prepared to provide such a plan for measurements of baseline indoor air quality data at the conventional research house.

1.2 OBJECTIVES

The primary objective of Phase I of the GARD IAQ project entitled "Examination of Indoor Air Quality Issues at the Conventional Research House" is to characterize the baseline levels of NO_2 and CO, as well as temperature, humidity, and air infiltration, under the current single-zone house configuration. Subobjectives for the project include characterization of emission rates from gas appliances in the house, characterization of decay rates and the fate of indoor pollutants, and characterization of the distribution of pollutants in the house.

The objective of GEOMET's monitoring test plan is to provide a research plan that (1) addresses the objectives of the project at the conventional research house, (2) is consistent with previous GRI IAQ work at the contemporary research houses, and (3) provides the highest level of comparability of data collected at the houses.

1.3 SCOPE OF THE MONITORING PLAN

The monitoring plan is a comprehensive document that specifies the tests to be performed and the general procedures to be followed in the conduct of those tests. The test plan includes the following elements:

- Measurement locations, parameters, and frequency (Section 2.0)
- Equipment specifications (Section 3.0)
- Test plan for baseline measurements (Section 4.0)
- Plans for specialized tests (Section 5.0)
- Summary of tests and test schedule (Section 6.0)
- QA and QC (Section 7.0).

Section 2.0

MEASUREMENT LOCATIONS, PARAMETERS, AND FREQUENCY

2.1 MEASUREMENT LOCATIONS

For the purposes of testing of space-conditioning systems, the conventional house has been divided into the following four zones:

- First floor living area
- First floor bedroom area
- Basement living area
- Basement furnace room.

Zones for pollutant monitoring will be consistent with the zones for space-conditioning tests to facilitate future IAQ monitoring with advanced HVAC systems and zoned delivery systems. For IAQ monitoring, the outdoors will be added as the fifth zone and the kitchen will be added as the sixth zone. Definitions of the monitoring zones are depicted in Figures 1 and 2.

IAQ monitoring probe locations are denoted in Figures 1 and 2 for each zone and described in Table 1. In all cases, the locations are consistent with the primary probe locations for measurements of temperature and relative humidity for the space-conditioning testing program.

Temperature and relative humidity (RH) sensors and the inlets of the sampling lines for sulfur hexafluoride (SF_6) and pollutants should be situated at a height of 43 inches above the floor. In zones 1, 2, 4, and 6,

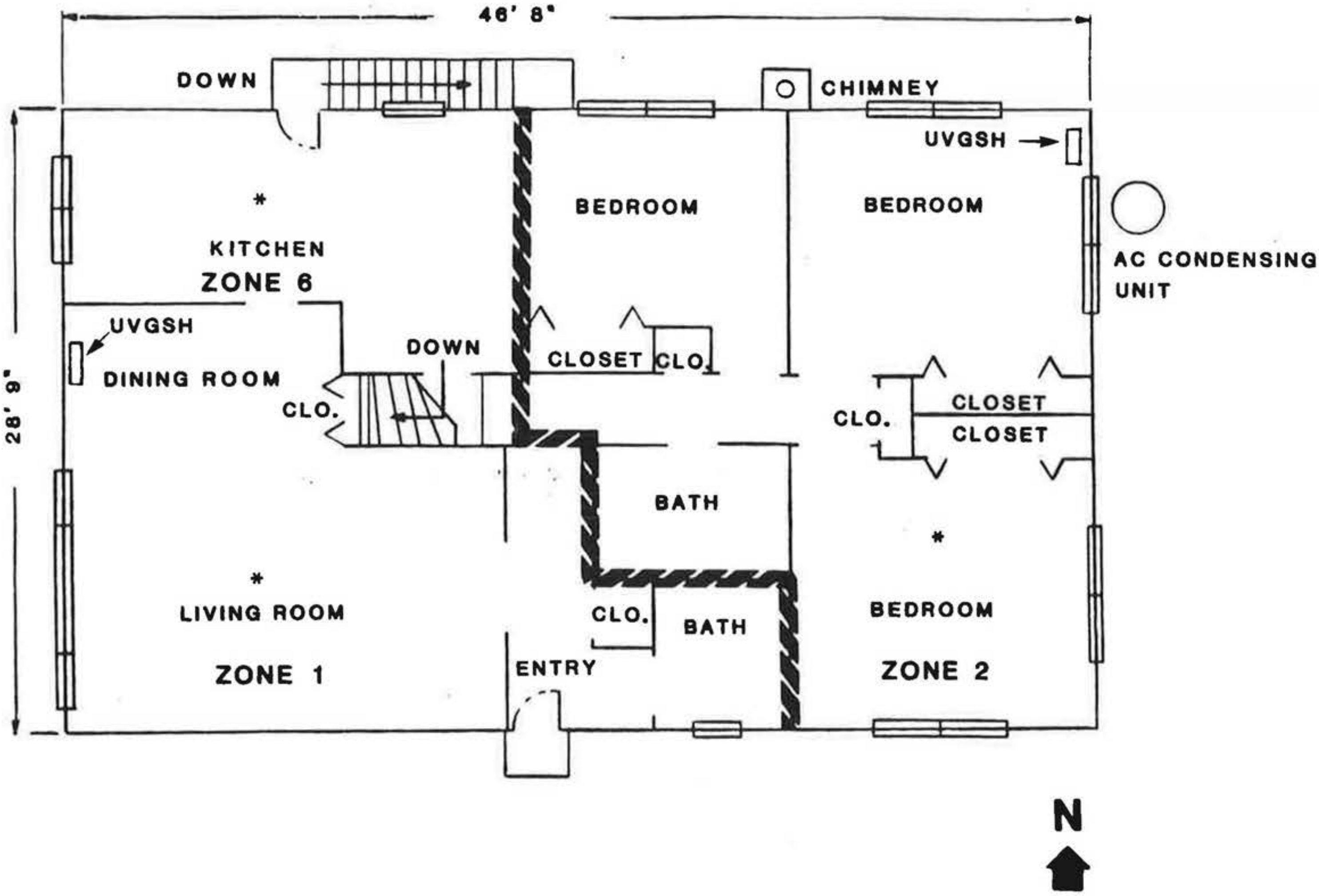

Figure 1. Conventional Research House--First Floor Plan with IAQ Monitoring Locations Indicated by Asterisk and Tentative Locations of Unvented Gas Space Heaters (UVGSHs)

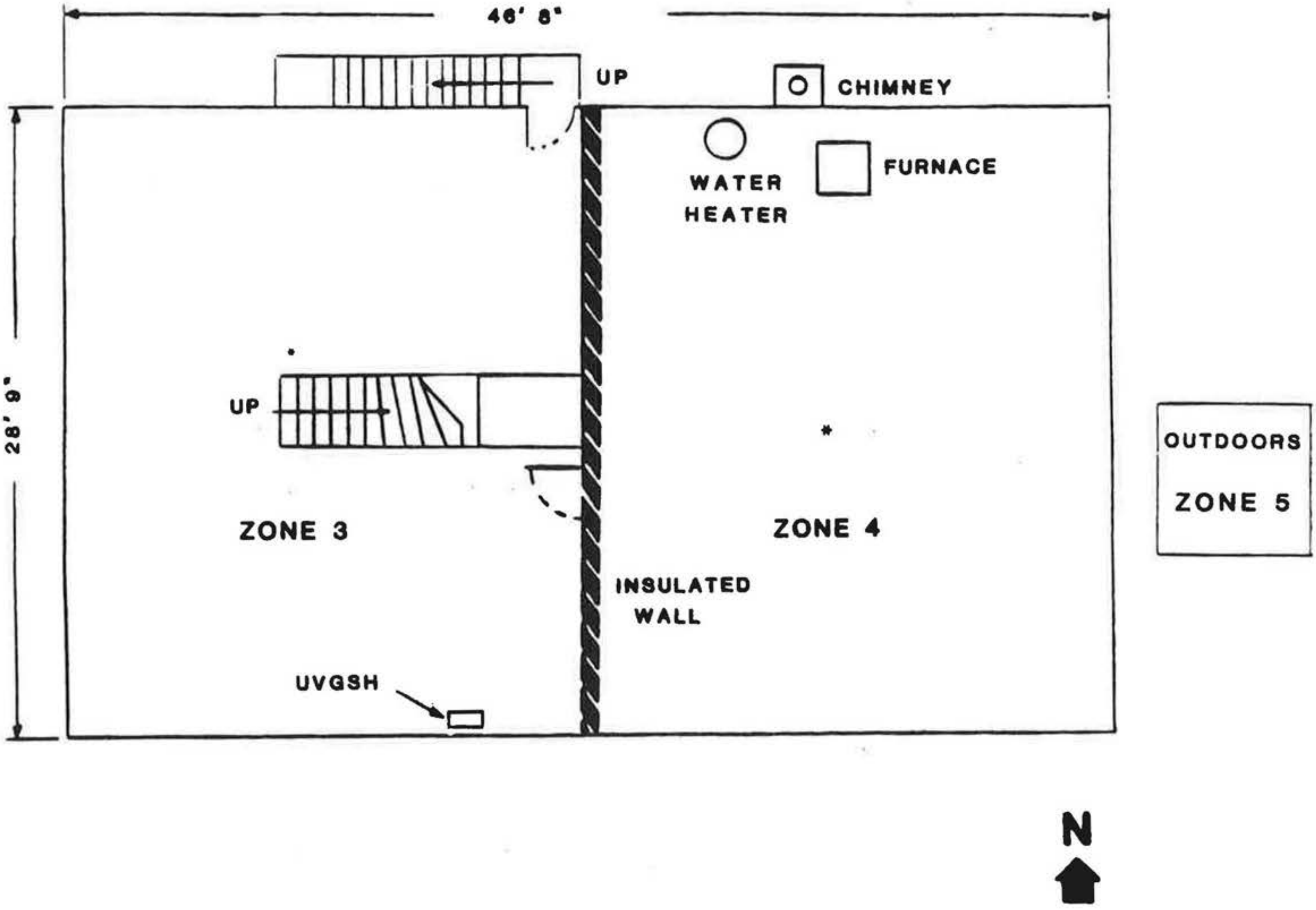

Figure 2. Conventional Research House--Basement Floor Plan with IAQ Monitoring Locations Indicated by Asterisk and Tentative Location of UVGSH

Table 1. Probe Locations for IAQ Monitoring in the Conventional Research House

Zone	Room	Description
1	Living Room	Center of room; 43 in above floor; colocated with temperature and RH sensor*
2	Master Bedroom	Center of room; 43 in above floor; colocated with temperature and RH sensors*
3	Basement	North of stairs; 43 in above floor; colocated with temperature and RH sensor*
4	Furnace Room	Center of room, 43 in above floor
5	Outdoors	Site away from house; probe site must be unobstructed, as far away from vegetation as possible
6	Kitchen	Center of room, 43 in above floor

* Primary sensor location in the zone for space-conditioning tests (currently in place).

the probe site is in the center of the room. In zone 3, the probe should be placed north of the stairs, a site that is near the center of the room. The exact location of the outdoor probe location is contingent on a number of factors, including security and presence of vegetation. General guidelines for siting the outdoor probe include the following:

- Probe site must be at least 6 feet above the ground.
- Probe site must not be directly adjacent to the house; it should be in an open area.
- Probe site must not be obstructed by buildings or vegetation; site as far from vegetation as possible.
- Probe site must be covered to protect inlet from rain and wind.
- Probe must be accessible to change particulate filter.

2.2 MEASUREMENT PARAMETERS

The following types of parameters will be monitored in this project:

- Outdoor environment
- Indoor/outdoor (air exchange)
- Indoor environment
- Pollutants
- Gas use
- Status of test conditions.

Table 2 provides a list of the measurement parameters. Many of the measurement devices are currently in place for the space-conditioning test project. However, pollutant measurements will be added to all six zones, as well as addition of SF_6 sampling and RH measurements to zone 4. It is also recommended that temperature be measured in the laboratory as a QC measure to account for instrument drift if problems with temperature control occur in the laboratory.

2.3 MEASUREMENT FREQUENCY

Measurements of IAQ parameters will be recorded automatically with the Metrabyte data acquisition system (DAS) currently installed for the space-conditioning testing. Outdoor environment parameters and indoor environment parameters (Table 2) will be scanned at lease once each minute and summary statistics (e.g., average, minimum, maximum, or accumulated counts) will be recorded each hour.

Measurements of nitrogen oxides (NO_x), nitric oxide (NO), NO_2, CO, carbon dioxide (CO_2), and SF_6 performed with the continuous analyzers will also be recorded automatically with the DAS. Special software routines should be developed for the data acquisition process to ensure that the measurement is representative of true concentrations by accounting for instrumental rise time. The software should incorporate processing for a routine similar to the following:

- Time 0 minute--sample collection begins from zone 1; no data scans in progress.

Table 2. Measurement Parameters for the IAQ Monitoring Program

Parameter	Monitoring Zone*	Notes
Outdoor Environment		
Windspeed	5	Measurement devices for outdoors are currently in place
Wind direction	5	
Solar radiation	5	
Precipitation	5	
Barometric pressure	5	
Relative humidity	5	
Air temperature	5	
Indoor/Outdoor		
Air infiltration	All*	SF_6 tracer decay method (sequential samples in six zones)
Interzonal airflows	1, 2, 3, 4, 6	PFTs (special tests)
Air temperature	Laboratory	QC measurement
Indoor Environment		
Temperature	All	
Relative humidity	All	
Pollutants		
NO_x, NO, NO_2	All	Chemiluminescent analyzer (sequential samples in six zones)
CO	All	Nondispersive infrared analyzer (sequential samples)
CO_2	All	Nondispersive infrared analyzer (sequential samples)
NO_2	All	Palmes Tubes (special tests)
Radon	1, 3, 4	Charcoal Canisters (special tests)

(Continued)

* Six zones: 1 = first-floor living area; 2 = first-floor bedroom area; 3 = basement living area; 4 = furnace room; 5 = outdoors; 6 = kitchen.

Table 2. Measurement Parameters for the IAQ Monitoring Program (Concluded)

Parameter	Monitoring Zone*	Notes
Gas Use		Individual meters on all gas appliances; automated data collection
Status		Manual recording of test conditions such as exhaust fan operation and range use

* Six zones: 1 = first-floor living area; 2 = first-floor bedroom area; 3 = basement living area; 4 = furnace room; 5 = outdoors; 6 = kitchen.

- Time 0 to 1.25 minutes--period of sample flow from zone 1 to the analyzers to flush sample lines and allow for rise time of instruments.
- Time 1.25 to 2.49 minutes--scan pollutant and SF_6 channels at least 10 times during "steady-state" period. Record average measurement for the period.
- Time 2.5 minutes--switch sample collection to zone 2.
- Time 2.5 to 3.74 minutes--no data scans.
- Time 3.75 to 4.99 minutes--record average measurement for zone 2.
- Repeat for zone 3 for period of 5 to 7.5 minutes.
- Repeat for zone 4 for period of 7.5 to 10 minutes.
- Repeat for zone 5 for period of 10 to 12.5 minutes.
- Repeat for zone 6 for period of 12.5 to 15 minutes.

With this processing routine, each zone is sampled once each 15 minutes for a total of four measurements per zone each hour.

Gas use by appliances will also be recorded automatically with the DAS. Records of total gas use per hour will be adequate for the gas range, the Sears convective unvented gas space heater (UVGSH), and the radiant UVGSH. However, the Japanese UVGSH is thermostatically controlled and cycles during operation. Records of gas use by this UVGSH on a more frequent basis may be valuable in the interpretation of variations in pollutant concentrations during use. During all experiments, gas meter readings should also be recorded manually at the start and completion of appliance operation. Gas use is an important parameter; manual backup of measurements is an important QC procedure.

Status parameters will be recorded manually for each experiment. The parameters to be recorded include the following and are described in more detail in Section 4.0:

- Appliance start and stop time
- Cooling utensil and water volume
- HVAC operation status
- Range fan exhaust operation (start and stop time)
- Status of windows and doors.

Section 3.0

EQUIPMENT SPECIFICATIONS

Section 3.0

EQUIPMENT SPECIFICATIONS

Instrumentation used for IAQ monitoring at the conventional research house will be comparable in terms of performance with that currently in use at GEOMET's contemporary research houses. Specifications for instrumentation are based on goals for measurement accuracy and precision that are consistent with the objectives of the project. Recommendations for specific devices and hardware are based on past experience by GEOMET in the field of IAQ monitoring.

Instrumentation to be used in the project is specified in the Research House Utilization Plan (GEOMET Report Number IE-1872) and Table 3. Only pollutant monitors and major pieces of support equipment are specified in Table 3.

The pollutant monitoring system consists of the NO_x/NO, CO, and CO_2 monitors and an appropriate pneumatic system to transfer the air sample from the house to the laboratory where the monitors will be located. The sampling system must be an all Teflon™/glass system. Inlets to the sampling lines must be fitted with Teflon™ filters to prevent entry of particles into the lines.

The SF_6 sampling system should consist of polypropylene tubing for sampling lines. Inlets must be fitted with particle filters. Teflon™ tubing, fittings, and filters should not be used for SF_6.

Table 3. Instrumenation to Be Used in the IAQ Monitoring Program

Parameter	Instrument (Manufacturer/Model No.)	Principle of Operation
NO_x, NO, NO_2	Thermo Electron 14B/E	Chemiluminescence
CO	Horiba APMA-300E/300SE	Nondispersive infrared
SF_6	Thermo Electron Model 621	Gas chromatography-electron capture detection
Temperature	Omega OL-700	Thermistor
Relative humidity	Vaisala HMP-11	Thin-film capacitance
Outdoor environment*		
Gas meters*		
Data acquisition system*		
Support Equipment		
Calibrator	TECO 146	Dilution/gas phase titration
Zero Air Supply	TECO 111	
Span gases/ regulators	Scott Specialty Gases	

* Specified in the Research House Utilization Plan (GEOMET Report Number IE-1872).

Both pollutant and SF_6 sampling systems must be configured with automated valve sequencers to facilitate sequential sampling in the six zones.

Instrumentation currently installed at the conventional research house for outdoor and indoor environment parameters, gas use, and data acquisition is appropriate for the IAQ project.

Section 4.0

TEST PLAN FOR BASELINE MEASUREMENTS

Section 4.0

TEST PLAN FOR BASELINE MEASUREMENTS

In this section, a plan is presented for the conduct of tests and collection of data to characterize baseline levels of NO_2, CO, CO_2, temperature, relative humidity, and air infiltration during operation of gas appliances in the conventional research house. The plan has been developed with the goal of achieving measurements in the conventional research house that are equivalent and comparable to previous measurements in GEOMET's research houses.

The intent of the test plan is to characterize baseline conditions in the research house. Subobjectives of the test plan are to characterize emission rates from gas appliances, decay rates, and the distribution of indoor pollutants. The emphasis of the test plan, however, is on a comprehensive baseline characterization. Therefore, we have included a high level of replication. Specialized tests that address the specific factors affecting NO_2 and CO concentrations in the house are not included in the test plan because they are outside the scope of Phase 1. Rather, the test plan uses the available resources to develop a comprehensive, high-quality baseline data base. The test plan addresses experimental work to be conducted for the following baseline conditions:

- Central heating/cooling
- Operation of unvented gas space heaters

- Operation of the gas range without range hood exhaust fan operation
- Operation of the gas range with range hood exhaust fan operation.

Plans for these four baseline conditions are presented in this section. The test plans for specialized tests are presented in Section 5.0. The specialized tests include the following:

- Use of Palmes tubes to measure the horizontal and vertical distribution of NO_2 during UVGSH and gas range operation
- Measurement of radon during baseline conditions and during periods of high furnace operation to address the effect of furnace operation on radon entry
- Measurement of interzonal airflows with perflourocarbon tracers (PFTs).

4.1 IAQ MONITORING DURING CENTRAL HEATING AND COOLING PERIODS

4.1.1 Objectives

The objective of IAQ monitoring during routine heating and cooling of the house with the central HVAC system is to collect baseline information (NO_2, CO, CO_2, temperature, RH, and air infiltration) for comparison to alternative heating and cooling systems to be installed in the future, including the UVGSHs.

4.1.2 Summary of the Tests

IAQ monitoring will be conducted for two 1-week periods during the winter and for 1 week during the summer. The central HVAC system will be used and all interior doors on the first floor will be open. The appliance simulation (including gas range operation) used for the space-conditioning test program will be implemented 2 days each week.

4.1.3 Operational Considerations

Operational considerations and test conditions for this series of tests are summarized in Table 4. For these monitoring periods, the house will be treated as a two-zone structure (first floor and basement) with a central forced-air heating or cooling system. All interior doors on the first floor should be open. The door to the basement and the door to the furnace room should be closed. Thermostat settings and setback schedules will conform to the protocol developed for the space-conditioning test program. During the 3 weeks of monitoring, 2 days will be included each week for the appliance simulation developed for the space conditioning test program. This schedule, presented in detail in Appendix A, includes operation of the gas range in the morning and late afternoon. Inclusion of this protocol will allow for characterization of pollutant distribution and decay under normal conditions of HVAC operation. Data for appliance simulation days will be compared with nonsimulation days when indoor pollutant concentrations can be attributed only to outdoor sources and the gas furnace, if any spillage is occurring.

Occupant simulation with heat simulators and moisture simulators will be conducted throughout the monitoring period. Lighting will also be simulated according to the schedule included in Appendix A. The protocols

Table 4. Operational Considerations for IAQ Monitoring During Routine Operation of the Central Heating or Cooling System

Parameter	Status
HVAC plant	Central forced air
Delivery system	Central
HVAC operation	On demand*
Thermostat setpoint--heating	72 °F**
Thermostat setpoint--cooling	75 °F**
Setback schedule	Space conditioning**
First floor interior doors	Open
Door to basement	Closed
Door to furnace room	Closed
Lighting simulation***	Implemented
Occupant heat simulation***	Implemented
Occupant moisture simulation***	Implemented
Appliance simulation***	2 d/wk

* In response to call for heating or cooling by thermostat.

** Setpoints and schedules as defined for space-conditioning test program.

*** Details on simulation protocols included in Appendix A.

will be consistent with the objectives of the tests of space-conditioning equipment, thereby allowing use of the data for both the IAQ and space-conditioning programs.

4.1.4 Measurement Parameters

Measurement parameters for these tests are described in Section 2.2. In addition to the routine measurements, radon will be measured during each week of IAQ monitoring. During these monitoring periods, interzonal airflows will also be measured with PFTs. Details related to these measurements will be presented in Section 5.0.

As described in Section 2.0, measurements will be performed at five indoor and one outdoor location. Gaseous samples will be collected from the six zones sequentially.

4.1.5 Test Schedule

Routine monitoring will be conducted during two 1-week periods in the heating season and one 1-week period during the cooling season. To maximize the amount of information collected, it is recommended that, during the heating season, 1 week be a low heating-demand week and the other be a high-demand week. During the cooling season, monitoring should be performed during a high cooling-demand week.

4.2 IAQ MONITORING DURING OPERATION OF UNVENTED GAS SPACE HEATERS

4.2.1 Objective

The objective of these tests is to collect baseline data on NO_2, CO, and CO_2 concentrations, temperature, RH, and air infiltration during periods when UVGSHs are used as the sole heat source in the house. The distribution of pollutants in the house during UVGSH operation will be characterized by sampling in the five indoor zones and by use of Palmes tubes configured in vertical arrays. Pollutant decay rates will be characterized by monitoring for at least 4 h after termination of UVGSH operation.

4.2.2 Summary of the Tests

Two series of UVGSH tests will be conducted. The first series of tests will involve sequential testing of three different space heaters at the same location in the dining room. The three heaters will be the following:

- Sears convective UVGSH--10,000 Btu/h
- Empire radiant UVGSH--15,000 Btu/h
- Japanese convective UVGSH--16,000 Btu/h with thermostat control and fan.

During these initial tests each heater will be operated independently on 2 days to characterize its NO_2, CO, and CO_2 emissions, pollutant decay rates, and the distribution of heat and pollutants in the house.

In the second series of UVGSH tests, three Japanese convective heaters will be located at the following sites, depicted previously in Figures 1 and 2:

- Dining room
- Bedroom (northeast corner)

- Basement living area.

The three heaters will be operated simultaneously, under thermostat control, as the sole heating source for the house. Testing with this configuration will be conducted for up to 5 weeks near the end of the heating season.

4.2.3 Operational Considerations

Operational considerations and test conditions for this series of tests are summarized in Table 5. During tests of the UVGSHs, the house will be treated as a single-story house with the basement isolated from the upstairs by the closed basement door. All interior doors on the first floor will be open. This would be the typical configuration for a home heated by UVGSHs. The central forced-air heating system will not be used during any tests of the UVGSHs.

Consistent with the conditions during the space-conditioning tests, the lighting, occupant heat, and occupant moisture will be simulated. However, there will be no appliance simulation. Simultaneous use of the gas range during UVGSH operation has been addressed at the GEOMET houses and is beyond the scope of work for Phase I monitoring in the conventional research house.

The Sears convective and Empire radiant heaters will be operated on their highest settings. The Japanese convective heater will be operated at 72 °F (22.2 °C), a setting consistent with the thermostat setpoint for the current testing of space-conditioning equipment. In the

Table 5. Operational Considerations for IAQ Monitoring During Operation of Unvented Gas Space Heaters

Parameter	Status
HVAC system (forced-air)	Off
First floor interior doors	Open
Door to basement	Closed
Door to furnace room	Closed
Lighting simulation*	Implemented
Occupant heat simulation*	Implemented
Occupant moisture simulation*	Implemented
Appliance simulation	None
UVGSH settings	
- Japanese convective**	72 °F (22.2 °C)
- Sears convective	High
- Empire radiant	High

* As scheduled in Appendix A.
** Thermostatically controlled.

first series of tests, the heaters will be operated for periods of 8 hours (maximum), as described subsequently in Section 4.2.5.

Because UVGSH tests will be conducted during high heating-demand weeks, the central forced air system may be required to provide heat overnight between the UVGSH tests. The central system should be set at 55° F so that temperatures are low in the house at the start of UVGSH tests. The central system should not be operated until at least 4 hours after termination of UVGSH operation.

4.2.4 Measurement Parameters

Measurement parameters for routine IAQ monitoring during UVGSH tests are described in Section 2.2.

During UVGSH tests, radon will also be measured to collect baseline data for a period of limited central forced-air heating system operation. These data will be compared with periods of more extensive use of the central HVAC system. Radon measurements are described in Section 5.0.

Interzonal airflows will be measured with PFTs during 1 week of simultaneous operation of the three Japanese UVGSHs, as described in Section 5.0.

The distribution of NO_2 during operation of the UVGSHs will be characterized by use of vertical arrays of Palmes tubes in addition to the zone samples with the continuous analyzers. Details of the test procedures for Palmes tubes are presented in Section 5.0.

4.2.5 Test Schedule

Up to 6 weeks of UVGSH operation are planned for the 1987/1988 heating season. One day will be included to conduct an initial pretest of operational protocols. A schedule of testing is presented in Table 6. The schedule provides for operation of the three different UVGSHs at the dining room location and simultaneous operation of three Japanese heaters for an extended period as the sole sources of heat in the house. During selected tests, measurements will also be performed with Palmes tubes, PFTs, and charcoal canisters (radon).

In the initial set of tests with the three different heaters, the UVGSHs should be operated continuously for 8 hours. Depending on outdoor conditions and the demand for heating, there may be some cases when the indoor temperature during UVGSH operation exceeds acceptable levels. For the purpose of these tests, indoor temperatures should not exceed 85 °F (29.4 °C). If the indoor temperatures reach 85 °F, the test should be terminated prior to the 8-hour target period of operation. The period of operation, however, should not be less than 4 hours. Duration of UVGSH operation, although targeted for 8 hours, should be addressed in the pretest. In the second series of tests with the three Japanese heaters, operation will be controlled by the heaters' thermostats.

4.3 IAQ MONITORING DURING OPERATION OF THE GAS RANGE WITHOUT THE RANGE EXHAUST FAN

4.3.1 Objective

The objective of these tests is to characterize baseline levels of NO_2, CO, CO_2, temperature, RH, and air infiltration during operation of

Table 6. Schedule for UVGSH Tests

Experiment Number	UVGSH(s)	Comments
Pretest	Sears convective	
1	Sears convective	Radon,* Palmes tubes**
2	Sears convective	Replicate
3	Empire radiant	
4	Empire radiant	Replicate
5	Japanese convective	PFTs
6	Japanese convective	Replicate
7-11	Three Japanese convective USVGHs	Simultaneous operation at three locations; thermostat control; up to 5 weeks; Palmes tubes***

* Weekly 3-d radon measurements should be performed throughout the UVGSH test period.

** Vertical arrays of Palmes tubes to be deployed during tests 1 to 4.

*** Vertical arrays of Palmes tubes to be deployed during 1 week of simultaneous operation of the three UVGSHs.

the range-top burner and/or the oven. The tests will also address the distribution of pollutants in the house, source emission rates, and decay rates.

4.3.2 Summary of the Tests

Gas range tests will consist of a series of tests with operation of either one range-top burner on high for 60 minutes, the oven operated at 350 °F for 60 minutes, or the range-top burner and the oven operated simultaneously. Tests will be conducted with the central forced-air system off so that emission rates and decay rates can be estimated without mixing by the HVAC as a confounding factor.

4.3.3 Operational Considerations

Operational considerations and test conditions during this series of tests are summarized in Table 7. The central forced-air heating/cooling system will not be used during range tests. Mixing by the central air handler will confound calculation of NO_2 and CO emission and decay rates. Range tests, therefore, will need to be conducted during moderate weather conditions.

During range tests, the house should be configured as a single zone on the first floor with all interior doors open to characterize the distribution of pollutants during range operation.

Lighting, occupant heat, and occupant moisture simulations normally performed for the space-conditioning testing program will not be performed during range tests. Because the level of heat output is varied

Table 7. Operational Considerations for IAQ Monitoring During Operation of the Gas Range Without Exhaust Fan

Parameter	Status
HVAC System	Off
First-floor interior doors	Open
Door to basement	Closed
Door-to-furnace room	Closed
Lighting simulation	None
Occupant heat simulation	None
Occupant moisture simulation	None
Range burner	Right front
Burner setting	High
Pan	ANSI
Pan load	2.3 L H_2O
Burner operational period	60 min
Oven setting	350 °F
Oven load	Ceramic pot
Pot load	0.45 L H_2O
Oven operational period	60 min
Range exhaust fan	Off

in the simulation schedule, it may confound interpretation of the results of range tests, particularly results related to the distribution of pollutants and room temperatures.

Range tests will be conducted using a single burner, the oven, or a combination of the burner and the oven. Settings for the burner and oven are presented in Table 7. Operation of the range-top burner on high has been used consistently in the tests at the GEOMET houses. The high setting is the most repeatable setting and produces levels of NO_2 and CO of sufficient quantity to allow calculation of accurate estimates of emissions and decay rates. The 350 °F oven setting, used in previous tests at GEOMET, is typical of normal use, and is consistent with the setting used for the appliance simulation in the space-conditioning test program. A load, consisting of the ANSI pan or a ceramic pot containing a fixed quantity of water (Table 7), will be used during operation of the range burner or the oven.

For this set of experiments, the range exhaust fan will not be used. Nor should any other fans, such as the bathroom exhaust fan or the central HVAC fan be used during the range tests. During the tests, door openings and technician activities in the house should be minimized to reduce disruption of normal air movements and distribution of NO_2 and CO in the house. It is recommended that entry into the house be through the living room entry door, rather than the kitchen door, to minimize the technicians' impact on air movement patterns in the kitchen.

4.3.4 Measurement Parameters

Measurement parameters for the range tests are described in Section 2.2. Additionally, radon and interzonal airflows will be measured during the period of testing as described in Section 5.0.

Records should be maintained of the start and stop times of range operation for each test. Gas use should also be recorded manually as a backup to the automated recording system and for purposes of quality control. The amount of water vaporized during each test should also be recorded by measuring the pan contents prior to and following the range operation.

4.3.5 Test Schedule

The range tests can be accomplished over a 5-day period. Tests should be conducted under moderate weather conditions because the central heating system will not be used during range tests. A proposed schedule for the tests is presented in Table 8. With this schedule, the range is operated twice each day. A 6-hour period separates operational episodes to allow a sufficient decay period for return of NO_2 and CO to near-background levels. As proposed, the schedule includes 1 day to pretest operational protocols, and provides for replication (triplicates) for each test.

4.4 IAQ MONITORING DURING OPERATION OF THE GAS RANGE WITH CONCURRENT OPERATION OF THE RANGE EXHAUST FAN

4.4.1 Objective

The objective of these tests is to characterize baseline levels of NO_2, CO, CO_2, temperature, RH, and infiltration during operation of the

Table 8. Proposed Schedule for Range Tests

Day	Time	Burner/Oven Operated
1	0900-1000 1600-1700	RF* burner--pretest Oven--pretest
2	0900-1000 1600-1700	RF burner Oven
3	0900-1000 1600-1700	RF burner Oven
4	0900-1000 1600-1700	RF burner RF burner plus oven
5	0900-1000 1600-1700	RF burner plus oven RF burner plus oven

* RF--Right Front.

range when the range exhaust fan is used concurrently. These tests specifically address the efficiency of NO_2 and CO removal by the range exhaust fan.

4.4.2 Summary of the Tests

This series of tests is identical to the tests described in Section 4.3, except that during all tests the range exhaust fan will be operated on the high setting concurrently with the operation of the range, i.e., fan turned on at same time the range is turned on and turned off when the burner and/or oven is turned off. Because the experiments are essentially identical, the reader should refer to Section 4.3.

4.4.3 Operational Considerations

The operational considerations for this series of tests are the same as those described in Section 4.3.3 and Table 7, except for the following:

- Range exhaust fan setting--high
- Range exhaust fan operation--concurrent with range operation.

4.4.4 Measurement Parameters

Measurement parameters are the same as those described in Section 4.3.4

4.4.5 Test Schedule

The gas range tests with concurrent range exhaust fan operation should be performed over a 5-day period in the spring under moderate weather conditions. A schedule similar to that proposed in Table 8 should be used.

4.5 GENERAL PROCEDURES FOR BASELINE MEASUREMENTS

The quality of the data collected during the tests described above can be strengthened substantially by use of standardized operational protocols and adherence to basic procedures for all tests. The following discussion highlights general procedures that should be followed during the tests.

4.5.1 House Configuration

For all tests, the house should be configured as a single upstairs zone (with all interior doors open) separated from the basement zone by a closed door. The basement should also be separated from the furnace room by a closed door. Prior to each test, the technician should ensure that all upstairs interior doors are completely open. All windows are to be closed for all tests. The bathroom exhaust fan should not be used during any test periods.

4.5.2 Technician Activity During Testing

It is important that the technician minimize activities in the house during tests. Although it is not necessary to document door openings during tests, the number of entries into the house should be minimized to avoid disruption of normal airflow patterns in the house; during gas range tests, entry to the house should be through the living room entry door. Activities not required for conduct of the tests should not be performed in the house during or following operation of the gas appliances. Following appliance operation, monitoring should continue for at least 4 hours to facilitate calculation of pollutant decay rates.

4.5.3 Air Infiltration Measurements and SF_6 Injection

During, and for at least 4 hours after termination of appliance operation, air exchange measurements must be performed to facilitate calculation of pollutant emission and decay rates. Therefore, it is important for the technician to ensure that there is sufficient SF_6 in each zone during the test period. For gas range tests, this can be easily accomplished by programming the system to inject SF_6 into the house at least an hour before each range operation episode.

Maintaining SF_6 levels in the house during UVGSH operations is somewhat more difficult, since the automated SF_6 injection system cannot be used during UVGSH operation and decay periods. The system cannot be used because operation of the central HVAC air handler to mix SF_6 will upset the normal patterns of pollutant movement and decay. Therefore, SF_6 must be "seeded" manually in the house. Prior to UVGSH operation the technician should force an SF_6 injection with the automated system to achieve a well-mixed, high level of SF_6 in the house. During UVGSH operation, when SF_6 levels approach the lower detection limit of the analyzer, the technician should manually release SF_6 in all parts of the house. This can be accomplished by filling syringes with pure SF_6, then slowly releasing it while walking (slowly) through all parts of the house.

The amount of SF_6 released should be referenced to the volume of each room and zone (1 cc of pure SF_6 released per m^3 of volume will give an initial concentration of 1 ppm). Subsequent to the manual seeding of the house with SF_6, at least 1 hour is required to ensure that the SF_6 is well mixed in the house. As an alternative to the method described above, an automated system with SF_6 release points in all rooms can be configured.

4.5.4 Pretests

The importance of conducting pretests of operational protocols cannot be overemphasized. Pretests for UVGSH and gas range tests are included in the test schedule. Operational protocols should be developed to guide the technician during conduct of the tests. Initially, these protocols should be comprehensive in scope. Operational considerations and test conditions, as defined in this plan, should be specified, and detailed procedures (step-by-step) should be provided to guide the technician's activities. The pretest should be used to provide the technician with a working knowledge of the operational protocols and an opportunity to detect shortcomings of the protocols. Following the pretest, the protocols should be evaluated and refined as appropriate.

4.5.5 Documentation

A strong emphasis should be placed on documentation of activities by the technician during tests. We recommend that the following types of documentation be used:

- Research house status log--document heating system in use, door openings, simulations ongoing, etc.

- Daily instrumentation checklist--document status of instrumentation in use at the research house (instruments on-line, etc.)

- Calibration/zero and span records--document current calibration status

- Research house log book--document daily activities at the research house, hardware and instrument malfunctions, and maintenance activities

- Test documentation--document start and stop times of appliance operation, gas use, water vaporized, and details related to problems encountered during tests.

Section 5.0

PLAN FOR SPECIAL TESTS

Section 5.0

PLAN FOR SPECIAL TESTS

In addition to the baseline measurements, special tests will be conducted to address specific subobjectives of the project. These special tests fall into the following categories:

- Palmes tubes measurements to address vertical stratification of NO_2 concentrations
- PFT measurements to characterize interzonal airflows
- Charcoal canister measurements of radon to characterize baseline levels and the effect of gas furnace operation on indoor radon concentrations.

In all cases, the special tests will be conducted in conjunction with the baseline measurements described in Section 4.0.

5.1 PALMES TUBES MEASUREMENTS

5.1.1 Palmes Tube Placement

Vertical arrays of Palmes tubes will be used to characterize the vertical and horizontal distribution of NO_2 concentrations in the major rooms of the house during UVGSH operation and gas range operation.

Vertical arrays of Palmes tubes at 6, 24, 43, 63, and 84 inches above the floor will be placed at the seven indoor locations described in Table 9. Use of the arrays at these locations will allow a more detailed characterization of the horizontal and vertical distribution of NO_2 in the house. Single tubes will be used at all heights, except 43 inches, where

Table 9. Locations and Configuration of Vertical Arrays of Palmes Tubes

Placement Locations

Zone	Room	Location
1	Living room	At (continuous) probe site
6	Kitchen	At probe site
2	Master bedroom	At probe site
2	Corner bedroom	Center of room
2	Third bedroom	Center of room
2	Hallway	Center of hall
3	Basement	At probe site

Array Configuration

Height Above Floor		Number of Tubes
cm	(inch)	
15	6	1
61	24	1
109	43	3
160	63	1
213	84	1

triplicate tubes will be deployed for QC purposes. Palmes tubes (triplicates) will also be deployed at the outdoor probe site.

5.1.2 Palmes Tubes Measurements During Baseline Heating and Cooling Tests

Four sets of Palmes tubes will be used to monitor NO_2 levels during the 3 weeks of baseline tests described in Section 4.1. The tubes will be placed at the probe site of the continuous pollutant monitors (at 43 inches above the floor) in the living room, bedroom, downstairs living area, and outdoors. A set of triplicate tubes is recommended at one of the locations.

5.1.3 Palmes Tubes Measurements During UVGSH Tests

As described in Section 4.2 and Table 6, UVGSH test numbers 1 to 4 consist of four consecutive days with operation of the convective and radiant UVGSHs that do do not have a fan. This period provides the opportunity for measurement of variations in NO_2 in different rooms at different heights under a relatively consistent set of operating conditions. Sufficiently high levels of NO_2 will be generated during this period to allow accurate measurements by the Palmes tubes.

Palmes tubes will be deployed at the sites described in Table 9 prior to initiation of test number 1. Caps will be removed from the tubes to initiate sampling just prior to the start of the test. The Palmes tubes will be exposed throughout the 4-day period of tests 1 to 4. Sampling should be terminated on the day following test number 4, approximately 12 to 16 hours after completion of operation of the UVGSHs.

Palmes tubes will also be deployed in vertical arrays during 1 week of simultaneous operation of three Japanese UVGSHs under thermostat control. Palmes tubes should be deployed as described above at the locations described in Table 9.

5.1.4 Palmes Tubes Measurements During Gas Range Operation

Palmes tubes will be deployed during the 5-day period of range (without exhaust fan) tests. During this series of tests the range burner, oven, and burner/oven combination will be operated. This series of tests provides the opportunity to characterize the distribution of NO_2 in the house from a single source located in the kitchen. Palmes tubes will be deployed throughout the 5-day period to ensure that sufficient NO_2 is collected.

The Palmes tubes will be deployed in the same locations and at the same heights as described in Table 9. Palmes tubes will be uncapped to begin sampling prior to the first range test, as described in Table 8. After 5 days of exposure and completion of all tests of the gas range without the range exhaust fan, sampling will be terminated by capping the Palmes tubes. If the five range tests cannot be completed during a consecutive Monday through Friday period, the tubes should be recapped over the weekend to suspend exposure, then reopened when the range tests are resumed.

5.1.5 Procedures for Palmes Tubes Deployment

Vertical arrays of Palmes tubes are easily deployed by simply using a string and rubber bands. A heavy string should be suspended from the ceiling. At the prescribed heights, a rubber band is knotted into the string so that the Palmes tube will be suspended by the rubber band at the appropriate height. The Palmes tube is suspended, with the open end facing down.

Sampling with the Palmes tube is initiated by removing the flanged cap and terminated by replacing the cap. Documentation for samples collected with Palmes tubes should inlcude the following:

- Palmes tube ID number
- Sample start date and time
- Sample stop date and time
- Tube placement site and height.

When using vertical arrays of Palmes tubes, triplicate tubes should be placed at the 43-inch height to determine measurement precision. Accuracy of the Palmes tubes measurements will be estimated by comparing the measurements with the Palmes tubes at 43 inches with the measurements by the chemiluminescent analyzer.

Outdoors, Palmes tubes should be placed under a cover to prevent exposure to the sun and heating of the tube. The tubes should also be shielded to prevent direct impact by the wind.

5.2 MEASUREMENT OF AIR INFILTRATION AND INTERZONAL AIRFLOWS WITH PFTs

5.2.1 Summary of PFT Experiments

Five experiments will be conducted with PFTs to characterize interzonal airflows in the conventional research houses. It is assumed that the PFT system available from Harvard University will be used for these tests. The system, consisting of two different types of perfluorocarbon sources and capillary adsorption tubes (CATs) for passive collection of the tracers, has been used previously at the conventional research house. The tests, to be performed in conjunction with the baseline measurements described in Section 4.0, are summarized in Table 10 and are described in the following subsections.

5.2.2 PFT Measurements During Operation of the Central Forced-Air Heating System

Two PFT experiments will be conducted during routine operation of the central forced-air heating system. As described in Section 4.1, IAQ monitoring should be performed during 2 weeks of the heating season. One week should be a low heating-demand week; the other, a high heating demand week. PFTs should be deployed for measurements during each of these weeks. Sampling should cover a 6-day period for each week.

Operational protocols for the use of the Harvard PFT system should be in accordance with the Harvard protocol. One type of PFT tracer should be used on the first floor; the other tracer should be used in the basement and furnace room. Tracer sources should be placed in every room

Table 10. PFT Experiments

Baseline Test	Monitoring Plan Section	Comments
Central forced-air heating	4.1	Low heating-demand week
Central forced-air heating	4.1	High heating-demand week
Central forced-air cooling	4.1	High cooling-demand week
UVGSH operation	4.2	Three Japanese heater tests
Gas range without exhaust fan	4.3	Two-d test

to ensure uniform concentration of the tracer in all rooms of each zone. In the first-floor zone, samplers should be located in the living room and in the master bedroom (both at the probe site). For at least one experiment, duplicate samplers should be used at the living room location to assess measurement precision. In the basement, one sampler should be placed in the living area and another in the furnace room because the two rooms are separated by a wall and closed door.

5.2.3 PFT Measurements During Operation of the Central Forced-Air Cooling System

To assess seasonal differences in interzonal airflows, PFT measurements should also be conducted during the 1 week of IAQ monitoring in the summer. Measurements should be conducted during a high cooling-demand week to determine the maximum differences in infiltration and interzonal flows between summer and winter. Procedures for the test are the same as those described above for the heating season (Section 5.2.2).

5.2.4 PFT Measurements During Operation of UVGSHs

Air exchange rates and interzonal airflows will also be characterized during the UVGSH experiments when the three Japanese UVGSHs operate simultaneously for week-long periods. PFT measurements should be performed for one of the test weeks using procedures similar to those described above for the central heating and cooling system tests.

5.2.5 PFT Measurements During Use of the Gas Range

PFT measurements will be performed over a 2-day period during gas-range tests to determine the effect of the source in the kitchen on air exchange rates and interzonal airflows in the house. The test period will cover days 2 and 3 of the range tests without the range exhaust fan (Table 8); those days have identical operational protocols. During this period, the central forced-air heating/cooling system will not be in use.

Sources and samplers should be deployed as described in Section 5.2.2 and in accordance with the Harvard protocol. Samplers should be exposed for approximately 48 hours during the 2 days of range experiments.

5.3 CHARCOAL CANISTER MEASUREMENTS OF RADON

Radon levels in the conventional research house will be measured each week during the heating season, with charcoal canister collection and analysis by gamma counting methods. By performing routine sampling, that is, one set of measurements each week, a data base will be collected that can be used for comparisons of periods of HVAC operation with periods of limited or no HVAC operation to determine if there is an effect of the HVAC system on radon entry into the house.

5.3.1 Placement Locations for Charcoal Canisters

Locations for placement of charcoal canisters are the following:

- Living room--one canister
- Basement living area--one canister
- Furnace room--two canisters.

All canisters should be placed near the center of the room at the probe site. Canisters should be 43 inches above the floor.

5.3.2 Test Schedule

One set of canisters should be exposed for one 3-day period each week during the winter and spring. The day that sampling is initiated should be uniform from week to week, except when overlap with baseline tests is required, as specified in Section 6.0. The 3-day sampling period should not include Thursday, the changeover/maintenance day for the space-conditioning test program. Procedures for use of the charcoal canisters will be provided with the canisters.

Section 6.0

SUMMARY OF TESTS AND TEST SCHEDULE

Section 6.0

SUMMARY OF TESTS AND TEST SCHEDULE

Table 11 presents a summary of the tests to be performed for the IAQ monitoring project. Tests with the central heating and cooling system consist of 2 weeks during the winter and 1 week during the summer. These tests parallel the ongoing space-conditioning tests.

Up to 6 weeks of testing will be conducted to monitor baseline conditions during operation of single and multiple UVGSHs. All UVGSH testing will be conducted in the winter.

Ten days of gas range tests are scheduled for the spring. These include tests both with and without the range exhaust fan.

Special tests, including PFTs, Palmes tubes, and radon measurements, overlap the baseline tests; no additional test days were added to accommodate special tests.

Table 11. Summary of Baseline and Special Tests for the IAQ Monitoring Project

Test Number	Test Description	Monitoring Plan Section	Special Tests	Schedule	Comments
1	Central heating baseline	4.1	6-d PFT* 3-d radon**	Winter	Low heating-demand week
2	Central heating baseline	4.1	6-d PFT 3-d radon	Winter	High heating-demand week
3	Central cooling baseline	4.1	6-d PFT 3-d radon	Summer	High cooling-demand week
4	UVGSH--pretest	4.2		Winter	Pretest
5	Sears convective	4.2	Weekly 3-d radon samples during all UVGSH tests; vertical Palmes tubes during tests 5-8***	Winter	
6	Sears convective	4.2		Winter	
7	Empire radiant	4.2		Winter	
8	Empire radiant	4.2		Winter	
9	Japanese convective	4.2		Winter	
10	Japanese convective	4.2		Winter	
11-15	Three Japanese UVGSHs	4.2	PFTs and vertical Palmes tubes--1 wk	Winter	
16	Gas range without exhaust fan	4.3	5-d vertical Palmes tubes; 3-d radon	Spring	Pretest
17	Gas range (without exhaust)	4.3	2-d PFT	Spring	No range exhaust fan
18	Gas range (without exhaust)	4.3	2-d PFT (continued)	Spring	
19	Gas range (without exhaust)	4.3		Spring	
20	Gas range (without exhaust)	4.3		Spring	Palmes tubes ends
21	Gas range with exhaust--pretest	4.4	3-d radon	Spring	Pretest
22	Gas range with exhaust	4.4		Spring	Concurrent operation of range exhaust fan
23	Gas range with exhaust	4.4		Spring	
24	Gas range with exhaust	4.4		Spring	
25	Gas range with exhaust	4.4		Spring	

* Section 5.2.
** Section 5.3.
*** Section 5.1.

Section 7.0

QUALITY ASSURANCE AND QUALITY CONTROL