Residential Combustion Venting Failure - A Systems Approach

Project 4

Assessing the Impact of Combustion Gas Spillage
on Indoor air Quality

RESIDENTIAL COMBUSTION VENTING FAILURE

A SYSTEMS APPROACH

FINAL TECHNICAL REPORT

PROJECT 4:

ASSESSING THE IMPACT OF COMBUSTION GAS SPILLAGE

ON INDOOR AIR QUALITY

COMPUTER MODELING RESULTS, FIELD MONITORING PROCEDURES,

AND PILOT TEST SIMULATIONS OF CHIMNEY FAILURE SCENARIOS

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January, 1987

STATEMENT OF PART V FUNDS

Canada Mortgage and Housing Corporation, the Federal Governments' housing
agency, is responsible for administering the National Housing Act.

This legislation is designed to aid in the improvement of housing and
living conditions in Canada. As a result, the Corporation has interests
in all aspects of housing and urban growth and development.

Under Part V of this Act, the Government of Canada provides funds to CMHC
to conduct research into the social, economic and technical aspects of
housing and related fields, and to undertake the publishing and
distribution of the results of this research. CMHC therefore has a
statutory responsibility to make widely available, information which may
be useful in the improvement of housing and living conditions.

This publication is one of the many items of information published by
CMHC with the assistance of federal funds.

SUMMARY

This report was prepared as a background document to explain the choice of equipment used for measuring pollutant concentrations in houses with venting problems. The final application of the equipment in problem houses is described in other reports produced as part of the overall research project in which this work took place, entitled "Residential Combustion Venting Failure - A Systems Approach."

A literature review was undertaken to determine what is known about the composition of gases venting from combustion appliances operating in different environments. The literature review revealed considerable information on wood stove operation, but little additional information on combustion emissions from other types of appliances prone to venting problems.

Based on the literature review, a table was prepared listing flue gas emission rates in microgram per kilojoule for different pollutants, appliances, and tuning conditions. Some general relationships between operating time, tuning condition, and pollutant generation rate were established. Generation rates were then used in conjunction with an interactive computer model to predict pollutant concentrations. The computer model was developed as part of this research project and incorporated a mass-balanced pollutant flow equation with an air infiltration model. The computer model was then used to predict the concentrations of various pollutants in houses experiencing different types of venting failures, and thereby to guide the selection of appropriate equipment for the field tests in problem houses. To establish the range of pollutant concentrations to be measured, typical indoor and outdoor ambient levels were compared with recommended indoor air quality standards and with the upper limit estimated from the computer modeling for problem events.

An attempt was made to develop an equipment package that allowed for accurate continuous monitoring with a data acquisition system, using electronic analyzers. Some difficulty was encountered in locating portable analyzers suitable for measuring pollutants in the predetermined ranges. No suitable equipment was found for measurements of nitrogen dioxide, formaldehyde, or hydrocarbons.

Sulfur hexafloride (SF_6) was evaluated as a tracer gas for determining the extent of spillage from combustion appliances and the air change rate in the house, but problems were experienced with decomposition of the gas in the combustion chamber of the appliance being tested. CO_2 concentrations were later used to determine the air change rates (based on decay of CO_2 following the failure event), but inadequate mixing of CO_2 indoors produced poor correlations.

To facilitate analysis of the mixing and distribution of pollutants indoors, a technique was developed using grab bags for storing samples during the combustion gas spillage event. The critical pollutants (NO_2, CO, CO_2) remained relatively stable in large plastic bags over the course of two to three hours.

A test protocol was developed for measuring combustion spillage events in problem houses, which included a variety of tests and computer simulations, as well as continuous monitoring of pollutant concentrations using a computerized data acquisition system while simulating or provoking a failure event in the house.

Pilot tests on a series of houses in Vancouver provided extensive information on the air quality in houses during and following backdrafting spillage events. Carbon dioxide concentrations were found to provide an excellent indication of the extent of spillage, and could be used as a surrogate for the distribution of other pollutants through the house. Peaks in other pollutants such as NO_2 and CO followed CO_2, but with less resolution.

Concentrations of pollutants measured in the return air plenum of a forced-air circulation system were shown to exaggerate the levels elsewhere in the house. This was due to the infiltration of pollutants into the plenum at the basement ceiling level. No significant CO concentrations were measured following pressure-induced spillage events. Because the hot spillage gases rose quickly to the ceiling, floor concentrations remained very low, and oxygen starvation never occurred.

High air exchange rates (due to exhaust fan operation) produced a rapid decay of concentrations between operating cycles and, consequently, concentrations did not exceed 5000 ppm, despite repeated combustion gas spillage.

In general the test protocol and equipment package appeared to characterize well the impact of combustion venting failure events simulated in the test houses, but the extent of information obtained was severely restricted by the availability of suitable, portable electronic analyzers for use in the field.

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LIST OF ILLUSTRATIONS

1.0 INTRODUCTION

An investigation of the health hazards associated with combustion venting
failures is being conducted as part of Residential Combustion Venting
Failures - A Systems Approach, a research project funded by the Canada
Mortgage and Housing Corporation. The objectives of the Health Hazard
Assessment are:

1) to provide a context for evaluating the severity of system
   venting failures in Canadian housing, and

2) to provide a vehicle for communicating the results to the
   project directly in terms of house risks.

The Health Hazard Assessment research began with a Literature Review by
Occupational Environmental Evaluation Controls (OEEC) Consultants Inc.
The purpose was to determine what is known about the composition of
combustion gases from venting combustion appliances operating in
different environments. The literature review by OEEC provided a
knowledge base from which to develop suitable procedures for follow-up
air quality monitoring in problem houses identified during the cross-
Canada survey of 1,000 houses with naturally-aspirating fuel-fired
heating systems. OEEC also provided recommendations for the types of
equipment suitable for measuring pollutant concentrations in houses with
venting problems. OEEC's review and recommendations can be found in
Appendix 1.

Discussions have since been undertaken with a number of consultants
contracted to assist in the identification of suitable technologies.
Following consultations, equipment was purchased or leased, and
evaluated. The objective of this stage of the work was to develop a
portable, rugged, and highly-sensitive air quality monitoring package,

and to field test the equipment and procedures on test houses in
Vancouver.

This report presents the results of these investigations and field tests.

It was initially proposed to combine two dynamic interactive computer
modeling programs developed for predicting combustion venting failures
and indoor pollutant concentrations. The FLUESIM computer model (Ref. 2)
developed by Scanada Consultants Ltd., for CMHC, was to be revised to
incorporate the INFIL program (Ref. 3) developed by Yuill & Associates
Ltd. for Energy, Mines and Resources Canada. INFIL was developed to
predict concentrations of pollutants in houses on the basis of pollutant
generation rates, weather variables, and house air leakage parameters.
Unfortunately, a lack of compatibility between program language and
inputs, and insufficient budget prevented the use of INFILL for this
project. As the next best alternative, a less dynamic model has been
developed by Sheltair and used to predict pollutant concentrations.

A research and development path was prepared to identify each step in the
development of procedures for problem house investigations. This plan is
presented step by step below. The plan parallels the format of Health
Hazard Assessment Research and Development Plan of this progress report.

    1.   Determine typical generation rates for combustion pollutant
          rates from different fuels and appliances.

    2.   Develop and program a computer model for predicting indoor
          concentrations of combustion pollutants.

    3.   Use the computer model to estimate concentrations of various
          pollutants for specific types of failure scenarios.

4.   For each combustion pollutant, identify the lower and upper
     limits that must be measured in the problem houses.

5.   Specify an appropriate package of equipment for monitoring and
     sampling pollutants during field testing.

6.   Obtain equipment and evaluate its performance.

7.   Outline a one-day field test procedure for obtaining the
     necessary data on problem houses.

8.   Simulate failures with gas-fired appliances and use the field
     test procedures to evaluate the impact on air quality in test
     houses.

9.   Simulate failures with oil-fired appliances as above.

10. Simulate failures with wood-burning appliances as above.

2.0 CHARACTERIZING THE IMPACT OF COMBUSTION GAS SPILLAGE ON INDOOR AIR
     QUALITY

2.1 Pollutant generation rates for different fuels and appliances

Information on emission rates of particular combustion pollutants from
various appliances operating under various conditions is not easy to
obtain. A review of the literature conducted by J.P. Farant (Ref. 4)
during Phase 1 of this project had identified a number recent research
reports which tabulated emission rate for particular appliances.
Unfortunately in almost all cases these reports focused on unvented
combustion appliances, such as, kerosene heaters and unvented gas space
heaters. Consequently, a more detailed review of literature over a
longer time horizon was conducted to obtain statistics on likely emission
rates for wood, gas, oil, and propane fired, vented appliances.

On the basis of an extensive literature review, Table 1 was prepared,
listing typical pollutant generation rates for different appliances. The
materials used in preparing this Table has been referenced at the end of
this report.

Wherever possible an attempt was made to establish both average emission
rates for well-tuned appliances, as well as the deviations. The worst
case emission rate for a particular appliance are assumed to be the one
standard deviation over the mean. These worst case emission rates have
been calculated and included in Table 1 (where information was
available). An attempt was also made to establish emission rates for
poorly-tuned appliances (both a mean and a worst case rate). On gas-
fired appliances worst case conditions have sometimes been stimulated
during research work by means of reducing the venturi intake of primary
air shutters. This produces a lower temperature flame due to poor
mixing, and elevates generation rates for most pollutants. A similar

technique can be used to reduce the primary air intakes through the
burner fan on an oil furnace.

Table 1

FLUE GAS EMISSION RATES (ug/kJ)
Extracted from various field research reports

| Pollutant | Gas Furnace | | | | Oil Furnace | Fireplace |
	Tuned Avg.	Std. Dev.	Untuned Avg.	Std. Dev.	Tuned Avg.	High Burn Average
CO	2.6	± 0.8	66.8	± 1.2	30	10×10^3
NO_2 (K = 0.82 hr^{-1})	2.36	± 1.2	4.86	± 1.94	100	150
CO_2 (X 10^3)	38.4	± 6.6	39.7	± 6.6	66	*
HCHO	0.062	± 0.048	0.217	± 0.141	*	*
SO_2	**	**	**	**	220	120
Hydrocarbons	*	*	*	*	3	2000
Particulates	*	*	*	*	30	1000
POM	**	**	**	**	0.003	20

Notes: 1.   Untuned refers to yellow flame conditions on a conventional gas
         furnace, caused by closing vent or primary air intake.

         2.   K for NO_2 refers to an average decay rate for use in the Air
         Quality.

         3.   Emissions are calculated on basis of rated appliance input (kJ) and
         the mass (ug) of pollutant in flue gases prior to mixing with
         dilution air.

 *   No reliable data available.

**   Insignificant

   Wood-burning fireplaces are not capable of being poorly-tuned. However
   the burn cycle produces varying generation rates which must be taken into
   account. As the fire burns down the combustion is less efficient and
   generation rates for carbon monoxide, hydrocarbons, and polycyclic
   organic materials increase geometrically. A fireplace operating at low
   burn is analogous to a gas or oil-fired appliance with restricted primary
   air.

A number of difficulties were encountered in compiling Table 1. Most notable were major discrepancies between reports from different organizations or researchers. Also confusing is the use of different units for describing emission rates. In addition to using a variety of imperial and metric units, there seems to be no standardization for expressing pollutant concentrations (e.g. ppm, mass), and no standardized approach to dealing with secondary and dilution air on appliances. Thus it is possible to have emission rates for carbon monoxide from gas-fired appliances presented in terms of parts per million per cubic foot air-free, and microgram per kilocalorie after dilution.

A review of field test data from reference reports (Ref. No. 6, 7) has provided a number of generalized insights into how pollutant emission rates might vary with the operation of an appliance. These are briefly itemized below:

1. A yellow flame on a gas appliance generally increases carbon monoxide and nitrogen dioxide concentrations, while reducing the total NOX concentration. (An exception to this rule would be new appliances designed to burn with a yellow-tipped flame.)

2. Inadequate air supply to the burner of a gas-fired appliance will sometimes reduce the nitrogen dioxide (NO_2) emissions but will greatly increase carbon monoxide (CO) emissions.

3. Excessive air supply to the burner of a gas-fired appliance usually has little effect on emission rates of CO or NO_2.

4. The temperature of the heat exchanger on a gas-fired furnace is unlikely to affect emission rates significantly.

5.   Low burn rates in a wood fire stove or fireplace are likely to be accompanied by increases in the production of carbon monoxide, hydrocarbons, and POM.

6.   Emissions from oil burners during the 10 to 30 second start-up period (when spillage is possibly most frequent) may contain increased particle and CO concentrations and may need to be separately analyzed. Gas furnace CO levels in the first several minutes of burn are up to 10 time the steady-state levels. This dynamic emission rate makes modeling more difficult.

2.2   A model for predicting indoor pollutant concentrations.

The development of a computer model for predicting indoor concentrations of combustion pollutants was seen to be an essential part of the problem house investigation. Such a model is required both for identifying worst case scenarios, and for determining the specification for air quality monitoring equipment. Ideally, the model would be simple enough to also be used during the field investigations, to identify unusual circumstances or problems with test technique.

In the absence of any existing, interactive computer models for predicting pollutant concentrations, work was undertaken to program a model for use during this project. Two separate equations were merged for this purpose. The first equation, presented in Figure 1, is a copy of an equation presented in Indoor Air Pollution, by R. Wadden and P. Scheff. The Wadden and Scheff equation is a mass balance pollutant flow equation. As noted in Figure 1, it has been applied by numerous researchers in analyzing pollutant concentrations indoors. This equation is sophisticated enough to satisfy most the requirements of testing problem houses for this project.

The second equation adopted for a computer model is the air infiltration model developed by Lawrence Berkeley Laboratories, presented in Figure 2. This equation is suitable for predicting air infiltration flow on the basis of house characteristics, weather variables, and the leakage area of the building. This infiltration equation is the same equation employed by Yuill in the INFIL model. (Note: Leakage area used for the LBL equation must first be converted to ELA as per the CGSB Standard. The leakage area calculated by LBL does not use a discharge coefficient, and is calculated at 4 Pascals as opposed to 10.)

To save time and space a computer model was programmed into a Symphony spreadsheet, as opposed to using a programming language. The spreadsheet allows all the variables of both equations to be viewed simultaneously, and allows the user to quickly alter variables as suits the purpose of the investigation. This approach seemed to have greater potential for quick modelling in field conditions than would an interactive program. A copy of the SYMPHONY spreadsheet variable listings is presented in Figure 3.

The spreadsheet program was used to prepare a series of tables and graphs which illustrate the concentrations of varying pollutants in house experiencing different types of venting failures. Characteristics of the Vancouver test houses have also been inputted into this spreadsheet program, and used to predict pollutant concentrations over time for comparison with empirical data.

Figure 4 illustrates the concentrations of carbon dioxide over a 60 minute period for Problem House No. 2129 (from the Country-Wide Survey). The computer inputs required for the spreadsheet program are those listed in Figure 3. Figure 5 is the actual concentrations of CO_2 measured in House No. 2129 during an identical failure event. The model and the field test data show a reasonable agreement. (Field concentrations are

slightly exaggerated at start-up, and throughout the test, due to the sample location at the return air plenum.)

Additional graphs could be generated for different types of venting failures, to predict concentrations for carbon monoxide, nitrogen dioxide, formaldehyde, sulphur dioxide, particulates, and humidity over the short term. The IAQ model can also be used to extrapolate concentrations over the long term.

Figure 6 shows the same house, but with CO_2 concentrations predicted over a 6 hour period, as the furnace cycles on and off. A steady-state concentration throughout the house is reached just above 3000 ppm.

Further modelling of field test houses is required, in combination with monitoring air quality concentrations during failure events, in order to improve the predictive capabilities of the model and to make the computer modelling a more effective tool for use during problem house investigations.

The model has been used further during Case Study investigations as part of the Canada-wide Survey. The Case Study Report (Project 6, Appendix A) contains comparisons between the pollutant concentrations predicted by the model, and actual concentrations of pollutants in house experiencing spillage problems.

AIR QUALITY MODELS

Several approaches have been used to estimate expected indoor pollutant concentrations. These include deterministic models based on a pollutant mass balance around a particular indoor volume; a variety of empirical approaches based on statistical evaluation of test data and usually least-squares regression analysis; and a combination of both forms, empirically fitting the parameters of the mass balance with values statistically derived from experimental measurements. Each approach has advantages. The mass balance model provides more generality in application. But empirical models, for application within the range of measurements from which they were developed, may provide much more accurate information.

ONE-COMPARTMENT MODELS

The mass balance for pollutant flow into and out of an indoor volume, including recycling and interior sources and sinks, is described in Figure 6.1 and expressed by

Air mass balance: $\quad q_0 + q_2 = q_3 + q_4 \qquad\qquad$ (6.1)

Pollutant mass balance: $\quad V\dfrac{dC_i}{dt} = kq_0 C_o (1 - F_0) + kq_1 C_i (1 - F_1)$

$$+ kq_2 C_o - k(q_0 + q_1 + q_2)C_i + S - R \qquad (6.2)$$

where C is concentration indoors (C_i) and outdoors (C_o); t is time; q is volumetric flow rate for make-up air (q_0), recirculation (q_1), infiltration (q_2), exfiltration (q_3), and exhaust (q_4); F is filter efficiency for make-up (F_0) and recirculation air (F_1) (often the same); V is room volume; S is indoor source emission rate; R is indoor sink removal rate; and k, a factor which accounts for inefficiency of mixing, is the fraction of incoming air which completely mixes within the room volume. The solution of Equation (6.2) for the change in C_i with t, holding all other factors constant and with boundary values $C_i = C_s$ at $t = 0$, is

$$C_i = \frac{k[q_0(1 - F_0) + q_2]C_o + S - R}{k(q_0 + q_1 F_1 + q_2)}[1 - e^{-(k/V)(q_0 + q_1 F_1 + q_2)t}]$$

$$+ C_s e^{-(k/V)(q_0 + q_1 F_1 + q_2)t} \qquad (6.3)$$

For the case where R is a first-order function of C_i, the solution will have the form

$$C_i = \frac{k[q_0(1 - F_0) + q_2]C_o + S}{k(q_0 + q_1 F_1 + q_2) + E}\{1 - e^{-[(k/V)(q_0 + q_1 F_1 + q_2) + \frac{E}{V}]t}\}$$

$$+ C_s e^{-[(k/V)(q_0 + q_1 F_1 + q_2) + \frac{E}{V}]t} \qquad (6.4)$$

where E is a proportionality constant for the particular pollutant of interest, such that $R = EC_i$. Steady-state values of indoor concentrations, $C_{i,ss}$, will result by letting t approach ∞ which, for Equation (6.4), results in

$$C_{i,ss} = \frac{k[q_0(1 - F_0) + q_2]C_o + S}{k(q_0 + q_1 F_1 + q_2) + E} \qquad (6.5)$$

Equation (6.3), or similar forms, have been applied in analyzing indoor ozone decay (Shair and Heitner, 1974; Sabersky et al., 1973; Allen et al., 1978; Selway et al., 1980), odor control (Turk, 1963), particulate matter and carbon monoxide (Cote and Holcombe, 1971), ozone and carbon monoxide (Allen and Wadden, 1982), particulate matter from cigarette smoke (Hoegg, 1972; Ishizu, 1980), CO_2 from respiration (Kusuda, 1976), a variety of pollutants in residential settings (Moschandreas et al., 1978), and energy efficient control strategies (Woods et al., 1981).
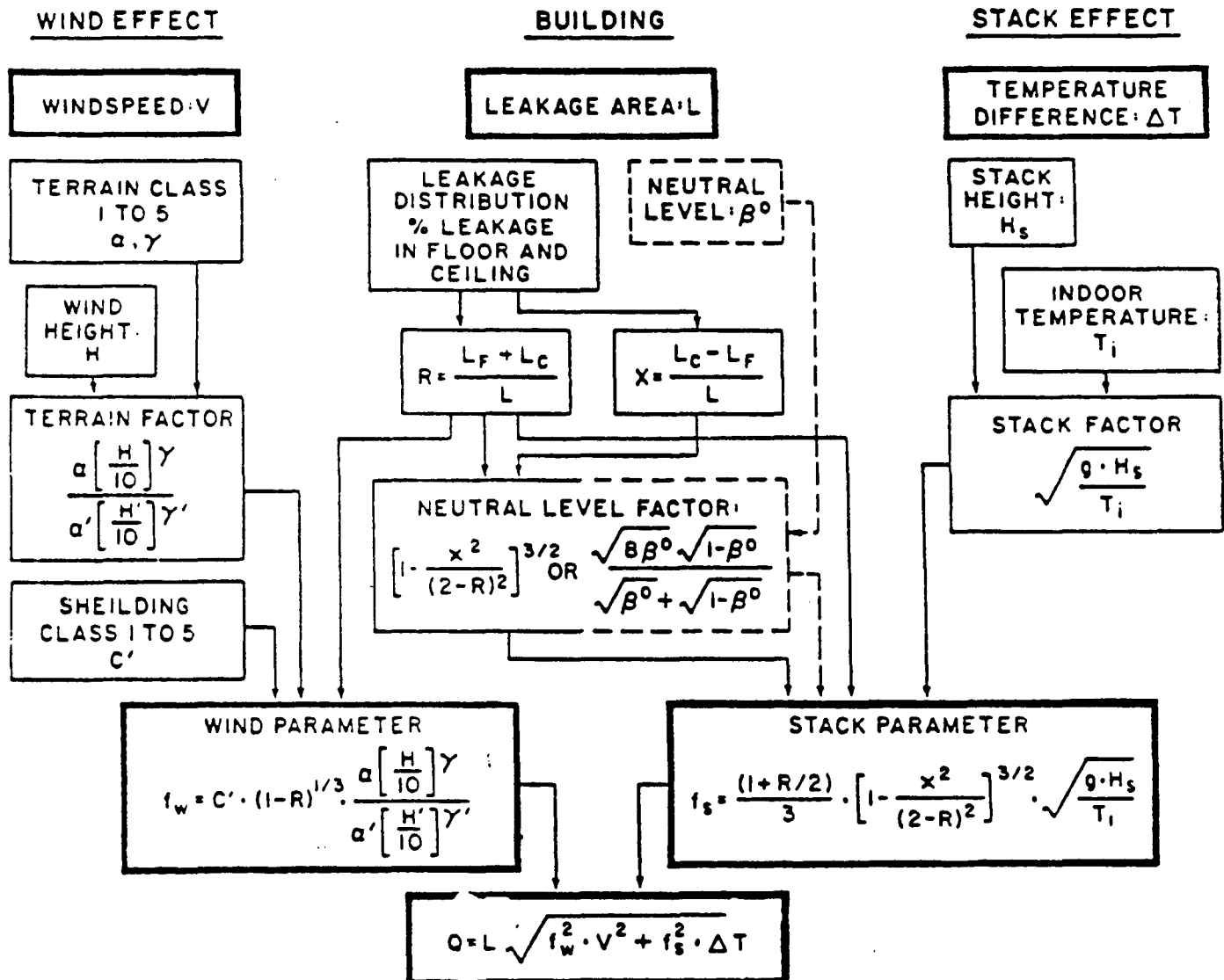
FIGURE 2:   Schematic Representation of LBL Infiltration Model

a_h	Terrain Class Constant for house (dimensionless)
a_m	Terrain Class Constant for wind measurement site (dimensionless)
C	Pollutant Concentration (Parts/m^3)
C^o	Pollutant Concentration at beginning of time step (Parts/m^3)
C^1	Shielding Coefficient for the house site (dimensionless)
ELA	Equivalent leakage area (m^2)
f_s	Reduced Stack Parameter (m/s^{o}C$^{1/2}$)
f_w	Reduced Wind Parameter (dimensionless0
g	Gravitational Acceleration (m/s^2)
v_h	Terrain Class Constant for house (dimensionless)
v_m	Terrain Class Constant for wind measurement site (dimensionless)
H_h	Ceiling Height above grade (m)
H_m	Height of wind measurement device (m)
L	Effective Leakage Area (m^2)
L_c	Ceiling Leakage Area (m^2)
L_f	Floor Leakage Area (m^2)
n	The Exponent on the pressure difference in the equation $Q = C \triangle P^n$ (dimensionless)
P_w	Wind Effect Parameter (dimensionless)
Q	Infiltration Rate (m^3/s)
R	Fraction of Leakage that is in the floor and ceiling (dimensionless)
r_o	Typical Canadian value of air velocity through the leaks in the house (m/s)
S	Pollutant Source Strength (Parts/s)
t	Time Step (s)
$\triangle T$	Indoor-Outdoor Temperature Difference (°C)
Ti	Absolute Indoor Temperature (°K)
U	Wind Velocity (m/s)
V	House Volume (m^3)
X	Fractional Difference between the ceiling leakage area and floor leakage area (dimensionless)

FIGURE 2 continued: Nomenclature List for LBL Model

MODEL INPUT SHEET   HOUSE #2129

House Data

	Heat Load of house at To - Ti (Kj/hr)	
V	House Volume (m³)	830
A	Envelope Area (m²)	332
	Surface Area (m²)	
ELA	House ELA @ 10 Pa (cm²)	587
n	Flow Exponent (n)	0.686
k	Mixing Factor (%)	0.85
H	Height of House (m)	3.5

Infiltration Model

H1	Height of Wind Measurement (m)	10
fw	Wind Parameter	0.126
C	Shielding Class	0.24
a	Terrain Class for house	1
y	Terrain Class for house	0.15
a1	Terrain Class for wind measurement	1
y1	Terrain Class for wind measurement	0.15
g	The Acceleration of Gravity (m/s²)	9.8
fs	Stack Parameter	0.130
r	Fraction of Leakage in Floor and Ceiling (R)	0.77
x	Fraction of Leakage Imbalance (X)	0.43
Ti	Indoor Temperature (K)	293
L	Effective Leakage Area (m²)	0.030
q0	Infiltration Rate (m³/s)	0.169
ACPH	Air Change Per Hour Rate (House Volumes/Hour)	0.733

Appliance Data   2

Ft	Appliance Type (Oil, Gas, Propane)	Gas
Fr	Appliance Firing Rate (btu/hr)	105,000
	Appliance Firing Rate (Kj/hr)	110,775
X	Pollutant as a Percentage of Combustion Gas	
	Fraction of Gas Spillage	1
	Fraction of Cycle that Spills	1
	Fraction of Time	1
Tc	Time Between Cycles (hr)	0.05

FIGURE 3: Spreadsheet Variable Listing for Modeling Pollutant Levels

Weather Data

dT	To - Ti at Start	5
To	Temperature Outdoors (K)	288
W	Wind Speed (m/s)	0

Flow Rates, House Depressurization, and Filtration

FO	Make-Up filter Efficiency (%)	0
F1	Recirculation Filter Efficiency (%)	0
q0	Make-Up Flow Rate (m³/s)	0
q1	Recirculation Flow Rate (m³/s)	0
q2	Infiltration Flow Rate (m³/s)	0.169
q*	Characteristic Flow Rate (Flow/time)	0.144
	Calculated Exhaust Flow (L/s)	
Ex	Default Exhaust Flow (L/s)	168.8
HDP	House Depressurization (Pa)	13.2

Pollutant Data CO_2

P	Pollutant Generation Rate Per (mg/Kj)	35.000
R	Pollutant Decay Rate	
K1	Inverse Deposition Rate	
Kdep	Deposition Velocity (length/time)	0.000
S	Indoor Source Strength (mg/sec)	1076.979

Steady State Pollutant Data CO_2

t*	Characteristic Time (hrs)	1.605
Css	Steady State Concentration (mg/m³)	8305.981
Cs	Start Concentration (mg/m³)	1170.000
CO	Outdoor Pollutant Concentration (mg/m³)	810.000
Ci	Concentration of Pollutants (mg/m³)	2386.788
	Steady State Concentration (ppm)	4651

FIGURE 3 continued

FIGURE 4: Predicted CO₂

Concentrations During

Furnace Venting Failure

for Test House No. 2129
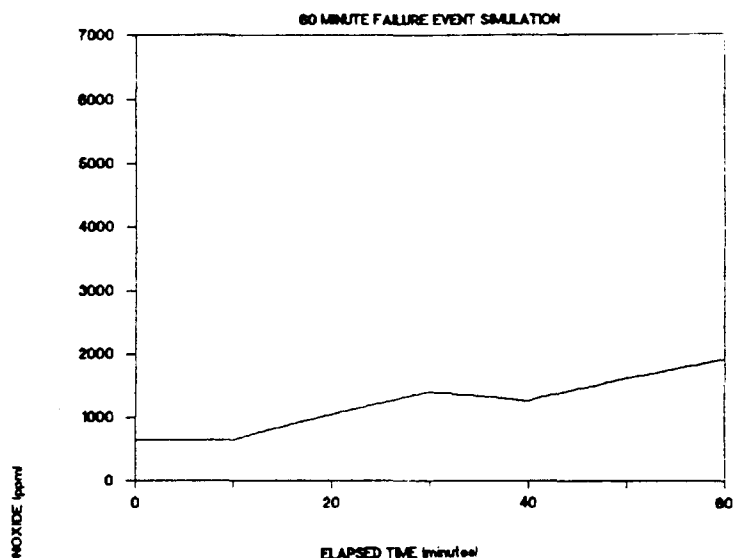
FIGURE 5: Measured CO₂

Concentrations in Return

Air Plenum During Furnace

Venting Failure for Test
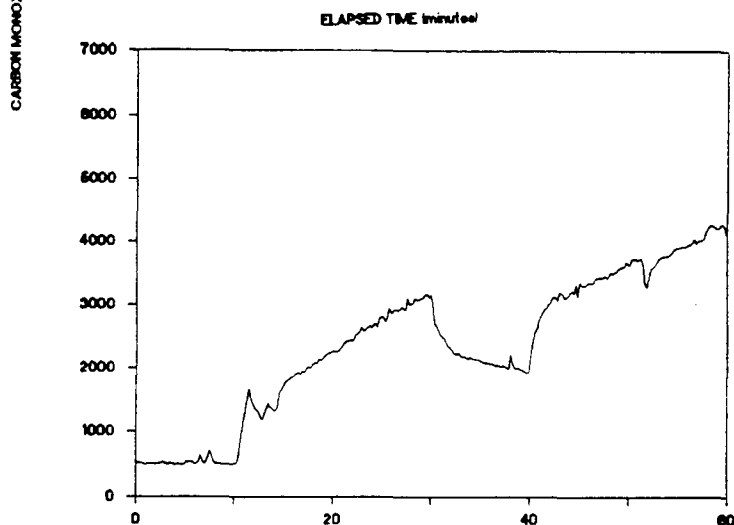
House No. 2129

FIGURE 6: Predicted Long-Term

CO2 Concentrations for Repeated

Venting Failures in Test

House No. 2129
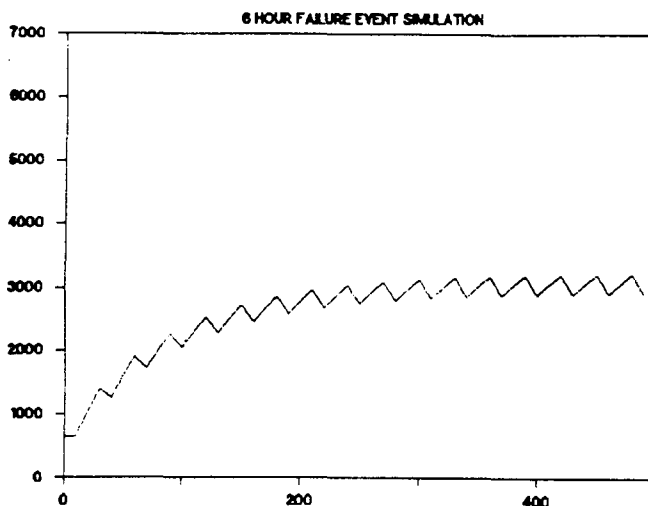
3.0   EQUIPMENT AND PROCEDURES FOR EVALUATING AIR QUALITY IN PROBLEM
      HOUSES

3.1   Choice of portable air quality monitoring equipment

3.1.1 Equipment Sensitivity Requirements

To establish equipment sensitivity requirements it was necessary to
identify ambient level for various combustion pollutants, indoors and
outdoors, and to estimate the worst case concentrations indoors during
failure scenarios. It was also important to identify the lowest
reasonable health limits for long-term exposure to each combustion
pollutant, since these are the concentration ranges where sensitivity and
accuracy are needed.

Ambient levels for combustion pollutants indoor and outdoors have been
extracted from the literature for this purpose.

Worst case scenarios for pollutant concentrations have been estimated
using the spreadsheet computer model, can thus be related to health
guidelines, at lest so far as they exist.

An effort was also made to obtain information on the soon-to-be-released
Federal Guidelines for Indoor Air in Canada. Unfortunately, these
guidelines, and the background reports which support the guidelines, have
not yet been released, and could not be referenced for this project.

Table 2 presents the range of combustion pollutant concentrations to be
measured in problem houses. The ranges presented in the Table are
intended to be conservative estimates, for use in determining equipment
specifications only.

3.1.2 Equipment Specifications and Performance

In most cases the recommendations for field monitoring equipment prepare
by OEEC Consultants presented two options for this project. The first
option was to use the most accurate continuous monitoring equipment that
could be obtained for portable purposes, and the second was to use a low
cost detector tube or passive badge technique.

The option selected for development of the field test procedures was to
employ sophisticated continuous (or semi-continuous) instrumentation
wherever possible.

Table 2

RANGE OF COMBUSTION POLLUTANT CONCENTRATIONS
TO BE MEASURED IN PROBLEM HOUSES

Combustion Pollutants	Units	Long-term Levels Acceptable for Outdoor Air		Long-term* Levels Acceptable for Indoors	Upper Limit ** Estimated for Problem Houses During Failure Events		
		Average	Limit		Gas	Oil	Wood
CO_2	ppm	350	N/A	600	5000	5000	1000
CO	ppm	1.7	9.0	10	400	400	4000
NO_2	ppm	0.026	0.11	0.1	2.6	***	***
HCHO	ppm	N/A	N/A	0.1	0.3	***	***
Particles (<2.5 um)	ug/m³	0.120	60	50	***	***	***
SO_2	ppm	0.01	0.06	0.1	***	***	***
Hydro-Carbons (non-methane)	ppm	0.32	0.24	N/A	***	***	***

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* Conservative approximation based on review of workplace TLV's and a review of literature on indoor air quality and health.

** Estimations based on mass balance modelling of worst-case failure scenarios.

*** Computer modelling of these pollutants was not completed.

N/A Not Applicable.

There are a number of obvious advantages to using continuous monitoring, including the ability:

- to collect large number of data simultaneously with a minimum amount of effort;

- to present and rapidly analyze the data that had been collected, and make the necessary adjustments to field procedures;

- to compare the performance of systems in the house simultaneously with predictions of the air quality model; and,

- to obtain with sufficient accuracy to extrapolate from short term test data to longer term scenarios for the house being tested.

The central component to this strategy was the use of data logging equipment with an affordable computer. A Symetrics data acquisition system was obtained for this project, in conjunction with a portable MS DOS microcomputer. By interfacing the air quality monitoring equipment with the computer logging system, it was possible to develope a precise, repeatable field test procedure. At the same time the computer was used separately to model the pollutant concentrations in the house prior to testing, and to model the flue performance using FLUESIM.

A data acquisition also permitted the collection of numerous other data on the house during the field testing. This was thought to be beneficial in evaluating Safety Check House Depressurization Limits, and validating the performance of FLUESIM in the test houses. Some of the house and system performance data that were collected simultaneously with air pollutant concentrations include:

- temperatures around the dilution air inlet of the appliance,
- indoor temperatures,

- outdoor temperatures,
- flue temperatures,
- indoor outdoor pressures,
- flue velocity pressures,
- wind speed,
- wind direction.

Temperatures will be recorded using Type E thermocouples. Pressures were recorded using a differential pressure transducer. The wind speed and direction were electronically recorded using a Model 2132 Weathertronix wind sensor, incorporating a three cup anemometor and an airfoil vane mounted on a common vertical axis.

The flue velocity pressure was thought to be particularly relevant for air quality monitoring, because it can be calibrated so as to indicate the quantity of combustion gas spillage into the house. Calibration required reducing house pressure until the point at which the flue begins to spill into the house. Any flue flow pressure less than the spillage pressure can be assumed to cause spillage indoors. In practice, this procedure was found to be very difficult due to constant fluctuations in flow and the flow in resolution as flow in the flue decreased.

Fully backdrafting flues were not suitable for pressure/flow monitoring. However, the quantity of spillage from a fully backdrafting flue is a function of the firing rate, and thus could be accurately predicted.

Equipment selected and tested for use in monitoring air quality in problem houses is listed and described below.

Carbon Monoxide

In accordance with the recommendations with OEEC an electrochemical analyzer was obtained for monitoring carbon monoxide in the field test houses. The CO monitor is a Nova Model 310, produced by Nova Analytical Systems Inc. of Hamilton, Ontario. The unit incorporates the British-made electrochemical cell. Both the manufacturer and users of the equipment claim the Nova Systems provides better accuracy than would be possible with infrared. The unit obtained for this project was specially produced to meet the wide range and high sensitivity requirements. The unit measure from 0 to 200 ppm with a double over range. Accuracy is plus or minus one percent of full scale.

Calibration of the Nova has been conducted according to manufacturer's specifications. It was first calibrated on April 1 using calibration gas of 197 ppm (balance N2). (The system was recalibrated April 16, at which time the calibration point again, equalled 197 ppm.) A small zero drift was noticed initially, but disappeared. At times, the unit was left running up to two days continuously with no zero drift.

An attempt was made to develop techniques for calibrating the Nova CO monitor during the field testing in other provinces. Pressurized containers with span gases could not be carried on airplanes, and consequently small amounts of extremely dilute CO were transported in tedlar bags for calibration purposes. The stability of calibration gasses transported in this manner appeared good, but the safety considerations raised by transporting such bags on airplanes were never solved.

As an option, it was proposed to have the gas sent BPX ahead of the research team. Eventually, a decision was made to calibrate the equipment in each city using span gases from local labs. In each location across Canada, a lab was found where span gases were available for use in calibrating instruments.

Carbon Dioxide

A Nova model 300DB portable carbon dioxide monitor was obtained for
monitoring carbon dioxide in problem houses. This is a portable digital
infrared metre. The unit was retrofitted to provide a millivolt output
and to allow for the nicad batteries to be switched off when operating on
VAC power for long periods. The scale is 150 - 5000 ppm CO_2. Accuracy is
plus or minus 2 percent of 1020 ppm (i.e. $\pm$ 20 ppm). The unit requires
ten to fifteen minutes warm up time before reaching full accuracy.

The CO_2 analyzer is calibrated with a cal check button for full scale,
and a CO_2 scrubber for zeroing. A 1020 ppm span gas was used during the
project tests. The unit appeared to perform very well for the first
month of operation (March), but thereafter showed substantial zero drift
and span drift. Long term monitoring would have required regular
recalibration accurate readings. However, the NOVA unit was acceptable
for three to four hours of continuous running in problem houses. It also
appeared to be relatively stable over two days of continuous running
during calibration.

Samples of CO greater than 5,000 ppm will not hurt the instrument, but
will not read. For sampling flue gas directly, another instrument was
required. A Rab Dedesco portable electronic flue gas analyzer was used
for this purpose.

Nitrogen Dioxide

The OEEC recommendation for NO_2 monitoring was to use a
chemiluminescence analyzer, if obstacles such as high cost and heavy
weight were not prohibitive. Discussions with Jeoffrey Berry of Chemical
Sciences of British Columbia Institute of Technology (BCIT), resulted in

a decision to experiment using a Interscan portable NO_2 monitor using an electrochemical cell.

The Interscan portable analyzer was used during the initial field evaluations. The unit was a 3.6 Kg portable digital analyzer with a millivolt output. It was calibrated with 10 ppm No_2 (i.e. full scale).

The Interscan monitor performed poorly during the combustion venting failure pilot tests. Although the instrument is specified accurate plus or minus 0.5 percent full scale, it experienced considerable zero drift problems during the real testing and calibration periods. In addition, it was common to obtain a negative reading from the instrument during heavy combustion gas spillage.

Zero drift problems are documented in Table 3. The zero drifts at a rate of approximately 0.1 ppm per hour.

Interferences were a greater problem than the zero drift. The electrochemical cell is sensitive to H_2S, SO_2, and Mercaptains. Negative readings of 0.2 to 0.3 ppm were common during the testing, especially with oil furnace flue gas spillage. During the longer term air quality monitoring the NO_2 metre showed definite correlation with CO_2 and CO, despite the interferences. A chemical scrubbing was felt necessary for reliability, however.

Because of poor stability and interferences it was decided that the electrochemical monitor was inappropriate for the field testing work. The health concerns raised by long-term, lower level NO_2 concentrations in houses emphasizes the need for accuracy in choice of this equipment.

Table 3
CALIBRATION RECORD FOR NO₂ MONITOR
April 14, 1986

Time	Zero	NO₂ (ppm)
11:30 a.m.	00.0	00.0 <---> 00.1
12:30 p.m.	00.2	00.1 <---> 00.2
1:30 p.m.	00.3	00.2 <---> 00.3
2:30 p.m.	00.4	00.3
3:30 p.m.	00.4	00.4
4:30 p.m.	00.4 - 00.5	00.4
5:00 p.m.	00.5	00.4

Arrangements were made to obtain a Monitor Labs chemiluminescent NO₂/Nox monitor for use during problem house testing. Unfortunately, this equipment was unsuitable for transporting by airplane, and could be used only in the Vancouver houses.

Sulfur Dioxide

The OEEC recommendations for SO₂ monitoring were limited exclusively to the Interscan SO₂ monitor. Because SO₂ concentrations are not sufficient to warrant concern in any but the oil-fired appliance problem houses it was felt to be a high priority for the P.E.I. investigations of the oil-fired appliance failures. Unfortunately, no SO₂ monitor was available in P.E.I.

Formaldehyde

The use of a continuous formaldehyde monitor was rejected for the reasons cited by OEEC (cost, lag time, waste, and expense). The use of passive badge type formaldehyde samplers was also rejected because of the minimum exposure time of one hour, and because of the accuracy of only plus or minus 25 percent.

The only option for sampling formaldehyde in problem houses was the active, time-weighted-average sampling using an impinger solution, to be analyzed by the chromotropic acid method. Arrangements were made with Can Test of Vancouver to obtain a high volume sampler and sodium bisulfate solution. Can Test prepared a package of equipment that permitted an accurate sampling of formaldehyde in periods of less than thirty minutes. This equipment was obtained from Can Test but was felt to be too awkward for field testing in problem houses.

Hydrocarbons

In accordance with the recommendations of OEEC investigations were made into obtaining a Foxboro continuous hydrocarbon vapour analyzer. An instrument of this type was determined to be available for use during the field testing. However, discussions with Jeoffrey Berry at BCIT resulted in the decision not to use the Foxboro analyzer or a Photovac portable gas chromatograph. Both these instruments are costly and difficult to transport, and do not provide sufficient information for health hazard assessment. Continuous portable hydrocarbon sampling seemed to entail a considerable amount of work for questionable information gain.

An alternative approach to hydrocarbon testing was developed with assistance from Rein Otson, from the Environmental Health Centre of Health and Welfare Canada. Otson had developed a technique for measuring polyaromatic hydrocarbons (PAH) in housing using passive devices. Otson felt it was impossible to identify beforehand which hydrocarbons might be typical of combustion. However, he felt it would be possible to use the passive device and test for the 10 or 20 PAH's most common in household air. The automated sampling system at Health and Welfare Canada helped to make this type of broad base analysis affordable.

The use of Protech Dupont badges was proposed because they are easily and
quickly obtained. A modified procedure was to be used for cleaning up
the badges and concentrating the extract, which makes measurement of
1/100th of occupation health and safety levels possible. A protocol was
prepared by Health and Welfare Canada for using the modified Protech
badges. Two hours of exposure was thought to produce dependable
readings. The GCMS analysis was to have been completed by Health and
Welfare Canada.

In the end, no hydrocarbon testing was completed. The hydrocarbon
analysis was felt to be most useful in houses with fireplace spills. The
investigation of spillage houses did not include fireplaces.

Particulates

A number of technologies were investigated for measuring particle counts
and density during the problem house investigation. Because of the use
of the data acquisition system, an effort was made to acquire a pulse
counter that would provide a signal for a digital storage. A Rion
particle counter 2100 was obtained for this purpose. Unfortunately, it
turned out not to be possible to record the readings from the Rion
counter using the data acquisition system.

The Rion 2100 is a light scatter metre. It measures particle
concentration from 0 to 30,000 particles in two sizes: 0.5 um, and 5 um.
The equipment automatically draws 283 ml of air through the photo
chamber, over a 60 second period. The two sizes of particles are
measured simultaneously with independent pulse counting circuits. The
equipment is lightweight, and easily calibrated with an automatic
calibration routine.

The Rion counter is often used for clean room monitoring, and is more
than accurate for purposes of testing problem houses. The Rion particle

counter provided useful data during the pilot testing in the Vancouver
test houses. However, constant operation and observation was necessary
to obtain data. A second problem with the equipment was translating
particle counts to particle density, something that eventually proved
impossible. These problems off set the advantages of high sensitivity,
continuous direct readout of particle counts, and ease of calibration.

Alternatives were investigated with help from the Harvard School of
Public Health. One option was to obtain a high volume portable RSP
sampler. These portable units have been specially designed by Harvard as
a portable indoor air quality sampling system. To permit rapid
measurements, they contain a 4 litres per minute pump combined with a
math post centrifugal sampler. This allows for more mass and a shorter,
more accurate measurement than is normally possible. The unit employs a
double stage impacter permitting measurements of particles in the range
of 2.5 or 10 um. Unfortunately, the units still require a sampling time
of at least 12 hours in order to obtain meaningful data on ambient indoor
and outdoor levels, which must be measured in combustion with failure
event levels. Consequently, this approach was rejected.

A final option considered for particulate sampling was the hand-held
aerosol monitor (HAM), which is a light scatter meter that provides
continuous data or particle density in air with results that are
reportedly a good match with more conventional techniques. The unit is
capable of being connected to the data acquisition system, and satisfied
all the needs of this project. Unfortunately, no HAM units were
available in Canada during this project.

3.1.3   Air Mixing and Air Change Measurements

During the pilot testing of the Vancouver Test Houses, procedures were
evaluated for determining the rate of air mixing and air change in a

house during a combustion venting failure. A grab bag technique was developed and evaluated as a means of determining the distribution of various pollutants throughout a house over time. Sulferhexafluoride (SF_6) was evaluated as a tracer gas for determining both the extent of spillage from a combustion appliance, and the rate of air change for the house. The result of these investigations are described below.

Air Mixing and Distribution with Grab Bags

The distribution of combustion pollutants in a house varies considerably with such factors as distance from source and door position. Although it is possible to use the return air plenum as a sampling location for average concentration levels in most houses, a more accurate determination of the occupant exposure to pollutants requires testing in various rooms of a house.

Continuous monitoring of concentrations did not allow for sampling in more than one location. Consequently, it was decided to use grab bag samples of household air from various locations in the house, as a way of typifying the rang e and distribution of the combustion pollutants. Grab bag samples were taken in rooms directly above the furnace room (eg. kitchen) and in far away rooms (eg. upstairs bedroom).

Because much of the air quality monitoring equipment was dedicated to the computer logging system during the failure events, it was necessary to temporarily store a grab bag sample until the monitoring equipment was available. The sampling technique also had to be capable of grabbing large quantities of air quickly in different locations. For this purpose, it was decided to use heavy duty green plastic bags, appropriately sealed and labelled. This technique proved practical and economical.

Since the combustion gases were stored in the bags for periods of two or three hours, an experiment was undertaken to determine the shelf life of the gases in the bag. Table 4 presents the results of the air quality sampling from two different green bags, containing a mixture of air and combustion gases. Both carbon monoxide and nitrogen dioxide remained relatively stable in the bags for a period of over two hours, at least within the sensitivity limits of the measurement equipment. Carbon dioxide was sampled and the ranges were read from the digital meter, so as to avoid errors resulting from the non-linear correction fluctuations. Although CO_2 showed some fluctuation, the difference between highest and lowest values for mean PPM varied no more than 2 percent. This variation is insignificant and possibly can be explained by the opening and shutting of the bag for analysis. Thus the technique was felt to be adequate for grab bag sampling of at least these three combustion pollutants.

Air Change Testing with SF6

The initial field testing protocol included the use of sulferhexafluoride (SF6) as a tracer gas. Using SF6 as a tracer gas offered the advantages of portability, accuracy, and safety, at a reasonable cost.

The SF6 tracer gas test equipment was obtained and configured in a manner similar to what is used for constant concentration air change measurements (Ref. 9). A Miran A1 infraspectrophotometer was used to monitor the SF6 using a 20.25 m path length. A 30 kg container of pressurized SF6 was obtained and connected to a two-stage, non-corrosive regulator, a small orifice, and a solenoid valve. Orifices were braised and custom drilled for small flow. The orifice provided a constant flow of SF6. As long as upstream pressures exceed downstream pressures by at least a factor of 2, the flow is stabilized at the speed of sound. The relay switches were controlled by the data acquisition system and allowed the computer to dictate when SF6 was flowing. This system was first

tested in a lab and found to work adequately. The calibration for SF_6 flow was completed using a bubble flow meter.

Table 4

'SHELF LIFE' OF COMBUSTION GASES IN GREEN GARBAGE BAGS

Time (p.m.)	Bag No.	NO_2 (ppm)	CO (ppm)	CO_2 Range (ppm)	CO_2 Mean (ppm)
3:35	Room Air	0.0	2 - 3	1185 - 1200	1192.5
3:30	1	0.1	4	2067 - 2090	2078.5
	2	0.1	4	2200 - 2227	2213.5
4:00	1	0.0	4	2093 - 2100	2096.5
	2	0.1	4	2257 - 2280	2268.5
4:30	1	0.1	4	2074 - 2092	2083
	2	0.1	4	2253 - 2282	2267.5
5:05	1	0.1	4	2051 - 2073	2062
	2	0.1	4	2222 - 2244	2233
5:30	1	0.1	4	2025 - 2081	2053
	2	0.1	4	2201 - 2236	2218.5

Time:	3:30	4:00	4:30	5:05	5:30
CO_2 in Bag 1	2078.5	2096.5	2083	2062	2053
CO_2 in Bag 1	2213.5	2268.5	2267.5	2233	2218.5

Highest-lowest value approximately 2% off for both (could be due to opening and shutting bag for analysis).

The intention was to use SF_6 for two purposes. First, by constantly providing a known flow of SF_6 into the combustion chamber of the furnace, it becomes possible to measure the quantity of combustion gas spillage from the appliance, and to determine the distribution of spillage through the house by sampling form grab bag samples. Secondly, by using the computer to monitor and control the release of SF_6 into ambient air, it becomes possible to maintain a constant concentration of SF_6 in a house during venting failures. Constant concentration tracer gas testing permits an accurate calculation of the air change rate on a minute to minute basis.

Unfortunately, the testing of the SF_6 test protocol in pilot test houses revealed a breakdown of SF_6 in the combustion chamber of an operating furnace, and, consequently, the technique was rejected. Initial references from gas reference books suggested that SF_6 would remain chemically inert. Even at a "red heat", SF_6 was reportedly unlikely to attach glass, or decompose, or react with H_2, H_3, O_2, or any other number of active substances.

However, the formation of sulphur was definitely evident during the pilot test. In addition to the odour and taste in the backdrafting gases, the entire house became inundated with strongly acidic sulphur compounds. Corrosion was also evident in the main valve of the cylinder.

A review of problems experienced with SF_6 was conducted by OEEC Consultants, who determined that molecular breakdown of SF_6 had been shown to occur by other research groups (Ref. 10, 11, and 12).

The accompanying figure shows some of the major decomposition products identified. Potential by-products of lesser abundance include SOF_4 and S_2F_{10}. It has been shown that sparked SF_6 exhibited strong cytotoxic effects and the toxicity was shown to increase with time and surfaces in excess of 550°C will produce a highly toxic sulfur tetrafluoride (SF_4) which has a low short-term limit exposure of 0.4 mg/m³. Therefore, it is highly likely that this gas and the other contaminants shown were produced during the pilot tests conducted in this project. The corrosion experienced during these tests was probably due to HF, F_2, and SO_2.

Thermal Decomposition of SF_6

$$SF_6$$
$$\downarrow \text{Heat}$$
$$SF_4 + 2F$$
$$\searrow MF_n$$
$$SOF_2 + 2HF$$
$$\swarrow \qquad \searrow$$
$$SO_2 + 2HF \qquad\qquad SiF_4 + 2H_2O$$
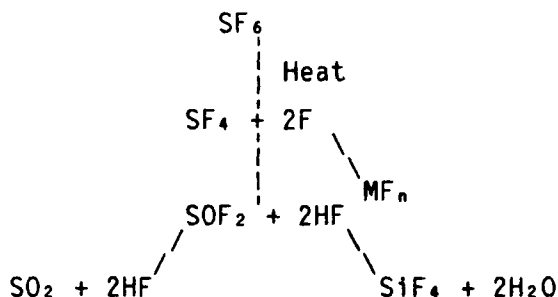
As an alternative to the use of SF_6, it was decided to measure the flow velocities in the flue and deduce the quantities of spillage that must be taking place during the venting failures.

To determine the air change rates in the house, it was decided to use the decay of carbon dioxide, during the period following the venting failures. CO_2 decay has been used in both offices and in houses as a means of establishing an accurate air change rate using the decay method (Ref. 13 and 14). Initial pilot testing indicated that CO_2 levels were in the 5,000 ppm range, sufficiently high to provide good resolution.

After completing many air change calculations on spillage houses using CO_2 decay curves, it was discovered that this technique is prone to error. Although concentrations of 5,000 ppm are well above ambient, the rapid dilution of CO_2 under high air change rates, and the inefficient mixing of CO_2 throughout the houses, produced poor correlations. It is suspected that a full hour of mixing is required before the CO_2 decay rate is indicative of air change (as opposed to mixing with indoor air). However, a mixing time of one hour was unsuitable for a busy test schedule, and also resulted in much lower CO_2 concentrations. As a result of these problems, the air change rates calculated using CO_2 decay rates are not reliable, and, because of poor mixing, are likely to exaggerate the air change rates experienced by the spillage houses.

3.2 Outline of Field Procedure

Field testing in the problem houses provided an opportunity to evaluate a number of issues related to combustion venting safety. Not all testing related to indoor air quality. The procedure included tests and investigations related to modelling of venting systems, safety test procedures, performance of protection systems, and other issues only indirectly related to health hazards. Because of the extent of testing, and the sophistication of the test procedures, an attempt was made to plan a field test procedure that made best use of the one day on site, without sacrificing air quality monitoring.

The test protocol is presented below:
1) Set up - warm up and calibrate equipment, set up instrumentation, and take measurements of building systems and components.
2) Sample indoor and outdoor air quality, as found.
3) Conduct a comprehensive safety check on the house, and, if possible, identify the cause and nature of combustion venting failures.
4) Conduct an air tightness test and measure exhaust and flows, to produce a vent pressure profile.
5) Model the vent performance in the house using FLUESIM.
6) Model the indoor air quality (worst case scenario) using the IAQ spread sheet program.
7) Estimate pollutant concentrations in the house for the failure mechanisms that have been identified.
8) Use the depressurization fan to purge the house with fresh outdoor air.
9) Begin monitoring of systems of systems performance parameters and combustion pollutants.
10) Simulate or provoke a venting failure according to evidence of the dot detectors, counters, or FLUESIM program.

11) Periodically conduct active pollutant sampling, and grab bag sampling in various locations in the house - particularly living area and bedroom.

12) Cycle appliance in typical fashion, and operate home in accordance with the worst case scenario.

13) Shut down the appliance after two hours of testing and disconnect all of the monitoring equipment (except carbon dioxide), to allow grab bag measurements.

14) Measure and calculate air changes per hour using decay of CO_2 (if possible).

15) Complete a health questionnaire with occupant (if possible).

16) Investigate or plan appropriate remedial measures.

17) Discuss follow-up actions and possible remedial measures with occupants.

18) Pack up equipment. Clean up and purge house.

19) Compare empirical data with computer modelling results and investigate discrepancies (as time permits).

4.0 SIMULATING COMBUSTION VENTING FAILURES IN TEST HOUSES AND MONITORING
     INDOOR AIR QUALITY

4.1 Simulating Failures in Gas-Fired Appliances

Delays in acquiring air quality monitoring equipment and continuous
changes to the test procedures, did not allow for a thorough evaluation
of the proposed field test protocol. However, extensive air quality
testing during simulated failures was conducted on four different test
houses in the Vancouver area and considerable amount of data was
successfully collected. The testing was more an evaluation of the
equipment and procedures than of problems in the houses. This section
describes results of air quality monitoring over one day in Test House 4.

The procedures followed in Test House 4 were similar to those proposed
for the problem houses, with the exception that a number of different
failures were simulated over the course of a day. Over a period of
several hours five different backdrafting episodes were simulated
increasing levels of house depressurization. The chimney was then
blocked, approximately 90 percent, and a single furnace cycle was
monitored, including a decay period following the furnace off time.
Outdoor temperature during the backdraft testing remained consistently
between 15°C and 16°C. Outdoor temperatures during the blockage averaged
14.5°C. Wind speed was calm.

Figure 7 illustrates temperatures in the furnace flue, and indicates that
the furnace was operating in a fairly conventional manner despite the
house depressurization. Figure 8 illustrates the temperatures at the
dilution air inlet, and indicates the extent dispelled during both the
furnace cycles. Figure 9 illustrates carbon dioxide concentrations in
the return air plenum of the house. The change in carbon dioxide levels
closely mirror the dilution air inlet temperatures. With minimal delay,
the CO_2 concentration rises proportionally to the spillage temperatures

and ratchets up as the furnace continues to cycle. Ambient CO_2 levels
and CO_2 levels in other locations in the house are noted on these
figures.

Figure 10 illustrates nitrogen dioxide concentrations over the same
period as Figures 7, 8, and 9. Note the indoor concentrations are lower
than outdoors at the start but rise at a continuous rate until they
exceed outdoor levels after 30 minutes of monitoring. Peaks in the NO_2
correspond also with the peaks in dilution air spillage temperatures.

Carbon monoxide concentrations were also monitored in the cold air
return. No significant CO pollution was measured.

The rapid rise in concentrations of CO_2 and NO_2 in return air duct
indicate how easily combustion gases spread through the house. There is
probably an exaggerated rise in the return air duct because of the static
pressure drop that is created by the furnace fan which draws the high
concentrations of combustion gases in the furnace room into the return
air plenum through leaks in the joins of the duct work. This may be a
disadvantage of using the return air as an indication of average
combustion pollutions for the house.

Figure 11 illustrates the furnace flue temperatures over the period of 70
to 130 minutes, from the start of monitoring. Note how the furnace on
times do not always correspond with the high flue temperatures, due to a
complete backdraft at points in each cycle. During the third furnace
cycle, the 8 Pascals of depressurization is sufficient to completely
back-up the furnace flue (except for a brief peak when a door was opened
as an occupant entered the house).

Figure 12 illustrates the dilution air spillage temperatures, also during
the 70 - 130 minutes period from the start of monitoring. Note how the
extra depressurization on the third cycle causes lower dilution air

temperatures due to outdoor air being drawn down the chimney.
Temperatures of spillage gases were measured at the top centre of the
inlet, the same location used for dot detectors in the country-wide
survey.

Figure 13 illustrates the carbon dioxide concentrations in the return air
during the more powerful back draft episodes. Once again, CO_2 apparently
reflects the extent of spillage from the furnace - in fact, more
accurately than either flue temperatures or inlet temperatures. The CO_2
level is ratcheting up during the first two cycles, but, at the end of
the third cycle, drops to close to ambient levels. The house is quickly
flushed with outdoor air because of powerful exhaust fan operation.
Leaky houses can still be susceptible to backdrafting, but the impact on
air quality is reduced by high rates of air change.

Figure 14 illustrates the nitrogen dioxide levels in the return air. The
gradual rise and peaks of the NO_2 are closely paralleling the CO_2 levels.

Figure 15 shows no change in CO levels over the 130 minutes of furnace
cycling. The small variations in Figure 15 are only instrument noise.

Figure 16 illustrates temperature monitoring in the vent of the furnace
at the flue collar. The chimney is blocked, sufficient to cause
approximately 50 percent spillage of combustion gases. A single cycle is
simulated for approximately 6 minutes, after which the furnace is off.

Figure 17 shows the temperatures at the dilution air inlet. These
temperatures are almost identical to those in the furnace flue. Note how
the combination of flue and inlet temperatures provides a clear
indication of the kind and quantity of spillage.

Figure 18 illustrates carbon dioxide in the return air plenum while spillage is induced by partial blockage. The steady rise in CO_2 concentrations indicates a continuous generation rate from the furnace.

After 11 minutes of monitoring, the CO_2 monitor was used to sample air outside of the air plenum at various locations in the furnace room. These samples provide an indication of how the return air plenum concentrations relate to concentrations next to the furnace. CO_2 concentrations on the furnace room floor are only half of the ceiling. The return air plenum appears to be an average of the two. The heat of the combustion gases is obviously contributing to their rapid rise into the lived-in areas of the house, and into the plenum itself. The warmed combustion gases are replaced with cool infiltrating air at the floor level. Presumably, this phenomenon helps prevent oxygen starvation of the furnace, and explains the consistently low CO levels (see Figure 19).

Figure 20 illustrates the nitrogen dioxide levels in the return air during partial blockage of the flue. Once again, the levels rise and fall with the CO_2 concentrations, although with longer response times. The differences between the furnace room ceiling and the furnace room floor are in the same direction but not to the same degree as the CO_2.
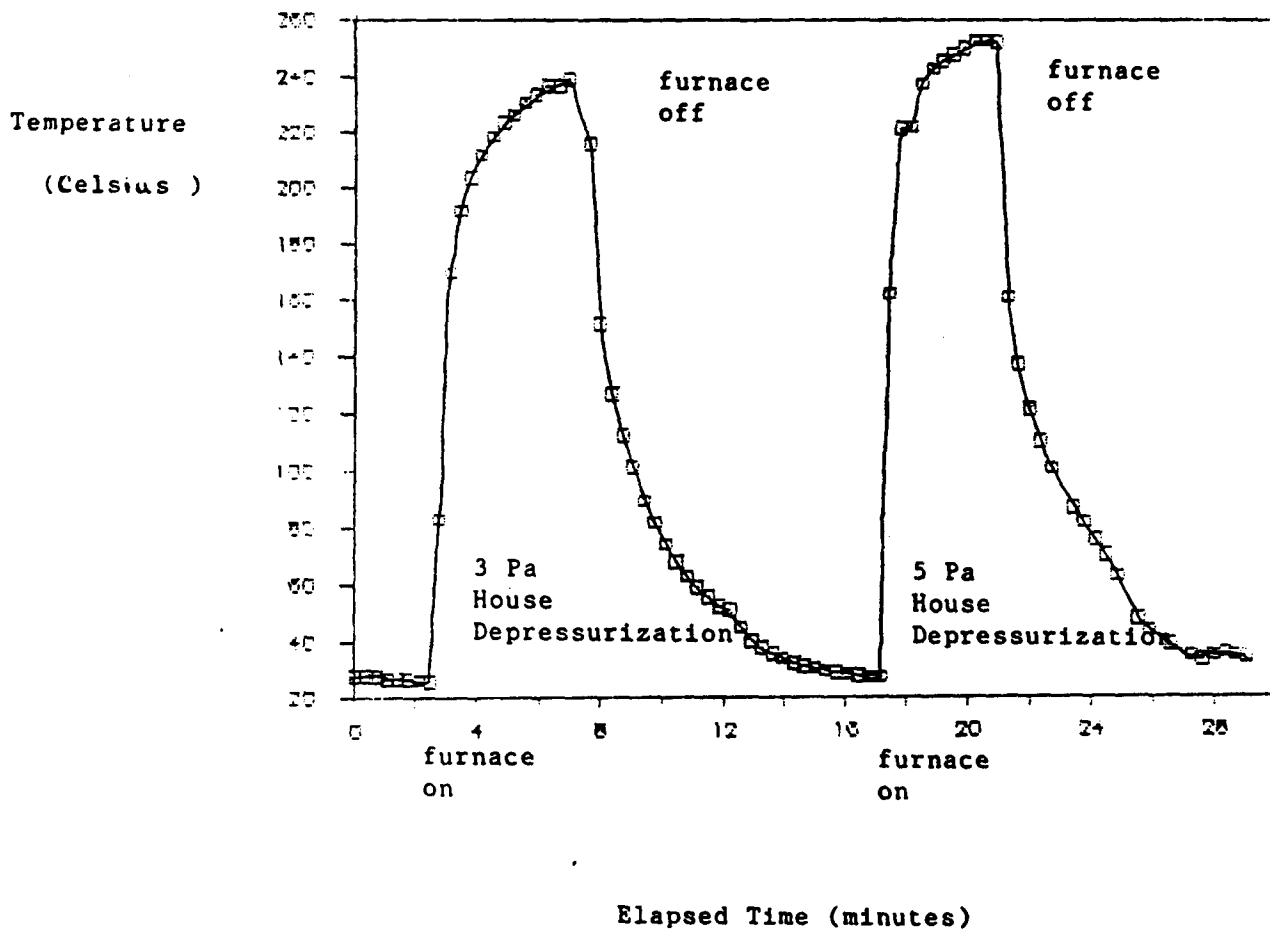
FIGURE 7: Temperature Monitoring Inside Furnace Flue Above Dilution Air
           Inlet During Backdrafting in Test House 4
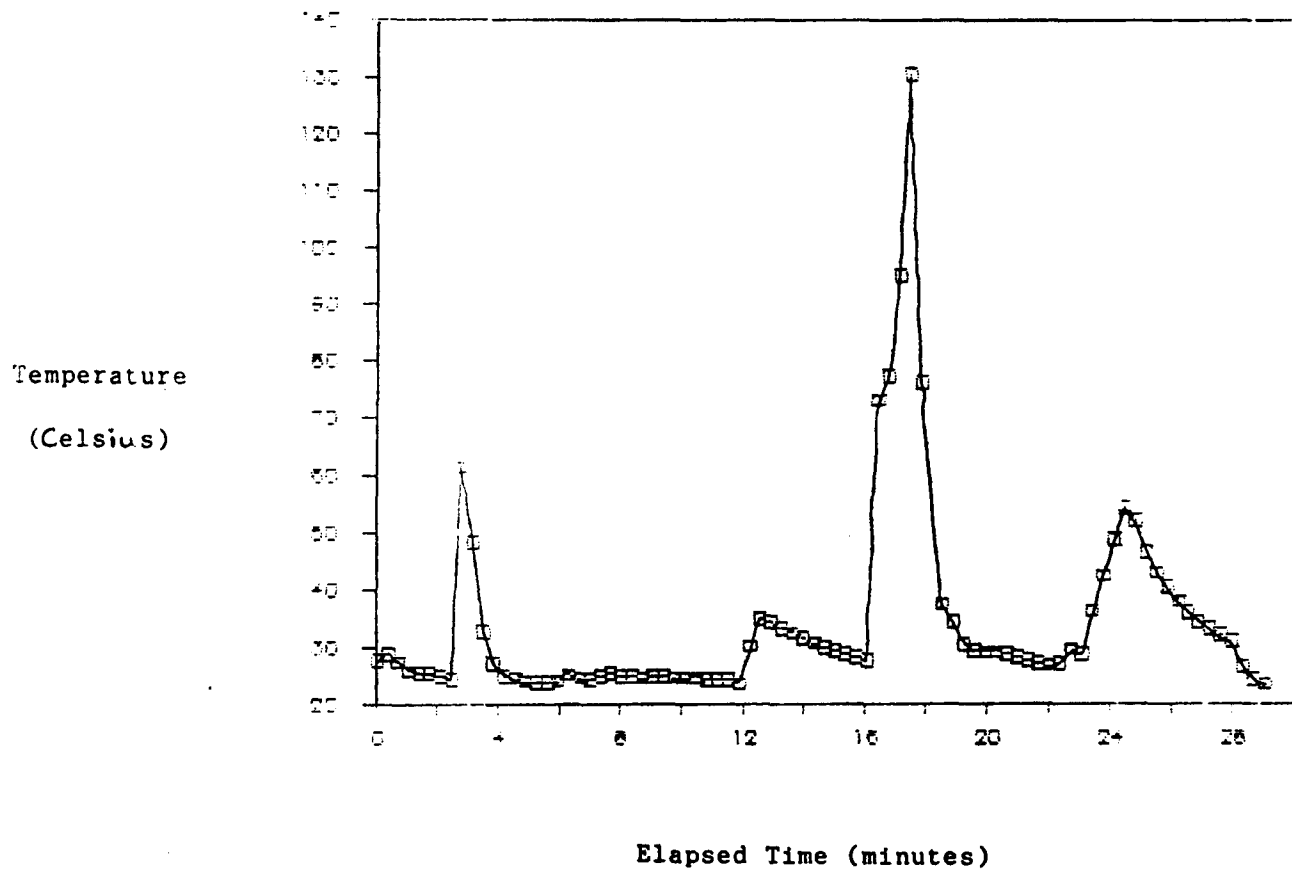
FIGURE 8: Temperature Monitoring at the Dilution Air Inlet

Elapsed Time (minutes)
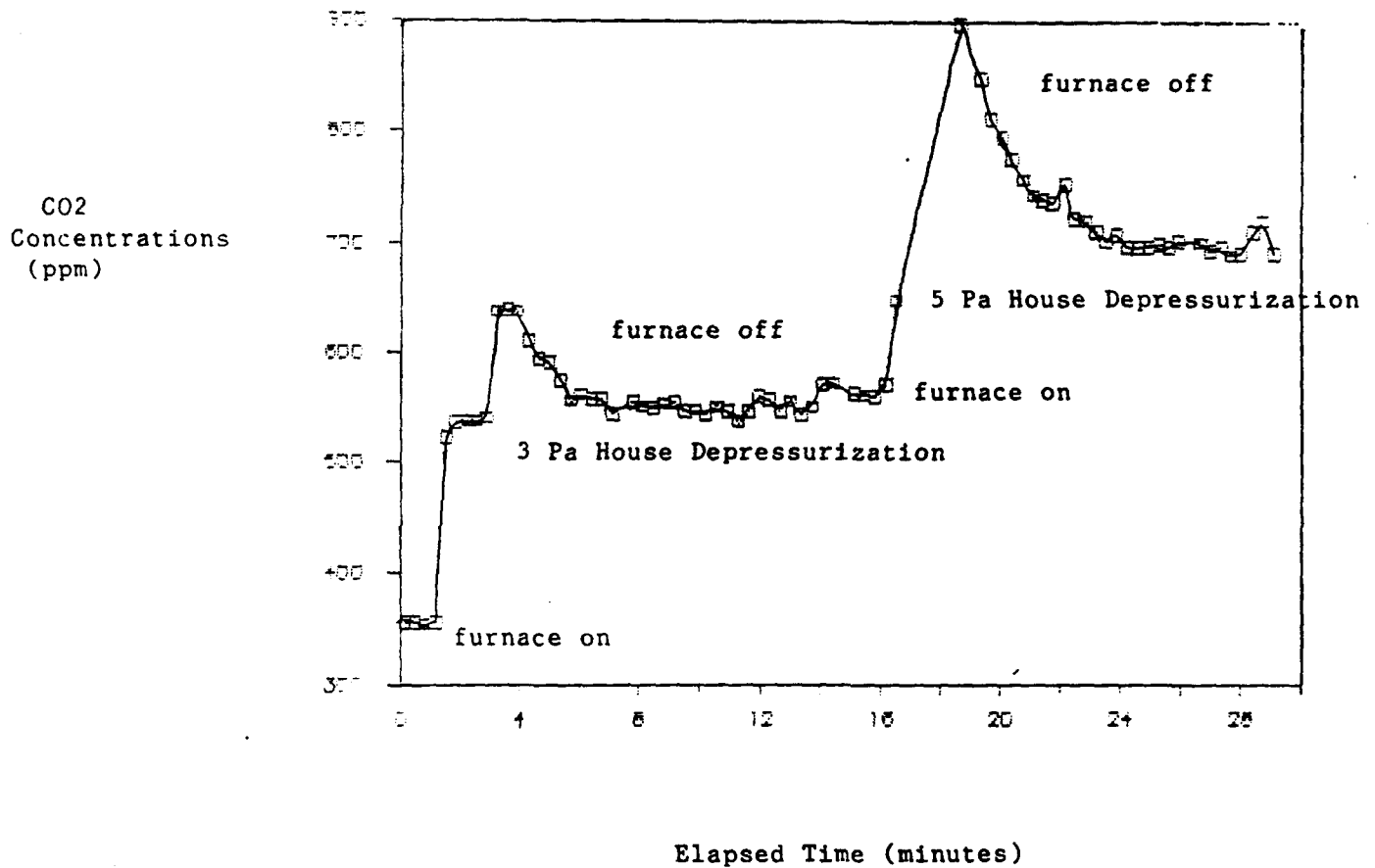
- At 16.5 minutes a living room bag sample showed 700 ppm

- At 16.5 minutes a bed room bag sample showed 700 ppm

FIGURE 9: CO_2 Monitoring in Cold Air Return During Backdrafting in Test
          House 4
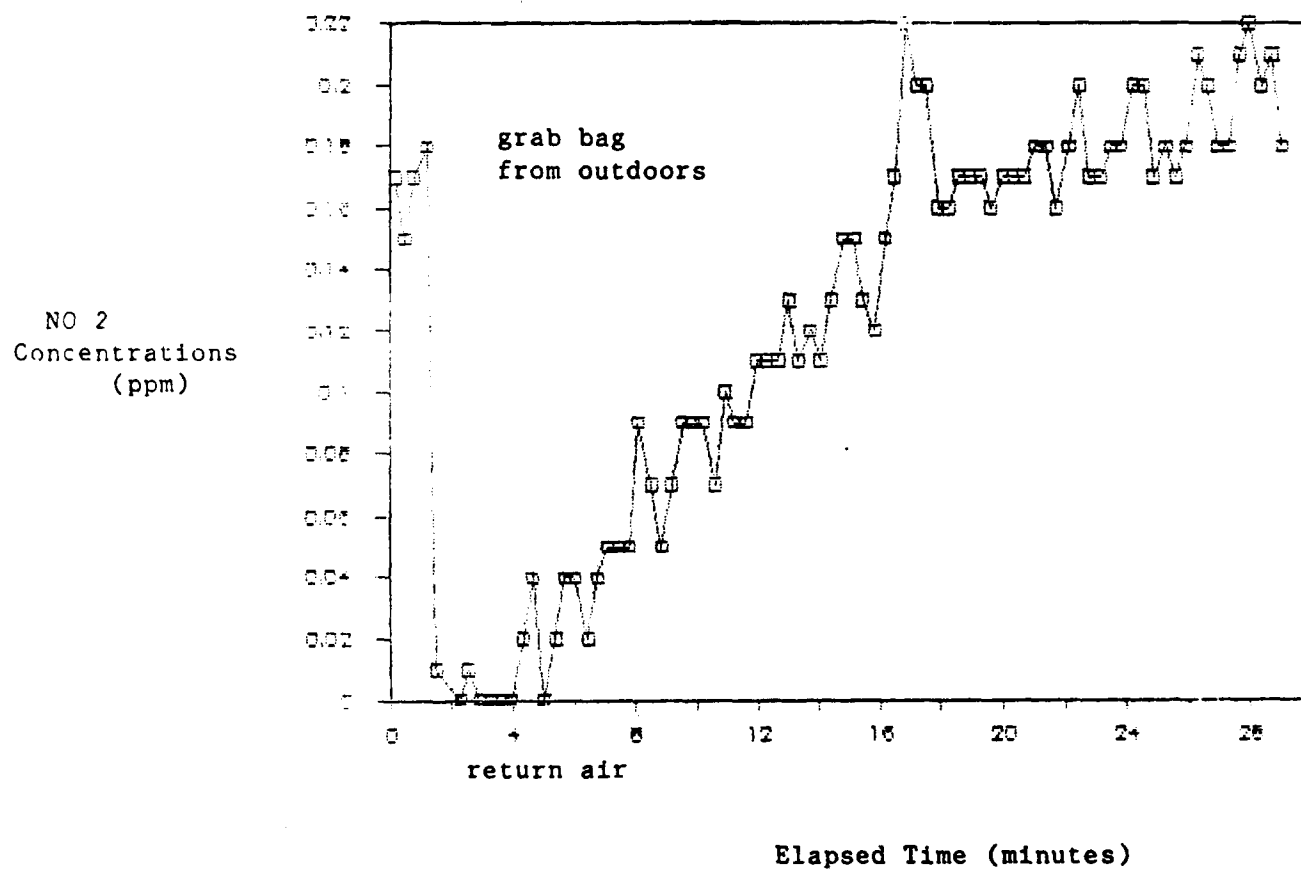
FIGURE 10: NO₂ In Return Air During Backdrafting in Test House 4

FIGURE 11:   Temperature Monitoring of Furnace Flue During Strong
Backdrafting in Test House 4

Temperature
(Celsius)

Elapsed Time (minutes)
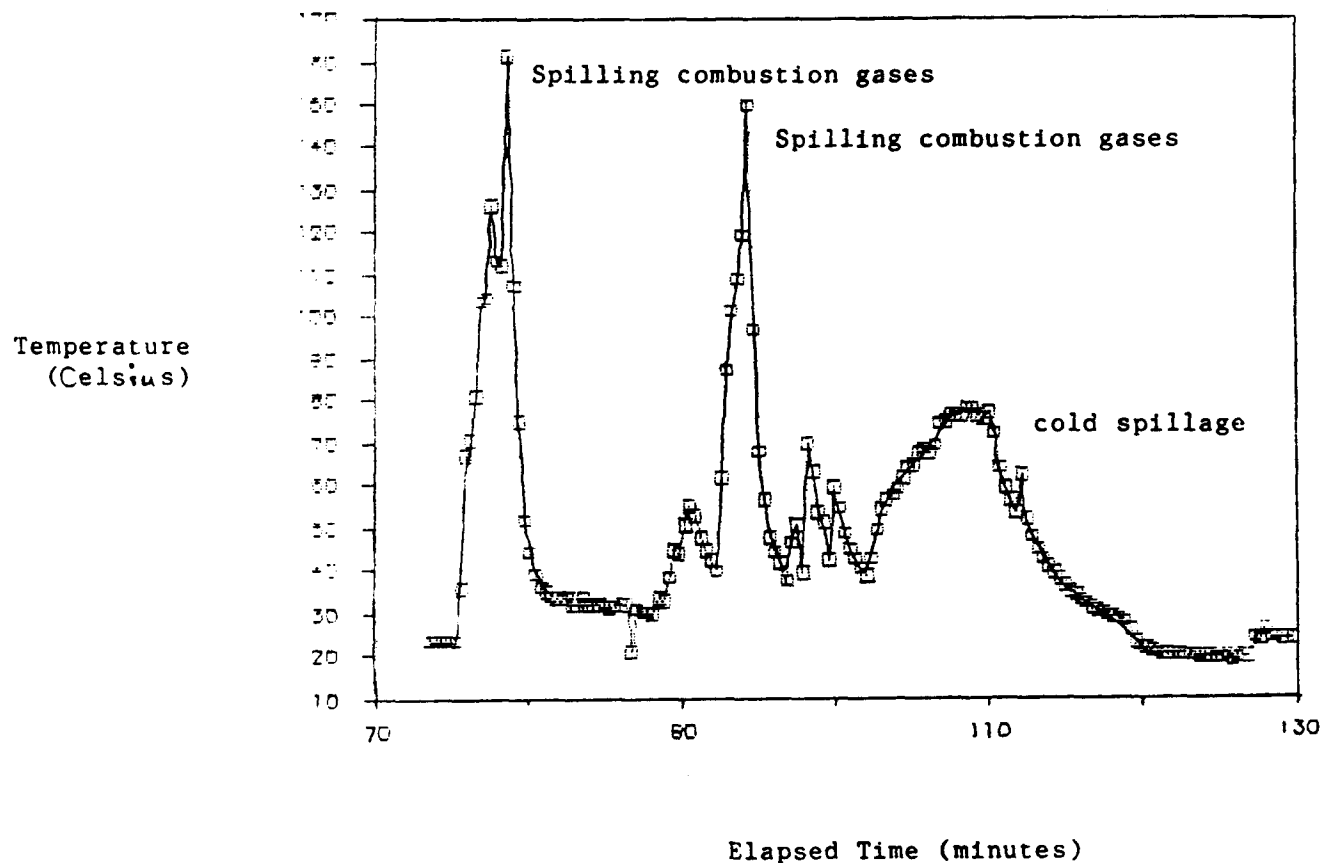
FIGURE 12:   Temperature Monitoring at Furnace Air Inlet During
              Backdrafting in Test House 4

Elapsed Time (minutes)
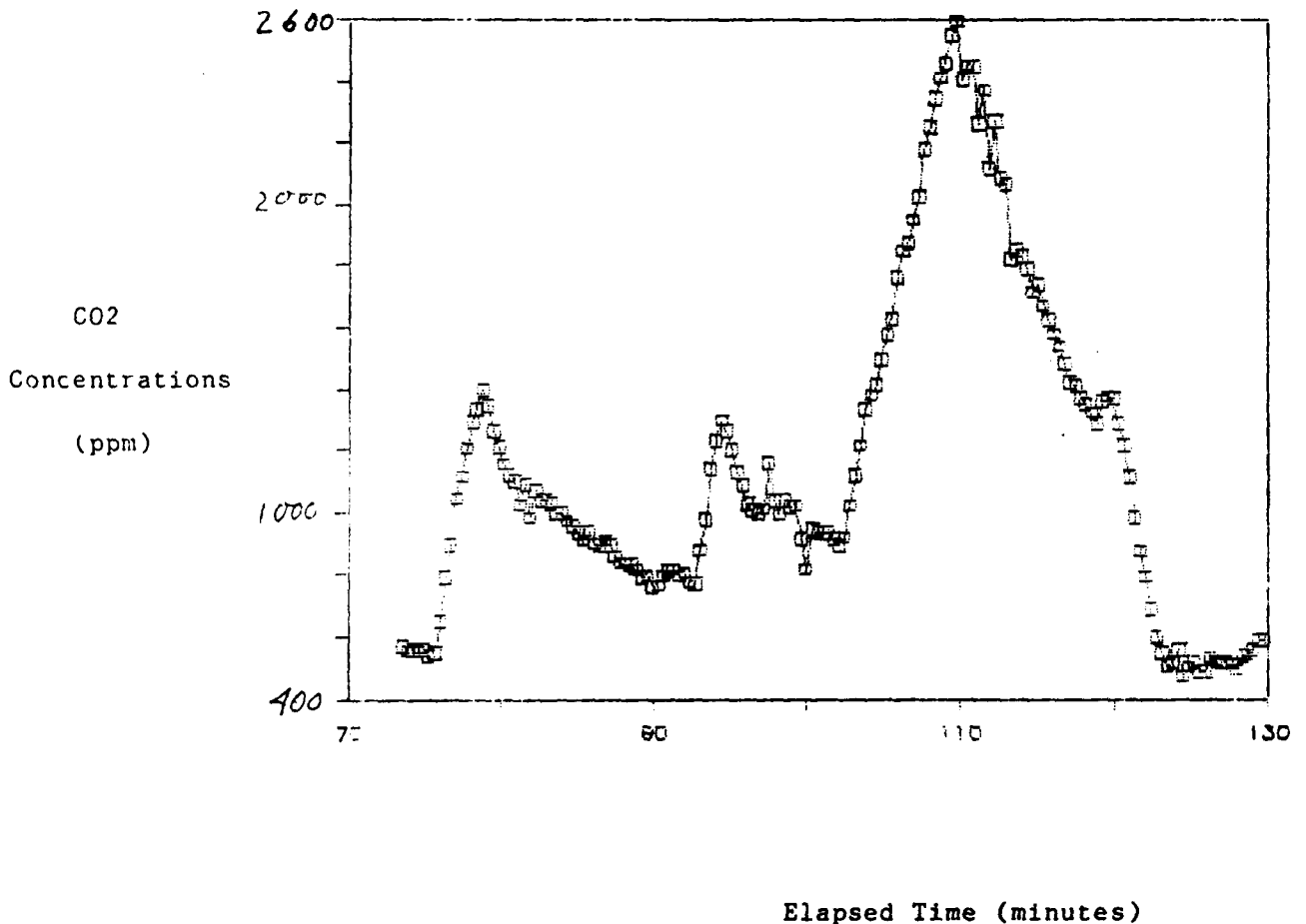
- AT 80 minutes living room grab bag sample showed 950 ppm
- At 80 minutes bed room grab sample showed 700 ppm

- At 112 minutes living room grab bag sample showed 1500 ppm
- At 112 minutes bed room grab sample showed 700 ppm

FIGURE 13: CO₂ Monitoring in Return Air During Backdrafting in Test
            House 4
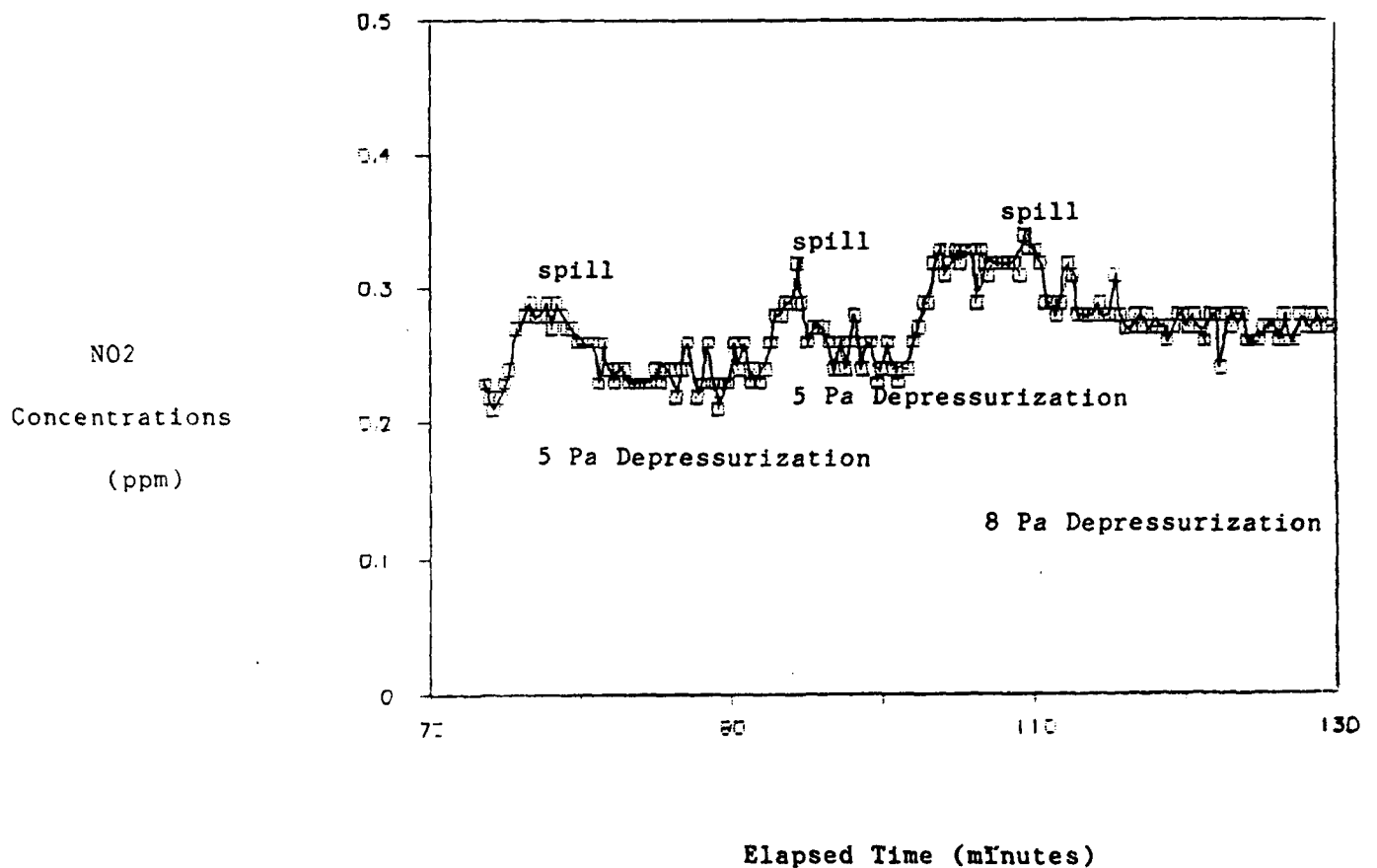
FIGURE 14:   NO₂ Monitoring in Return Air During Backdrafting in Test
             House 4

CO

Concentrations

(ppm)

Elapsed Time (minutes)
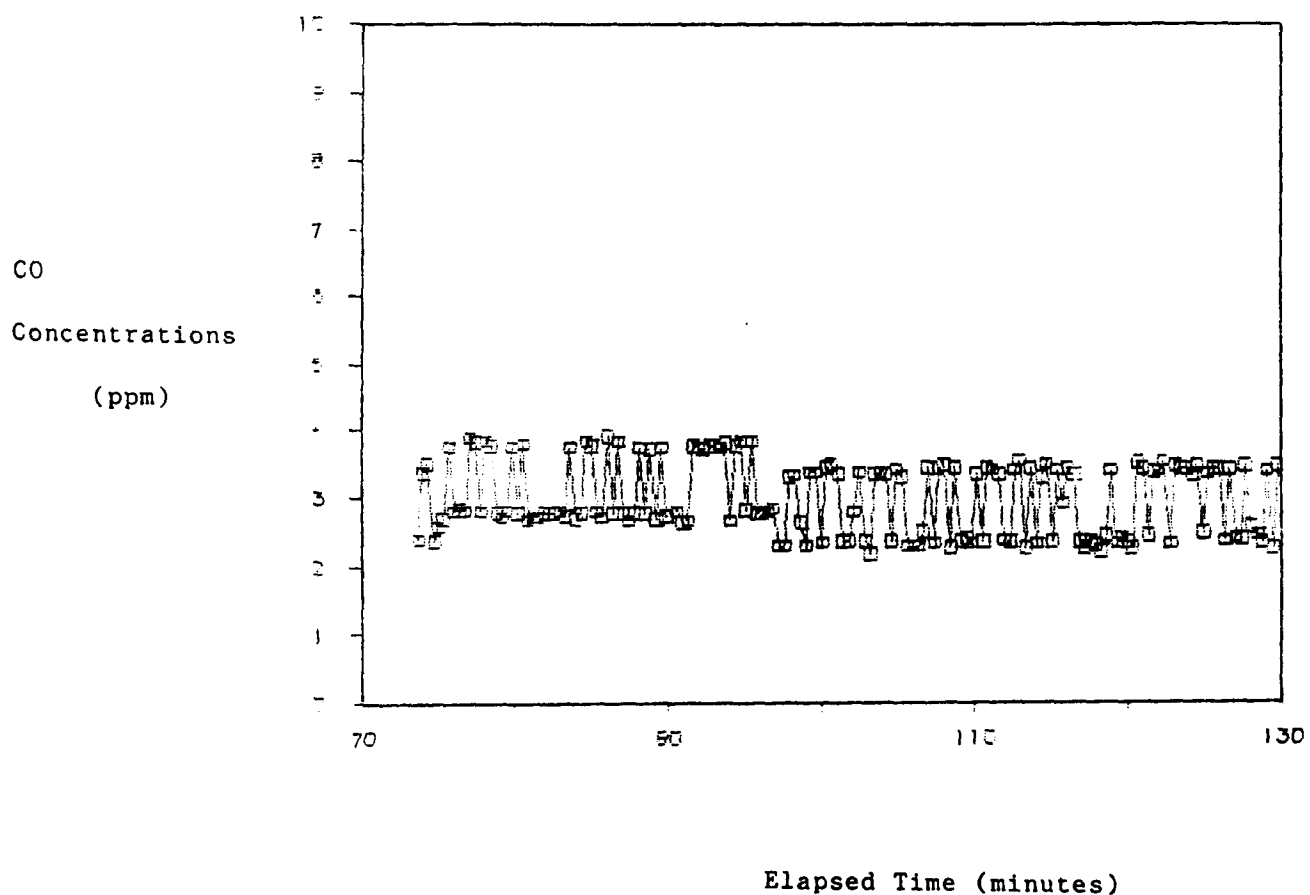
FIGURE 15:   CO Monitoring in Return Air During Backdrafting in Test
             House 4
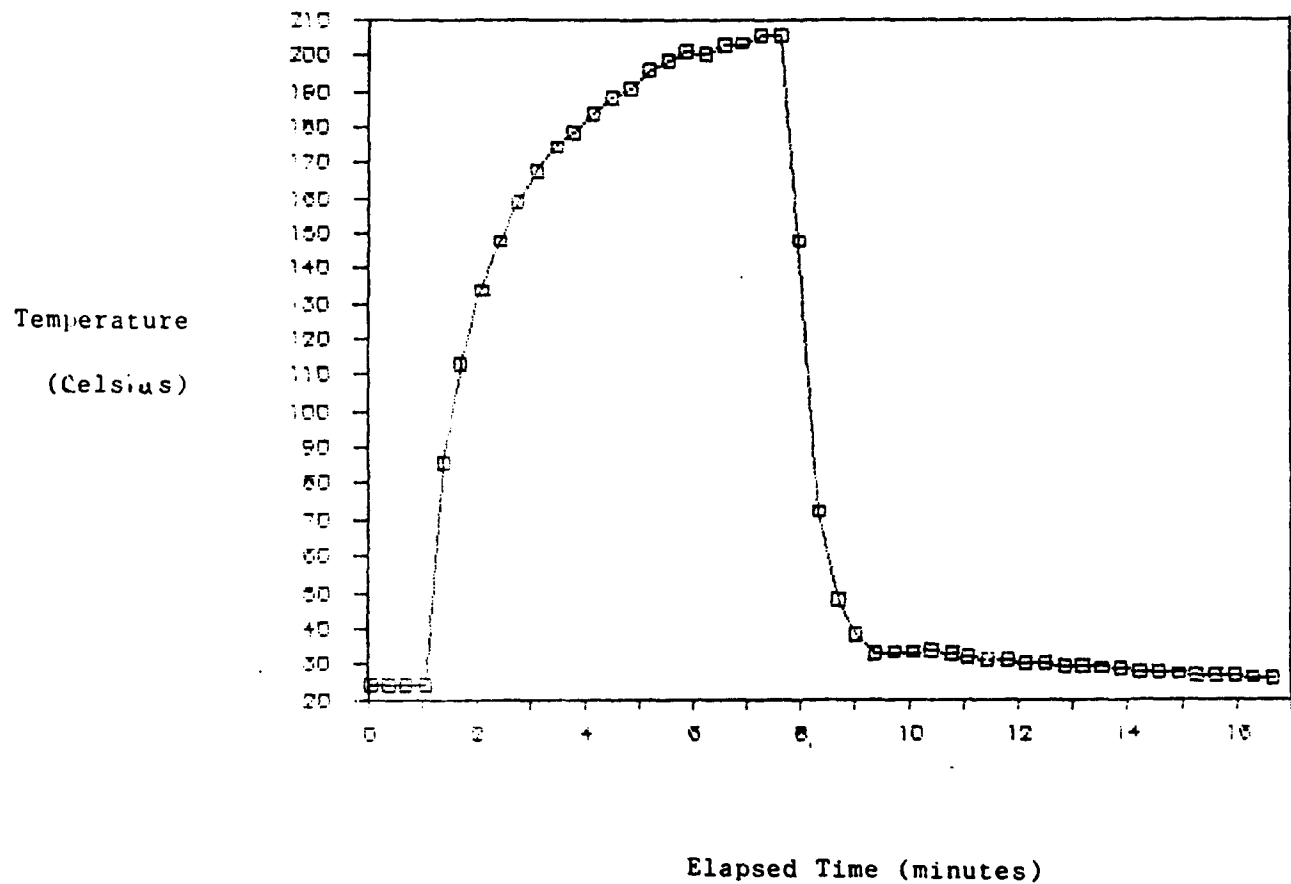
FIGURE 16:   Temperature Monitoring Inside Furnace Flue During Partial
             Blockage in Test House 4
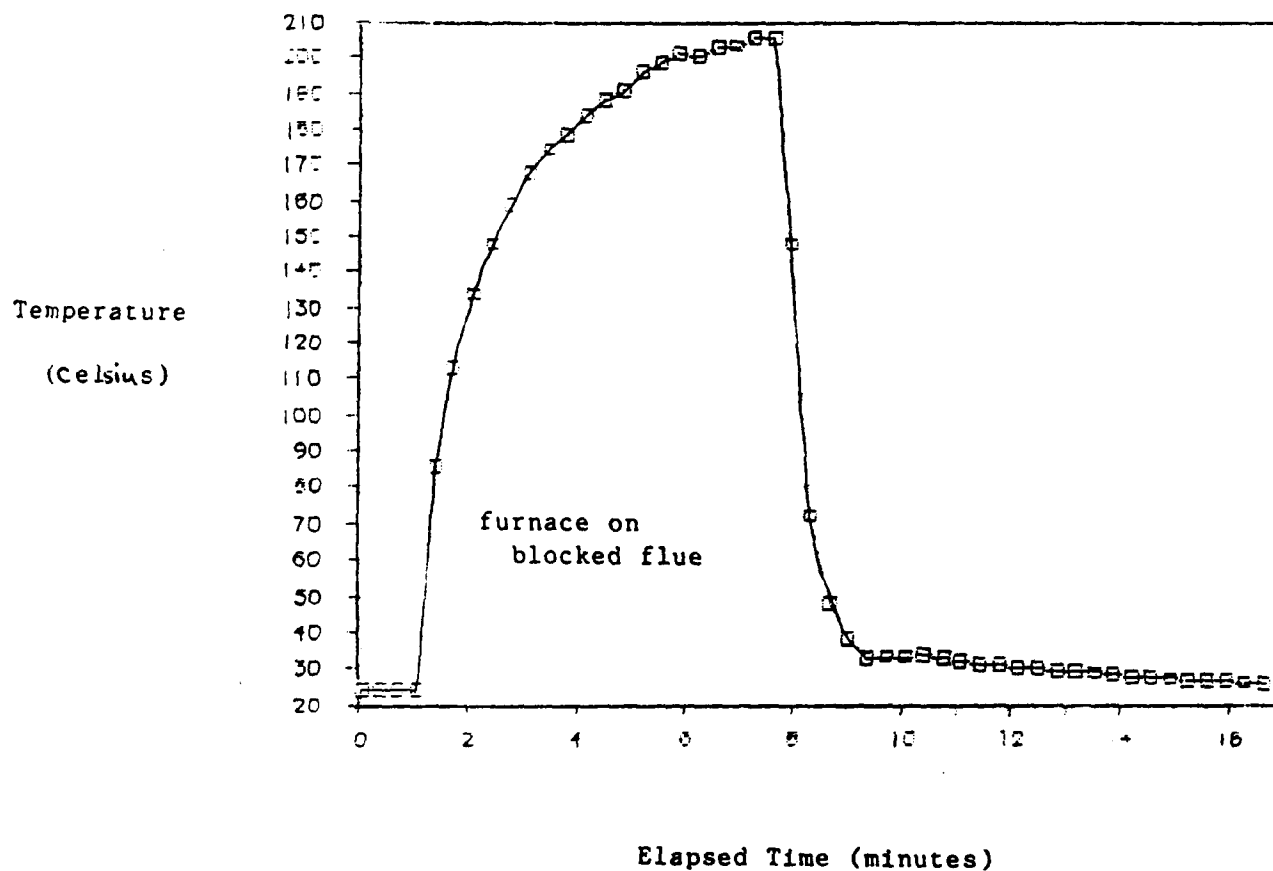
FIGURE 17:   Temperature Monitoring at Furnace Inlet During Partial
              Blockage in Test House 4
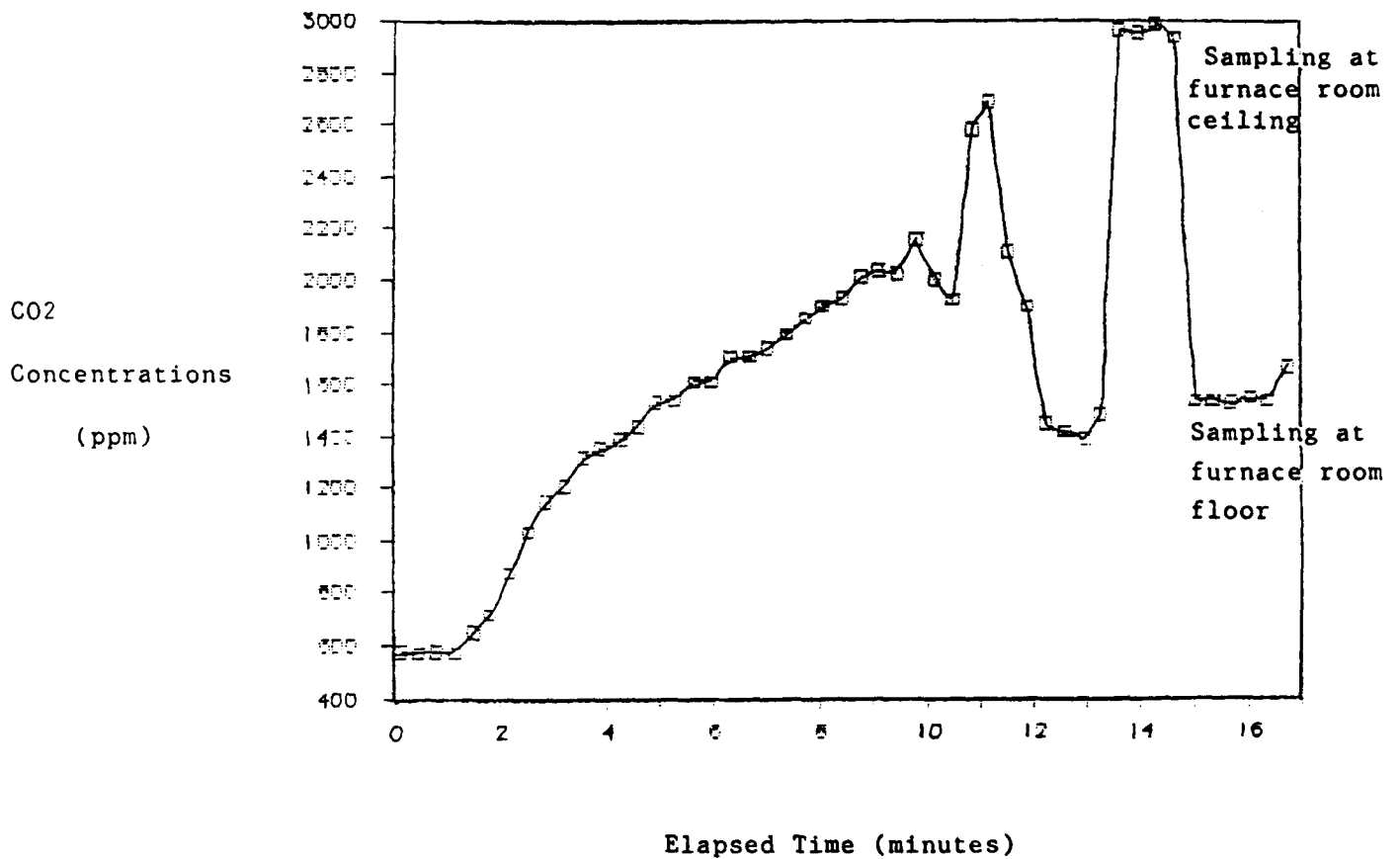
FIGURE 18: CO_2 Monitoring in Return Air During Partial Blockage in Test House 4

CO

Concentrations

(ppm)

Elapsed Time (minutes)
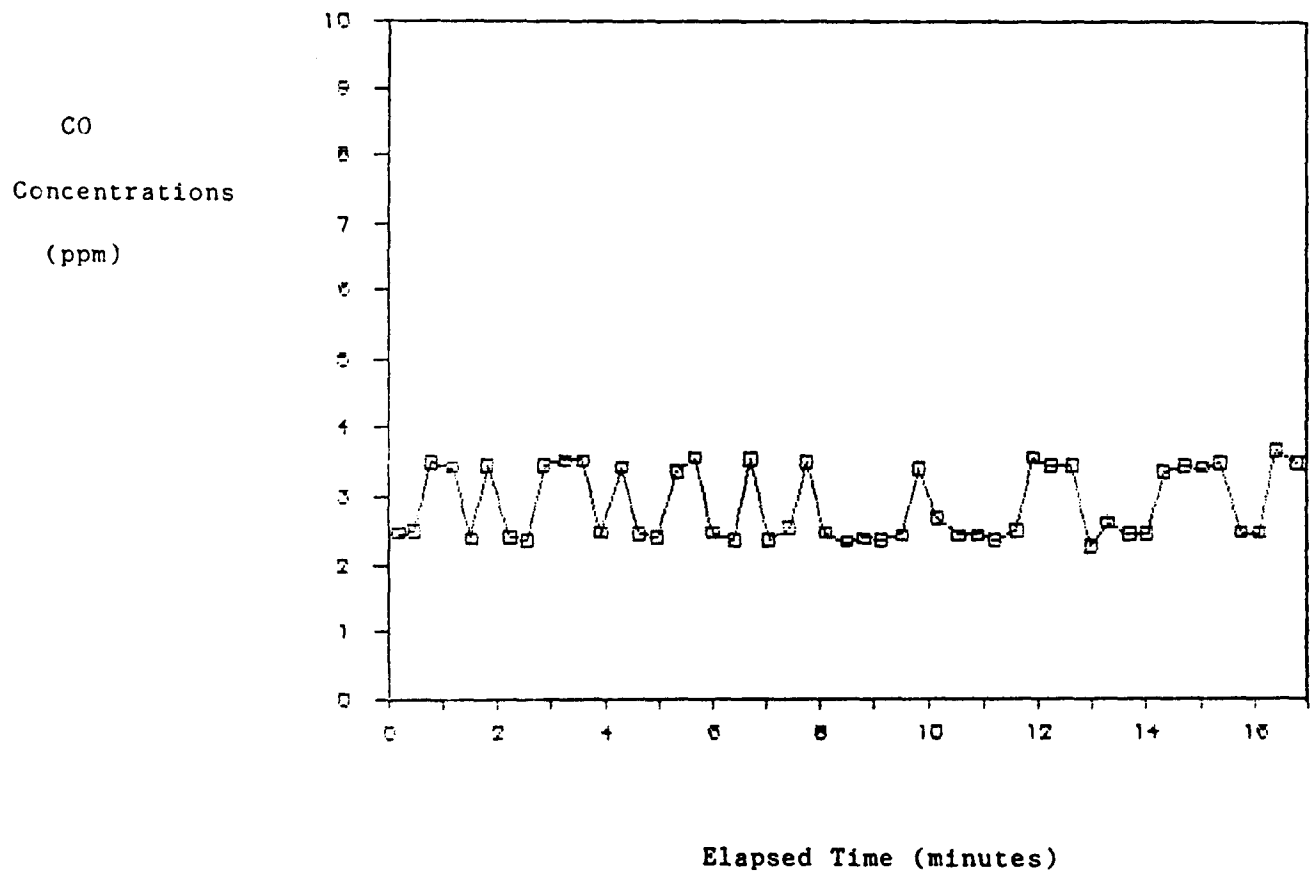
FIGURE 19:   CO Monitoring in Return Air During Partial Blockage in Test
             House 4
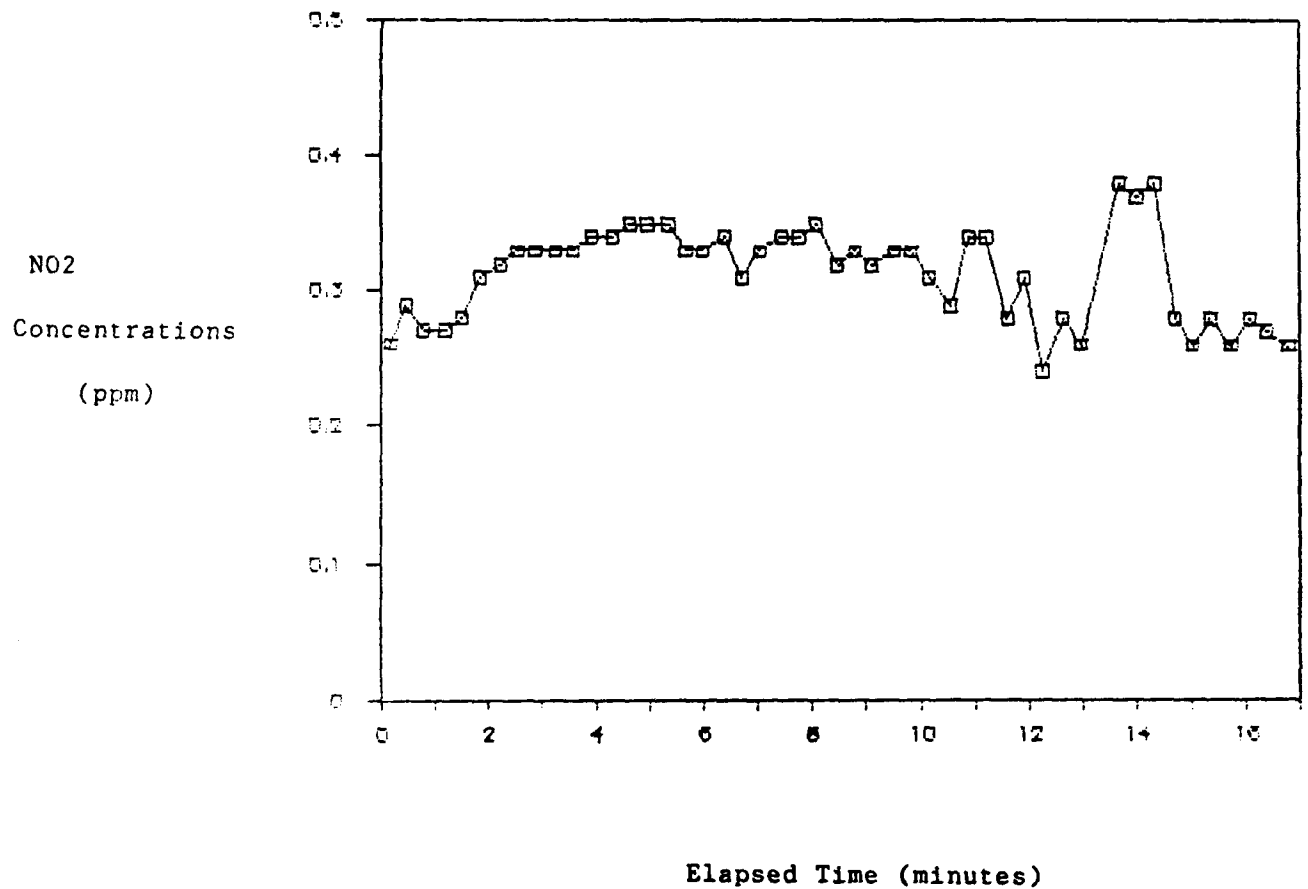
FIGURE 20: NO₂ Monitoring in Return Air During Partial Blockage in Test
            House 4

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RESIDENTIAL COMBUSTION VENTING FAILURES

A SYSTEMS APPROACH

PROJECT 4:

ASSESSING THE IMPACT OF COMBUSTION GAS SPILLAGE
ON INDOOR AIR QUALITY

COMPUTER MODELING RESULTS, FIELD MONITORING, AND
PILOT TEST SIMULATIONS OF CHIMNEY FAILURE SCENARIOS

APPENDIX 1

COMBUSTION DERIVED INDOOR AIR POLLUTANTS RELEASED
DURING CHIMNEY FAILURE SCENARIOS:

A REVIEW OF THE LITERATURE (1983 - 1986)
AND RECOMMENDATIONS FOR MONITORING

Prepared for:
Sheltair Scientific Ltd.

Prepared by:
OEEC Consultants Inc.

1986

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Introduction

An adequate understanding of indoor air quality as it relates to the performance of combustion appliances requires the knowledge of the nature and concentrations of pollutants emitted by combustion appliances and the effect of maintenance and/or proper adjustment (tuning) of the these appliances on their emission.

Literature Review (1983-1986)

In this regard the following information sources have been accessed for this report:

1. 27 original article journals;

2. 4 recent (1978-1983) indoor air pollution texts;

3. a detailed literature search at the National Research Council Library and Building Research Centre (NRC, Ottawa);

4. computer access to the 1985 Lawrence Berkeley Laboratory Indoor Air Pollution Data Base;

5. discussions with resource persons within the field on indoor air quality control. These include Mr. R. Otson (Environmental Health centre, Health and Welfare Canada, Ottawa) and Dr. Vic Armstrong, Environmental Health Centre, Health and Welfare Canada, Ottawa).

A bibliographic list of journals, symposia, texts, and data bases cited is appended.

General Perspective and Background

The major pollutants associated with indoor combustion are carbon dioxide, carbon monoxide, sulfur dioxide, ozone, nitrogen oxides, aldehydes and other organic compounds, and fine particles [1,2,3,4]. Indoor concentrations of these pollutants, obtained from the information listed above for the period 1983-1986, are shown in Table 1.

Although gas water heaters, furnaces, stoves, gas clothes driers and oil-fired space heaters have been considered important sources of indoor air pollutants [5,6,7], research and monitoring studies, within the period from 1983 to 1986, have apparently been oriented towards gas and kerosene heaters, and wood burning appliances [8,9,10,11].

Combustion Appliances: Pollutant Emission Rate Determinants (1983-1986)

Comprehensive studies concerning the factors which determine the amount of pollutants emitted from combustion appliances have been extensively reviewed by at least three Canadian groups. These are listed in Table 2.

Within the last three years, particular emphasis has been placed on the study of the factors which determine the combustion efficiency of unvented gas or kerosene-fired space heaters [13, 15]. The following discussion will indicate that major determinants of pollutant emission in these units are the size (output) of the unit, its state of fuel/oxidant

TABLE 1. Reported Ranges of Combustion Pollutant
Concentrations in Homes (1983-1986)

Pollutant	Concentration	Source/Comments
Nitrogen dioxide	0.020-0.1 ppm	137 homes/highest levels in those with gas stoves (12)
Nitrogen dioxide	0.40-1.46 ppm	projected concentration within a 240 m^3 research house with 0.36 to 1.14 air changes per hour after a 4-hour operation of a gas-firedspace heater (13)
Carbon dioxide	1930-11300 ppm	gas-fired space heater/ concentration within a 240 m^3 research house with 0.36-1.14 air changes per hour after 4-hour operation (13).
Gases listed above plus sulfur dioxide	SO_2= 0.8-46.6 ppm	300 homes with kerosene heaters/concentrations of CO_2, NO_2 within ranges stated in above cited studies and in previous literature reviews (5, 6, 7). SO_2 levels not significantly higher than ambient
Carbon monoxide	1.0-26 ppm	conditions as stated above (14)
Formaldehyde	13-66 ppb	radiant and convective kerosene space heaters/ concentration within a 27 m^3 test chamber with 0.4 air changes per hour (15).
Respirable Particulate	8-29 ug/m^3	19 homes with wood-burning appliances, final conclusion: no difference found when RSP data compared to that in homes without wood-burning (19).

TABLE 2. Pollutant Emission Rate Studies:
Canadian Research Contacts

Principal Investigator	Subject	Contact
Dr. Vic Armstrong	Relative emission rates of indoor pollutants	NHW
Mr. R. Otson	Woodburning appliance pollutant emission rates and their determinants	NHW
Mr. G. Wilson	Home furnace pollutant emission rates and their determinants	EMR

adjustment (tune), its type, manufacturer, the volume and air exchange rate of the house, and the occupant usage pattern. Furthermore, these determinants have also been associated with combustion emissions from gas water heaters, furnaces, stoves (including wood), gas clothes driers and oil fired space heaters.

It should be noted that the emission rates for the units to be discussed (kerosene and gas-fired space heaters) will be stated in units of microgram pollutant per kilojoule *ug/kJ) output. This will facilitate the calculation of pollutant concentrations in nearly all enclosures where (1) volume of input space and (2) the air-exchange rate is known. The calculation is as follows:

$$X_p = Q \times E \: / \: d \times V$$

where:

X_p = fraction of pollutant in air (steady state)
Q = heater energy release rate (fuel consumption (kJ/h)
V = enclosure air flow rate (cu.m/h)
E = pollutant emission rate (ug/kJ)
d = density of pollutant at STP

i) Kerosene space heaters: emission determinants (1983-1986)

Initial studies of kerosene space heater pollutant emissions involved the use of environmental chambers to simulate ventilation in typical houses [16,17]. In two independent chamber studies, ambient air health standards for NO_2 were exceeded for both radiant and convective types of kerosene heaters [16,17]. It has also been observed that reduction of the burner wick height led to reduced rates of combustion, but carbon monoxide and formaldehyde emissions were increased [17]. Furthermore, the decay (elimination) process of NO_2 generated from a convective heater was shown to follow first order kinetics within a living room 18].

Recently (1986), the combustion characteristics of radiant, convective and multistage kerosene heaters were determined and compared [15]. The convective and multistage heaters produced the smallest amounts of CO per kilojoule output. The radiant heater type consistently produced the largest amounts of CO, and the smallest amounts of NO_x. The convective heater produced the largest amounts of NO_x. The data from this comparative study is summarized in Table 3.

It is imperative to note that it was observed (not shown in Table 3) that the fuel consumption, carbon

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dioxide and nitrogen oxides emission decreases with decreasing burner wick height [17]. The air dilution in the combustion manifold decreases with increasing wick height since the combustion products are a larger part of the bulk flow. Wick position and age were also shown to alter combustion efficiency.

TABLE 3. Comparison of Kerosene Heater Emission Rates[*] [15]

Heater	Fuel Consumption (kJ/h)	Emission Rates (ug/kJ)		
		CO	NO	NO_2
Radiant	8160	125	1.4	3.7
Convective	11600	0.8	15.5	3.0
Multistage	14800	1.0	5.7	
	14600		5.3	2.8
	16000	1.7	7.2	2.2

[*] Emission rate computed from exhaust measurements (adjusted for background) and fuel consumption, and all measurements performed at high wick position.

As shown in Table 3, the carbon monoxide emission rates were largest for the radiant heater and smallest for the multistage heater. The design of the convective and multistage units allowed for more complete combustion of the fuel. Total nitrogen oxide emission was greatest for the convective heater. It was suggested that the formation of nitrogen oxides was a function of air entrainment and a thermal mechanism (Zeldovich process).

To summarize, this comparative study of three forms of
kerosene space heaters facilitated further definition of
basic processes of combustion product emission determinants.
Appliance effect on air quality was shown to be affected by
(1) heater design, (2) air/fuel tuning, (3) wick height and
(4) burner unit age. Without sufficient ventilation,
pollutant levels emitted from these appliances could , as has
been shown, exceed standards for ambient air quality.

ii) Gas-fired space heaters: emission determinants
(1983-1986)

A major combustion pollutant source in Canadian homes
is gas-fired appliances. It has been demonstrated
that the operation of unvented gas combustion
appliances indoors increases the concentrations of
carbon monoxide, nitrogen oxides, carbon dioxide,
sulfur dioxide and respirable particulate (refer to
ref. 5,6,7,8,9).

A recent (1985) study involving unvented natural gas-
fired space heaters (UVGSH) attempted to quantify
pollutant emission rates in the laboratory as a
function of varying gas/air tuning quality under both
laboratory and field conditions [13]. Carbon
dioxide, oxygen (consumption), carbon monoxide, and
nitrogen oxide, particulate and formaldehyde were the
levels used to measure the effect of gas-fired heater
operation on air quality in a test home.

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Table 4 presents the test results for eight well-tuned heaters operated in an environmental chamber at full output.

TABLE 4. Gas-Fired Heater Pollutant Emission Rates: Environmental Chamber Studies [13]

Heater	Fuel (kJ/h)	Emission Rates (ug/kJ)							
		CO	NO	NO_2	NO_x	P*	HCHCO	O_2	CO_2
12A	10,100	114	9.6	20	11	3.20	4.20	-67400	50000
20A	22,800	29	23	13	14	0.39	0.61	-71700	50100
30A	35,400	25	22	11	14	0.06	0.59	-72900	49900
16B	17,900	165	14	18	12	0.49	0.55	-71900	51500
40B	44,700	63	17	20	14	0.09	0.96	-68900	51000
20C	22,800	14	16	11	11	0.79	0.91	-73700	50100
30C	31,900	11	19	9.6	12	0.64	0.43	-73700	52600
40C	43,000	13	19	10	12	0.24	0.61	-71000	54600

* P = total particulate, mass from 0.0056 to 0.56 um diameter.

A, B, C = different heater manufacturers

As noted in Table 4, the nitrogen oxide emission rates were fairly consistent for all eight heaters. However, individual emission rates for NO and NO_2 varied between heaters. The CO emission rates were much more variable than the rates of the other pollutants. Five heaters had CO emission rates of

less than 30 ug/kJ while the other three heaters had much higher rates, up to 165 ug/kJ.

It is important to note that the CO emission rates across all natural gas appliances appears to be log-normally distributed [8, 9]. This study, with eight natural gas heaters, helps verify this observation. HCHO emission rates were also observed to follow a log-normal distribution. Furthermore, all products of incomplete combustion tend to distribute in this manner. That is, when fuel consumption (x axis) is plotted against pollutant output (y axis), the CO and HCHO emission rates are highest for the heaters with the smallest fuel comsumption rate. Indeed, heater 12A had the highest HCHO emission rate, base on three tests. This heater also had the highest particulate emission rate. As characteristic of incomplete combustion product emissions, the particle emission rates followed a log-normal distribution pattern.

Of much interest for many combustion appliances is the study of the effect of air/fuel mixture (tuning) on pollutant emission rates. The results obtained from three heaters studied in an unoccupied field research house is summarized in Table 5.

As noted in Table 5, CO emission rates increased dramatically when excess fuel conditions were applied. The emission rate profile was more complex.

TABLE 5. Gas-Fired Heater Pollutant Emission Rates:

Research House Studies [13]

Heater	Fuel Consumption (kJ/h)	Emission Rates (ug/kJ)				State of Tuning
		CO	NO	NO_2	NO_x	
12A	9510	32	24	8.6	14	well tuned
30A	31400	11	11	7.5	16	well tuned
30A	31500	37	37	9.0	13	excess fuel
30A	31900	620	<0.1	20	6.1	excess air
16B	16800	190	190	18	15	well tuned
30C	31200	12	12	7.4	15	well tuned

Although not all determinants of nitrogen oxide emissions are known, three general factors can be cited. First, the NO_x emission rate rapidly increases while the heater is warming up, that is, the flame temperature is increasing. Second, the NO_x emission rate decreases as the O_2 level (air mix) decreases and the CO_2, and other combustion products concentrations increase. Excess air may cause cooling of the flame, thus accounting for the decrease of NO_x emission rates. The NO and NO_2 emission rate profile were more complex (see Table 5), probably because their emission depends on factors other than those mentioned. It is apparent,

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that NO_x emission may be more dependent on flame temperature than the emission of other nitrogen oxides.

The overall particulate and formaldehyde emission rates were low [13]. Interestingly, the highest output of particulate was found under well-tuned conditions. Of all tests applied for formaldehyde emissions, only one heater (30A) gave high output rates of this compound during excess air conditions. The formaldehyde (HCHO) emission rate was estimated to be 14 ug/kJ.

Conclusion and Final Comments

The effective period of this report is from 1983 to 1986. It is a synopsis and reference source for the study of indoor pollutants emitted by home combustion appliances. Specific sources of information can be accessed via (1) the bibliographic references and other literature material as appended, and (2) the scientific contacts listed in Table 2.

At least three comprehensive reviews concerning combustion appliance air emissions have been produced since 1982. In addition, specific reports concerning particular home combustion appliances have been cited [20,21,22,23,24,25,26,27]. It may be concluded that these reports largely reflect the data reported previous to 1982.

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A current trend in combustion appliance studies is the specific study of pollutant emission rate determinants. These include (1) type of appliance, (2) manufacturer, (3) unit age, (4) tuning (fuel/gas mixture optimization), and (5) building specific factors such as occupant use patterns and ventilation. Little work has been conducted concerning gas water heaters, furnaces, stoves (including wood), gas clothes driers and oil fired space heaters [2,5,7,26].

Indoor Air Pollutants

According to the literature review discussed above it is apparent that combustion-derived indoor air pollutants released in homes during chimney-failure scenarios include: carbon monoxide, carbon dioxide, sulfur dioxide, nitrogen oxides, aliphatic, aromatic and polycyclic hydrocarbons, aldehydes and particulates. Of these, the pollutants of main concern for the health of exposed occupants following a failure scenario would include: carbon monoxide, sulfur dioxide, nitrogen oxides, aldehydes and certain hydrocarbons. These indoor pollutants should be considered for monitoring in field test houses during simulated combustion ventilation system failures. Our recommendations concerning monitoring technologies will, therefore, focus on these indoor air pollutants.

Indoor Air Quality Monitoring Technologies

The pollutants listed above can be monitored either continuously (or semi-continuously) with sophisticated instruments, instantaneously with detector tubes or on a time-weighted average (TWA) basis by absorption on or reaction in a proper medium. Each approach has certain merits in the context of this project. An evaluation of existing methods will be based on the following criteria: sensitivity and limit of detection, specificity, accuracy and precision, ease of calibration, response time, dependability, simplicity, portability, ruggedness, availability,

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serviceability, and cost. The method(s) that we recommend for each pollutant must meet most, if not all, of these criteria.

Carbon Monoxide

The ASHRAE recommended standard for continuous exposure to CO is 9 ppm. Thus, the method eventually selected for this project will have to allow an accurate measurement of this gas at relatively low concentrations, that is, in the 0-10 ppm range.

a) Instrumental

Presently, there are two types of instruments used to measure CO: one based on an electrochemical reaction (electrochemical analyzer) and the other on the absorption of infrared radiation (infrared analyzer).

i) Electrochemical analyzer. Examples of electrochemical gas detection instruments have been developed which use a hydrated solid polymer electrolyte (SPE) voltammetric sensor cell to measure the concentrations of specific gases including CO, NO_x, SO_2 in ambient air. These instruments are a spin-off of the aerospace fuel cell technology. Electrochemical analyzers used to monitor carbon monoxide include the Interscan and Ecolyzer instruments. Both instruments permit the measurement of carbon monoxide concentrations with a precision of + 1% full scale have a detection limit of 1 ppm; are

portable (battery operated), rugged, simple to use, readily available (rental or purchase) and have a fast response time. They are relatively dependable and are usually repaired within one month by the manufacturer. Large concentrations of hydrocarbons such as ethylene or acetylene can interfere with the measurement (100 ppm - 15 ppm CO). Although they are easily calibrated, they do require the transportation of a cylinder of zero and standard gases (available from Matheson Gas Ltd. and Linde) to and from the survey site. Calibration is usually performed before the investigation and at least every two hours thereafter. Purchase cost is $5,000.00 + and rental cost can range from $25.00-50.00 per day.

One major disadvantage is the electrochemical cell which can cease to function with little warning. Also, both instruments' cells are subject to drying out. The Interscan instrument has reportedly been modified for continuous monitoring for long periods. Concluding remarks. This type of instrument is easy to operate and allows the continuous and specific monitoring of carbon monoxide at concentrations > 2 ppm with a precision of + 1% full scale. It is easily transported to and from the survey site. Calibration requires both a zero and standard gas cylinder. The instrument may be purchased or rented.

ii) <u>Infrared analyzer.</u> There are several commercially available carbon monoxide analyzers including the Miran (1A or 80) and Bendix non-dispersive infrared analyzer(model 8501-5CA). These are invariably heavy instruments (>50 lbs) requiring a source of AC current. They are based on the absorption of infrared radiation at a wavelength of 4.65 micrometers by CO. The gas is measured continuously with a reported accuracy of +2% down to 0.5 ppm. Response time for certain instruments (e.g. Miran) can be rather slow (5 minutes or more). They also require a source of zero and standard gas for calibration. One distinct advantage is that they require infrequent calibration (before and after the investigation). Few, if any, other gases or substances interfere with the measurement of CO. However, the instruments are rather complicated to operate and require a certain level of training in their operation. One major disadvantage is cost ($15,000) although it is possible to rent a Miran ($450-$650/week).

<u>Concluding remarks.</u> Infrared analysers allow the continuous, specific and accurate measurement of CO concentrations down to a level of 0.5 ppm. Calibration requires a cylinder of zero and standard gas and they maintain calibration for prolonged periods. The major disadvantages are cost and transportability.

b)   Detector tubes

The two types of detector tubes most used to measure
CO are Gastec and Drager tubes. The Gastec kit (pump
and tubes) has the advantage of being comparatively
cheaper. Tubes of various ranges (low, high) are
available. The attainable precision is +25% or less
and the detection limit is generally > 5 ppm. The
air pumps require periodic checking and calibration.
Several other substances can interfere with the
measurement of CO concentrations (SO_2, NO_2, H_2S). The
measurements are simple to perform and the kit is
portable. The cost of the air pump and tubes is
reasonable (Gastec pump, approximately $100.00;
$10.00/box of 10.

Concluding remarks. Detector tubes can measure
carbon monoxide concentrations with a stated
precision of +25% or less down to a concentration in
excess of 5 ppm in an unspecific manner. The main
advantage is cost, ease of operation and no
requirements for calibration gases. Only short-term
(<1 minute) sampling is possible.

c)   Time-weighted average sampling. Carbon monoxide can be
sampled over long-term periods in a time-weighted average
manner either actively or passively.

Active sampling is accomplished with a detector tube
(Gastec or Drager) by long-term sampling tube connected

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to an air pump (Gilian, Dupont). Both the air pump and detector tube require calibration prior to performing an investigation. The remaining advantages and disadvantages are much the same as those mentioned above for detector tubes. Pumps can either be purchased ($1,000) or rented ($10/day).

Passive sampling is accomplished with gas badges (Willson Safety Products) which sample the gases by diffusion. No air pumps are required and the concentration (TWA) of CO can be read directly from the badge. Carbon monoxide concentrations can be measured with an accuracy of + 15% down to a nominal concentrations of 5 ppm. Few substances reportedly interfere with the measurement except strongly reducing substances (H_2S). The cost per badge is reasonable ($5.00). The shortest recommended sampling period (both passive and active) is 60 minutes. Concluding remarks. CO concentrations can be sampled either passively or actively for periods in excess of 60 minutes with an accuracy of +15% down to a concentration of 5 ppm. Gas badges have the added advantage of reasonable cost and few interfering substances. No calibration is required.

Recommended CO monitoring method

Depending on budgetary constraints and the duration of the test period, two methods are recommended. One is the electrochemical analyzer, although cost/field test house may

be a problem. Other disadvantages include the requirement of transporting both zero gas and standard gas cylinders to and from the survey site. However, these disadvantages are outweighed by the portability and ease of operation of the instrument, the ability to perform continuous recording during the whole test period and obtain a recording of each test for further reference.

The second method is the passive badge CO sampler. Portablility, no calibration, ease of application, low cost are some of the advantages. However, low accuracy and high detection limit (> 5 ppm) and the requirement for a minimum sampling period (60 minutes) must be considered. A permanent record of each test is also obtained.

Nitrogen Oxide

The standard (ASHRAE) for indoor exposure to nitrogen dioxide (NO_2) on a continuous basis is 0.3 ppm and methods which are used to monitor this indoor pollutant should detect it at this concentration.

a) Instrumental. As for CO there are two principal instrumental methods of monitoring NO_x, electrochemical and chemiluminescence.

    i) Electrochemical. Both Ecolyzer and Interscan market a NO_x monitor similar to that described earlier for CO and several of the comments made for the CO monitor apply equally well here. That is, the instrument is portable, battery-operated, requires

zero and standard gases for calibration, requires frequent calibration, and is simple to use. It is relatively specific for NO_x although there are interfering substances (example acetylene) and its response time is rapid. NO and NO_2 concentrations can be measured at the 0.2 ppm level with 1% full scale precision. Continuous monitoring is also a problem. In addition, both instruments have a tendency to be unstable at low concentrations and it is often difficult to obtain meaningful measurements in the low range. Calibration gases in the range required <5 ppm are also difficult to obtain and have a limited lifetime. An alternative would be to obtain a relatively high concentration standard (>100 ppm) and making appropriate dilutions as required.

Concluding remarks. The electrochemical NO_x analyzer shares many of the advantages and disadvantages discussed earlier for the CO electrochemical monitor. However, it has the additional disadvantage of instability in the low concentration range (range of interest) and the difficulty of obtaining and keeping an appropriate calibration gas mixture for a long period.

ii) Chemiluminescence analyzers. Typically, these analyzers function on the basis of the measurement of the chemiluminescence produced as a result of the reaction of nitric oxide (NO) with ozone. Total

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nitrogen oxides (NO_x) are measured in a similar manner after NO_2 is first catalytically converted to NO. There are few important interferences to this measurement although nitrogen species sometimes present in combustion systems have been reported to interfere. There are several commercially available instruments (Bendix, Philips, Monitor Lab) with operating ranges of 0-0.5 ppm to 0-10 ppm. Detection limits are typically in the low ppb (<2ppb) and precision is often better than +2%. Response times are typically short (<10 seconds). The instruments are usually calibrated with a mixture of NO in nitrogen gas once a day or less. Although reportedly for field use, the instruments are far from portable (>50 lbs.). In addition, they are rather expensive (>$10,000). In the past, it was often possible to obtain one of these instruments on loan from either a provincial or federal environment agency. This possibility should be explored.

A major disadvantage is that the instruments in question are somewhat sophisticated and require some prior training and technical ability to operate.

Concluding remarks. Chemiluminescence analyzers for NO_x afford a continuous recording of either NO or NO_x levels down to the low ppb level with a +2% precision. Few substances interfere with the measurement. However, the instruments are not really

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portable and are expensive.

b) Detector tubes

Both Gastec and Drager have detector tubes for NO_2. They afford an instantaneous measurement of NO_2 concentrations at the 0.2-5 ppm level with a precision no better than +50%. The advantages associated with the use of detector tubes, mentioned earlier on for CO detector tubes, apply equally well here, i.e. cost, portability and ease of test performance. However, several substances can seriously interfere with the measurement (ozone and chlorine).

Concluding remarks. NO_2 detector tubes can furnish instantaneous measurements of the gas at the 0.2 ppm level with a +50% precision. Several substances can interfere with this measurement.

c) Time-weighted average sampling

Most (TWA) air sampling of NO_x is conducted with passive gas badge samplers, although homemade air samplers can be prepared for use with air pumps. In both instances NO_2/NO molecules are trapped onto a matrix coated with triethanolamine (TEA). NO is oxidatively converted to NO_2. It should be noted that samplers are available which are specific for NO_2. Thus exposure of both a NO_x and NO_2 sampler afford the concentration of NO. The NO_2/NO_x samplers are then analyzed by colorimetry. Cost of the samplers (including analysis) is in the $35.00-$45.00 range/sample. Again, no air pumps, calibration or

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calibration gases are required and the tests do not require special training. The samplers have a life expectancy of nearly one month following their use. MDA does offer a complete NO_2/NO_x passive sampling kit including a portable colorimeter. Concentration values are given in ppm.hour NO_2 (or NO_x). Precision is of the order of +20%. It is interesting to note that with the MDA kit, new samplers can be home made.

As for the CO passive samplers, minimal exposure time per test to maintain the stated precision must be carefully taken into consideration. For instance, exposing the samplers to 1 ppm NO_2 for 1 hour results in the collection of 2.3 nanomoles of NO_2. A recently produced passive (NO_2) sampler (TOYO - available from Levitt Safety Ltd.) can circumvent this problem. The badge's sensitivity is reportedly 66 ppb.hour, and its accuracy +20%. However, the badges must be analyzed soon after collection (24 hours). This badge remains effective after seven days of exposure. A similar badge for NO is also available. Both badges are little affected by other contaminants at high relative humidity levels.

Concluding remarks. NO_2/NO_x concentrations down to 6 ppb can be passively sampled with gas badges with a stated accuracy of +20%. The cost/field test house could be reasonable if air samples were prepared in-house. The colorimetric analysis of the samplers is straight forward and could be performed by anyone after a short training

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session. One drawback is the requirement to perform this analysis within 24 hours after the test.

Recommended NO$_2$/NO$_x$ Monitoring Method

As for CO, two methods are recommended again depending on budgetary constraints and the duration of the test period--the chemiluminescence analyzer and the passive badge sampler. The chemiluminescence analyzer fulfills most of the criteria except that this instrument is not readily portable and its cost is prohibitive. The latter drawback could be surmounted by investigating the possibility of obtaining such an instrument on loan from an environmental pollution agency (provincial or federal). A viable alternative to be investigated is the passive badge sampler--it has few drawbacks and is economical.

Sulphur Dioxide (SO$_2$)

The recommended standard for continuous exposure in dwellings is 0.2 ppm (ASHRAE) and a monitoring method will have to ensure the precise measurement of this gas at that level.

a) Instrumental

SO$_2$ can be monitored with an electrochemical analyzer manufactured by Interscan or with more sophisticated instruments usually used to monitor this gas in the outside environment.

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i) Electrochemical. This instrument has all the
    advantages of the similar instruments used to monitor
    CO and NO_x discussed earlier. SO_2 can be continuously
    monitored at the 1 ppm concentration level with a
    precision of + 1% full scale. Response time is
    rapid. Standard gas concentrations of 0.5-10 ppm SO_2
    in N_2 can be obtained from various suppliers and have
    a relatively long life expectancy.

    Concluding remarks. SO_2 can be monitored
    continuously at the 1 ppm level with a precision of +
    1% full scale with an electrochemical analyzer.

ii) SO_2 monitors. A variety of ambient air SO_2 monitors
    are available commercially. The monitors available
    mainly differ in the type of detector used. At
    present, the monitors most used employ either a
    flame photometric detector (Meloy) or fluorescence
    (Monitor Lab - total sulfur analyzer). These
    instruments invariably can measure SO_2 continuously
    at the low ppb level with an accuracy of +2% and
    their response to changes in concentration is rapid
    (<30 seconds). They can also maintain their
    calibration for extended periods (1 week). However,
    similar to the sophisticated instruments described
    for monitoring NO_x and CO, they are not truly
    portable, require an AC current source, are rather
    expensive ($15,000+) and require training.

Concluding remarks. Although these instruments allow the measurement of SO_2 concentrations at low ppb levels with great accuracy, they are not portable, require training in their operation and are prohibitively expensive.

b) Detector tubes

Detector tubes are available from Gastec and Drager to measure SO_2 in the 1-5 ppm range with an accuracy of no better than 50%. Several substances can interfere with the measurement including H_2S and NO_x.

These detector tubes have all the advantages and disadvantages discussed earlier for the NO_2 and CO tubes. Concluding remarks. SO_2 detector tubes can measure this gas down to the 1 ppm level with an accuracy of <50%.

Recommended SO_2 Monitoring Method

Apparently, the only viable alternative for monitoring this indoor air pollutant is an Interscan SO_2 monitor.

Aldehydes

At present, there is no universally accepted field method for the sampling of trace levels of aldehydes except formaldehyde. Thus, the chromotropic acid method is limited to formaldehyde and is subject to interferences while other colorimetric methods, such as the MBIH method, does not allow the measurement of individual aldehydes. Direct gas

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chromatography (with flame ionization detection) of aldehydes is not applicable to formaldehyde and is fraught with difficulties for other aldehydes or their derivatives. Ambient measurements using Fourier transform infrared spectroscopy are limited to formaldehyde and are not field applicable.

In view of the limitations of the methods cited above, we suggest methods applicable only to formaldehyde and a novel approach developed recently by Grosjean et al. (1980) for the measurement of aldehydes [1].

Formaldehydes

Concern with formaldehyde levels of 100 ppb or less produced by urea formaldehyde foam insulation in homes insulated with this material has given rise to many commercially available passive samplers based on the chromotropic acid method for sampling this compound. This procedure and an instrumental continuous monitoring of formaldehyde will be briefly reviewed.

[1] "Measurement of aldehydes in the air environment," D. Grosjean, K. Fung and R. Atkinson. 73rd APCA meeting, Montreal, Quebec (1980).

a) <u>Instrumental</u>

An instrument, manufactured by CEA Instruments Inc., the CEA 555 air monitor, is based on a method, modified Schiff procedure, developed by Lyles, Dowling and Blanchard (J.A.P.C.A., 15:106 (1965). Formaldehyde is absorbed in a sodium tetrachloromercurate solution containing a fixed quantity of sodium sulfite. Acid bleached pararosaniline is added, and the intensity of the color produced measured at 550 nm. The instrument's operating ranges are 0-0.5 ppm to 0-10 ppm. Its sensitivity is 1% full scale. Calibration is readily accomplished and need be done only before and after each test. It has a minimum detection limit of 10 ppb on the 0-1 ppm scale. A main drawback is its lag time which can exceed 4 minutes. Few substances interfere seriously with the measurement of formaldehyde. The accuracy and precision is reportedly within 5% and 1% respectively. The instrument has been conceived for field use. However, its operation requires an extensive apprenticeship and familiarization period (>2 weeks) and the instrument is rather expensive (>$10,000).

<u>Concluding remarks.</u> The CEA 555 formaldehyde monitor can monitor formaldehyde at the 10 ppb level with an accuracy of +5% on a continuous basis. However, it has a considerable lag time, requires extensive training and is expensive.

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b) Detector tubes

Both Gastec and Drager sell detector tubes for
formaldehyde which measure concentrations of this
substance down to the 0.5 ppm level with an accuracy of
less than 50%. Many substances interfere with this
measurement including other aldehydes, acrolein, and
styrene.

These detector tubes have all the advantages and
disadvantages inherent with this type of device and
discussed at length earlier.

Concluding remarks. Formaldehyde detector tubes can
measure this substance down to the 0.5 ppm level with
less than 50% accuracy. There are several potentially
serious interferences with this measurement including
other aldehydes.

c) Time-weighted average sampling

As with CO, NO_x and SO_2, there are two sampling
approaches, active and passive. The active sampling
procedure uses glass impingers, filled with an absorbing
solution either water or a 1% sodium bisulfite solution,
and connected to an air pump. The impinger solution is
then analyzed by the chromotropic acid method. This is a
reference method for formaldehyde, i.e., a sensitive test
with a proven record. However, it is rather a cumbersome
field method and the collected samples have a limited
storage time (approx. 24 hours) before analysis and

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require storage at low temperatures. Minimal sample duration at a 1 litre per minute sampling rate may exceed 1/2 hour at low concentrations (one hour usually recommended). The method's accuracy has been reported to be +10%. Cost of analysis ranges from $20.00-30.00 per sample. This determination is relatively free of interferences.

An alternative to the above method is the passive sampling of formaldehyde with badge-type samplers. The basis of these samplers is again the chromotropic acid method with all its advantages and disadvantages. The reported accuracy for these samplers is +25%. Their main advantage over the impinger method is greater field compatibility, no need for pump calibration or air pumps, longer life expectancy following sampling (approx. 1 week). However, it has similar disadvantages including minimum exposure time (approx. 1 hour) at low concentrations and it is costlier--that is, in addition to the analytical cost, one must add the cost/sampler which can range from $20.00-$30.00. However, cheaper devices are available commercially (these include analysis cost). For more information call the UFFI Centre).

Concluding remarks. TWA sampling in field test houses can be more easily accomplished with passive sampling devices. These have all the advantages of the reference impinger method and are more field compatible. This cost

per test would range from $20.00-$40.00 (including analysis). Exposure time limitations will have to be carefully considered.

Recommended Formaldehyde Monitoring Method

If sampling periods are of short duration (less than 1/2 hour) and there are no budgetary constraints, the best method is the use of the CEA 555 monitor. (A loan of this instrument could be arranged.) However, it will require a training period, the instrument, although portable, is heavy and requires the handling of solutions, some corrosive.

If sampling periods are >1/2 hour and as long as one hour, the best option would be a passive sampling device. They are field compatible and their cost (including analysis) is reasonable.

Other Aldehydes

The method developed by Grosjean et al. (appended) is recommended for the measurement of individual aldehydes. Although the efficiency of the collection method for most aldehydes leaves something to be desired, and the technique is largely experimental, there are few alternatives.

Hydrocarbons

Hydrocarbons generated by the combustion of oil, gas or wood-fired appliances indoors are generally an intractable mixture of aliphatic, aromatic and polycyclic hydrocarbons. The analysis of individual hydrocarbons (identification and concentration determination) would be prohibitively expensive as it would require a gas chromatography/mass spectrometry analyis of each individual component of the mixture. An alternative is the analysis of selected components, for instance, benz(a)pyrene. However, this would likewise be expensive. A final and, less satisfactory, alternative, healthwise, is the analysis of total hydrocarbons without regards for individual components. This latter alternative should be considered by Sheltair. Monitoring could be approached either instrumentally or on a TWA basis.

a)   Instrumental

There are several commercially available total hydrocarbon analyzers. One interesting possibility is the Foxboro Organic Vapor Analyzer which is designed to measure trace organic chemicals in air. It incorporates a flame ionization detector and has the capabilities of a gas chromatograph. Reportedly, it can measure hydrocarbons in the presence of moisture, NO_x, CO, CO_2 and would be suitable to measure total hydrocarbons in combustion emissions. Its sensitivity is 1 ppm (methane), and response time is two seconds. It is battery operated, weighs nine pounds and requires a 75cc

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tank of hydrogen gas fillable while in the case. The unit could either be purchased (>$7,000) or rented. Another alternative is the Photovac Portable Gas Chromatograph. However, this unit is more sensitive and yields a separation of mixture components.

b) Time-weighted average sampling

Combustion emissions can be sampled on activated charcoal or Tenax for periods of 30 minutes to one hour at a flow rate of 100 ml per minute with an appropriate low-flow air pump. The samples are then desorbed with an organic solvent and analyzed by gas chromatography for total hydrocarbons (cost: $30.00-50.00/sample).

Recommended Monitoring Methods for Total Hydrocarbons

The least costly method is the TWA sampling of total hydrocarbons on an appropriate sorbent followed by gas chromatography analysis. However, the possibility of using an instrument such as the Foxboro Organic Vapor Analyzer should be explored as it affords immediate results.

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RESIDENTIAL COMBUSTION VENTING FAILURE

A SYSTEMS APPROACH

PROJECT 4:

ASSESSING THE IMPACT OF COMBUSTION GAS SPILLAGE
ON INDOOR AIR QUALITY

COMPUTER MODELING RESULTS, FIELD MONITORING, AND
PILOT TEST SIMULATIONS OF CHIMNEY FAILURE SCENARIOS

APPENDIX 2

OVERALL PROJECT SUMMARY

Prepared for:
The Research Division
Policy Development and Research Sector
Canada Mortgage and Housing Corporation

Prepared by:
Scanada Sheltair Consortium

January, 1987

The project reported on here was designed to expand on previous studies
of the problem of incomplete venting of combustion products from heating
appliances in order to approach a more nearly comprehensive understanding
of the extent and nature of the problem in the Canadian housing stock.
This project, which was carried out for Canada Mortgage and Housing
Corporation by the Scanada Sheltair Consortium Inc., consisted of the
seven sub-projects described below.

PROJECT 1 COUNTRY-WIDE SURVEY

Spillage detectors were installed on the draft hoods or barometric
dampers of gas and oil furnaces and water heaters in 937 houses spread
throughout the Vancouver, Winnipeg, Toronto, Ottawa and Charlottetown
regions. The detectors were left in place for approximately 2 months in
late winter.

Of the gas heated houses surveyed, 10% had experienced prolonged and
unusual amounts of combustion gas spillage and 65% had experienced either
short duration start-up spillage or prolonged spillage of small amounts
of combustion gas. Of the oil heated houses, 55% had experienced
significant spillage of high temperature combustion gas, but some of
these spillage events may have been of only short duration.

Preliminary analysis indicates that spillage problems seem to be related
to the following house or heating system characteristics:

- Winnipeg houses (believed to be more nearly airtight due to
  extensive use of stucco)

- pre-1945 houses	- masonry chimneys with under-sized metal liners
- post-1975 houses	- houses with three or more exhaust fans
- one storey houses	- houses with two open masonry fireplaces
- exterior chimneys	- poorly maintained heating appliances

PROJECT 2 MODIFICATIONS AND REFINEMENTS TO THE FLUE SIMULATOR MODEL

FLUE SIMULATOR, a detailed theoretical computer-based model of the
combustion venting process had been developed for CMHC prior to this
project. It is intended for use as an aid in understanding the
mechanisms of combustion venting failure and the circumstances that give
rise to them. The modifications undertaken in this project were intended

to make the program easier to use and to allow it to model a wider
variety of furnace/flue/house systems. The modifications included -

o   refinements to algorithms
o   more efficient operation of the program
o   modelling additional features and system types
o   user-friendly input and output

The modified model was validated against field test data and used to
investigate a number of issues.

A separate developmental version of the program, called "WOODSIM", was
successfully developed to model the combustion and combustion venting
process in wood stoves and fireplaces.

PROJECT 3 REFINEMENT OF THE CHECKLISTS

A procedure for identifying and diagnosing combustion venting failures
had previously been developed for CMHC - the Residential Combustion
Safety Checklist. This project provided an opportunity to refine the
checklist and develop variations of it suitable for a variety of possible
users such as furnace service personnel, air sealing contractors,
homeowners, etc. Early in the project, it was decided to separate the
identification procedures from the diagnostic procedures. This allowed
the process of identifying houses with potential for combustion venting
problems to remain relative simple and allowed the diagnostic process to
become more complex since it would only be used on houses where the extra
effort would likely be worthwhile. Thus the original backdraft checklist
has grown into five separate tests/procedures -

Venting Systems Pre-test
-    a quick, visual inspection procedure which identifies a house as
     either unlikely to experience pressure-induced spillage or requiring
     further investigation

Venting Systems Test
-    a detailed test procedure for determining to what extent the
     combustion venting system of a house is affected by the envelope
     airtightness and operation of exhaust equipment, perhaps the
     clearest descendent of the old backdraft checklist.

Chimney Performance Test
-    a simple method of determining whether a chimney is capable of
     providing adequate draft

Heat Exchanger Leakage Test
-    a quick method of determining if the heat exchanger of a furnace has
     a major leak

Chimney Safety Inspection
-    a visual check for maintenance problems in the chimney system

These tests/procedures are all presented in a manual entitled "Chimney
Safety Tests". Full trials of the procedures were carried out on the
case study houses investigated in Project 6.

PROJECT 4 HAZARD ASSESSMENT

Although little was known at the outset of this project about the
frequency of combustion spillage, even less was known about how much of a
health hazard such spillage represents. Therefore this sub-project was
included to investigate the real nature of the health and safety risk
associated with venting failures. The work was divided into five tasks -

1.   Review of current knowledge on pollutant generation due to improper
      venting of combustion appliances (literature review).
2.   Development of a computer program to predict levels of various
      pollutants under various combustion venting failure scenarios.
3.   Acquisition and calibration of a set of instruments required to
      measure the various pollutants at the levels predicted by the
      computer model.
4.   Monitoring pollutant levels in problem houses identified in the
      Country-wide Survey (Project 1) using the instruments acquired in
      Task 3.
5.   Analysis of the results of Task 4 to arrive at an overall assessment
      of the health hazard represented by combustion venting failures in
      Canadian houses.

The results indicate that, in most houses, one would rarely encounter
acute, immediately life-threatening concentrations of pollutants as a
result of combustion spillage from furnaces or water heaters. However,
chronic health risk due to low level, long term exposure to pollutants ,
particularly NO_2, may be a more significant problem which requires
further investigation. High levels of CO do not seem to be caused by the
problems which cause spillage and thus occur in spillage events only as a
result of coincidence.

PROJECT 5 REMEDIAL MEASURES

Remedial measures for pressure-induced combustion venting problems were
identified and researched for a number of different types of combustion
appliances.

The remedial measures identified for FIREPLACES were:

Spillage Advisor
-       This is an adjustable volume alarm triggered by a combination
        of particulate and CO detectors and intended to be mounted on
        the front of the mantle or on the wall just above the fire-
        place.

Airtight Glass Doors Combined With An Exterior Combustion Air Supply
Duct
-       The research indicated that conventional glass doors are not
        nearly airtight and do little to separate the fireplace from
        the house's pressure regime. Prototype doors using special
        glass, heavier than normal steel frames and special sealing
        techniques were fabricated and installed and tested. It was
        found that these doors increased the level of house depres-
        surization required to cause prolonged spillage from the
        fireplace from 3 Pa to 22 Pa. It is estimated that the
        installed cost would be $600. Further research on the effect
        of airtight doors on temperatures within the fireplace and flue
        and the possible hazard to surrounding combustible materials is
        required.

The remedial measures identified for GAS-FIRED APPLIANCES were:

Spillage Advisor
-       This could be similar to the fireplace spillage advisor but
        would be triggered by a heat probe mounted in the dilution port
        of the appliance. The heat probes investigated could also be
        used to trigger other remedial measures discussed below.

Draft-inducing Fan
-       A paddle-wheel-type fan mounted in the vent connector was found
        to increase the level of house depressurization required to
        cause irreversible spillage from a naturally aspirating gas
        furnace from 7 Pa to more than 20 Pa.

Draft-assisting Chamber
-       A chamber surrounding the appliance's dilution port and
        extending downwards contains combustion products flowing out of
        the dilution port and prolongs the period before they are

actually spilled into the room. It was expected that the
chamber would also use the buoyancy of the contained combustion
products to assist the flue in developing upward flow and thus
would increase its resistance to house depressurization;
however, the results obtained with the prototype tested did not
live up to expectations. It is expected that modification of
the design and testing with a furnace/flue/house combination
more prone to pressure-induced spillage will improve this
aspect of the chamber's performance.

The research on remedial measures for OIL-FIRED APPLIANCES indicated that
stable backdrafting is unlikely to be a problem with oil-fired appliances
since the pressure generated by the burner blowers is able to rapidly
overcome backdrafting due to house depressurization and initiate upward
flue flow. However, this pressurization of the flue system is what
accounts for the start-up spillage associated with oil appliances and it
is the duration of this spillage that remedial measures must address.
The measures identified were:

Solenoid Valve
-    By delaying the start of combustion until the burner has had a
     chance to overcome backdrafting and initiate upward flue flow,
     the solenoid valve reduces the duration of spillage but does
     not eliminate it altogether.

Draft-inducing Fan
-    A fan, similar to that described above under gas appliances,
     mounted in the flue pipe downstream of the barometric damper is
     not needed to overcome backdrafting since the burner blower can
     do this. However, it does relieve pressurization of that
     portion of the flue pipe upstream of itself and hence reduces
     spillage from that portion. There can still be spillage from
     the downstream portion; but, since that portion does not
     include the barometric damper, it is easier to seal.

Elimination of the Barometric Damper
-    Provision of a well-sealed flue pipe without a barometric
     damper is one obvious way to reduce spillage. However,
     elimination of the barometric damper exposes the burner to the
     full chimney draft and disturbs the combustion process of
     conventional burners. Therefore this procedure must include
     replacement of the conventional burner with a high pressure
     burner which is less influenced by flue pressure. Provision of
     an insulated flue liner is often included as part of this
     measure.

The work on MAKE-UP AIR SUPPLY remedial measures was less directed towards specific measures but served to clarify a number of general air supply issues. It indicated that the provision of additional supply air is not likely to be effective as a remedy for pressure-induced spillage of combustion products if the supply air is introduced unaided through an envelope opening of any size likely to considered practical. It is only likely to be effective if a supply air fan is used and if that fan has a capacity at least equal to the total capacity of all exhaust equipment it is attempting to counteract. The discharge from such a supply air fan can be introduced essentially anywhere in the house, but is likely to create fewer thermal comfort problems if introduced in a normally unoccupied area such as the furnace room.

The knowledge generated in the remedial measures research and already available to Consortium members was synthesized into the draft Remedial Measures Guide, a manual intended to be a decision-making guide for tradesmen and contractors who have identified pressure-induced spillage problems in houses with vented fuel-fired appliances and want to know how best to remedy these problems. It is designed to accompany the Venting Systems Test. Although the draft Guide is not yet comprehensive and in some cases describes procedures which have not been thoroughly field tested and/or approved by regulatory authorities, it is hoped it will stimulate thought and discussion and improve current trade practices.

PROJECT 6 PROBLEM HOUSE FOLLOW-UP

Twenty of the houses identified in the country-wide survey as experiencing the worst combustion spillage problems were visited with the following objectives:

-     to categorize and quantify the nature of venting failures
-     to isolate contributing factors
-     to collect field data on venting failures for use in the flue simulator model validation
-     to measure the frequency and quantity of spillage in problem houses
-     to measure the approximate impact on air quality of venting failures in houses
-     to evaluate the effectiveness of the chimney safety tests in diagnosis of failures and identification of remedial measures
-     to evaluate communications techniques
-     to evaluate remedial measures under field conditions

In most of the houses, there were several factors that were assessed as contributing causes of the combustion spillage problem - thus confirming the "systems" nature of the problem. It is also worth noting that, in many houses, although the spillage observed was indeed pressure-induced,

it occurred at quite low levels of house depressurization because the
chimneys were only able to generate very weak draft due to some problem
such as a blocked or leaky flue. The main problem in these cases,
therefore, was not depressurization but weak chimneys.

PROJECT 7 COMMUNICATIONS STRATEGY

As the survey revealed that the problem, while substantial, is not
epidemic in proportion, there is no need to create widespread alarm in
the general public. A communication strategy has been drafted with this
in mind. It places emphasis on motivating the heating and housing
industries to be aware of the combustion venting problem and its causes
and to make effective use of the diagnostic tools and preventive and
remedial measures developed in this project.

OVERALL PROJECT SUMMARY AND CONCLUSIONS

The project has gone a long way towards meeting its original objectives
and has significantly advanced the state-of-the-art in this field.

It has led to improved understanding of the combustion venting process
and confirmed the "systems" nature of the failures that lead to
combustion venting problems.

It appears that a significant portion of the Canadian housing stock has
potential for combustion venting failure to occur on a regular basis. In
most cases, this is unlikely to lead to immediate life-threatening
pollution levels, but long term chronic health hazards could be a
problem; however this latter concern requires further investigation
before any definite conclusion can be reached.

A number of techniques are available for identifying houses prone to
combustion venting failure and for diagnosing the causes of such failure.
There are also available a number of measures for preventing combustion
venting failure in new houses and for remedying it in existing houses. A
communication strategy has been drafted for conveying these techniques
and measures to relevant people in the housing and heating industries and
for encouraging them to make use these tools.