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INVESTIGATION OF CHIMNEY BACKFLOW CONDITIONS: A CASE STUDY IN A WELL-SEALED HOUSE

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ABSTRACT

Developments in Canadian houses during the past several decades have increased the possibility of backdrafting (also known as reverse flow) in natural-draft chimneys. These developments include:

a. *the use of high-power-range exhaust fans capable of creating a negative pressure sufficient to backdraft chimneys.*
b. *the use of more tightly sealed exterior envelopes of houses, which make it easier for exhaust equipment to create a strong negative pressure within houses.*

Recent reports by White (1984), Swinton et al. (1985), and Moffatt (1986) provide useful background material concerning backdrafting.

A pamphlet entitled "Ventilation and Air Quality in Homes" (Saskatchewan Power Corp. 1985) describes practical measures that can be used to reduce the problem of backdrafting of furnaces.

In this report a theory will be presented that illustrates the conditions under which backdrafting can occur in a house. In addition, measured data from an experiment performed on a very well-sealed house incorporating a natural-draft chimney are presented and the results are compared with the theory.

SIMPLIFIED THEORY

Swinton et al. (1985) present a detailed dynamic mathematical model of the operation of a chimney/furnace combination. A different approach is taken in this report. A static model only will be illustrated, because the onset of backdrafting approximates a static condition and the static condition is readily explained in quantitative terms.

The following theory is developed to determine quantitatively under which conditions backdrafting will occur.

Sketches of the pressure profiles in the house are presented in Figures 1a, b, and c for three cases:

a. normal furnace operation,
b. operation of the house with the chimney blocked at the lower inlet to the furnace, and
c. operation of the furnace at the point of backdrafting.

The reference point chosen for the pressure measurements is at the top of the chimney.

In the normal furnace operation mode (Figure 1a), the inside air pressure line intersects the outside air pressure line at a point relatively close to the chimney top in the example chosen. The slopes of both the outside and inside pressure lines are functions of the air density only. The chimney pressure profile line is positioned such that there is a net inward pressure difference (negative pressure) at the furnace inlet and a net outward pressure (positive pressure) for the chimney at the chimney outlet. The slope of the chimney air pressure line is not a simple function of air density, since the chimney fluid is not static, and frictional pressure losses and velocity pressure effects along the chimney affect the line.

In Figure 1b, the chimney inlet at the base of the furnace is blocked. In this case, the chimney fluid is now static, and the slope of the chimney pressure profile is a simple function of density. The neutral pressure plane is lowered, as the draft caused by the chimney is no longer present. (In effect, the pressure within the house is raised, causing the inside air pressure line to move to the right in the figures.) The outside pressure profile is unaffected.

In Figure 1c, the pressure profiles that occur when the chimney is backdrafting are presented. At the point of backdrafting, the exhaust fan has significantly lowered the

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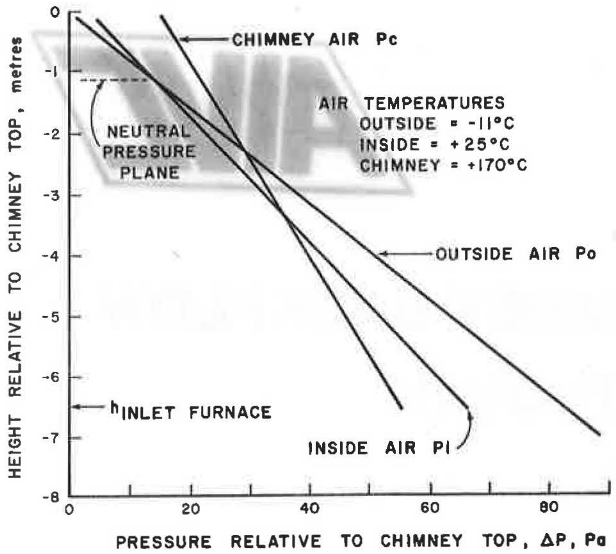

Figure 1a *Pressure profiles in the chimney, inside air, and outside air during normal furnace operation*

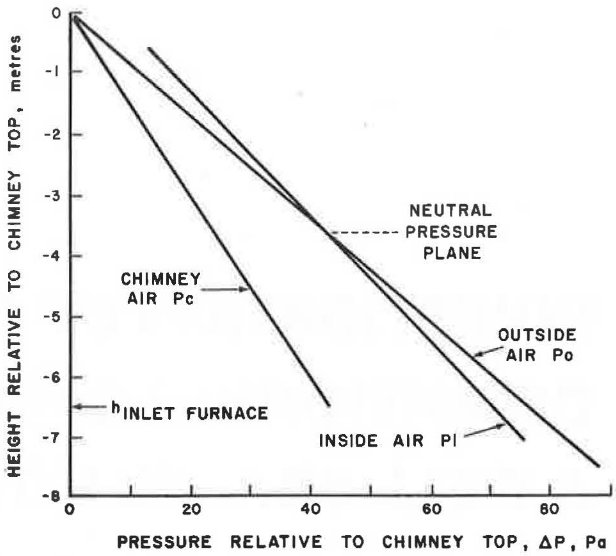

Figure 1b *Pressure profiles when the chimney is blocked at the bottom*

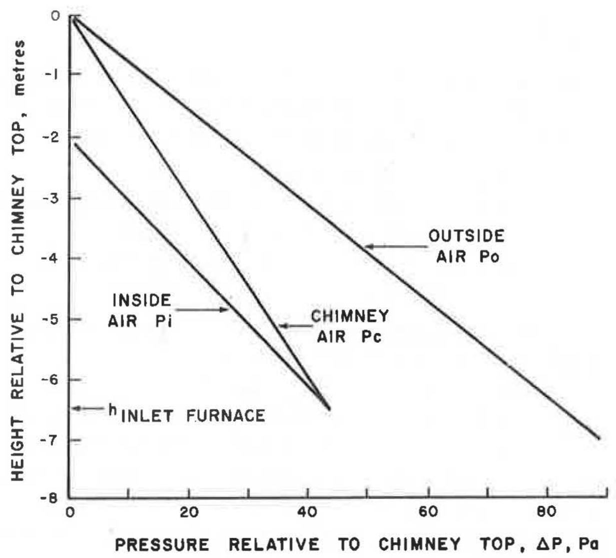

Figure 1c *Pressure profiles at the point of chimney back-drafting (exhaust fan operated to create a negative pressure in the house*

internal pressure in the house, moving the inside pressure profile to the left. The furnace backdrafts when the inside air pressure is less than the chimney air pressure at the furnace inlet. The chimney air pressure profile is a function of the air density only, as the fluid is static. Again, the outside pressure profile is unaffected. The fan pressure required to cause the furnace to backdraft is the difference in the inside house pressure at the furnace inlet, as shown in Figure 1c, and the inside pressure in the house at the same elevation when the chimney was blocked, as shown in Figure 1b.

The equations for calculating this pressure difference, which will cause the chimney to backdraft, are developed as follows:

The rate of pressure change with height in a static fluid is:

$$\frac{dp}{dh} = -\rho g \qquad (1)$$

This equation may be integrated for the chimney as follows, assuming constant air density:

$$p_{c_{(h)}} = p_{o_{(h_{ct})}} - (\rho_c g h) \qquad (2)$$

where

$p_{c_{(h)}}$ = pressure in the chimney at height h (Pa)
$p_{o_{(h_{ct})}}$ = atmospheric pressure at the top of the chimney (Pa) (as all pressures measured are differences, this pressure is set to zero)
ρ_c = density of air in the chimney (kg/m³)
g = gravitational constant (9.81 m/s²)
h = height relative to top of chimney (m); the direction upward is taken as positive

For the outside air, a similar expression may be developed:

$$p_{o_{(h)}} = p_{o_{(h_{ct})}} - (\rho_o g h) \qquad (3)$$

where the subscript *o* refers to the outside air.

In the physical experiment conducted, a set of differential pressure sensors was used to measure the pressure difference across the house envelope at the sensor location. The intersection of the inside and outside pressure lines marks the neutral pressure plane location for the house.

The pressure profile inside the house may be expressed as:

$$p_{i_{(h)}} = p_{o_{(h_{np})}} - \rho_i g(h - h_{np}) + p_{fan} \qquad (4)$$

where the subscript *i* refers to the air inside the house, and

$p_{o_{(h_{np})}}$ = atmospheric pressure at the neutral pressure plane (Pa)
p_{fan} = pressure caused by action of an exhausting device other than the chimney (Pa).

As noted earlier, the chimney will backdraft if the internal pressure at the inlet to the furnace, $p_{i_{(h_{inlet})}}$, is less than the chimney pressure, $p_{c_{(h_{inlet})}}$, at that height. The stall condition (start of spillage) will occur when:

$$p_{i_{(h_{inlet})}} = p_{c_{(h_{inlet})}} \qquad (5)$$

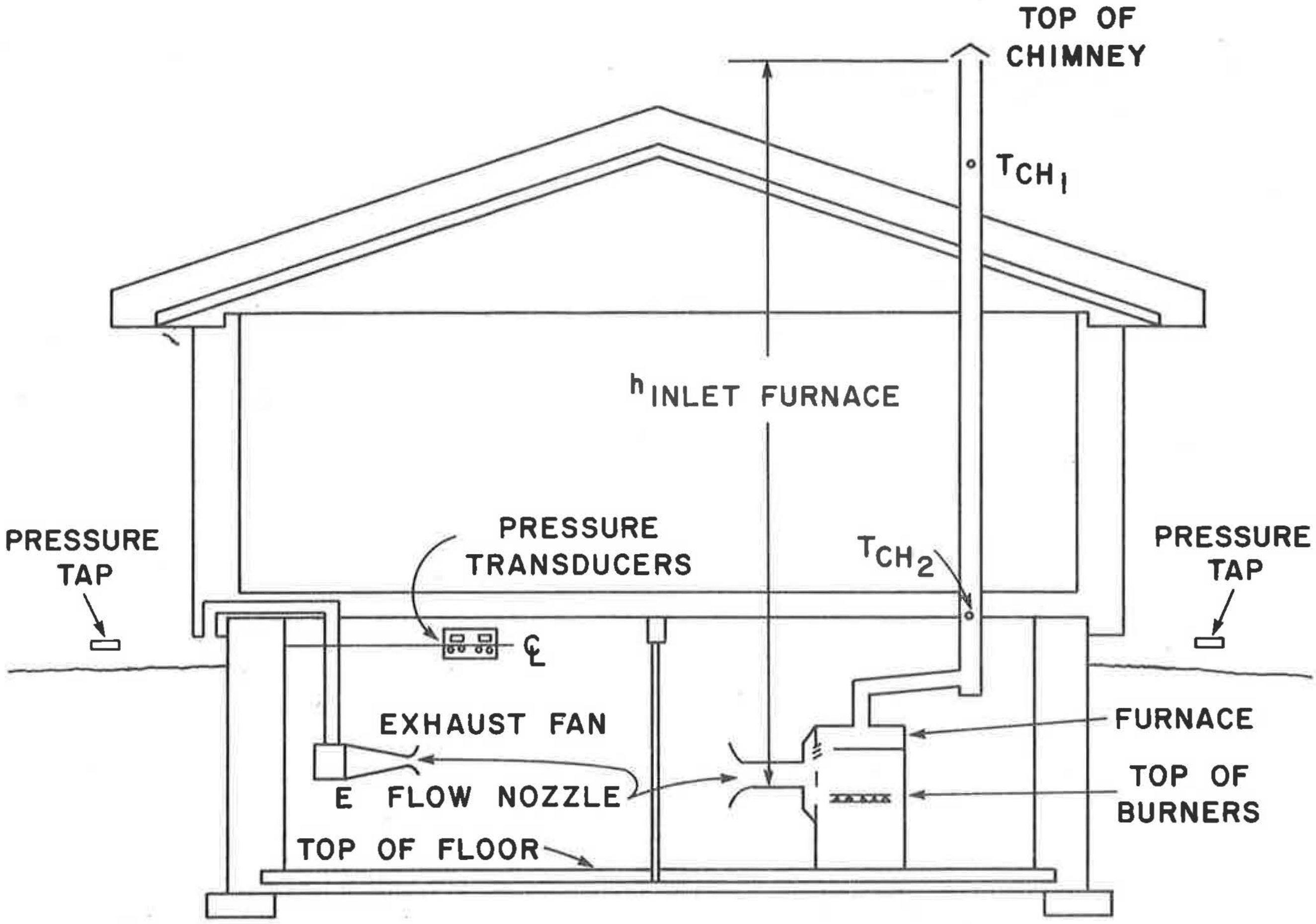

***Figure 2** Cross section of house showing furnace, chimney, and exhaust fan*

Substituting Equations 4 and 2 into Equation 5, and letting $p_{o(h_{np})} = -\rho_o g h_{np}$ from Equation 3, the value of the fan pressure needed to cause the start of spillage can be expressed as:

$$p_{fan} = g[h_{np}(\rho_o - \rho_i) + h_{inlet}(\rho_i - \rho_c)] \qquad (6)$$

In Appendix I, a sample calculation using Equation 6 is presented.

From Equation 6, it may be seen that in order to have a high negative pressure threshold in the house before which the chimney will backdraft, the following conditions are desirable:

a. a large negative value of h_{np} (i.e., the neutral pressure plane should be at a low level. Recall that distances downward are negative with respect to the top of the chimney). This low location for the neutral pressure plane is often difficult to achieve in a well-sealed house. Introducing an intentional hole at a low location in the house would lower the neutral pressure plane location, but at the expense of adding another hole to the house.
b. a large value of $\rho_o - \rho_i$; i.e., the difference in densities between the inside and outside air should be large. In mild weather, however, the density difference will be small.
c. a large value of h_{inlet}. In other words, a tall chimney will offer a greater margin against backdrafting.
d. a large value of $\rho_i - \rho_c$; i.e., the difference in densities between the inside air and the chimney air should be large. In mild weather, with infrequent use of the heating apparatus, the chimney air temperature will be close to the inside air temperature; hence this density difference will be small.

Given that a natural-draft chimney is used in a particular house, two direct means of increasing the operational margin against backdrafting are to increase the chimney height or to introduce a direct combustion air supply to effectively lower the neutral pressure plane in the house. A third measure would be to place the furnace in an enclosure that is isolated from the house air and to supply combustion air directly to the furnace. Given the difficulty of sealing a furnace room and the problem in colder climates of freezing in a small room with a combustion air duct, this approach is infrequently used in Canada. However, in the United States, the use of such an isolated furnace room is the prescribed method of installing a non-weatherized furnace in the recently enacted United States legislation for rating furnaces for annual fuel utilization efficiency and is called an "isolated combustion system."

Another means of avoiding backdrafting of natural-draft chimneys is to use heating systems that have induced or forced draft exhaust systems that avoid the problems associated with natural draft chimneys.

EXPERIMENTAL PROCEDURE

The apparatus shown in Figure 2 was used to test the validity of the theory.

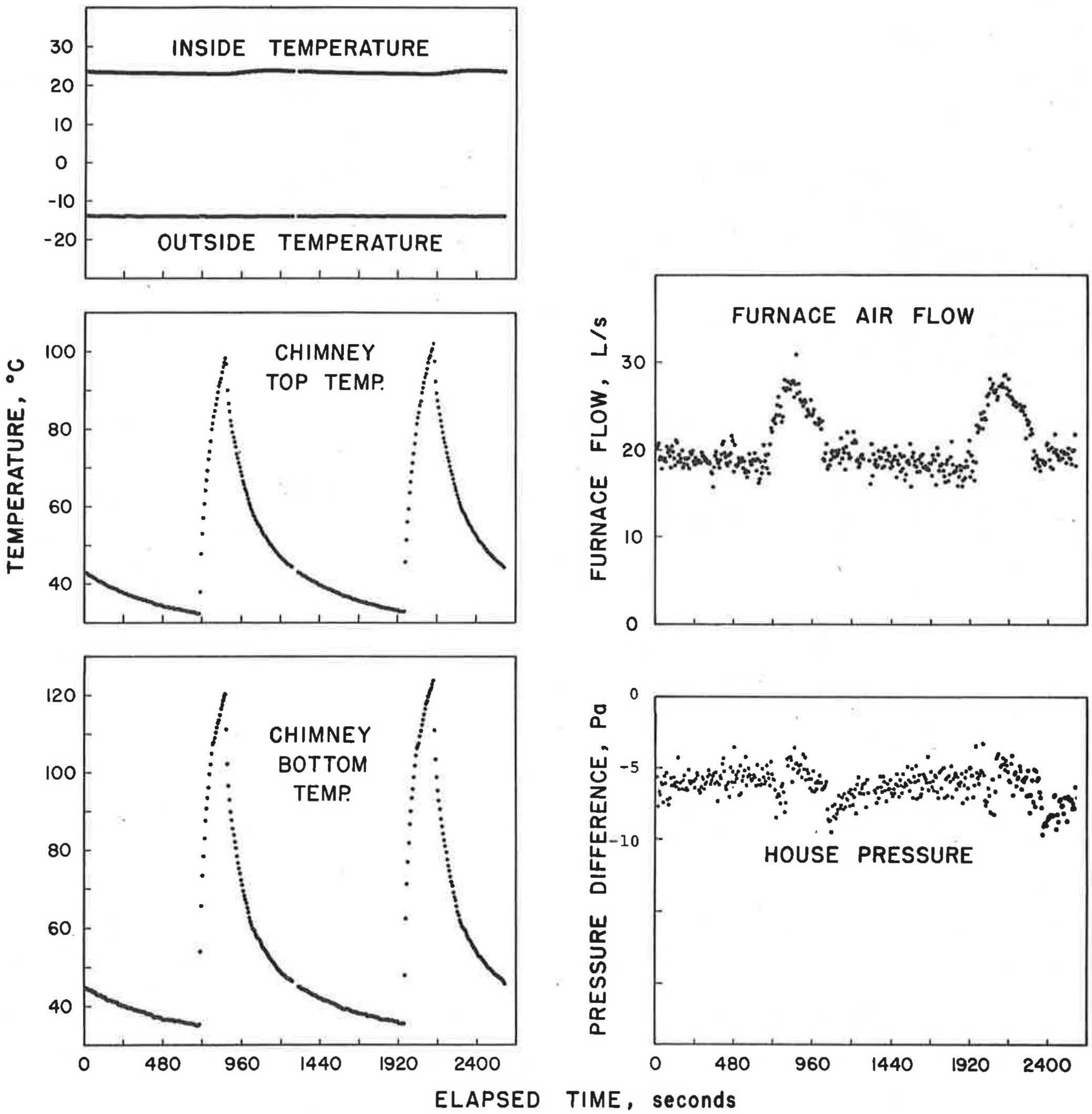

***Figure 3** Plots of temperatures, flow, and pressure during normal furnace operation*

A data logger connected to a microcomputer was used for data gathering. The data logger had a scanning frequency of approximately one channel per second. For plotting, the data were collected on floppy disk and transferred to a spreadsheet program for data analysis, and then plotted using a pen plotter.

In the experiments, the following data points were recorded continuously: outside air temperature, inside air temperature, exhaust gas temperature 940 mm from the chimney top, exhaust gas temperature 685 mm from the chimney bottom, pressure difference between the house interior and the front yard (west side), pressure difference between the house interior and the back yard (east side), air flow through the exhaust fan used to depressurize the house, and air flow through the furnace.

The gas furnace used in the house was a forced air upflow natural draft furnace with an input capacity of 32.2 kW and a bonnet capacity of 25.8 kW. The gas furnace was made in the late 1960s and featured no special options such as intermittent ignition or powered vent damper.

In order to measure the air flow into the furnace, a 280-mm diameter flow nozzle was placed over the inlet to the furnace, as shown in Figure 2. The placement of the flow nozzle results in some obstruction at the front of the furnace. Normally both the combustion air inlet and the draft-diverter opening are directly open to the air space at the front of the furnace. For experimental purposes the flow nozzle was used.

Since the flow nozzle was located below the draft diverter inlet, it increased the effective length of the chimney by a small amount. Normally the effective height of the chimney would be measured from the top of the draft-diverter opening on this type of furnace.

The house in which the experiment took place had been extensively retrofitted for energy conservation, and the peak heat loss of the house had been reduced to approximately 5 kW at −34°C. A report by Orr and Dumont (1987) presents further information on the house. As the bonnet capacity of the furnace was about five times as great as the design heat loss of the house, the furnace would at most run about 20% of the time during normal operation even at the coldest time of the year.

EXPERIMENTAL RESULTS

Normal Furnace Operation

A plot of the normal operation of the furnace system is shown in Figure 3 for a period when the outside temperature was about −14°C and the inside temperature was about 23°C. As may be seen from Figure 3, the chimney air temperature at the top varies from a low of 32°C to a high of about 100°C. At the bottom of the chimney, the temperature varied from a low of 35°C to a high of about 125° C. Air flow up the chimney varies from a value of about 19 L/s during the off cycle to a high of about 29 L/s. The air pressure difference between the inside and outside of the house measured at the floor joist level is approximately 6 Pa. During the firing cycle, there is some fluctuation of this pressure due both to the effect of the warmer chimney and to the operation of the circulation fan on the furnace. (The circulating fan was not run continuously.) The relatively large negative pressure of 6 Pa results from the fact that the neutral pressure plane in the house is located near the ceiling on the main floor of the house. The house is a very well-sealed structure. With the chimney blocked, the pressure test reading using a blower door was 0.29 air changes per hour (ach) at 50 Pa; the equivalent leakage area was 64 cm^2. This is the area of a 90 mm (3.5 in.) diameter vent.

As the house is very well sealed, the chimney penetration of the ceiling has raised the neutral pressure plane location. As the neutral pressure plane height is increased, the pressure difference across the house at the floor level is increased considerably.

Backdraft Test

Backdraft With the Furnace Off Backdraft tests were performed with the furnace in both the on and off conditions. In the off condition, the chimney temperature was generally in the range of about 30°C during the tests, although the chimney temperature can vary over a much wider range.

The backdrafting test was performed as follows:

1. The furnace thermostat temperature setting was lowered to prevent the furnace burners from igniting during the test.
2. The exhaust fan inlet nozzle was temporarily blocked to prevent reverse flow, and the furnace chimney was temporarily blocked. The reason for blocking the chimney is explained in Appendix II. Readings of the pressure difference across the house walls were then taken. This pressure difference is used to determine the neutral pressure plane location. The nozzle and the furnace chimney were then unblocked.
3. The exhaust fan (marked E in Figure 2) was turned on and the volume flow increased in stages. The volume flow was increased until the point at which the chimney began to backdraft. To help indicate the point of backdraft, a narrow strip of tissue paper was placed at the inlet to the furnace. At the point of backdrafting, reverse flow through the chimney caused the tissue paper to extend away from the furnace. The point of backdraft is also indicated by a drop in the pressure difference across the house envelope as the cold air enters the chimney and reduces the chimney draft.

Backdraft While Furnace is On A second set of tests was performed with the furnace burners on. The furnace circulating fan was on. As with the first set of tests, the exhaust fan flow was gradually increased until the backdraft occurred. Because the air temperature in the chimney was much greater, the pressure required to backdraft was much greater as well.

Tests to Determine if the Pilot Light on the Furnace Would Extinguish during Backdrafting A number of tests were performed to determine if the pilot light would extinguish under conditions of backdrafting. The tests were done under the two furnace burner operating modes, on and off. For both cases (burners off and burners on), the pilot light did not extinguish even though a strong backdraft was created by the exhaust fan (a negative pressure level of 50 Pa was achieved in the house during each backdrafting test).

RESULTS

Results from the two sets of tests are recorded in Table 1.

The data collected from the experiment can be used to compare the measured pressure required to backdraft the chimney with the calculated value. A plot is presented in Figure 4 comparing the calculated and measured values. The calculated values were found using Equation 6 to determine the pressure difference required by the fan to cause the chimney to stall.

TABLE 1
Summary of Backdraft Test Results

Test No.	Outside Temp. (°C)	Inside Temp. (°C)	Average Chimney Temp. (°C)	Calculated Fan Pressure to cause backdrafting (Pa)	Measured Fan Pressure to cause backdrafting (Pa)
1	−10.9	22.2	30.0	−5.8	−6.5
2	−12.0	23.6	37.8	−7.5	−6.0
3	−8.7	22.7	29.4	−5.3	−4.9
4	−21.7	21.9	31.8	−7.7	−7.2
5	−9.2	22.9	33.5	−6.3	−5.3
6	1.1	22.2	31.8	−4.7	−4.3
7	−10.9	25.2	169.2	−27.5	−25.5
8	−8.8	26.0	163.3	−26.5	−24.2
9	−8.9	24.8	162.1	−26.5	−23.4
10	−8.9	25.8	145.0	−24.4	−21.3
11	−9.3	27.2	151.4	−25.0	−21.4
12	1.0	24.5	153.4	−24.3	−22.4

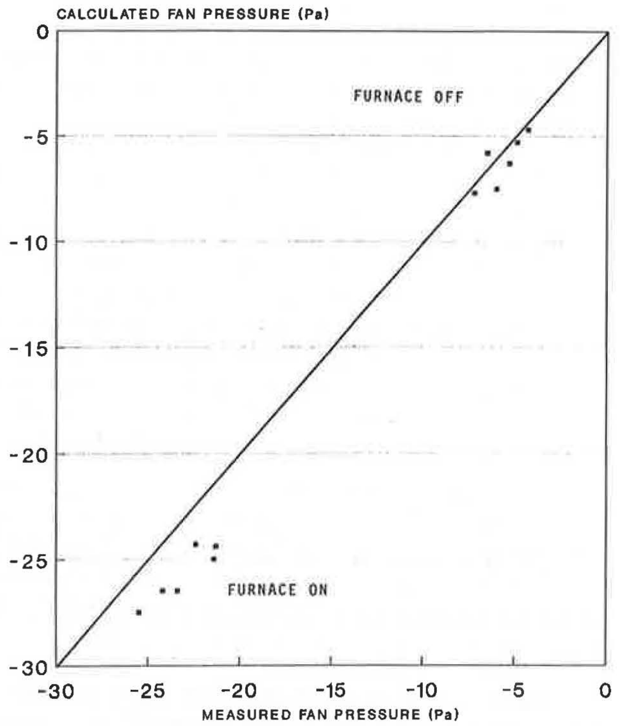

***Figure 4** Comparison of calculated and measured fan pressure required to cause backdrafting*

As can be seen from Figure 4, there is relatively good agreement between the calculated and measured pressure differences required to backdraft the chimney. With the furnace off, the pressure required to backdraft was in the range of 4 to 8 Pa for outside temperatures ranging from +1° to −22°C. With the furnace on, the pressure required to backdraft ranged from 21 to 26 Pa with chimney temperatures in the range of 145° to 170°C with an overall chimney hight of 6.5 m. There is an offset of several Pascals for the case of those tests done with the furnace on. When the furnace is on, the chimney air temperature can change relatively quickly. Note from Figure 3 that during the normal furnace cycling, the maximum chimney exhaust air temperature was approximately 120°C. However, when the exhaust fan is operating, it creates a negative pressure which reduces the flow of air up the chimney, causing the chimney exhaust temperature to rise. At the point of stagnation, the air temperature in the chimney can fluctuate considerably. This is believed to be one of the reasons why the agreement is not as close at the higher pressure differences.

DISCUSSION

The experiments in this house have demonstrated that the theory as presented does adequately predict (to within normal experimental error) the onset of backdrafting in a natural-draft chimney.

For a chimney with a height of 6.5 m at outside temperatures in the range of +1° to −22°C, the fan pressure required to cause backdrafting was in the range of 4 to 8 Pa when the furnace burners were off. With the burners on, the corresponding fan pressure required to cause backdrafting was in the range of 21 to 26 Pa.

In order for backdrafting to occur in a properly installed chimney, disregarding wind effects, one of two conditions must apply:

a. The temperature outside must be warmer than the temperature inside the chimney. In this particular furnace/chimney combination, the chimney temperature would stabilize at approximately 30°C with the burners off and the room temperature at approximately 22°C. There is a temperature rise of about 8°C in the chimney due to the heat from the pilot light, which contributes about 300 W to the exhaust airstream. For this particular furnace, the outside temperature would have to exceed the chimney temperature of about 30°C for the chimney to backdraft. In addition, the wind velocity outside would have to be relatively low.

   This combination of low wind and temperatures exceeding 30°C occurs only infrequently in Saskatoon. According to long-term weather records (Environment Canada 1983), the mean number of days each year with a maximum temperature exceeding 30°C is 12. On average, there are no days each year with a maximum temperature exceeding 35°C.

   When backdrafting occurs in periods when the furnace burners are off, a small amount of combustion product from the pilot light is introduced to the house.

b. The second condition that would cause backdrafting is the operation of a fan or other device such as a fireplace chimney, which could create a sufficient negative pressure. A chimney is most easily backdrafted in warm weather, as the stack effect is smallest under those conditions.

   A report by Perricone (1978) presents the following approximate exhaust air flows from common household equipment:

Device	Approximate air flow (L/s)
Bathroom exhaust fan	20
Kitchen exhaust fan	70
Clothes dryer	65

   In addition to the above exhausting devices, there are also fireplaces and high-powered electric range exhaust fans that can exhaust quantities of air in the range of 200 L/s.

   The exhaust flow values quoted above are average values for units installed in houses of average tightness. The ability of such exhaust devices to cause a chimney to backdraft will depend on a number of factors: a key factor related to the exhausting device itself is its flow vs. pressure characteristic. An exhaust fan that can develop only a few Pascals' pressure is much less likely to backdraft a chimney than a fan with a high maximum pressure capability.

As can be seen from Equation 6, a chimney is most easily backdrafted in mild weather, as the stack effect is smallest at this time.

The ANSI Z21 Accredited Standards Committee's Subcommittees on Standards for Gas-Fired Central Furnaces, Water Heaters, and Boilers are addressing spillage of combustion products from draft diverters caused by blockage by including vent safety shutoff system requirements in their standards in the United States.

Conversion Table

1 L/s = 2.12 cfm
1 Pa = .00402 in. W.G.

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APPENDIX I

Sample Calculation

A sample calculation using Equation 6 is presented.

Input data:

Outside temperature (°C)	= −10.9
Inside temperature (°C)	= 22.2
Average chimney temperature (°C)	= 30.0
h_{inlet}	= −6.5 m

The height of the neutral pressure plane (h_{np}) is found from the inside-outside pressure difference measured with the transducers and by knowing the density of air inside and outside. The neutral pressure plane is shown schematically in Figure 1b.

Using the perfect gas equation, the densities of air are calculated as follows for an atmospheric pressure of 96.0 kPa:

Outside air density (kg/m^3)	= 1.275
Inside air density (kg/m^3)	= 1.132
Chimney air density (kg/m^3)	= 1.103

For this test run, the neutral pressure plane was at a height of −2.82 m relative to the chimney top.

The above values for the air densities and heights of the neutral pressure plane and the furnace inlet are substituted into Equation 6, and the calculated value for p_{fan} is found to be −5.8 Pa.

APPENDIX II

The following material is included to explain why the chimney is blocked at the base at the beginning of the downdraft test.

The chimney acts as an exhausting device and raises the neutral pressure plane during normal operation. When the chimney is on the point of backdrafting (i.e., at the stall condition), there is no flow up the chimney, and the chimney flow does not influence the pressure profile in the house. The purpose of temporarily blocking the chimney at the start of the experiment is to establish the neutral pressure plane of the house in the absence of chimney air flow.

At the beginning of the experiment and at the stall condition, equal conditions of no flow up the chimney are achieved.