RESIDENTIAL COMBUSTION VENTING FAILURE A SYSTEMS APPROACH

FINAL TECHNICAL REPORT

PROJECT 2

MODIFICATIONS AND REFINEMENTS TO THE FLUE SIMULATOR MODEL

Prepared for:

The Research Division

Policy Development and Research Sector

Canada Mortgage and Housing Corporation

Prepared by:
Scanada Consultants Limited
Scanada Sheltair Consortium

July 16, 1987

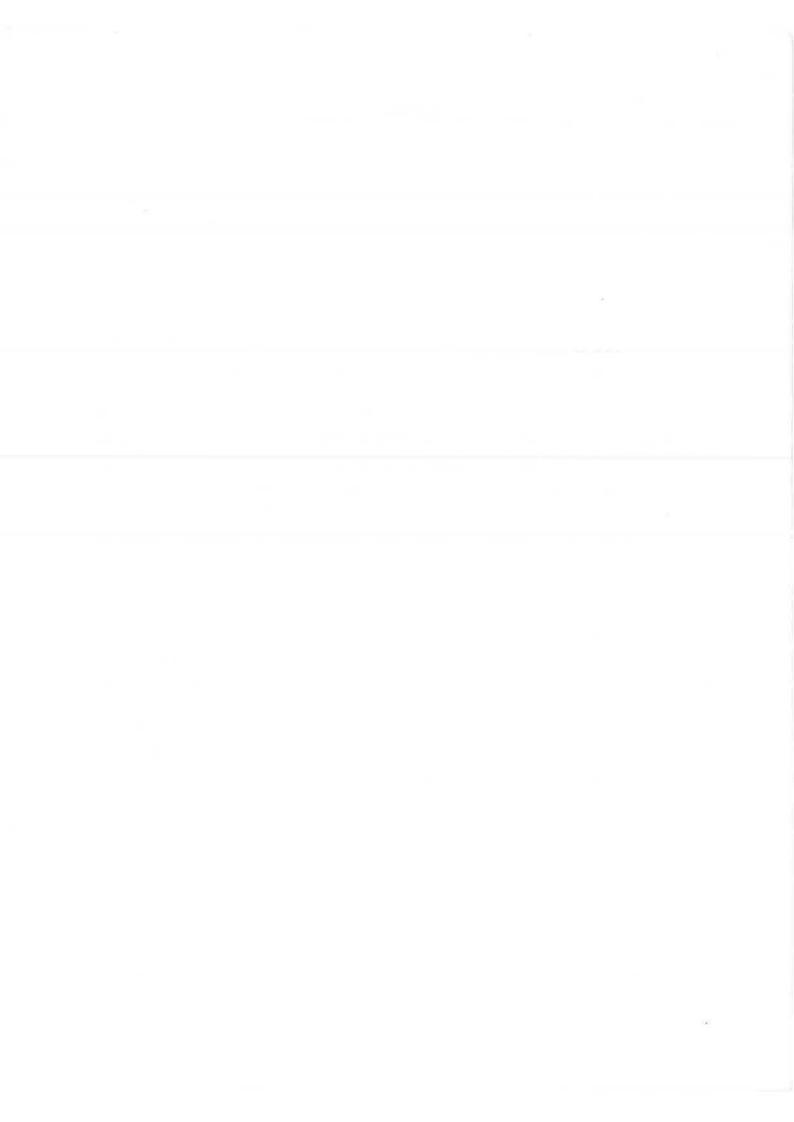
Canada Mortgage and Housing Corporation, the Federal Government's housing agency, is responsible for administering the National Housing Act.

The 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.



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Prepared by:

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July 16, 1987

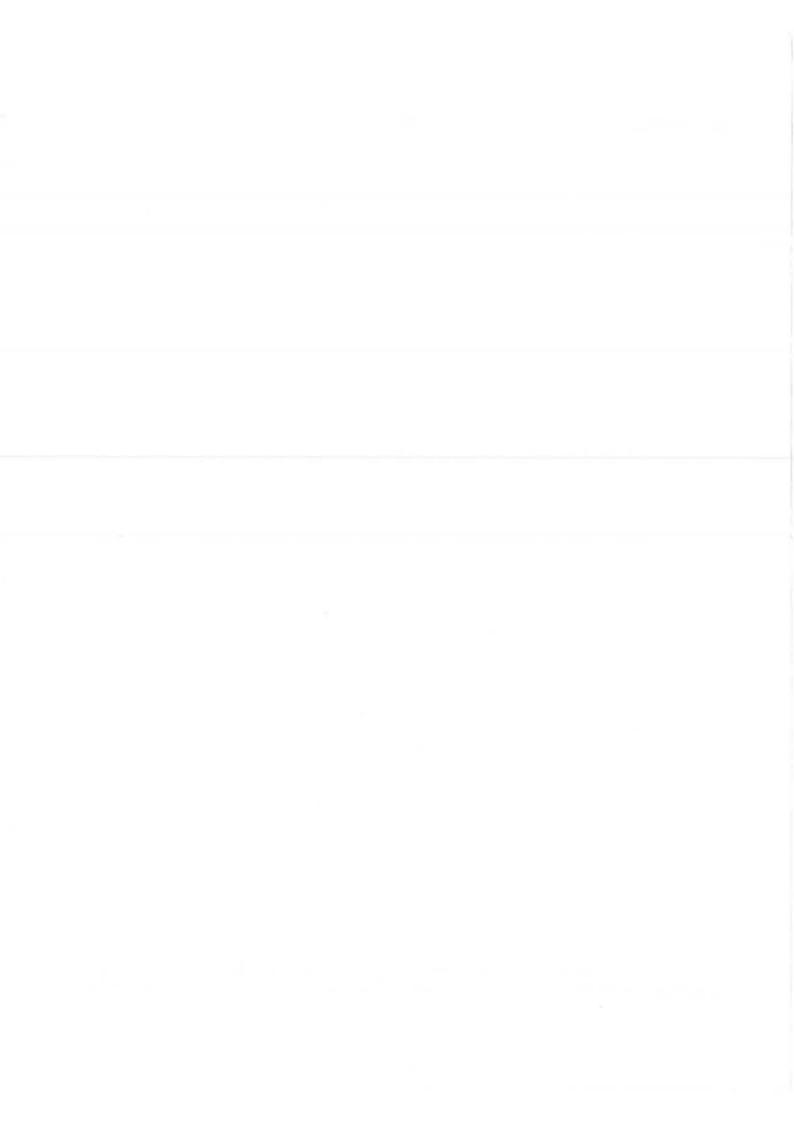
ABSTRACT

The Flue Simulator computer model, developed for CMHC by Scanada Consultants Limited in 1984 to 1986, has been expanded, refined and validated, resulting in a generally accessible research tool for investigating combustion gas spillage and backdrafting in houses. The model is now capable of simulating the influence of key design features of the house envelope and of the furnace and venting system on venting performance for any given set of operating conditions.

The model has been used to evaluate various remedial measures. Most of these measures provide some benefit by extending the range of limiting conditions under which the venting system can function properly. However, no single measure was seen to be a total solution on its own. The model was used to indicate the benefits and limitations of those measures.

The design of the flue pipe and chimney, and the location of each, were shown to be especially important with respect to venting performance of the flue when the house is under moderate depressurization. These aspects of the venting system were also shown to play an important role in avoiding/promoting condensation in the flue, thereby affecting the durability and integrity of the venting system.

A developmental version of the model was produced to simulate wood burning in fireplaces and wood stoves. A fireplace was shown to be susceptible to spillage for prolonged periods after lighting, and it in turn could subject the house to potentially high levels of depressurization for very long periods, increasing the probability of spillage from the main heating system.



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PROJECT 2:	MODIFICATIO	ONS TO TH	HE FLUE	SIMULATOR	MODEL.	

This project was funded by the Canada Mortgage and Housing Corporation and the Panel for Energy Research and Development (PERD), but the views expressed are the personal views of the authors, and neither the Corporation nor PERD accepts responsibility for them.

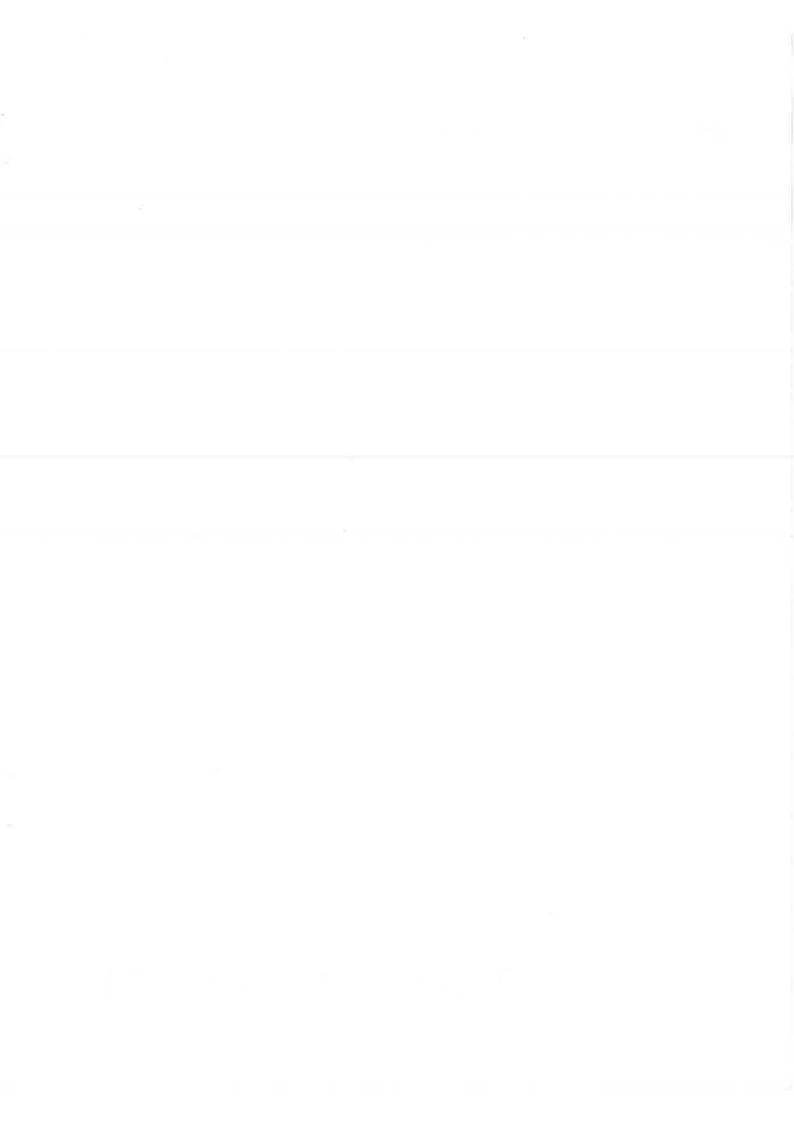
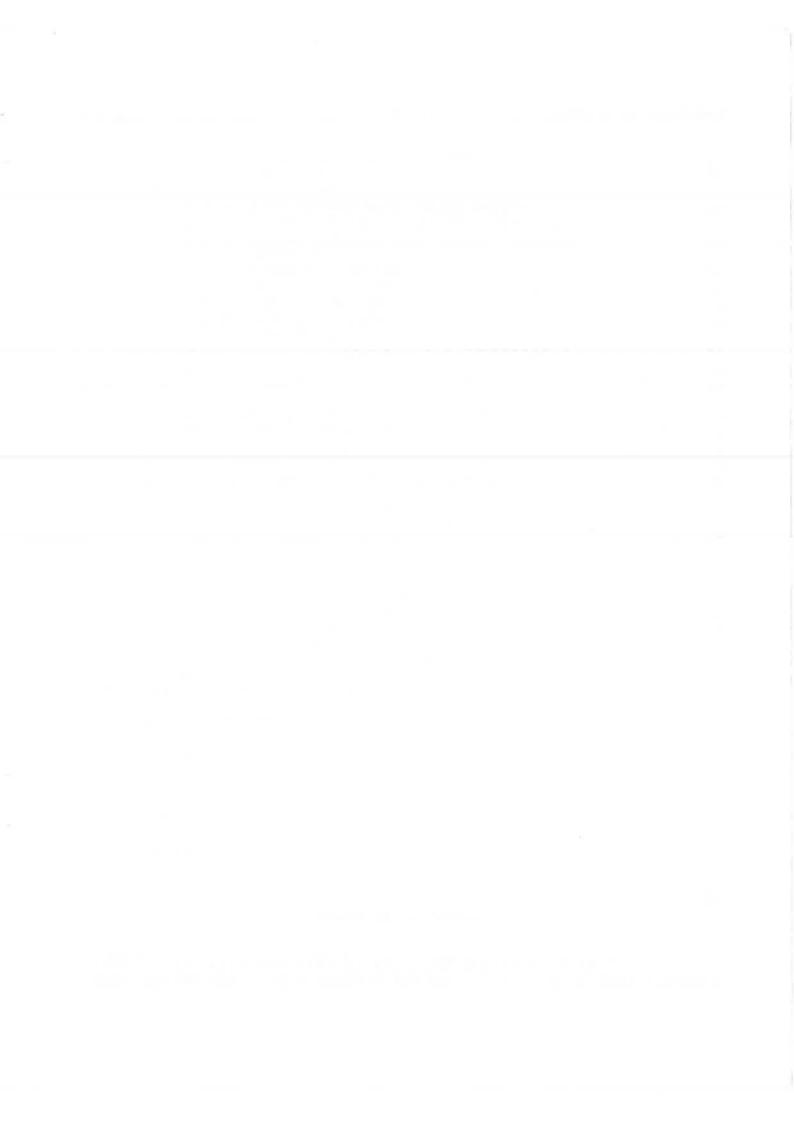
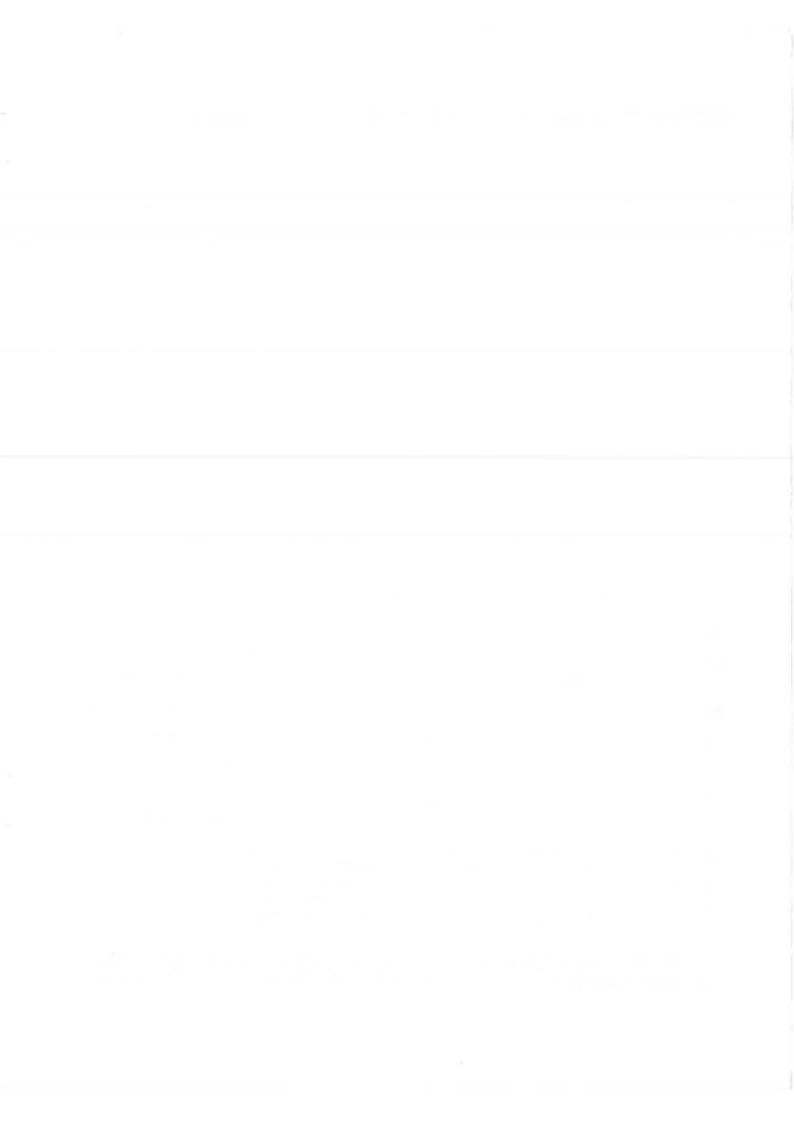


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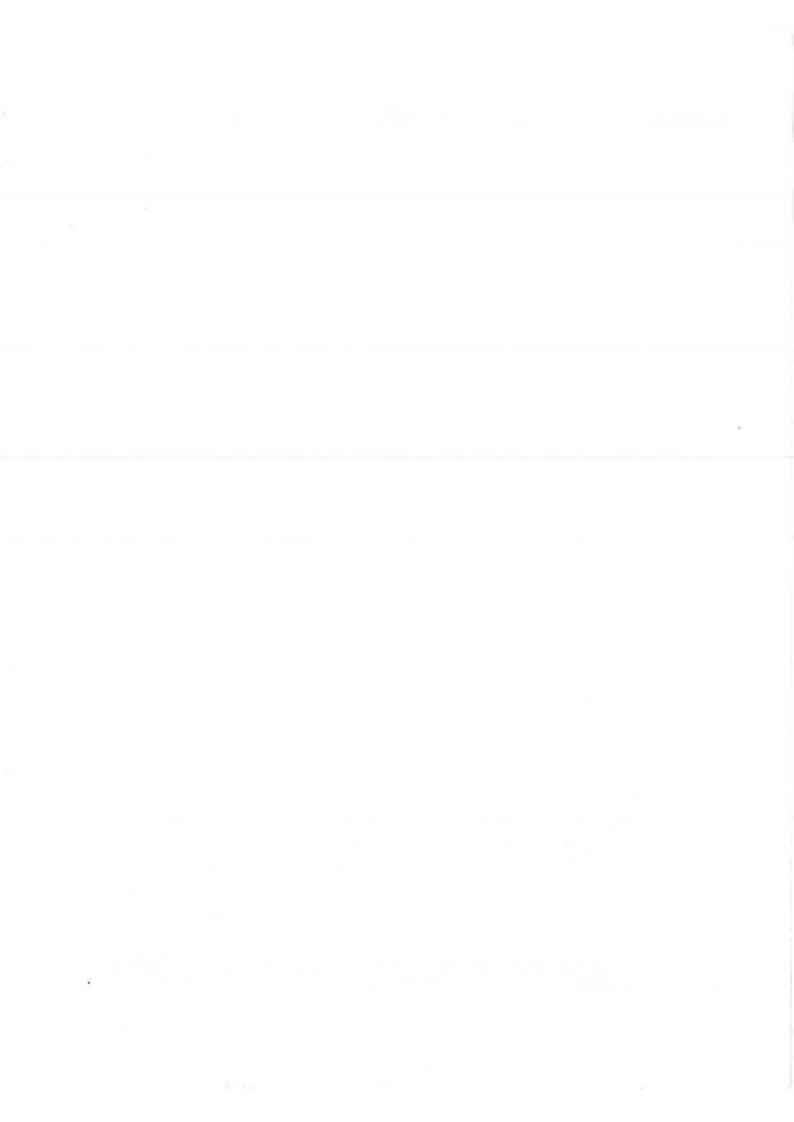


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EXECUTIVE SUMMARY

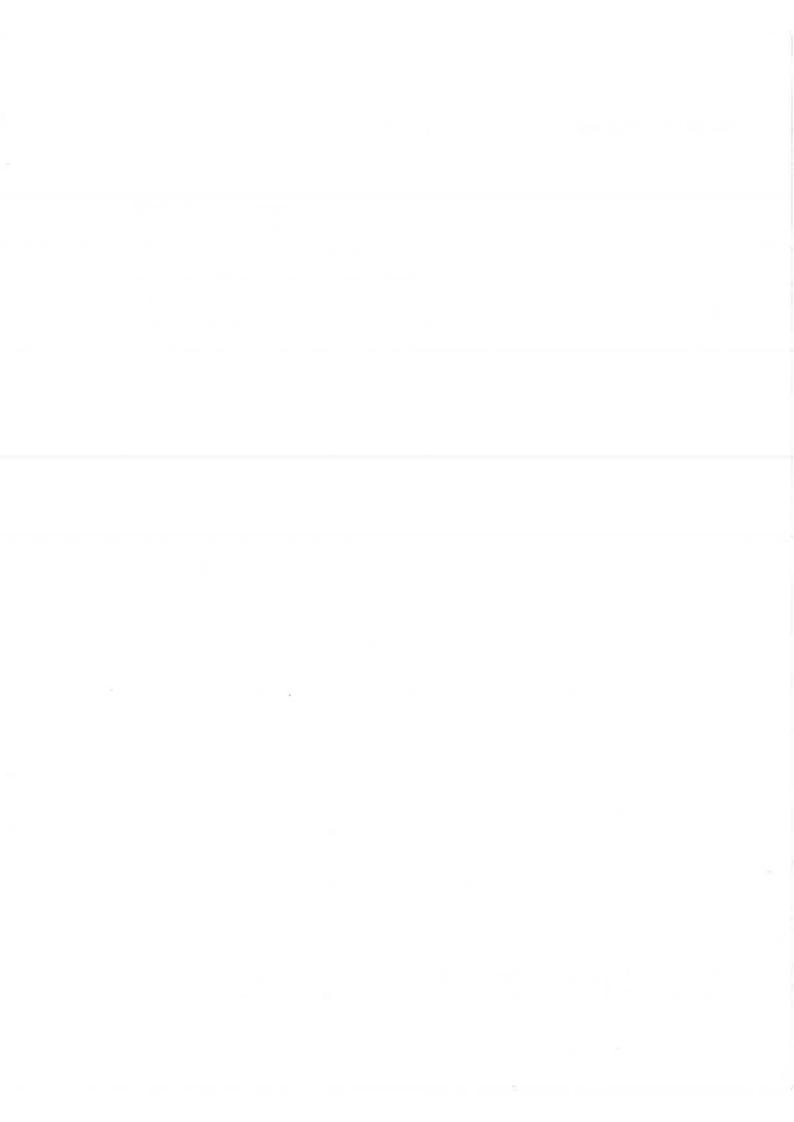
The FLUE SIMULATOR computer model was developed to investigate problems in venting of combustion products from combustion appliances in houses. The primary focus of the model is to predict the interactions between components of the venting system which lead to venting failures. The first generation program, developed under a previous contract for CMHC, was able to meet its main objective, in spite of the many simplifications, assumptions and unvalidated algorithms that were used in the model.

The objective of this study was to improve the model in the following ways:

- to refine the accuracy of critical components (or modules) of the model
- to investigate more complex phenomena that appeared to have a critical role in determining venting performance
- to expand the capability of the model to encompass a wider variety of combustion devices and installations
- to improve the accessibility of the model for ease of use.

The work performed in the course of this project was executed in seven main tasks:

- review the existing FLUE SIMULATOR program
- refine the algorithms
- modify the program for more efficient operation
- extend the model to simulate additional features and system types
- develop more "user-friendly" input and output processing
- update the User's Manual
- validate and use the model



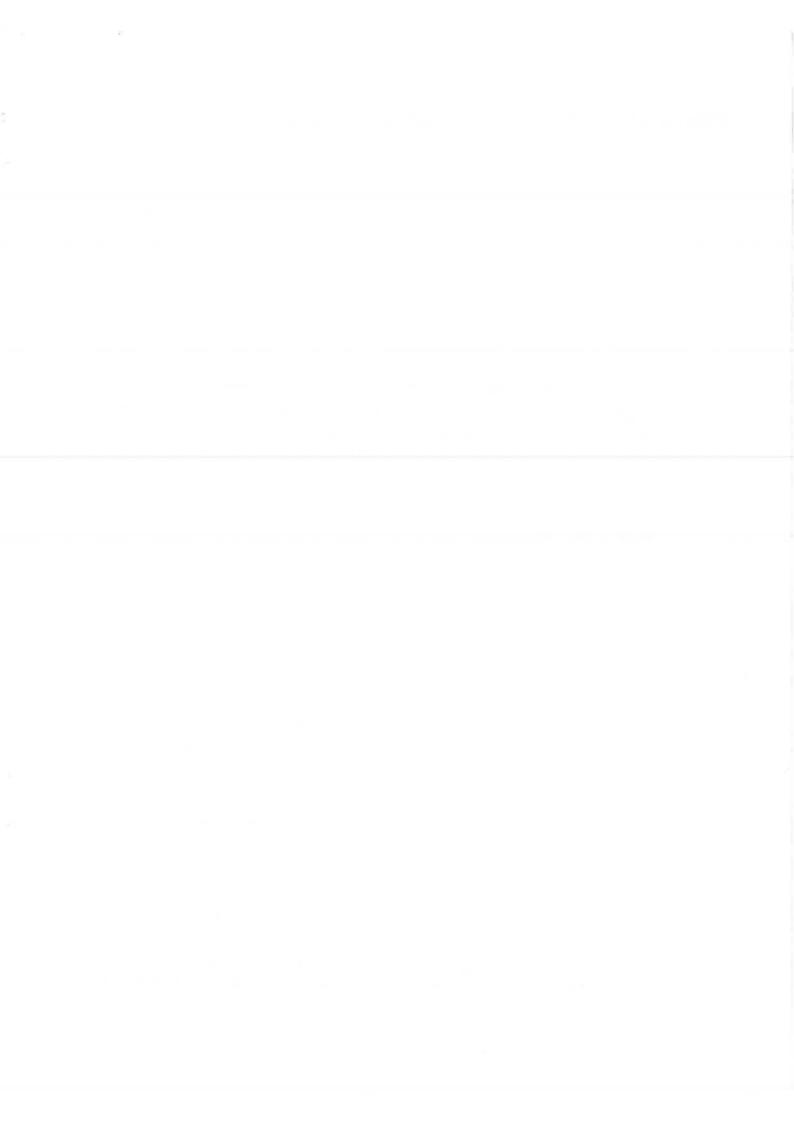
Additional features were added to the FLUE SIMULATOR model. These include:

- effect of wind on house depressurization
- outdoor air intakes
- flue pipe characteristics
- shared flues
- flue pipe draft inducers
- potential for condensation in the flue
- thermostat control of furnace

A separate version of the model has been developed to model combustion and combustion venting in wood-burning appliances. This has been kept separate because it is not as advanced, in terms of validation, testing and refinement as the main model.

A number of simulations were executed to test the model's new features. These produced useful information on venting system design factors and remedial measures for combustion venting problems.

The Flue Simulator computer model has been expanded, refined and validated, resulting in a generally accessible research tool for investigating combustion gas spillage and backdrafting in houses. The model is now capable of simulating the influence of key design features of the house envelope and of the furnace and venting system on venting performance for a wide range of operating conditions.



1.0 INTRODUCTION

This report describes one of seven sub-projects of an overall project entitled -

RESIDENTIAL COMBUSTION VENTING FAILURE - A SYSTEMS APPROACH

- which was carried out for Canada Mortgage and Housing Corporation by the Scanada Sheltair Consortium Inc. A summary of the overall project is provided in Appendix C.

This is the final report on the second sub-project - "Modifications and Refinements to the FLUE SIMULATOR Model". This sub-project was concerned with refinement and extension of the FLUE SIMULATOR computer model, a detailed theoretical computer-based model of the combustion venting process and its interaction with the building envelope and building ventilation system. The model had been developed by Scanada under the sponsorship of Canada Mortgage and Housing Corporation (CMHC) and Energy Mines and Resources Canada (EMR). It is intended to be used primarily 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.

2.0 OBJECTIVES

The following were the specific objectives of the project:

- To identify the critical phenomena requiring further research and modelling using the FLUE SIMULATOR Model.
- To describe the basic principles involved in each phenomenon under study, in terms of fundamental heat and mass transfer concepts.
- To propose a modelling approach that simulates the effect of the phenomenon as simply and accurately as possible, while ensuring that the resulting module can be linked to the main program.
- To specify the algorithms of each new module, where applicable. (Wherever possible, existing algorithms of FLUE SIMULATOR were used, if adequate.)
- To identify key parameters of the phenomena and perform an order of magnitude study of these.
- To integrate these parameters and algorithms into the FLUE SIMULATOR Model.
- To perform test simulations to illustrate the effects of the various phenomena studied.
- To make the model generally easier to use and specifically to facilitate the entry of input data to the model and the interpretation of the model's outputs.

3.0 LIST OF PHENOMENA

The following is a list of the phenomena identified for incorporation in the model:

- wood burning (from lighting to burn out)
 - in fireplaces:

open, no outdoor air intake
open, with fresh air intake
with loose fitting doors, no intake
with loose fitting doors, with intake
with tight doors and intake
with tight doors and forced combustion air
with inserts

- in wood stoves: conventional and airtight
- effect of outdoor air intakes to the house and to the combustion appliance
- bi-directional flows in the vent connector (flue pipe) and flue (reported under separate cover by the Saskatchewan Research Council)
- effects of vent connector (flue-pipe) design: number of elbows, rise and length of each segment, materials & insulation
- effect of the barometric damper
- wind effects on the envelope and fresh air intakes
- effect of shared flues (furnace and hot water heater)
- effect of the dynamics of the heat loss through the house's envelope, and of the furnace control system
- effect of draft-inducing fans
- prediction of occurrence of condensation in the flue, and its effect on flow in the flue

4.0 BASIC PRINCIPLES AND HYPOTHESES

4.1 Wood Burning

The number of issues related to fireplaces and stoves listed in the previous section can be reduced by grouping these into "generic" issues:

- wood burning
- thermal characteristics of the wood burning enclosure, or firebox
- air supply: room air & outdoor air intake

The approach used to model air supply for wood burning devices also applies to other combustion appliances.

4.1.1 Simplifying Hypotheses for the Initial Model

A number of trial hypotheses have been postulated concerning the nature of wood burning in an attempt to reduce the complex set of events that we refer to as "burning wood" into the simplest expression of those events. These are recorded below.

1. Although wood burning can be described as a series of chemical reactions involving changes in the molecular composition and phase of the mass (from solid to gas), with heat being released in the reaction, all accompanied by changes in composition of the remaining material, it is theorized that the <u>thermal</u> aspects of wood burning can be studied independently of the chemical realities of the process. That is, the principles of mass flow and heat transfer can be applied to develop a realistic model of wood burning without modelling the changes in composition of the matter - only the changes in thermal and flow properties need to be specified. The characteristics of wood burning will thus be described in terms of the following:

- rate of heat generation
- heat retention in the wood
- radiative, conductive and convective heat transfer into and from:
 - the burning wood
 - adjacent wood in the pile
 - local air stream & flame
 - flue gas
 - walls (back & sides)
 - floor of the firebox
 - the room

Although heating values are published for various types of wood, and thus the total available heat can be calculated for a given wood pile with a simple calculation, the key modelling issue is to determine the rate at which that heat is released over the duration of the fire and what controls that release rate.

2. The quantity of wood that is "candidate" or ready for combustion at any given time is one factor controlling burn rate, and thus can be defined as the portion of a wood piece that is above the threshold temperature of combustion, and is within a minimum distance from the

surface of the piece, thereby allowing the gasification of that wood.

- 3. The availability of oxygen at the surface of the wood (i.e. air flow rate through the pile) is another main determinant of the rate of burn.
- 4. It is probable that wood surface temperature also influences the rate of burn, however this functional relationship was not postulated. Rather, except for the fact that wood temperature determines whether or not combustion will take place, temperature is treated as a property that is dependent on the rate of burn not vice versa. More specifically, wood temperature will be determined by the rate of combustion, degree of heat retention of the generated heat, quantity of heat from other pieces, and heat capacity of the wood.
- 5. It is hypothesized that there exist typical rates of combustion that are characteristic of wood burning and that can be expressed as Rate of Combustion per Unit Area (RCUA) of exposed surface of wood pieces, and that these characteristics can be established by analysis of measurable quantities in tests. Such characteristics might take the following forms [numbers are just examples at this stage, based on trial calculations and limited CCRL test data (1)(2)(3)]:

 $RCUA_1 = 0.003 \text{ kg/s.m}^2$ for well ventilated wood piles

Inherent in use of this characteristic is the assumption that the total burn rate for the wood pile is largely a

function of the quantity of exposed wood area that is above the ignition temperature, and that a sufficient quantity of air sweeps these surfaces to support this rate of combustion.

Alternately these characteristics might be expressed in the following form:

 $RCUA_2 = 0.0005 \text{ kg/L.m}^2$ to a maximum defined by stoichiometric conditions

where L represents the quantity of air available for combustion.

This unit rate would be multiplied by the candidate wood surface area (m²) and air flow rate through the wood pile (L/s) to establish the total rate of burn of a pile at any given point in time. A check would have to be made on these rates to ensure that combinations of large candidate surface areas of wood and low air flow rates do not result in burn rates that exceed what is possible at conditions of 100% air (i.e. stoichiometric conditions).

6. It is theorized that the <u>type</u> of wood does <u>not</u> strongly influence the RCUA itself. Wood type does affect the heating value of the wood, and how quickly the wood can heat up to above ignition temperature (i.e. the time constants of wood mass at and below the surface are important). It is thus theorized that less dense wood pieces burn out more quickly only because the wood mass heats up more quickly, and there is less mass to burn for a given size of piece. Under this hypothesis, the RCUA of wet wood would also be the same as dry wood, but the

actual performance of the fire would be poorer because of the additional heat capacity of that wood (thus taking longer to heat up), and of the large quantity of released heat needed to evaporate the water in the gasification process.

In summary, if the above hypotheses are correct, the total rate of heat released by burning a wood piece is a function of the surface area of the piece that is above the threshold ignition temperature and the air flow rate over that piece. Of that produced heat, some is retained and some is transferred to other wood pieces, some is transferred to the air stream and lost up the flue, and some is radiated to the surroundings, including the firebox and the room. The heat that is retained by the wood and transferred to adjacent wood results in the chain reaction that is characteristic of wood burning. The rate of that chain reaction is dependent on the net heat retention of each piece and how quickly the temperatures of the wood layers in those pieces respond to that increase in internal energy. The heat radiated to the room from the wood surface and from the flame is the gross heat gain to the house from the fire. The energy in the air going up the flue is the gross heat loss of the system. The rise in the total rate of burn of the wood pile after ignition is a strong function of the time it takes for the surface layers of each piece to reach ignition temperature. The decay is a function of the decreasing exposed surface area of the pieces as they are consumed. Both of these effects are handled by the model. Combustion air supply controls both heat up and burn down stages.

Trial calculations and exploratory modelling were undertaken to test these hypotheses. Results of these tests are reported in Section 5.1.

4.1.2 Firebox Performance

The thermal and flow performance of the firebox, whether a fireplace or a wood stove, can be modelled by specifying the thermal characteristics of the structure and the mass flow characteristics of the openings. All of these features are presently modelled generically in FLUE SIMULATOR.

For example, the open fireplace can be modelled with the present model by arbitrarily dividing the opened face into upper opening (dilution) and lower opening (intake). Because both of these portions are so large, and because the constriction to flow is minimal, the sensitivity to the location of this arbitrary division should be small.

Similarly, the leakage area of glass doors can also be divided into inlet and dilution opening areas but it would be more sensitive to placement of this division.

4.2 Outdoor Air Intakes

(Note: The following discussion on outdoor air intakes applies to all types of combustion equipment, not only to wood burning equipment.)

There are two types of outdoor air intakes to be considered: openings that lead to the house air, and openings that lead directly into the firebox. These differ considerably in performance from each other. The opening to the house air affects the pressure of the house by providing a relief opening in the envelope (i.e. increases the envelope ELA), and it lowers the neutral pressure plane of the house if, as is common, it is located at the base of the house wall - both aspects can improve the performance of the venting system. However the house air remains in series with the combustion venting system, and therefore the latter is still very much dependent on the conditions of the former.

If the air supply into the firebox is sealed or isolated from the house air, it effectively "short circuits" the house from the venting system, and a new, parallel venting system is created that is relatively independent of house conditions (that "independence" is a function of how leaky or airtight the combustion and venting systems are). Theoretically, with this air supply system, the level of house depressurization should not affect the venting performance. The negative aspects of this decoupling are that the inlet air stream is no longer preheated to room temperature, which can have a significant cooling effect on the flue at standby. Furthermore, there is no longer an easy way to balance the inlet and outlet pressures of the furnace by simply locating an opening at the outlet (i.e. the dilution device).* It is interesting

^{*} NOTE: The above discussion of the dilution device problem with fresh air intake to the firebox has some very important ramifications concerning fireplace operation. Open fireplaces generally have "built-in dilution devices" by virtue of their large opening at the top of the firebox - i.e the upper part of the fireplace opening. In a backdrafting situation, most

to note that the "isolated furnace room" addresses the latter problem in that it <u>is</u> a quasi-direct fresh air intake system for both the furnace and dilution device. However, the lack of standby preheating of air is still a problem, especially for small rooms. And complete sealing of the system from the main house and the air handling system is difficult to achieve, especially for the larger rooms.

The FLUE SIMULATOR Model has been modified slightly to accommodate the fresh air supply to the house. A new house ELA and a new Vertical Centre of Leakage is calculated. The existing mass flow calculation in FLUE SIMULATOR needs no modification. For the direct (sealed) air supply to the firebox, the pressure drop along the flow path that leads to the furnace can be simulated by:

of the down-drafting air and smoke would spill into the house at the point of least resistance - the top part of the opening, which is acting as a dilution device. On the other hand, the fireplace with fresh air intake and doors has effectively no dilution device. Backdrafting air - induced by down-drafting winds during a slow burn for example - would have no other course than to sweep over the combustible material (e.g. coals) in a weak burn, and carry hot gases out through the air intake. Due to swirling flow, this may also occur even if the intake is located higher up in the firebox box. This type of problem has been documented. One solution is to reintroduce the generous dilution opening at the top of the firebox in the form of a second connection to the outdoors, near the intake. Even low heat generation of coals should maintain upward flow in the firebox during backdrafting, as the pilot light does in atmospheric gas burners. Thus even in a backdrafting situation, the down-drafting air would tend to go out the upper outdoor air connection and not pass over the hot coals.

- using the ELA characteristics of the air supply ducting rather than the ELA characteristics of the house envelope
- specifying a room temperature equal to outside temperature, and
- specifying the vertical centre of leakage level to be that of the intake. The fresh air intake effectively replaces the envelope as an air flow path.

4.3 Effects of Vent Connector Design

Vent connector (flue pipe) design can affect the flow up the flue in three ways:

- the number of elbows and length of pipe influence flow friction
- the thermal characteristics of the walls affect the flue-gas temperature and thus the buoyancy of the flue gas
- the rise of the pipe and the location of that rise relative to the furnace also affect buoyancy (the closer the rise is to the furnace, the faster the buoyant forces are established at start-up)

The FLUE SIMULATOR Model has been modified to allow up to five straight segments of connector pipe, with up to seven elbows. Each segment has a specifiable rise and length, so that the model accounts for the differences between horizontal and vertical segments, as well as those at an angle. The flow characteristics of the flue pipe as expressed in terms of ELA, take into account additional elbows and the length of the vent

connector (flue pipe). The thermal properties of the vent connector wall are specified in a similar fashion as those of the flue. The flow areas of the flue pipe and flue are specified separately.

4.4 Wind Effect on the Envelope

The central approach to the pressure parameter routine used in the model has been to separate the effects of the buoyancy and envelope pressure drop terms and express these as unique and independent pressure parameter terms. The "Vertical Centre of Leakage" (VCL) of the envelope was introduced in the original version of FLUE SIMULATOR as a fixed characteristic of the envelope's vertical distribution of leakage sites, to separate the effects of buoyancy gain and envelope pressure drop, thereby allowing each to be modelled separately based on their own unique causal factors. This contrasts with the variable "Neutral Pressure Plane" concept, which has been useful in field work because it can be measured, but which varies according to wind, buoyancy, and envelope friction characteristics in an as yet un-modelled fashion. The NPP is a dependent variable - an experimental or modelling result, not an input. (The variable NPP concept also becomes difficult to conceptualize for conditions that result in the NPP being mathematically located above the roof line. For example, what are the leakage characteristics of the imaginary column of room air above the ceiling, and how would this affect a plot of air change vs NPP location for points plotted above the roof line? What does wind do to the angle of the NPP, and can this be predicted via a model based on NPP?).

Because of these considerations, and because the fixed VCL holds the best promise of allowing the model to account for wind effects on the envelope with its own separate pressure parameter, the existing approach based on the VCL has been retained for modelling purposes. (It should be kept in mind that the model can predict NPP, so that validation with experimental results are possible with this approach.)

The same wind pressure parameter format for wind acting at the chimney top was used for predicting the effect of wind on the envelope:

Pwenv = Cpi \cdot 1/2 $\cdot \rho$ v^2

where Pwenv - pressure change of the interior of the house due to wind acting on the envelope

Cpi - wind pressure coefficient (dimensionless)

P - density of outdoor air (kg/m^3)

V - local wind speed (m/s)

As a rough initial guide, the Cpi can be estimated using the guidance provided in the Supplement to the National Building Code (4) for wind load design, reproduced in the following figure and table. As will be noted in the table, a concentration of leakage openings on the windward side of the house would tend to pressurize the envelope (positive Cpi), and thus assist flue flow. Concentrations of openings on any of the other sides would result in negative Cpi, which would tend to depressurize the house and resist flue flow. An additional category, not present in the NBC table, has been added to the model: "envelope leaks largely sheltered from the wind". It is assumed that, for this category, wind would neither pressurize nor depressurize the house, hence, for this category, CPi = 0.

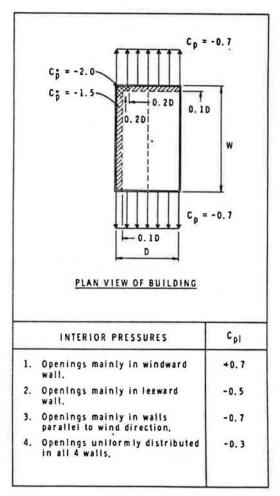


Figure B-11

End wall pressure coefficients, local suction maxima on the roof and interior pressures for use with Figures B-6 to B-10

Notes to Figure B-11:

(1) Local maximum suctions: the coefficients C_p* for the roof surface occur for wind at an angle to one corner, and are used in the design of the roofing itself and its anchorage to the structure. C_p* are not to be added to the C_p for determining total uplift on the roof.
 (2) End walls: the end walls are the ones parallel to the wind direction and have a uniform pressure distribution over the whole building height, except for local maximum suction as indicated in Figure B-10.
 (3) Reference height for exposure factor: for the calculation of external pressures on end walls use H, the total height of the building. For the calculation of internal pressures, use ½ H unless there are dominant openings in the windward wall, in which case use Z, the height to the highest such opening.

Reproduced from the Supplement to the National Building Code of Canada, (4).

The induced envelope pressure drop/rise is added numerically to the net driving pressure parameter. It is assumed that the drop/rise in house pressure due to wind acting on the envelope is relatively insensitive to whatever other flows are occurring across the envelope. This is not to say that the effect on the flue flow will be linear; on the contrary, because of the envelope flow coefficient and of the turbulent flow regime assumed for the flue flow (exponent of 0.5), and because these are acting in series, the response of the flue flow to this effect will be a somewhat complex in nature, and will have to be investigated by trial runs or by parameter analysis before the relationship between wind speed and flue flow can be expressed explicitly.

4.5 Effect of Shared Flues

The effect of a flue being shared by the furnace and the domestic hot water heater has been modelled with small modifications to the existing program. These are:

The mass flow of the water heater combustion products into the main flue is calculated by finding the pressure difference between the room air and the gas in the main vent connector (flue pipe) and specifying the resistance to flow of the water heater branch. In essence, when the water heater is at standby, that branch represents an additional dilution area that can be added directly to that of the dilution device. When the water heater is on, the additional flow through its vent connector is due to the additional head built up by the hot gas in the connector.

The water heater stream also represents an additional energy input to the main flue. This is handled by specifying how much of the water heater pilot light and burner heat is reaching the flue - i.e. all burner heat that has not been transferred to the water. The user is given the option of specifying whether the water heater system is at standby or at full operation for the duration of the run of the main appliance. This option can be used to study the effects of shared flues without having to model the dynamics of the water heater system.

4.6 Dynamics of the House Heat Loss

The principle effect of the dynamics of the house's heat loss is to determine what are typical and what are exceptional furnace on-times and standby times for given house types and thermostat control systems. The importance of this is illustrated in Figure 1 which shows mean flue gas temperatures decaying with time, after furnace shut-off following eight minutes of gas furnace operation, for various flue designs. It will be recognized that the longer the standby periods and/or the shorter the furnace operating periods the lower will be the driving forces on the flue gas at the start of the next cycle. These driving pressures are predicted to be very low for exterior unlined chimneys after modest standby periods in calm conditions. However, even the better chimneys show low driving pressures after prolonged standby periods. The house heat loss dynamics thus determine how

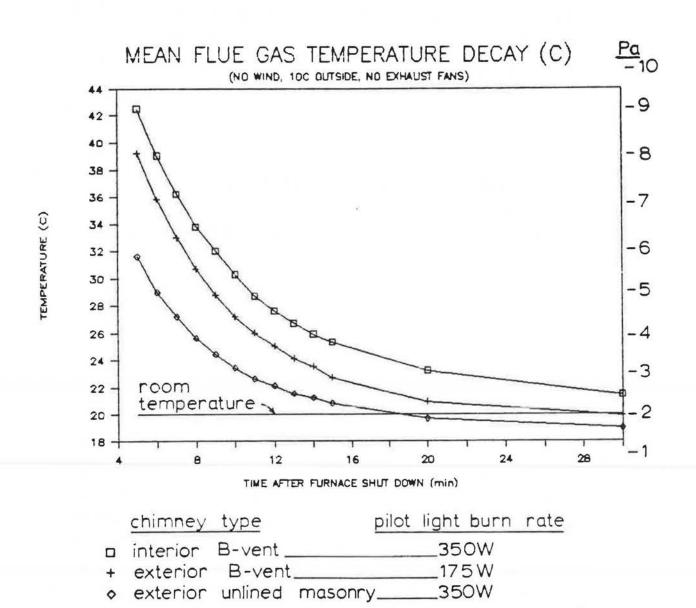


FIGURE 1: Decay of the Mean Flue Gas Temperature at Standby

frequently a venting system will be subjected to low driving pressures and how low these will be. One especially pressing question is "How long will a system stay in standby mode in cold weather with nighttime thermostat setback?". This question is critical for unlined exterior flues and damped exterior flues which can cool to a point where the higher buoyancy of the house air causes the flue to backdraft at the next start-up.

A simple three time-constant model has been used to simulate the house dynamics:

- a fast time constant which, on heat up, is a function of the mass of the heated air in the house and the heating capacity of the furnace
- a "medium" time constant which is a function of air mass and "instantaneous" heat loss to the outdoors (air change and window losses)
- the slowest time constant which relates to the massive elements of the structure, and how well they are coupled to indoor and outdoor air

The model is based on the algorithms that are elaborated in (5), with the added medium range time constant.

4.7 Draft-Inducing Fan (Draft Inducer)

The draft-inducing fan is installed in the vent connector (flue pipe) and develops a pressure difference across itself which assists the flue flow. This driving pressure is a function of the flow rate through the vent connector section. Characteristic curves have been obtained from one manufacturer of such devices*.

To model the effect of the draft inducer, the FLUE SIMULATOR program simply adds the driving pressure contribution of the draft inducer to the Net Driving Pressure Parameter. The resulting solution satisfies both the pressure/mass flow characteristics of the flue and house envelope, and the flow characteristics of the draft inducer.

4.8 The Thermal and Friction Effects of Condensation

When flue gas comes into contact with the surfaces of the chimney that are below the dew point temperature of that gas, condensation occurs on that surface. This has the effect of increasing the heat transferred to the liner from the gas (gain from the released latent heat) and also changes the friction characteristics of the surfaces.

The model predicts surface temperature of the chimney liner, at 10 or more locations up the flue pipe and flue. Using these temperatures, the program calculates the temperature of the boundary layer separating the free stream flue gas and the

^{*} Field Controls, Kinston, North Carolina, Model DI.

flue wall. When the furnace is operating and the temperature of that layer falls below the dew point of the flue gas (assumed to be 54°C) condensation is predicted to occur. These predictions are recorded for each time step, and the accumulated duration of condensation is reported at the end of the run.

NOTE: The condensation phenomenon in the flue affects both the thermal and flow characteristics in the flue. Inasmuch as the model has been calibrated against field data, these factors are accounted for by the model implicitly, by the way of an algorithm that is based on Reynolds number. However, the explicit link between occurrence of condensation and thermal and flow characteristics has not been made.

4.9 Bi-directional Flow

The Flue Simulator model is based on the assumption that all flows within the various portions of the venting system are in the same direction at any given time. However, trial runs of the model have shown that under certain circumstances, the flue gas is predicted to flow upward or downward for the same ambient conditions and house pressure, depending on whether the flue gases are initially specified to be hot or cold. Given that the same external conditions can support either upward or downward flow in the flue, it is possible that under certain circumstances both hot stream (flowing upwards) and cold stream (flowing downwards) could coexist in the same flue.

Under subcontract to the Scanada-Sheltair Consortium, the Saskatchewan Research Council has developed a separate experimental bi-directional flow module to investigate the

combinations of factors that might lead to bi-directional flow and the effect that this occurrence might have on flue flows. If such an investigation indicates that bi-directional flow is likely to be a significant phenomenon and that it helps to explain field data that cannot be reproduced or explained using FLUE SIMULATOR, then the module can be integrated into FLUE SIMULATOR. However, this investigation and possible integration are beyond the scope of the present project.

5.0 KEY PARAMETERS AND ORDERS OF MAGNITUDE

A study of key parameters was undertaken for the issues that require algorithms not already included in the model. These issues are:

- wood burning
- wood burning enclosure
- outdoor air intakes
- dynamics of house heat loss

Details of the analysis are in Appendix "A".

5.1 Wood Burning

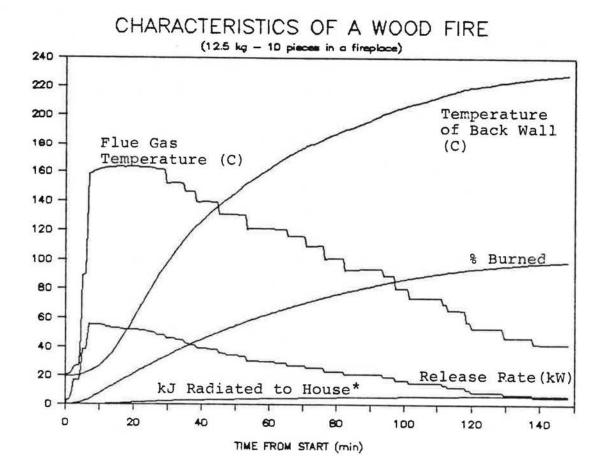
It was found that key parameters in wood burning are the time constants of heat propagation through the wood and through the enclosure surfaces, as well as surface heat transfer time constants. A key factor affecting the time constant of heat propagation through the wood is the "characteristic thickness" of the wood pile (defined as the volume of the pile divided by the surface area) which is a function of its shape. Large round pieces of wood have high characteristic thickness resulting in long heat up time constants (over 1 hour) for the 10" hardwood log studied). By cutting this piece into 4 (pie shaped pieces), the characteristic thickness is cut in half and the heat up time constant is cut by 80%.

Another key parameter is the burning duration time constant, which gives a rough measure of how long a piece of wood will burn. The overall duration of the burn is dependent on this parameter; and more importantly, if the burning duration time constant of the kindling is very much smaller than the heat up

time constant of the larger pieces, the small piece will burn out before igniting the large ones. This phenomenon was predicted successfully in a trial run of a test model based on large round logs. Subsequently, care was taken to specify log geometries with large surface to volume ratios (i.e. split logs). The results of a preliminary run of this trial model with successful ignition is shown in Figure 2 to illustrate the progress in applying the wood burning algorithms. As can be seen, the model is not yet completed. The radiative heat transfer to the room from the log surface was calculated to be a small quantity. This suggested that the majority of the heat transfer from the flame, which is not yet modelled. This will be modelled in such a way that results will show typical energy balances of the wood burn.

5.2 Wood Burning Enclosures

The key parameter identified for modelling the performance of wood burning enclosures is the "Heat Up Time Constant" - that is, the typical time it takes for the enclosure to approach an equilibrium temperature with its surroundings - i.e. the fire. A metal enclosure has a very short internal heat transfer time constant (much less than 1 second), whereas the brick fire-place wall has a time constant for the metal enclosure is the surface heat transfer time constant which is slow because of the surface films: 24 seconds. Surprisingly, the ashes on the floor of the firebox have a long time constant (about ½ hour) by virtue of their high thermal resistance.



*Radiation from log surfaces only. Flame radiation not yet modelled.

FIGURE 2: Simulated Characteristics of Wood Burning.

5.3 Outdoor Air Intake

The effect of the outdoor air intake was studied by parameterizing the characteristics of the opening in terms of added ELA to the house, and lowered the Vertical Centre of Leakage (VCL). These effects were tested using the algorithms of the model. The results are shown in Figure 3. The effect of the size of the fresh air opening on the VCL and hence the buoyancy term is small. The effect of the opening size on the relief of house depressurization is a function of how large the effective ELA of the opening is compared to that of the house. In the example shown in Figure 3, a 160 mm diameter opening is required to give a 1½ Pa relief in depressurization, just enough to regain a positive margin of driving pressures in the example shown.

This algorithm has been programmed into FLUE SIMULATOR.

5.4 House Heat Transfer Dynamics

The dynamics of heat transfer into and out of the house involves two main masses: the house air, and the structure. The degree to which each of these are linked to the furnace heat exchanger in the heat up phase, and to the outdoors in the cool down phase determines their characteristic heat transfer time constants. In the simplified analysis shown in Appendix "A", the characteristics of the gypsum board interior finish were studied, as separated from the outside by the insulation of the wall. Typical heat up and cool down times are shown to be a function of the rates of heat loss and gain, and the total heat capacity of the material (air or gypsum) multiplied by the temperature variation allowed by the

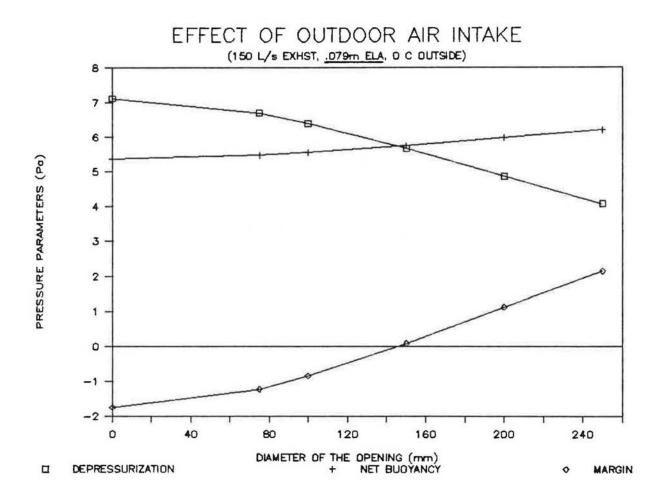


FIGURE 3: Effect of Outdoor Intake Size on the Margin of Pressure Driving the Flue Gases.

thermostat temperature band (e.g. 2°C). Heat up times were of the order to 1½ to 6½ minutes for the air and gypsum respectively. The cool down times are 3½ times longer for the air and almost 7 times longer for the gypsum. The shorter time for the air to cool is due to the fact that the air is subjected to higher rates of heat loss due to infiltration and all of the conduction losses of the envelope including windows.

The heat up time <u>constants</u> are a function of the heat transfer coefficient across the heat exchanger in the furnace. Based on the calibration work done with FLUE SIMULATOR, this heat transfer coefficient was shown to be of the order of 125 W/°C. The heat up time constants are of the order of 1½ to 7½ hours. The cool down time constants range from just under 1 hour to 7 hours for air and gypsum.

The significance of these results is as follows: because the time constants of these processes are large compared to the typical heat up times that are characteristic of the 2°C temperature band, a <u>linear</u> approximation of these heat up and cool down times will be accurate enough for modelling purposes.

6.0 SENSITIVITY STUDIES

A number of simulations were undertaken to demonstrate the sensitivity of the new features to variations in inputs. These are presented below.

6.1 Wood Burning

Although the WOODSIM program has not been developed and refined to the extent that FLUE SIMULATOR has, the program is advanced enough to illustrate some of the key features of the model, including the interactions of the combustion venting system with the air handling in the rest of the house.

Figure 5 shows the start-up performance of an open fireplace in a moderately tight house (ELA - 670 cm²). The chimney is at room temperature at time of lighting the fire, and there is a 15 L/s exhaust fan causing a slight depressurization in the house - less than 1 Pa. There are ten pieces of wood in the pile, five kindling (cedar) and five pieces of hardwood (maple) cut from round logs. Stacking scheme shown in Figure 4.

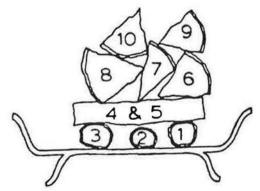


FIGURE 4: Stacking Scheme for the Wood Fire Simulated by WOODSIM

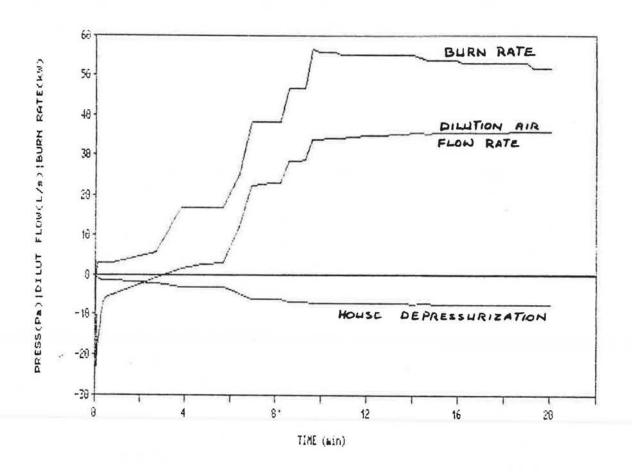


FIGURE 5: Start-up Characteristics of a Wood Fire in a Fireplace (Weak Draft at Start-up)

The steps in temperature over the first ten minutes indicate when the surface of the pieces catch fire. The small initial steps are due to the kindling pieces catching fire. The larger steps for the hardwood pieces. (Note: Two of the large pieces ignite almost simultaneously after about six minutes.)

Two points are of interest in this simulation. The first is that the dilution flow at the top of the fireplace opening is negative for the first three minutes. This indicates smoke spilling into the room. When the chimney is cold and there is no wind, even small house depressurizations will prevent the chimney from venting all the flue gases for considerable start times, even though the chimney flow is upward.

The second point arises from the high mean flue gas temperature in the chimney after about ten minutes of burning. gives rise to total flow rates up the flue of about 175 L/s (not shown). This depressurizes the house to 7 Pa in the example run - enough to backdraft other flues in the house when their appliances are standing by. Furthermore, the conditions that resulted in a low draft at start-up of the wood fire will also result in low start-up draft of the main combustion appliance. The combination of severe house depressurization caused by the fireplace operation and poor draft conditions at the appliance flue would almost certainly result in prolonged spillage of the main appliance at startup should it operate over that period. Thus, over the two hour duration of burning, in this example, both the open fireplace and the main appliance are likely to spill combustion gases at different intervals. This would compound the

air quality problem of the house, and make it difficult to diagnose the source of the problem.

The longer term burn characteristics of the same fire are shown in Figure 6. Note the gradual heating and cooling of the clay liner. Because the duration of the burn is long, the heavy liner is predicted to heat up and actually promote greater draft in the later stages of the fire. After about two hours, the burn rate of the pile has dropped to the extent that the flue gas is cooler than the liner. The gas is thus being heated on the way up. This simulation suggests that, although the massiveness of the chimney may be contributing to part of the spillage problem after lighting the fire by virtue of being cool for a prolonged period, it probably has positive benefits at the end of the fire.

A similar run was attempted using the same woodpile in a wood stove fitted with an A-vent. Because of the low draft condition at start-up and the lower rates of air flow through the restricted air intake of the wood stove (as compared to a fireplace), and because the kindling pieces are large, the other kindling pieces did not light in 20 minutes. tion not shown.) To obtain the example runs shown in Figure 7, a cooler day with an 18 km/hr wind had to be specified to induce more air flow through the wood pile and therefore increase the rate of combustion. Once the larger logs did ignite, the resulting temperatures in the firebox were very high due to the relatively low excess air flowing through the pile. (Note the different temperature scales in Figures 6 and A more appropriate wood pile thus needs to be defined for wood stove simulation. Also, as it is common practice to control the air intake opening during start-up,

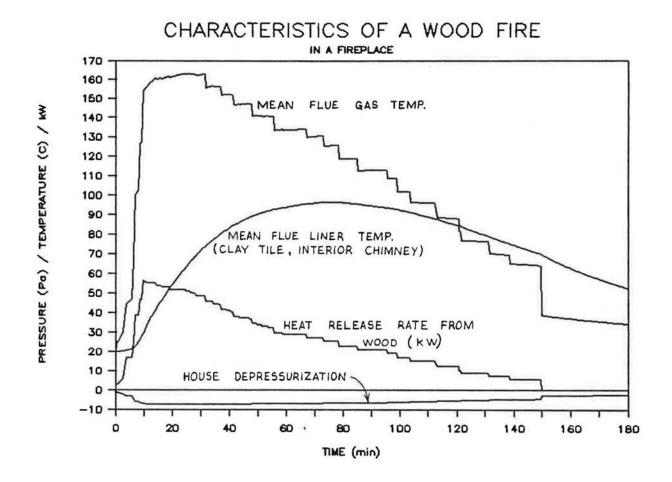


FIGURE 6: Simulated Characteristics of the Performance of a Fireplace over the Full Burn Cycle

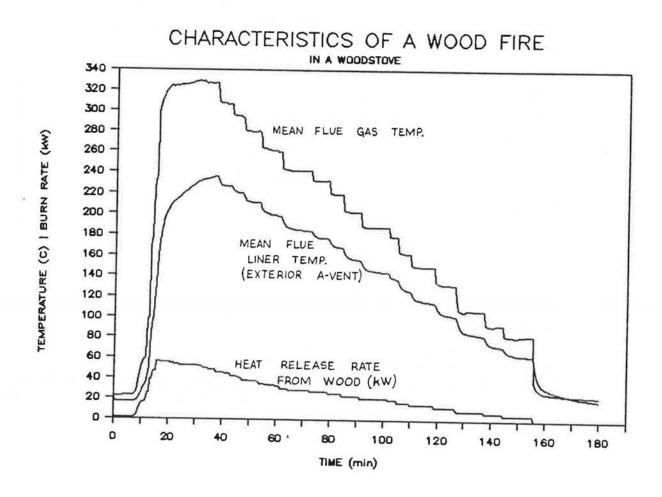


FIGURE 7: Start-up Temperature Profiles for a Wood Stove (Strong Draft at Start-up)

the capability of specifying a schedule of air intake opening should be included in the model.

6.2 Sensitivity to Component Characteristics

The performance of the venting system of a naturally aspirating gas furnace was evaluated for design changes to various components in the system. A reference case was chosen such that exhaust fans, envelope airtightness and ambient conditions combined to depressurize the house to its House Depressurization Limit (HDL)* of about 7 Pa. The duration of spillage of combustion gases under these conditions was predicted to be 30 seconds, as shown by the negative dilution flow line in Figure 8.

A number of design changes were made to the reference house one change at a time - and the results were investigated using FLUE SIMULATOR 3.0. These are reported in Table 1 and discussed below.

6.2.1 Number of Elbows in the Flue Pipe

One additional elbow (the total - three elbows) was included in the flue pipe. This produced a slightly longer spillage duration as would be expected.

The House Depressurization Limit (HDL) is defined as the limit of house depressurization below which a combustion appliance will spill continuously after start-up.

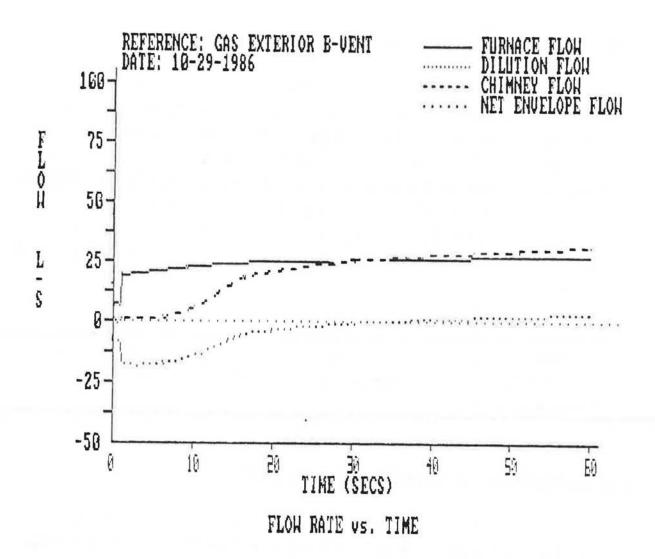


FIGURE 8: Reference Case: Start-up of a Gas Exterior B-Vent at House Depressurization Limit

TABLE 1: SENSITIVITY OF DURATION OF SPILLAGE TO CHANGES IN SYSTEMS DESIGN

CASE	DURATION OF COMBUSTION GAS SPILLAGE (S)
REFERENCE* HOUSE (2-storey)	30
one additional elbow in flue pipe	36
one additional meter length in flue pipe	irreversible backdraft
lined flue pipe	28
interior B-vent	25
150 mm fresh air intake to the basement (Envelope ELA increased by 20%)	17
draft assisting chamber	12 to initiate enough flue flow, but little or no spillage to the room if properly designed
mechanical in-line draft inducer	0
<pre>envelope leaks predominately windward</pre>	12
envelope leaks predominately leeward	- irreversible backdraft
flue shared with water heater	- irreversible backdraft
* REFERENCE CASE - 2 STOREY HOUSE	
GAS FURNACE (30 kw) EXTERIOR B-VENT ENVELOPE ELA = 670 cm ²	<pre>Indoor Temp. = 20°C Outdoor Temp. = -5°C Local wind speed = 11 km/hr</pre>
Envelope sheltered from wind Two meter flue pipe with two elbows No fresh air intake No hot water heater	EXHAUST FAN OPERATION: 75 L/s exhaust fan on for 2 minutes. Another 50 L/s turns on just before the furnace turns on.

6.2.2 Length of Flue Pipe

One additional meter of flue pipe was added to the reference case (total length = 3 m). Surprisingly this resulted in an irreversible backdraft. Two points are illustrated by this result. First, the start-up performance of the venting system at its HDL is very sensitive to small changes in pressures (driving or reversing pressures), so that a small decrease in driving pressure at start-up results in total backdraft in these conditions. Second, the longer flue pipe has three strikes against it. By virtue of its longer length, the flue gases have more time to cool before reaching the chimney. greater length increases the flow friction, slows the gas flow which again results in more cooling of gas in the flue pipe section. Third, and perhaps more importantly, the longer flue pipe is fitted to the same furnace and flue and is therefore shallower in slope (i.e. the furnace is the same height as the reference furnace, but is moved 1 m farther from the base of the chimney). The hot furnace gases therefore take more time to create the vertical column of air needed to increase the driving pressure (draft). All three factors combined in this case to tip the scales the wrong way.

6.2.3 Lined Flue Pipe

The lined flue-pipe reduced spillage duration marginally (two seconds) from the duration produced by the single walled flue pipe. For longer flue pipes this effect will be more pronounced.

This effect is small for two reasons. Firstly, the standby temperature of the inner wall of the flue pipe is close to the furnace room air temperature regardless of the presence of a liner. This is because the room air surrounds the flue pipe both at the outer jacket and inside. Secondly, for either the lined or the single-wall pipe the initial temperature of the inner surface of the liner controls the heat transfer rate from the gas until it heats up. Since the time constant of that process is of the order of a minute, (i.e. it takes minutes for the inner liner to heat up regardless of whether there is a jacket or not) significant differences in temperatures will not be noticed until conditions approach steady state.

6.2.4 Interior B-vent

The interior location of the B-vent resulted in a 1 Pa advantage over the exterior B-vent at start-up, resulting in a House Depressurization Limit of 8 Pa in the example. However this was only translated into a reduction in spillage duration of five seconds. This rather small effect is due to the dynamics of furnace heat up. For the particular system and ambient conditions in question, the mean flue gas temperature must exceed 65°C to eliminate all combustion gas. The corresponding furnace stack temperature is about 122°C. Regardless of flue location and design, it takes the furnace over 20 seconds to deliver flue gas temperatures that are hotter than 120°C.

6.2.5 Fresh Air Intake

A 152 mm fresh air intake (with grill and one elbow in the duct) increased the effective ELA of the envelope of the reference house from 670 to 810 cm², and lowered the Vertical Centre of Leakage of the envelope by 0.85 m. The net effect was to relieve house depressurization by 1.6 Pa and increase the Net Driving Pressure at standby by 1.1 Pa for a net benefit of 2.7 Pa. The resulting spillage duration was almost halved: 17 seconds.

6.2.6 Draft Assisting Chamber

The "draft-assisting chamber" is the subject of a proprietary device designed by Scanada with a pending patent. It becomes part of the venting system of a naturally aspirating combustion appliance and is intended to function in two ways:

Contain initial spilled combustion products until proper draft is established.

Assist in the initiation of proper upward flue flow in a stalled or backdrafting situation, yet have no effect during normal flue operation. Thus it is not intended to interfere with the normal combustion process or efficiency of the furnace.

This proprietary chamber is not yet commercially available but has been proposed as a refinement to the venting system of naturally aspirating gas appliances. In the simulation, the effect of the draft assisting chamber was shown to reduce the time required for the flue to completely evacuate all furnace combustion gases by 18 seconds, and reduce the spillage duration to an even shorter time (0 spillage if properly sized to contain all the gas). This is due to two factors: The draft assisting chamber collects spilled gases in a <u>vertical</u> chamber extending downward from the normal dilution port, maximizing the buoyant effect of those gases rather than losing this to the room air. Secondly, the flow through the furnace is momentarily reduced by about 10% due to the opposing buoyant forces in the chamber, resulting in slightly hotter stack gases that drive the venting process.

This simulation shows the Draft Assisting Chamber in its best light. Preliminary field tests (6) and simulations have shown that, at a house depressurization 1 Pa or more higher than the HDL, these processes are overwhelmed by the full backdrafting of cold air down the chamber. Nevertheless, up to and just above the house HDL, the above described mechanisms appear to help the venting process. Optimization of the design of the chamber may extend its range of usefulness.

6.2.7 Draft-Inducing Fan (Draft Inducer)

The draft inducer modelled is capable of developing 20 Pa of driving pressure in a 125 m flue pipe under stalled flow conditions. (This is also born out by testing results - ref.6) This is more than enough to overcome the house depressurization of 7 Pa - and no spillage is predicted. The model does not simulate the inertial characteristic of the inducer

fan at start-up and thus predicts that 20 Pa are available instantly. In reality, inertial effects would result in a slight time delay before full driving pressure can be developed, resulting in a small amount of spillage of combustion gas at start-up, as was observed in field testing.

Field testing has shown this device to be effective for more serious house depressurizations, and this is borne out in the simulation results shown in Figure 9. Here the draft inducer was able to counteract the effects of 300 L/s exhaust air flow (e.g. effects of an operating fireplace and a range top barbecue combined - resulting in 12 Pa house depressuriza-The success of the draft inducer is shown by the rapid rise in chimney/house buoyancy at start-up. However, the simulation also shows that after seven or eight minutes of cool down (both furnace and inducer are shut off), such strong house depressurization results in backdrafting of the chimney. The resulting back pressure on the furnace outlet interferes with standby air flow in the furnace as shown by the rapid fluctuation of furnace buoyancy (after seven minutes on the graph). (The peaks shown by the model are caused by stalling of the flow in the furnace.) The model is not rigorous enough to simulate what really occurs in these conditions, however it does signal that the pilot light is probably burning under

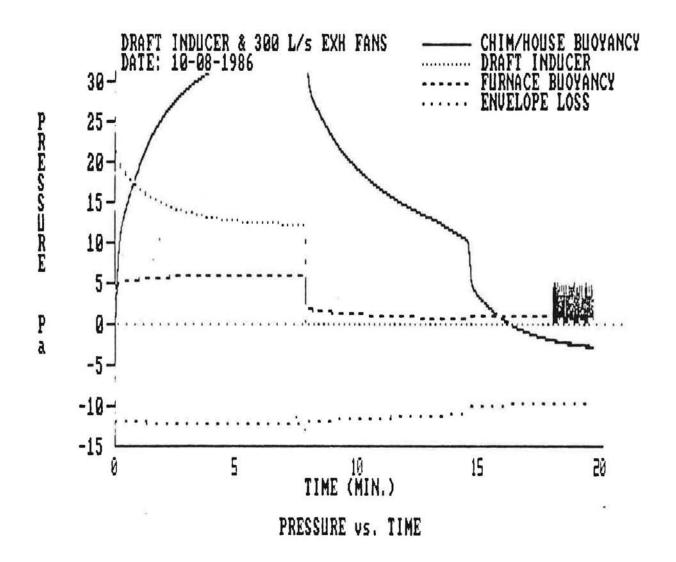


FIGURE 9: Pressure Characteristics of the Venting System with a Draft Inducer (house initially depressurized to 12 Pa)

difficult conditions (if it is not blown out). This suggests that in severe cases where draft inducers are prescribed to promote proper venting, other measures should nevertheless be considered to minimize the interference with combustion appliances at standby when the draft inducer is shut down.

The figure also illustrates the ability of the model to predict house depressurization as a function of the flue flow. As flue flow picks up, the house pressure is shown to gradually dip. As backdrafting occurs at about 14 minutes, the house pressure is released slightly.

6.2.8 Distribution of the Envelope Leaks

Although the distribution of the envelope leaks relative to wind direction is not usually under the control of the house designer, the effect of leak distribution should be known. This may impact on the positioning of fresh air intakes for instance. The model showed that the effect is enough to tip the scale one way or the other. A mainly leeward concentration of leakage sites depressurized the house even more than the reference case which had a sheltered envelope. This resulted in an irreversible backdraft. The mainly windward leakage concentration reduced the spillage duration to 12 seconds.

6.2.9 Flue Shared with Water Heater

Adding a water heater branch to the reference system had the result of full and irreversible backdraft. This is because the additional opening provided by the hot water branch served

as a pressure relief opening so that the furnace exhaust gas could not build up enough pressure to oppose an impending backdraft. In such a case, the hot furnace gas would probably flow up the furnace flue pipe branch and down the hot water branch. In this mode, bi-directional flow streams could set up above the hot water branch and could conceivably reverse the flow eventually. However the current version of FLUE SIMULATOR does not model this phenomenon.

6.3 Miscellaneous Features

A number of simulations were undertaken to illustrate new features of the model. These features are prediction of duration of condensation in the flue, and the effects of house dynamics and thermostat control.

6.3.1 Condensation

Figure 10 shows the durations of condensation predicted for four flues: an interior B-vent, an exterior B-vent, an interior masonry chimneys without liners, and an exterior masonry chimneys without liners. The same two storey house heated by a gas furnace was used for all simulations. The durations of condensation are plotted against location up the flue pipe and flue. For the interior chimneys, elements 9 and 10 are in the attic, exposed to outside air at -10°C. For the exterior chimneys, elements 3 to 10 are exposed to the outside air.

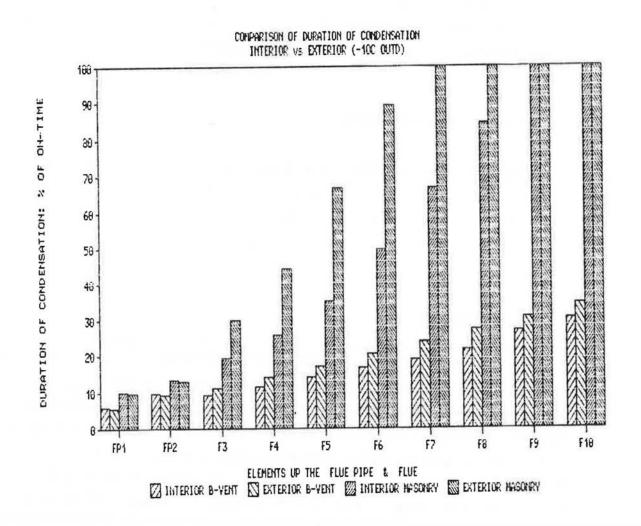


FIGURE 10: Comparison of the Condensation Potential of Interior and Exterior Placement of B-Vents and Masonry Chimneys With No Liner

6.3.2 Interior vs Exterior B-Vent

For all elements of the flue (elements 3 to 10), the interior B-vent is predicted to experience condensation for less time than the exterior B-vent. The largest difference occurs at element 8 - the last element of the interior B-vent inside the envelope. The seemingly exponential rise of duration vs location suggests that differences would be much more pronounced for the upper elements of three-storey and taller flues.

6.3.3 Interior vs Exterior Masonry Chimney (no liner)

The simulations for the masonry chimney were performed over a two hour period, with the furnace operating in cycles of about five minutes, and standby periods of about 15 minutes. This was done to allow the masonry liners to reach realistic operating temperatures. Both masonry chimneys are predicted to experience more condensation than the B-vents. This is due to the mass of the material which is cool at start-up and which cannot warm fully over a five minute run of the furnace. Also, the difference between interior and exterior performance is significant for elements 4 through 8. Elements 9 and 10 are exposed to outdoor air for both chimneys, and these lengths would apparently experience condensation 100% of furnace operating time at -10°C.

One apparent oddity in the results of both B-vents and masonry chimneys is that flue pipes connected to <u>exterior</u> chimneys perform slightly better than those connected to interior chimneys in terms of warming to above the dew point temperature. All four cases show different results in-spite of the

fact that the flue pipes are identical. These elements start at the same temperature and are surrounded by room air and might be expected to perform the same. However, the initial draft on the exterior B-vent is lower at start-up than the interior B-vent and combustion gas spillage occurs over a slightly longer period than for the interior B-vent (i.e. five seconds). The exterior B-vent thus vents no dilution air at start-up and warmer flue gases in the flue pipe section result. The gas thus condenses for a slightly shorter period but this advantage is quickly lost as the flue gases hit the cooled surfaces of the exterior flue. The flue pipes connected to masonry chimneys heat up more slowly because there is greater flow through these and more dilution air - the masonry flue being oversized.

6.3.4 House Dynamics

Figure 11 simply illustrates the capabilities of the model to simulate the rise and fall of house temperatures and the resulting control of the furnace operation. The lags in the response of the house temperature behind the furnace on/off points are due in part to the thermal inertia of the house air and structure and in part to the inertia of the furnace heat exchanger. These inertial effects are most pronounced just after start-up and after shut-down.

The figure shows the temperature response of the three main mass systems of the model: the house air/envelope, the furnace, and the flue. Because these systems are largely interdependent and include many mass elements, the validation

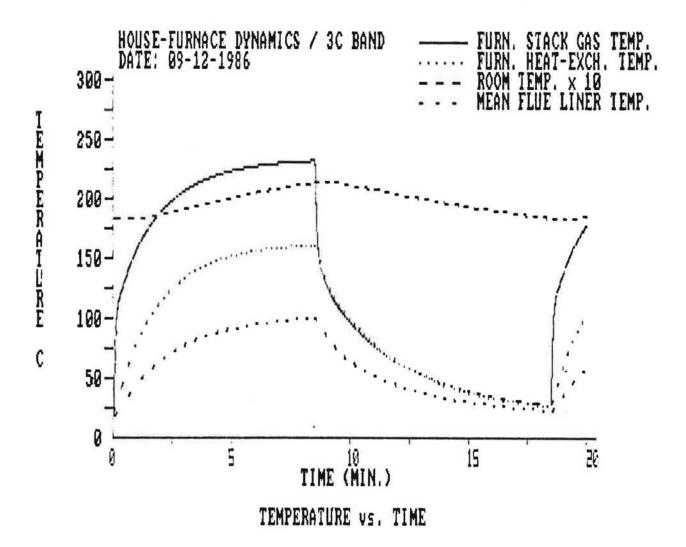


FIGURE 11: Temperature Profiles of the Room Air and Elements of the Heating System as Controlled by a Thermostat

of the total model including house dynamics is difficult as there are so many degrees of freedom to the system. This validation of the whole model has not been undertaken; however, the house dynamics model has been adjusted to give reasonable results. The furnace and flue systems have been validated separately, as discussed in Section 6.

6.3.5 Flue Construction and Location, Duration of Standby and Pilot Light Strength

A final set of tests were undertaken to illustrate the interrelation between flue construction and location, duration of standby and pilot light strength on the performance of venting systems.

Figure 12 (reproduced from Figure 1) was generated using FLUE SIMULATOR for various kinds of flues with different pilot light capacities. The resulting driving pressures are indicated on the right-hand scale. Three cases studied were:

FLU	E CONSTRUCTION	PILOT LIGHT CAPACITY (W)
#1	Interior B-Vent	350 W
#2	Exterior B-Vent	175 W
#3	Exterior Masonry (unlined)	350 W

Two other cases were run but are not shown. These are: exterior B-vent with 350 W and interior B-vent with 175 W. Their results fall approximately in between the first two results shown, with differences of less than ½°C in the mean

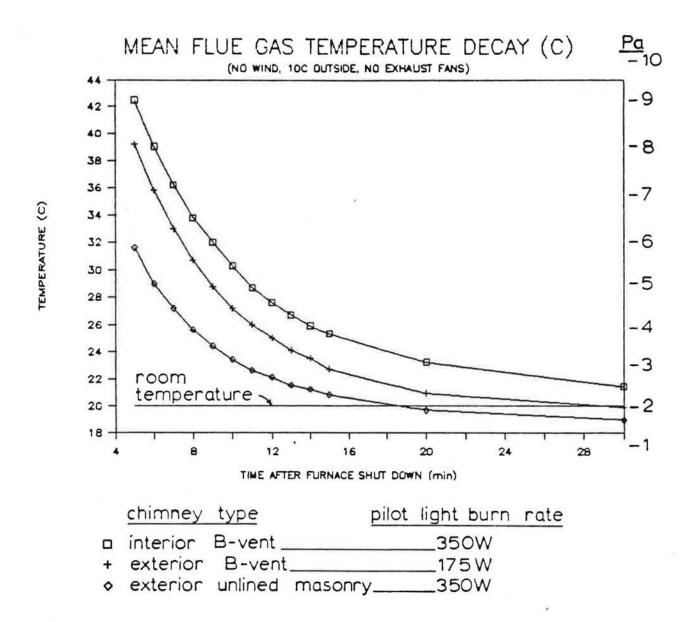


FIGURE 12: Differences in the Thermal and Draft Performance of Various Flues at Standby (No House Depressurization)

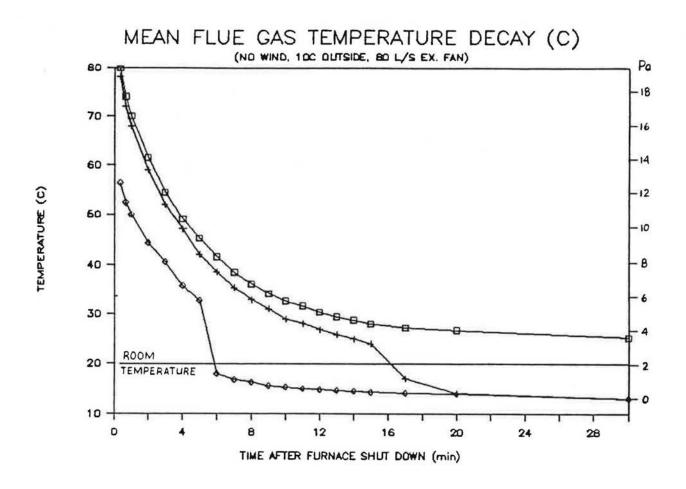
flue gas temperature from the interior B-vent with 350 W pilot.

Figure 12 shows that the <u>duration</u> of standby and the flue <u>construction</u> are critical elements of the problem. Also, by implication, furnace mass plays an important role and is interrelated to the effect of standby duration. Note that the driving pressures are very low after half hour of standby.

Figure 13 shows the performance of the same chimneys and pilot lights with 3 Pa house depressurization. From the previous figure (Figure 12), one would have expected that:

- Flue #1 would start backdrafting after about 20 minutes of standby.
- Flue #2 would start backdrafting after about 14 minutes of standby.
- Flue #3 would start backdrafting after about 10 minutes of standby.

However, these predictions were not substantiated by the actual FLUE SIMULATOR simulations. Flue #1 did not backdraft within a half hour, as shown in the next figure, and actually took about one hour to backdraft. The greater resistance to flue flow that occurred because of house depressurization resulted in less dilution flow through the dilution device relative to furnace stack gas flow. Thus warmer flue temperatures and more resistance to backdraft resulted. This warmer flue gas was also experienced by the exterior B-vent initially, although that flue experienced faster cooling of the flue gas as it approached stall conditions. The backdrafting



SYMBOL	CHIMNEY TYPE <u>& LOCATION</u>	PILOT LIGHT STRENGTH
	B-vent - interior	350W
+	B-vent - exterior	175 W
\Diamond	masonry - exterior	350W

FIGURE 13: Differences in the Thermal and Draft Performance of Various Flues at Standby (House Depressurized to 3 Pa)

occurred approximately as predicted, due to these cancelling effects.

The exterior masonry chimney (no liner) fared poorly in comparison because the cold liner cooled down the flue gas even more rapidly, and this more than offset any gains in warmer chimney entrance temperatures caused by the slower air flow at standby.

7.0 VALIDATION

Two of the most significant modifications to the flow module of the FLUE SIMULATOR Model over the course of this project were the incorporation of a boundary layer/displacement thickness and the ability to specify the flue pipe design in detail. As a result of these new features, the new model was able to predict the heat-up/cool-down performance of a naturally aspirating gas and oil furnace with good accuracy at all points of the cycle, and for all components of the system. Furthermore, the model was able to simulate these systems using NRC test results for flue friction factors (10), and handbook values for elbow losses (11). The results of this validation exercise are discussed below.

7.1 The Consumers Gas Data Set

Figure 14 shows the comparison between simulated (S) and measured (M) results for stack gas temperatures, and chimney entrance and exit temperatures for a naturally aspirating gas furnace (7). The only inaccuracies in this simulation appear to be slight over-prediction of steady state stack gas temperature and the more rapid cooling of the furnace after eight minutes of cool down.

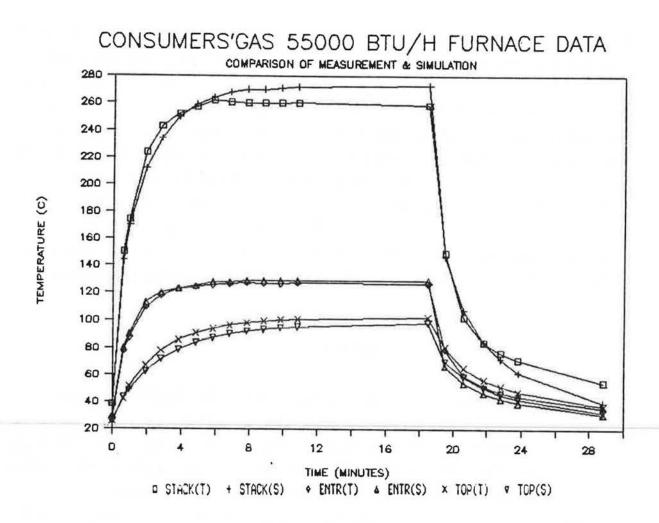


FIGURE 14: Comparison of Measured and Simulated Furnace and Flue Gas Temperatures in a Heat-up/Cool-down Test of a Gas Furnace

7.2 The Esso Data Set

Figure 15 shows test and simulated temperature profiles of stack gas and flue gas for the heat up and cool down of an oil furnace (8). Here again the fit is very good. Figure 16 shows the tested and simulated temperatures of flue gas at the chimney exit. The two sets are free stream temperatures and boundary layer temperatures at the liner wall. The prediction of boundary layer temperature is a new feature of the model and this algorithm appears to be working well as witnessed by the close match.

7.3 The Armstrong Data Set

A final validation exercise was undertaken using test data on spillage duration collected by Scanada for CMHC in 1985 - the Armstrong test data (9). This data set consists of measurement of duration of combustion gas spillage after start-up of an oil appliance in a depressurized house. Four flues were individually tested on the same furnace in one test period - a calm and cool (0°C) February evening - for a number of house depressurizations.

The four chimneys were -

- an interior A-vent,
- an exterior A-vent,
- an interior masonry chimney, and
- an exterior masonry chimney.

The masonry chimneys did not have a metal liner.

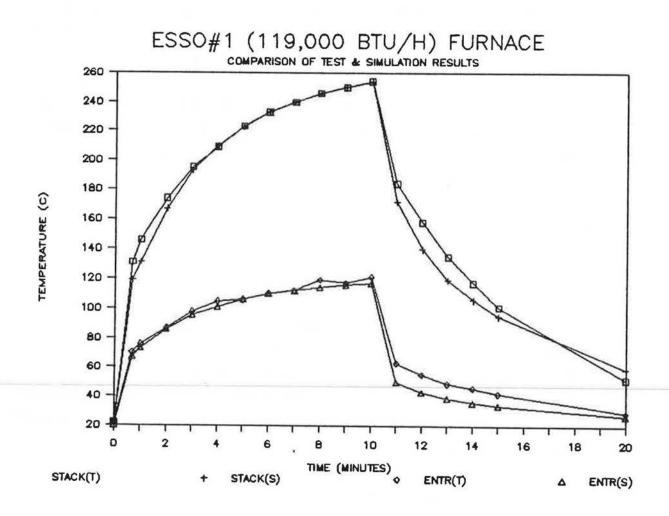


FIGURE 15: Comparison of Measured and Simulated Furnace and Flue Gas Temperatures in a Heat-up/Cool-down Test of an Oil Furnace

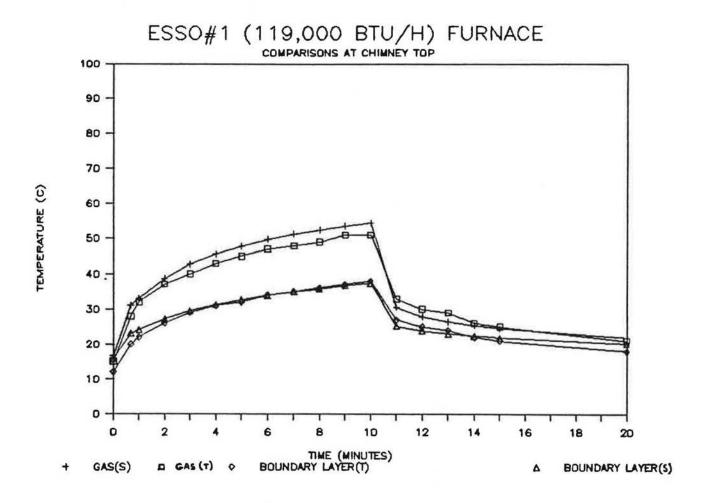


FIGURE 16: Comparison of Measured and Simulated Flue Gas and Boundary Layer Temperatures at the Exit of a Chimney in a Heat-up/Cool-down Test of an Oil Furnace

Heat-up/cool-down test results were used to define the required furnace characteristics. Simulations were then made of the heat-up/cool-down tests. The model simulated the furnace performance properly but could not reproduce the very high flue gas temperatures at the chimney entrance for all but the interior A-vent. After analysis of field and simulation results it was concluded that the likely cause of the high flue gas temperatures tested in the field was an improperly mounted barometric damper which likely did not open enough to allow adequate dilution air into the flue. Fortunately this did not affect the "spillage duration" tests for which the barometric damper is closed until spillage stops due to the positive pressure inside the flue pipe.

Figure 17 shows the comparison of the tested and predicted duration of spillage for three levels of depressurization for three of the four chimneys. (The A-vent was tested at different pressures and is shown on the following figure.) The results in Figure 17 show very good agreement between test and simulation results for each level of depressurization shown, and for each of the three chimney types shown on the figure.

Figure 18 shows the comparisons for the interior A-vent which was tested over a broader range of house depressurizations. (Note that the levels of depressurization are not spaced out to scale on the graph.) At low depressurization levels (0 and 7.2 Pa), the agreement is good and results are consistent with those of the previous figure. At the higher levels (24.5 Pa and 29.6 Pa - levels that are not likely to occur in a house) the simulation over-predicts spillage duration significantly. Examination of the simulation results reveal that there is

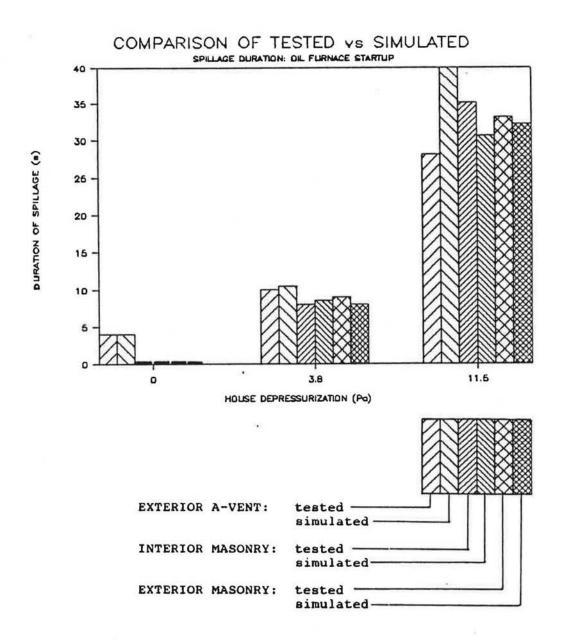


FIGURE 17: Comparison of Measured and Simulated Duration of Spillage for Various Types of Flues and Levels of House Depressurization - Oil Furnace

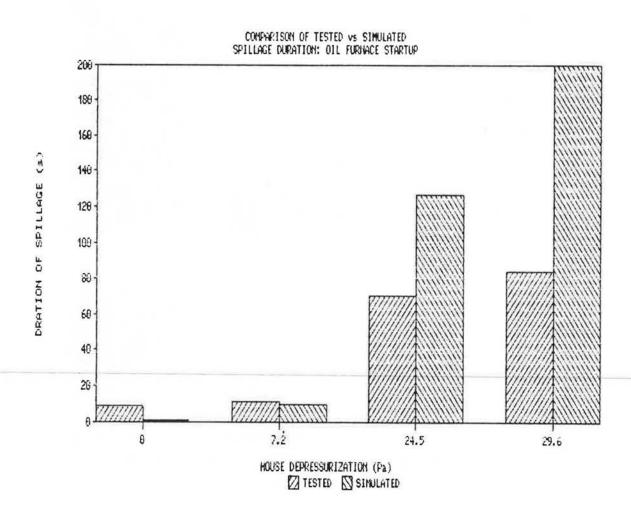


FIGURE 18: Comparison of Measured and Simulated Durations of Spillage for an Interior A-Vent at Moderate and Extreme House Depressurization - Oil Furnace

considerable flue flow and considerable theoretical draft (33 Pa) developed in the A-vent after 1½ minutes of furnace operation. However, the flow through the furnace is also considerable - about 1 L/s more than the flue flow. The resulting spilled quantity is very small and diminishes very gradually as the furnace and flue heat up with time. Under these conditions, small errors in predicting the driving pressures developed by the flue - or small errors in predicting the flue friction factor - get amplified greatly when expressed as spillage duration. This very gradual reduction in small quantities of spillage that mark prolonged spillage episodes in oil furnaces made it difficult to observe the exact point of the elimination of spillage in the field, as attested by the field testing crew.

Finally, it will be noted that neither the field nor simulation results show significant differences in the short term venting performance of the four flue types tested. As indicated in the sensitivity analysis section of this report, the differences in performance of the four flues are more likely to show up after long periods of cool down, where differences in the temperature of the surroundings (i.e. inside vs outside placement) and insulation level (masonry vs A-vent) would show up.

8.0 CONCLUSIONS

An updated version of the Flue Simulator Model has been successfully developed and modified to address the growing number of questions on combustion venting failures. A number of key issues can now be investigated for their effect on venting performance including the following:

- fresh air intakes
- flue pipe/vent connector design
- draft-inducing fans (draft inducers)
- flues shared with water heaters
- wind effects on the envelope
- thermostat setback and thermostat band

These and other refinements to the algorithms have been packaged into a user friendly program that features graphic guides, libraries of typical heating and venting systems, graphical outputs, and a users' manual.

As well, a new preliminary model has been produced to simulate wood burning in fireplaces and wood stoves. Like the original program, the wood burning program predicts duration of spillage of smoke into the room at start-up and cool-down, as well as the house depressurization caused by the operation of the wood burning appliance and other exhaust devices in the house.

A sensitivity analysis was performed to investigate the influence of the above factors on venting performance. The following factors were shown to improve the venting performance of flues on naturally aspirating gas furnaces that are starting up in low draft situations:

- Draft inducers should eliminate most or all spillage and backdrafting at start-up for the majority - if not all - house depressurizations that can be encountered. However, the standby operation of the pilot light is not protected by this device.
- Providing a fresh air intake in the envelope will improve start-up draft by increasing the effective ELA of the envelope and by lowering the centre of leakage in the envelope. The effectiveness of this measure is proportional to the size of the opening relative to the ELA of the envelope. The smaller the envelope ELA, the larger the opening required to counteract a given amount of exhaust flow.
- The draft assisting chamber (device not yet approved by regulatory bodies) should eliminate most or all start-up spillage for house depressurizations up to the system's house depressurization limit. For severe depressurization cases, other measures are required to prevent or reverse backdrafting.
- Interior location of the chimney will help maintain a better minimum start-up draft after a prolonged standby period than an exterior location. The superiority of the interior location is most pronounced when house depressurization at standby is resisting air flow up the flue, or similarly if there is a flue damper that prevents flue flow at standby.
- Location of a flue inside the building envelope also contributes to preventing condensation from the flue gas on the flue liner. Although the B-vents studied showed a marginally

greater potential for condensation when located outside, exterior masonry chimneys without metal liners showed substantially greater condensation potential than the same chimney placed inside.

Other key observations resulted from this work:

- Masonry chimneys without liners are predicted to experience much more condensation than B-vents when venting gas furnaces in cold weather (-10°C).
- The longer duration of a wood fire results in substantial heat up of even a massive masonry chimney, and this stored heat may help maintain higher draft during the low burn period at the end of the fire. However, this massiveness may also be contributing to prolonged spillage in low draft start-up.
- Wood burning in open fireplaces can cause so much house depressurization over prolonged periods that the likelihood of wood smoke spillage and main heating appliance spillage in the same two hour period is high.

Finally it should be noted that the interrelations between the various elements of the venting system are indeed complex. For instance, under conditions that are favourable for proper venting: regular cycling of the furnace, moderate temperatures outdoors, draft inducing winds at the chimney top, the differences in performance of various types of venting systems lessen. Depending on the ambient conditions selected to investigate the effectiveness of one design over another, or one remedial measure over another, the conclusions drawn from those investigations may vary greatly. For example, under normal operating conditions,

different types of flues and different locations of those (inside vs outside) may not appear to make much difference. This was the conclusion taken after limited investigations with the first version of FLUE SIMULATOR. More detailed investigation in this report has shown that under circumstances that are less favourable to proper venting, the differences in performance of various configurations can be significantly different. Thus, because of the vastly differing ranges of climate in Canada, and because of the broad range of construction practice of Canadian homes, no single recommendation can be made that applies cost-effectively for all types of installation. results and conclusions taken in this report should be used as general indicators of what can lead to venting problems in certain circumstances and what measures can be considered to resolve these problems. To take the next step, the FLUE SIMU-LATOR Model has been refined and made user friendly to assist in evaluations of individual installations and of potential remedial

measures.

9.0 REFERENCES

- 1. Fuel Variations Through the Burning Cycle: Implications foe Indirect Efficiency Measurements. R.W. Braaten and A.C.S. Hayden, Canadian Combustion Research Laboratory, EMR, Ottawa
- Efficiency of Wood-Fired Appliances. Paper by A.C.S. Hayden, Canadian Combustion Research Laboratory, EMR, Ottawa.
- Personal Communications and Wood Burning Data provided by A.C.S. Hayden and Fernando Preto of Canadian Combustion Research Laboratory, EMR, Ottawa, December 1985.
- 4. Supplement to the National Building Code of Canada, 1985. Issued by the Associate Committee on the National Building Code.
- 5. "Time Constant" Test Theoretical Development. Peter Rowles, et al, for Canada Mortgage and Housing Corporation.
- Residential Combustion Venting Failures A Systems Approach: <u>Project 5.3: Research on Remedial Measures - Remedial Measures for Gas-Fired Appliances</u>, May 9, 1986.
- 7. J. Rinella, Consumers' Gas, personal communications, April 1985.
- 8. H. West, Esso Petroleum Canada, Letter to Scanada, May 7, 1984.
- 9. Thermal and Aerodynamic Performance of Chimney Flues Armstrong House Field Testing Phase I and 2, Scanada Consultants for Canada Mortgage & Housing Corp., July 1985.
- 10.Draft Performance of Chimneys, W.G. Brown, C. Wachmann, ASHRAE TRANSACTIONS, February 1960.
- 11. ASHRAE Handbook of Fundamentals 1985.

APPENDIX "A"

PARAMETER ANALYSIS AND ORDER OF MAGNITUDE STUDY

APPENDIX "A"

PARAMETER ANALYSIS AND ORDER OF MAGNITUDE STUDY

The following pages show four order of magnitude analyses that have been set up on spreadsheets to test out sensitivities and quickly plot results where needed. The analyses are for:

- wood burning
- wood burning enclosures
- house heat transfer dynamics
- outdoor air intakes to the house.

The first three are analyses of the dynamic processes of heat transfer and follow the same format. For several materials:

- thermal properties are defined
- typical physical dimensions are specified
- heat transfer characteristics of their environments are specified
- and parameters are defined and resulting order of magnitude are shown.

The results for the analysis of the dynamic heat transfer parameters appear to be believable and instructive for the modelling task, with the possible exception of the results for wood ashes. The high density of ashes reported in Reference 11 (density higher than for softwood) results in an unexpectedly long heat up time. Further investigation is needed here.

The effect of the outdoor intake on the house depressurization and the net buoyancy of the house/chimney is studied by looking at a particular example: a two storey house with Equivalent Leakage Area (ELA) of the envelope of 0.079 m^2 , and a fan exhaust flow rate of 150 l/s. (Original house depressurization of 7.1 Pa.)

The opening of the fresh air intake is varied from 0 to 250 mm diameter, and the resulting effects on house depressurization Vertical Centre of Leakage (VCL) and Net Chimney/House Buoyancy (labelled "NEW BUOYANCY") are shown. A graph (Figure Al) was produced of the result. The original house depressurization is relieved by an opening that is just over 150 mm. That opening had an ELA of about 15% of that of the envelope.

The same exercise was done for an "airtight house" with ELA of 0.035 m², with the same fan exhaust flow rate. Here, it took an opening of 300 mm diameter to reinstate positive pressure margins, and this represents increasing the total house ELA by 150%. Again, as shown in Figure A2, this opening has a greater effect in relieving depressurization (17 Pa relief in depressurization) than in increasing buoyancy (1.5 Pa increase) due to lowering of the VCL. The buoyancy term would gain importance in cooler weather.

ORDER OF MAGNITUDE ANALYSIS: WOOD BURNING

PROPERTIES OF WOOD

TRUITER TIES OF WOOD	DIVITO	3111202	(PINE)	(MAPLE)	
DENSITY HEAT CAPACITY HEATING VALUE THERMAL RESIST.	(kJ/kg)	HV		2300 18000	
RATE OF COMBUSTION (property defined :		RCUA2	0.0002	0.0002	
KEY WOOD PIECE DIME	ENSIONS			HARDWOOD (full log)	
LOG LENGTH LOG DIAMETER	(m)			0.38 0.25	St. 17A11
PORTION OF THE ROUN SURFACE AREA(exc) & VOLUME MASS HEATING VALUE OF P	ends) (m2) (m3) (kg)	VOL M	0.072 0.00117 0.502 2.65	0.298 0.02026 14.591	3.64
AIR FLOW CHARACTER	ISTICS				
AIR FLOW THROUGH WO			30 33	77.03	8
PARAMETER ANALYSIS					
EFFECTIVE THICKNESS EFFECTIVE CONDUCTAN					
HEATUP TIME CONSTAN SURFACE HEAT TRANSF BURNING TIME CONSTA	ER T.C. (s)	T5*=MCp/ThfA	130 34 1168	342	1

UNITS SYMBOL SOFTWOOD HARDWOOD

Densities, Heat Capacities, and Thermal Resistivities were obtained or derived from cef. 6. The heating values are from ref. 7.

ORDER OF MAGNITUDE ANALYSIS: WOOD BURNING ENCLOSURES

PROPERTIES	UNITS	SYMBOL	METAL (STEEL)	MASONRY (BRICK)	ASHES
DENSITY HEAT CAPACITY (3 THERMAL RESIST. ((m2		Ср	7830 500 0.022		640 800 14
KEY DIMENSIONS					
LENGTH HEIGHT THICKNESS	(m) (m)	L H T	1.5 1 0.002	1.5 1 0.089	0.5 0.5 0.05
SURFACE AREA VDLUME MASS TOTAL HEAT CAPACITY CONDUCTIVITY	(m2) (m3) (kg) (kJ/K) (W/m2 C)	A VDL M HC U	1.500 0.003 23.5 11.7 22727	0.134 263.0 242.0	0.013 B.O 6.4
AIR FILM CHARACTERIST	IC 				
FILM HEAT TRANSF COEF	(W/m2 C)	hf	33	33	33
PARAMETER ANALYSIS					
EFFECTIVE THICKNESS HEATUP TIME CONSTANT SURFACE HEAT TRANSFER	(5)	T*=MCp/17UA	0.002 0.035 24	0.089 2036 490	0.050 1816 89

Properties are from ref. 6.

ORDER OF MAGNITUDE ANALYSIS: HOUSE HEAT TRANSFER DYNAMICS

PROPERTIES	UNITS	SYMBOL	ROOM AIR	GYPSUM
DENSITY HEAT CAPACITY (J/ THERMAL RESIST. ((m2	(kg/m3) (kg.K)) C)/W)/m	ROW Cp R	1.21 1005 41.7	1200 1080 2.33
KEY DIMENSIONS				
LENGTH	(m)	L	10	36
HEIGHT	(m)	н	7.5	7.5
THICKNESS	(m)	T	В	0.0095
SURFACE AREA	(m2)	Α	270	270
VOLUME	(m3)	VOL	600	2.57
MASS	(kg)	M	724	307B
TOTAL HEAT CAPACITY	(LJ/K)	HC	727	3324
SYSTEM HEAT TRANSFER CH	HARACTERIS	TICS		
FILM HEAT TRANSF COEF	W/m2 C)	hf	5	5
HEAT LOSS FACTOR	(W/C)	UA	250	128
FURNACE DUTPUT CAPACITY	(W)	HEATf	17500	17500
FURNACE HEAT EXCHANGE	DEF (W/C)	UAex	125	125
THERMOSTAT BAND (C)		Bt	2	2
INDOOR/OUTDOOR TEMP DIF	(C)	DT	20	20
PARAMETER ANALYSIS				
		CpxBt/HEATf	83	380
COOLDOWN TIME			291	2598
HEAT UP TIME CONSTANT		M. N. M.	5819	26591
COOLDOWN TIME CONSTANT			2909	2597B
SURFACE HEAT TRANSFER T	.C.(s) T	S*=MCp/hfA		2462

Properties are from ref. 6.

ORDER OF MAGNITUDE ANALYSIS: DUTDOOR AIR INTAKES LEADING TO THE HOUSE

EXAMPLE CALCULATIONS

					DENSITY
					(kg/m3)
To	0	0	273.15	K	1.29
Ti	20	C	293.15	K	1.21
Tchim	24	C	297.15	K	1.19

TWO STOREY HOUSE

7,77			
5.7			
3			
0.038	s3/s Pa^n		
0.7			
0.079	4		
150	L/s	0.15	m 3/5
7.11	Pa		
5.36	Pa		
-1.75	Pa		
	5.7 3 0.038 0.7 0.079 150 7.11 5.36	7.77 m 5.7 m 3 m 0.038 m3/s Pa^n 0.7 0.079 m 150 L/s 7.11 Pa 5.36 Pa -1.75 Pa	5.7 s 3 s 0.038 s3/s Pa^n 0.7 0.079 s 150 L/s 0.15 7.11 Pa 5.36 Pa

SIZE OF OPENING AT GROUND LEVEL	AREA OF OPENING	ELA OF OPENING	TOTAL ELA DF HOUSE	INCREASE	NEW DEPRESS.	NEW	NEW BUDYANCY	NET MARGIN
(as)	(22)	2 elbows	(m2)	(%)	(Pa)	(m)	(Pa)	(Pa)
0	0.0000	0.0000	0.0793	0.0	7.11	3.00	5.36	-1.75
75	0.0044	0.0034	0.0827	4.3	6.70	2.88	5.47	-1.22
100	0.0078	0.0061	0.0853	7.6	6.40	2.79	5.55	-0.85
150	0.0176	0.0136	0.0929	17.2	5.67	2.56	5.75	0.0B
200	0.0313	0.0242	0.1035	30.6	4.86	2.30	5.97	1.12
250	0.0489	0.0379	0.1172	47.8	4.07	2.03	6.20	2, 13

ORDER OF MAGNITUDE ANALYSIS: DUTDOOR AIR INTAKES LEADING TO THE HOUSE

EXAMPLE CALCULATIONS

				DENSITY
				(kg/m3)
To	0	C	273.15 K	1.29
Ti	20	C	293.15 K	1.21
Tchia	24	C	297.15 K	1.19

TWO STOREY HOUSE

15 #3/5

SIZE OF OPENING	AREA DF	ELA DF	TOTAL ELA	INCREASE	NEW	NEW	NEW	NET
AT BROUND LEVEL	OPENING	OPENING	OF HOUSE		DEPRESS.	VCL	BUDYANCY	MARGIN
(ee)	(e 2)	2 elbows	(#2)	(%)	(Pa)	(a)	(Pa)	(Pa)
0	0.0000	0.0000	0.0355	0.0	22.43	3.00	5.36	-17.07
75	0.0044	0.0034	0.0389	9.6	19.68	2.74	5.59	-14.09
100	0.0078	0.0061	0.0415	17.1	17.91	2.56	5.74	-12.16
150	0.0176	0.0136	0.0491	38.4	14.10	2.17	6.09	-B.01
200	0.0313	0.0242	0.0597	68.3	10.66	1.78	6.42	-4.24
250	0.0489	0.0379	0.0733	106.8	7.95	1.45	6.71	-1.24
300	0.0705	0.0545	0.0900	153.8	5.93	1.18	6.94	1.01

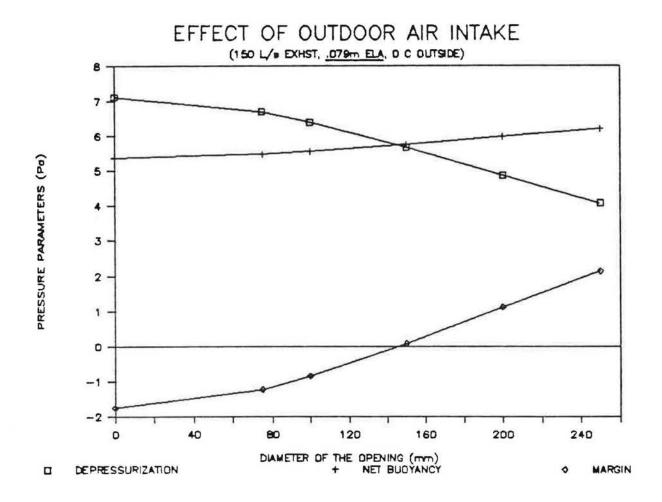


FIGURE Al: Effect of Outdoor Intake Size on the Margin of Pressure Driving the Flue Gases. Loose Envelope.

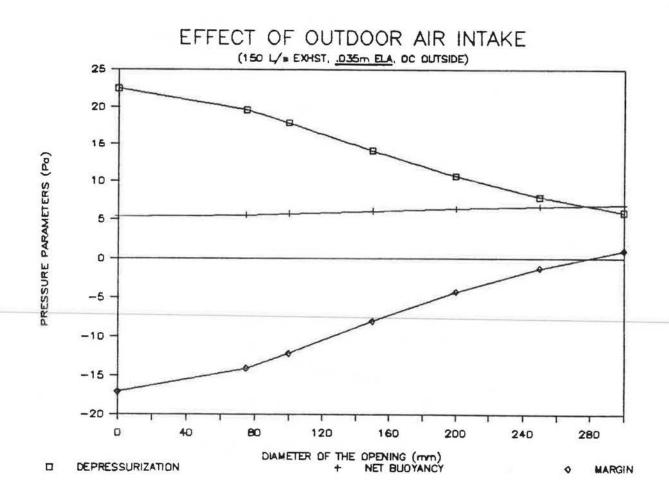


FIGURE A2: Effect of Outdoor Intake on the Margin of Pressure Driving the Flue Gases. Tighter Envelope.

APPENDIX "B"

FLUE SIMULATOR PROGRAM REVIEW

RESIDENTIAL COMBUSTION VENTING FAILURES: A SYSTEMS APPROACH

PROJECT 2 MODIFICATIONS AND REFINEMENTS TO THE FLUE SIMULATOR MODEL TASK 1: FLUE SIMULATOR PROGRAM REVIEW

Adapted from Progress Report
Prepared by:
SCANADA CONSULTANTS LIMITED
January 21, 1986

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CONTEXT

The FLUE SIMULATOR MODEL Version 1.0 was a first generation research tool that was developed to investigate problems in venting of combustion appliances in houses. The primary focus of the model was not the performance of individual components of the system but the <u>interactions</u> between those components which lead to venting failures under circumstances that would not normally be considered hazardous.

The first generation version of the program was able to meet its objectives, in spite of the many simplifications, assumptions and theoretical but unvalidated algorithms that are used in the model. The next logical step is to apply the model in a more demanding context: predicting the flow performance and venting success or failure of individual house/heating systems in particular circumstances and, based on this modelling of actual houses, developing of realistic guidelines for safe installation and operation of combustion appliances in houses.

Before undertaking further development of the model, it is necessary to have a detailed plan of action based on a thorough review of the model's current capabilities and its possible areas of improvement.

OBJECTIVES

The following were the objectives of the review process:

- to highlight the simplifications, assumptions, and hypothesis used in the model, as well as phenomena not modelled
- to suggest how these might lead to error and by what order of magnitude and in what circumstances
- to identify shortcomings in the present scope of the model (i.e. what other types of combustion systems should it be able to model?)
- to identify shortcomings in usability of the model (accessibility, ease in making inputs, clarity of outputs, completeness of documentation)
- to develop a comprehensive research plan that will address the identified shortcomings of the existing program.

APPROACH

The FLUE SIMULATOR PROGRAM was provided for review to the following individuals:

- J.H. White/D. Fugler, CMHC
- S. Moffatt, Sheltair
- A.C.S. Hayden, F. Preto, CCRL
- D. Eyre, SRC
- G.K. Yuill, G.K. Yuill & Associates
- G. Mousseau, Domus Software Limited

Review comments were transmitted by interview and/or written notes. As well, the Program was reviewed internally by Scanada, using results of field tests collected in two previous projects as a basis for evaluating the accuracy of the model.

The results of this review process were consolidated and organized, and are reported herein.

NOTE: A. L. Cautillo of CGA, and F. Stauder of Union Gas also provided constructive suggestions for refinement of the model and the default data files, while attending a pilot training course on FLUE SIMULATOR. These suggestions, which related to flue gas temperatures and levels of excess air predicted by the model, were used in fine tuning.

SUMMARY OF COMMENTS

The following is a summary of comments made by all reviewers of the model to date. (Appendix A is a more complete record of comments and suggestions made by each reviewer.)

On the Algorithms

The assumption of incompressibility of air will be in error for rapid changes in house pressure. A change of 1 Pa of house pressure over 1 sec. will result in a change in density of that air (perfect gas law), which would correspond to approximately 5 1/s of flow across the envelope that is not accounted for in the present model. This phenomenon would occur when exhaust fans turn on, or when the flue reinitializes. This same compressibility effect was investigated for its impact on the flue buoyancy (by J.H. White) and was shown to be insignificant for that aspect of the model.

A similar order of magnitude of error (i.e. 5 1/s) in the handling of "continuity of mass" for the air volume of the house would occur because of the flexibility of the drywall. This flexibility would result in a dynamically variable house volume that would respond the rapid changes in interior house pressure.

The "slug flow" model for gas flow up the chimney will not properly account for cooler and slower (or even reversing) boundary layers, nor for possible two-way flow that may be occurring at start-up. Alternate models should be investi-

gated, including "boundary layer/displacement thickness" models, a concentric cylinder flow model, a two-way flow model, and combinations.

The wind induced pressure distribution about the envelope of the house can have a significant effect on the interior pressure relative to ambient. This effect should be included in the model.

The accuracy of the dynamic flue flow calculation, and the time step of that calculation might be increased by using an exponential expression of temperature change of the flue gas over the time step rather than the linear expression being used.

The effect of condensation of the moisture in the flue gas has not been modelled. High condensation rates will affect the heat transfer rate from flue gas to liner, and the friction factor of the flue. The present model features high friction factors and heat transfer coefficients to compensate for this effect.

On Access and Ease of Implementation

The hardware compatibility appears to be very good - no computer incompatibilities have been reported to date. However several users of the program do not have access to a "wide" printer (i.e. 240 column width in compressed mode). A narrow printer version has been provided for temporary use, with some sacrifice on the quantity of information printed at every time step. The next generation program should offer

the user the option of which parameters he wishes to print out. This would allow the user to tailor the output to his/her needs and limitations.

The need to indicate the library copyright for the compiled version of the program has been cited as an impediment to program dissemination. Total freedom of program dissemination should be the objective of future versions of the program.

Preparation of Inputs

The engineering or physical significance of some of the inputs required by the model are not immediately clear to the user, and therefore may result in faulty inputs. More guidance or explanation is needed for some inputs (e.g. furnace heat exchanger mass and heat capacity). Computer graphics are needed to assist in visualizing key dimensions of the installation (e.g. vertical centre of leakage). The use of a "mouse" to assist in inputs should be investigated.

Other guidance on inputs could include:

- example input screens reproduced in the manual, with relevant explanations superimposed
- eliminate reported confusion on the inputs
- standard "materials property libraries" should be drawn up for various furnace flue types, so that only the types would need to be specified and all the appropriate properties would be loaded automatically

- more flexibility is needed in specifying the flue-pipe characteristics, and as well as for that portion of the flue which extends above the ceiling line in the attic

Finally, it should be noted that increasing the flexibility of inputs on the one hand, and standardizing the inputs by way of providing libraries of common material properties on the other, are interdependent tasks: the more the flexibility the more difficult it becomes to standardize, and vice versa. At present, the need for guidance and standardization of inputs is thought to be stronger than the need for more flexibility, and this will be pursued first. As much flexibility as can be achieved within the context of a library driven input routine will then be built in.

Operation of the Program

The determination of the calculation interval (time step) within the program has been the object of many questions. We have concluded that more explanation is required in the user's manual concerning the determination of the calculation time step within the program.

As well, it has been noted that the time step only gets smaller than the initial value specified or it stays the same — it never increases even though an increase may be justifiable in a given case. The model has not been programmed to check whether larger time steps could be tolerated. This one-way adjustment was used intentionally to satisfy the following conditions: "the program should not override the user's choice of time step unless it has to". This condition could be made optional, in the interest of promoting faster execution in simulation time.

Other points made:

- Control over the operation of exhaust fans during the execution of a run should be given to the user (e.g. specify on/off times, and steps).
- Control over the operation of the furnace air circulation fan, in terms of delay after burner start-up and shut down, should be given to the user.
- Since the furnace air circulation fan can have the effect of either pressurizing or depressurizing the house, the user should be allowed to specify the magnitude and sign of this effect, and the effect should be "turned on" automatically by the model when the furnace circulation fan is "turned on". As it stands now, the program only models the heat transfer effect of the circulation fan and it is assumed that any (de)pressurization effect it has is included in the exhaust fan capacity specified by the user.
- The execution speed of the compiled version of the program was reported to be "just tolerable" by one user, and any increase in speed would be welcomed.

Program Outputs

The significance of many output parameters is not immediately clear. More explanation of results is needed in the manual. This applies to all types of outputs made by the program.

Other comments:

- More outputs should be parameterized; e.g. the program should print out the <u>effective</u> height of the chimney - the height of an ideal chimney that would provide the same buoyancy as the actual chimney with the same input temperature at the base, but with no heat loss, and no friction loss.
- Graphical outputs of key parameters should be displayed on the screen as the run progresses.

Reliability and Efficiency of the Program Code

Some features of the BASIC language could be used to better advantage in the program, to improve speed and accuracy of execution. Examples of these are:

- Use of "double precision" in the iteration routine could improve the convergence of that routine.
- Declaring variables that are used as whole integer numbers will increase the execution speed of the program and will eliminate possible inconsistencies in round-off.
- Because of a bug in the "INPUT" command of the BASIC language, the use of the "WRITE" statement for storing the default files should be replaced by the "PRINT" statement.

 (The WRITE-INPUT combination has caused inconsistent data transfer in other similar programs developed by Scanada, although none have been reported to date for the FLUE SIMULATOR program fortunately such gross errors in information transfer are obvious when they occur. This bug in the language has been independently reported by Domus.)

NEED FOR ADDITIONAL MODELLING CAPABILITIES

The topic of spillage of combustion products is broad and the concerns and questions about the functioning of combustion appliances cover a wider scope than can presently be addressed by the FLUE SIMULATOR model. Previous research for CMHC and review of this work by interested parties has led to the identification of different types of combustion systems that can be subject to spillage of combustion products due to systems-type failures similar to those already identified for oil and gas furnaces. These combustion systems are based on wood burning:

- open fireplaces without fresh air intakes
 - with fresh air intakes (either in firebox or in room)
- fireplaces with loose fitting doors without fresh air intakes
 - with fresh air intakes
- fireplaces with tightly fitting doors and fresh air intakes
- fireplace inserts
- fireplaces with forced air jetted into the firebox
- wood stoves conventional
- wood stoves airtight
- and all of the commonly occurring chimney designs for these systems (e.g. masonry chimneys with clay tile liners, and A-vents).

Modelling Considerations Highlighted in the Review

Burning Rates of Wood

Unlike the firing rates of gas and oil appliances - which can be assumed to be fairly constant given an adequate supply of combustion air flowing through the firebox - the burn rate of a wood fire is variable and dependent on a large number of factors:

- quantity, quality (e.g. moisture content) and type of wood
- size and placement of the wood in the firebox
- effectiveness of the design in providing combustion air supply into, and eliminating combustion products from the burn area
- the composition of the combustible material which changes over the various stages of the fire (e.g. paper, kindling, surface of logs, outer portion, inner portion, coal, ashes)
- the temperature of the combustible material which is in turn a function of:
- the burn rates at previous instants and the net retention of that heat within the combustible material. That "retention is a function of:
- the effectiveness of the firebox in retaining/reflecting heat back to the wood (size, shape, materials, open/closed, quantity of ashes at the base, etc.)
- the cooling effect of excess air flow

The opinion was expressed that a strict cause-effect model of the burn rate of a wood pile may not be a fruitful exercise at this stage, since not all the causal mechanisms are known (i.e. the above list is incomplete), and the indicated interrelationships are not easily established or verifiable using existing test data or methods.

As an initial approach, a burn rate which is only a function of time, (and perhaps quantity of wood) could be modelled as an "independent" heat source in the firebox. By "independent" it is meant that the burn rate would be predetermined by a time-dependent function and not determined by the chimney draft or any other factor listed above. A check on the availability of oxygen for combustion would be made, to signal problematic or unrealistic combustion conditions. CCRL has provided data that could be used to develop this time-dependent burn rate. simplification is considered justified since it is the ability of the chimney system to ventilate combustion products from a fireplace that is the focus of this work, not the intricacies of wood fires and the effect of fireplace and wood-stove designs on the behaviour of these. The extent to which these two phenomena can be modelled independently will be determined in the next stage of work.

Other issues related to fireplace/wood stove and chimney modelling were put forward:

- The fresh air intake to the fireplace represents a third air stream into/out of the house. The added complexity of another air stream through the envelope, presents a problem for the iteration routine, which already requires excessive computation time for determining the existing two unknowns in

the mass flow equations: furnace inlet air flow, and flue inlet air flow. The handling of the fresh air intake stream will also have to be flexible enough to differentiate between the introduction of that air into the firebox and just outside the firebox. The latter case could be handled by increasing the envelope ELA by the appropriate amount, and adjusting the envelope's Vertical Centre of Leakage downwards.

- Phase change energies in the chimney will have to be accounted for.
- Kinetic and potential energy interactions in the space above the flame of an open fireplace: how are these swirling flow conditions best modelled to determine whether spillage occurs? How are the control volumes best drawn? These questions will be addressed in the next phase.

PLAN OF ACTION

The review process has highlighted the major issues that will be dealt with in the proposed research plan, and has served to focus and direct that plan. However no major redirection of work from that elaborated in the contract document has resulted from this review. Rather, the review has served as a confirmation of the research needs elaborated in the contract document. The details of the work plan are therefore not repeated here.

The exception to the above statement is the modelling of the burn rate of a wood pile (either in a stove or a fireplace). This phenomenon appears to be a function of so many interdependent causal factors that a "first generation" wood burn rate model should be developed before a more rigorous cause-effect model is attempted. This simple model would be used to investigate chimney venting performance as it responds to other factors in the house/exhaust fan/envelope system. A more detailed wood-burn model that responds to such factors as firebox wall characteristics could be attempted if funds permit; however, a full investigation of such a model would run the risk of cutting out other planned refinements (given the present budget for the modelling work).

The phenomena that will be studied and modelled are:

- the burn rate of a wood pile in fireplaces and wood stoves (first generation model)
- the performance of fireplace chimneys:
 - open, no fresh air intake
 - open, fresh air intake

- with loose fitting doors, no intake
- with loose fitting doors, with intakes
- tight doors and intakes
- inserts
- with forced air jetted into box
- wood stoves conventional, airtight
- mixed flows or two way flows in flue pipes and flues (SRC work plan in Appendix "B")
- pollution impact of combustion gas spillage (YUILL work plan in Appendix "C")
- friction factors in the flue pipe, flue and furnace
- effect of shared flues
- the modelling of the performance of various remedial measures identified in Project 5. (Draft inducers in-line power venters, combustion gas spillage chamber, etc.)
- refinement of the mathematical handling of the pressure/mass flow and dynamic equations (subcontract to mathematics advisor)
- improving the accessibility and ease of use of the model (with the help of DOMUS SOFTWARE LIMITED)
- wind effects on envelope
- house mass

NOTE ON ACCESSIBILITY AND EASE OF USE

Considerable inroads have already been made in planning improvements to the accessibility and ease of use of the model. A "Screen Handler" program has been purchased from Domus. This program allows the customizing of graphic input screens which graphically identify the required input data and capture data inputs directly from the screen. When integrated to the input module, this feature will reduce greatly the confusion concerning the meaning of physical dimensions requested by the program. The program also allows elaborate "Help" screens (graphics and/or text) for additional assistance to the user. Finally, the Screen Handler screens are pseudo-graphic text screens which can be generated on a system that has a video adaptor without graphics capability. This means that the resulting input routine will still be compatible with virtually all hardware. The setting up of these screens will be undertaken in the next phase.

Additional features of the BASIC language can and will be exploited: simultaneous graphs of key outputs (temperature, mass flows) can be prepared on "alternate hidden screens" - these are prepared by the program but are invisible to the user. The user could "call" these alternate outputs to be displayed to the screen at will. Dumping these graphs to printer will also be possible. These features will be used in the next generation of the model.

An "install" program will be developed to allow the user to specify (once and for all) the type of printer, screen and other hardware that he has, so that the appropriate outputs (i.e. outputs compatible with the hardware) are automatically generated by the code.

Other advanced BASIC languages were investigated to facilitate the addition of more modules to the existing code. One promising such language was "BETTER BASIC" which would, among other features, allow the addition of completely independent modules to the code without interfering or destroying the integrity of the existing code. Unfortunately the BETTER BASIC code would not be compatible with the Domus "Screen Handler" code. Since the "Screen Handler" features are a priority, the BETTER BASIC option had to be dropped.

ATTACHMENT "A"

POINT-FORM SUMMARY OF REVIEW COMMENTS ON THE FLUE SIMULATOR PROGRAM

ATTACHMENT "A"

POINT-FORM SUMMARY OF REVIEW COMMENTS ON THE FLUE SIMULATOR PROGRAM

The following is a point-form summary of comments made by the reviewers of the FLUE SIMULATOR model, as understood and recorded by Mike Swinton. Because of the inexact nature of the recording procedure, odd phrasings and missed points should be attributed to the procedure rather than the reviewer.

Reviewers: J.H. White, CMHC

D. Fugler, CMHC

A.C.S. Hayden, CCRL

F. Preto, CCRL

D. Eyre, SRC

G.K. Yuill, G.K. Yuill

G. Mousseau, Domus Software & Associates

INTERVIEW WITH J.H. WHITE, D. FUGLER, OF CMHC, Nov. 26/85

- wood burning appliances are a priority area of research for the modelling process
- fireplace chimney drafting design is complex see "Fireplace
 Technology in an Energy Conscious World" by H. Morstead
- the following fireplace configurations should be considered
 - open fireplace, no outdoor air supply
 - fireplace with leaky doors
 - fireplace with fresh air supply
 - a) supply into firebox
 - b) supply into the room and the fireplace
 - fireplace with tight doors and fresh air supply
 - fireplace inserts
 - forced air supply (jetted into fireplace)
 - free standing (interior chimney with large diameter "bell")
- the impact of wind conditions on chimney flow <u>and</u> air intake flow should be modelled
- different type of chimney structures should be investigated (clay liner/A-vent)
- key parameters (characteristic lengths and velocities) should be used in the analysis
- phase change energy, kinetic and potential energy are needed to describe the wood burning process

- radiant energy out of and reflected back into the fire has to be accounted for
- the physical placement of the fire is a factor that affects spillage
- care has to be taken in defining the <u>control volume</u> in which the burning process takes place. Flow vectors into and out of that volume have to be identified
- the nature of the ash bed influences the wood burning process by way of an effective heat transfer rate down from the fire
- how does the "energy return" affect the firing rate?
- firebox surface temperatures, surface film, absorptivity/ reflectivity, emissivity characteristics have an influence
- in the chimney, the concept of "displacement thickness" to model the "zero" flow boundary layer should be used
- glass doors should be modelled as two distinct surfaces:
 - solid surfaces
 - gaps
- quantity of wood will affect the burn rate
- there are several stages of the fire to consider
 - light-up
 - blazing
 - late blazing
 - coals

Other general comments about the FLUE SIMULATOR model:

- the concept of boundary layer "displacement thickness" should be used to model flue flow
- more dimensional detail and flexibility is needed to model flue pipe and portion of flue running through the attic
- flue performance results should be explained in terms of "equivalent chimney lengths" or other related "visual"quantities
- graphical aids for impacts and graphical outputs are needed
- a library of standard materials properties and/or typical chimney construction should be available for selection by the user. The user would then have the option of simply calling up the type of chimney or material, or enter the properties himself.

INTERVIEW WITH SKIP HAYDEN AND FERNANDO PRETO OF CCRL, Dec. 16/85

On wood burning:

- most open fireplaces operate at very high excess air: 1200-1800%
- with tight fitting doors this can be reduced to say 150% excess air
- the burning rate is affected by many factors. For example, the way the wood is put in and stacked, the size of the wood pieces, etc.
- the firing rate can be tripled by having a previously warm fireplace
- instances have been recorded of tight wood stoves "throwing" their flames out of the door when they are opened
- a good fire in a fireplace can burn 12 kg of wood per hour in a fireplace. Typical such fires can produce flue flows of 200 1/s.
- Fernando Preto is presently (Dec./85) working on a fireplace combustion model to determine flue size and fresh air intake size. (Should be ready by end of January)
- 400°F is a typical minimum flue gas temperature for a fireplace at steady-state operation
- modelling of a wood burn, based on all known causal factors, is considered impractical because the interrelationships are unknown and have not all been measured

Typical combustion data was provided, as well as CCRL research reports and related documents

EXCERPTS FROM WRITTEN COMMUNICATIONS WITH DAVID EYRE, SRC, Dec. 9/85

Note: Only the portions of these communications that relate to model review have been reproduced here



15 Innovation Biva Saskatoon Sask Canada S7N 2X8 Phone (306) 933-5400 Telex SARECO 074-2484

December 9, 1985

Mr. John Haysom
Project Coordinator
Scanada-Sheltair-Consortium Inc.
436 MacLaren Street
Ottawa, Ontario
K2P OM8

Dear John,

Re: Modification and Refinement of FLUESIM Model.

- LNRELATED TO THE EVALUATION -

At the present time my knowledge of FLUESIM is limited to the Flue Simulator report dated June 12. This gives me only a rough descriptive outline, lacking the detail that I have requested above. Once I get this information I will be able to serve you much better in this respect.

On the basis of the information you have supplied so far, I have three constructive suggestions:

- 1. I am a firm believer in the use of a "mouse" in connection with programs like FLUESIM, and I recommend that you consider incorporating the necessary software and hardware. It would enormously improve the "user-friendly" aspects and is well suited to MENU applications.
- 2. I suspect that the "vertical centre of leakage" could be made much more flexible and meaningful, but I would have to see more details before making specific recommendations.
- 3. I think that the success of the FLUESIM model will eventually rest on how effectively it accounts for wind effects. The Consumers Gas study, conducted for BETT, has shown that the backdraft effect in both steady state and start-up is very sensitive to wind conditions. The dynamic velocity head of the wind could be several hundred Pascals, yet the critical dividing line between backdraft and normal operation may depend on changes of the order of 1 to 2 Pascals. If only a trivial fraction of the dynamic wind head is impressed on the house, it could have a considerable effect on flue performance.

Although FLUESIM should work equally well for all houses, its greatest application will be found in relatively airtight houses, where the risk of backdrafting is generally higher. I suspect that such houses, with their smaller range of air leakage openings, are much more sensitive to wind direction than the average leaky house. Thus, we may have to deal with wind directional effects in addition to wind speed effects.

In FLUESIM, these issues reduce to two basic questions: how can we best introduce wind effects through input pressure differences between points 1, 2 and 3 (figure 1)? and how can we do the same between points 8 and 9?

As far as I am aware, the state of the art gives us little useful guidance. What is needed, as a first step in solving the problem, is a careful monitoring of wind pressure effects at air supply inlets (close to ground level) and at the top of the flue. I have suggested this on several occassions, but no-one has ever seemed

Sock alchewan

recognize the importance of such work. Simple exploratory tests could be conducted quite cheaply in situ, using well-instrumented test houses such as the one we have at SRC. If you would like to discuss this further, please contact me.

- UNRELATED TO THE EVALUATION -

Yours sincerely,

Dan Gar.

D. Eyre
Energy Program Manager
Buildings & Energy Technology Program
Resources Sector.

DE/sn

Enclosure.



TELEPHONE INTERVIEW WITH GREN YUILL, Nov. 19/85 and Dec. 30/85

(written communications, also attached)
[comments by M.C. Swinton are in square brackets]

General comments on ease and access and use of the FLUE SIMULATOR model:

- more detailed drawings of both oil and gas furnaces would help the data preparation process
- explanations are needed about mass and heat capacity of furnace heat exchangers which are requested or shown in the input module
- more background is needed on material properties (for example, what is the heat exchanger made of in the default file?) [steel]
- are the heat loss equations from the flue one dimensional?

 Do they take into account the increasing surface area in the radial direction? [One dimensional, increasing areas accounted for at each node.]
- the input screens with the default data should be printed out to assist in the preparation of data, and training new users
- the linearization of the heat transfer equations can result in error for larger time steps [this is why it has to be kept so small in most cases]. An exponential decay type of equation might allow larger time steps.

- what triggers the furnace air circulation fan to turn on/off? How is this observable in the outputs? [The on/off times are preset at 50 seconds after furnace start and 30 seconds after shutdown, lines 1150 and 1120 of the code.]
- some changes in inputs (e.g. fan exhaust rate) made while a run is interrupted are not carried through when run is resumed. [the "interrupt-resume" feature assumes that no changes are made during the interruption. To change fan exhaust rate, abort run at desired stage, store that end state in a file, then start with that file as the new default file with any desired change made to the new data set. This procedure needs explanation in the manual.]
- assumption of incompressibility of air in house can lead to error - see attached letter by Yuill
- manual needs a "How do I know this works?" chapter validation results etc.
- the option to select the desired parameter to print out would be desirable
- more definitions and explanations of outputs are required
- less confusing terminology should be employed: flue, flue-pipe, chimney, flue gas, stack gas - all of these terms are separate physical entities yet have related names that do not necessarily convey the separate entities to the user. Perhaps a few figures with labels would help.



Consulting Engineers

FILE: 5141, DD#24, W

JAN 6 1986

DECEMBER 30, 1985

Mr. Mike Swinton SCANADA CONSULTANTS LTD. 436 McLaren Street OTTAWA, Ontario K2P OM8

Dear Mike:

I hope my comments about FLUESIM in today's phone conversation were helpful to you.

It will take a net inflow of 5 L to pressurise the air in a house by 1 Pa. This magnitude of pressure change sometimes occurs in one second in some of the runs I have made, so it could be a significant element of the flow balance. As I recall, the expansion of the walls of a house with pressure is even greater than the compressibility of the air in the house, so the combination of these effects could be significant.

I gather than your flow model in the chimney is that of a set of fully mixed slugs. This will underestimate the temperature of the gas leaving the chimney (and overestimate the buoyancy of that in the chimney) in a transient start-up situation, because the hot core flow will move faster. This is particularly true in this case, where viscosity and buoyancy combine to retard the boundary layer. It might be worthwhile doing some analysis to see if this is important.

Since most houses are either pressurised or depressurised by their furnace fans, it might be a good idea to build this effect into the program, so that the fan flow would change by a specific amount when the furnace fan goes on.

As I told you on the phone, I am very impressed with the capabilities of FLUESIM. I have done quite a few consistency checks on the output data and everything seems to work just as it should. The only concerns I have about the model you use are those mentioned above. The first two probably have an insignificant impact on program accuracy, and the third relates to program capability rather than accuracy. Apart from the few

G.K. Yuill & Associates Ltd.

Consulting Engineers

minor points which I made in our phone conversation, I found the program easy to use and to understand.

I will now develop a plan for building a CO source model and fan and chimney air flows into my INFIL program. I will carry this out in as much detail as is possible within the budget you have allowed me for this segment of the project.

Sincerely,

G. K. YUILL AND ASSOCIATES LTD.

G. K. Yuill Ph.D., P.Eng.

GKY:al

NOTES OF COMMENTS MADE BY GILLES MOUSSEAU OF DOMUS SOFTWARE LIMITED - Dec. 11/85

- there is a "bug" in the BASIC language involving the "WRITE" and "INPUT" statements - data in a file can be misread with these sequence of statements. The FLUE SIMULATOR program should be reviewed and tested to ensure that this problem will not occur.
- a "zero" line can be created in the program to store procedure messages that will make the program easier to modify in the future. This will also ensure that only one version is needed for both interpreted and compiled runs.
- care should be taken to define/declare the type of variable that is being used: - Integer
 - Floating Point
 - Double Provision

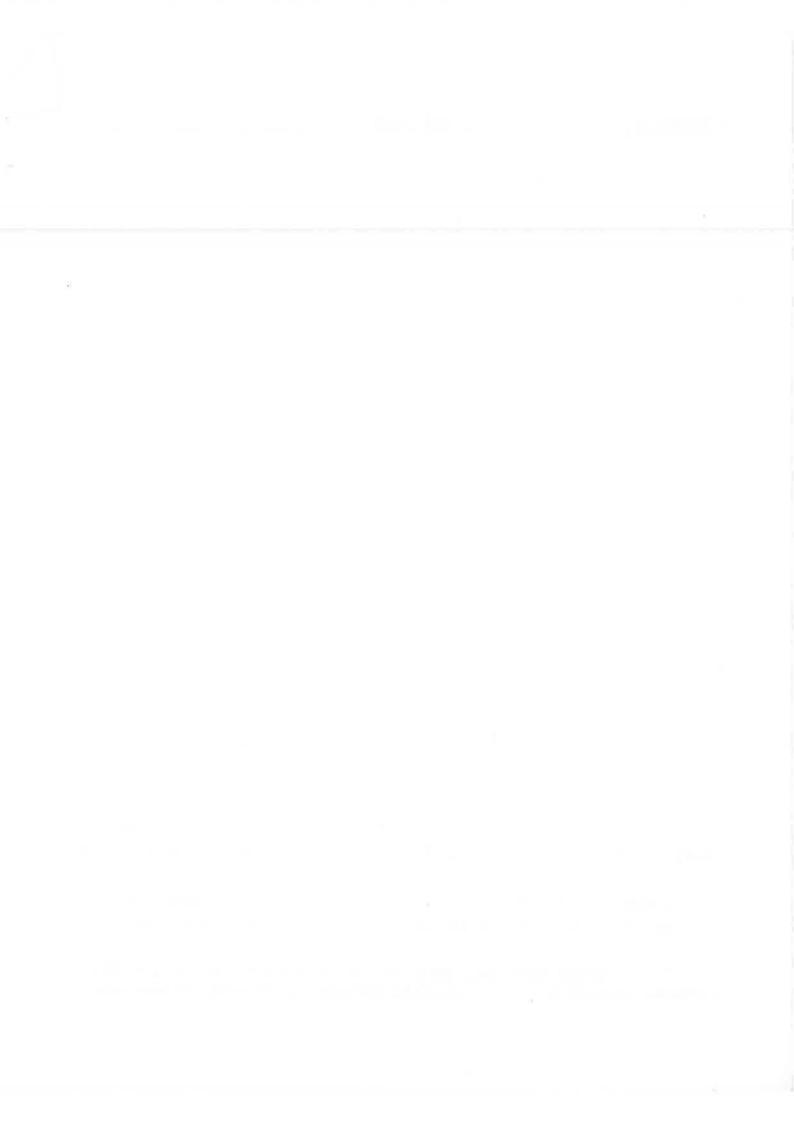
When conversions between these are left up to the machine, it takes more time, and round-off errors can occur

- all user inputs should be handled by "FLUEIN" at present, some inputs are in FLUE SIMULATOR, and this can get in the way of production runs
- the use of "double precision" in the interaction routine could improve convergence of the routine
- line 26021 should read:
 "IF Y > = 3" NOT "IF Y > 3"

as a result of this error, the flue gas velocity of element 2 in the flue pipe is being used in element 3 instead of its

own calculated value. [This is minor consequence to the accuracy of the model, but it is an error nevertheless.]

A considerable number of tips were given by Mr. Mousseau to clean up the code, and improve the execution speed.



ATTACHMENT "B"

THE DEVELOPMENT OF A BI-DIRECTIONAL FLOW MODEL FOR THE FLUE SIMULATOR PROGRAM

1. INTRODUCTION

SRC is pleased to be selected as a sub-contractor by the Scanada Sheltair Consortium Inc. for work relating to the project entitled "Residential Combustion Venting Failure - A Systems Approach: Project 2 - Modification and Refinement of the FLUESIM Model".

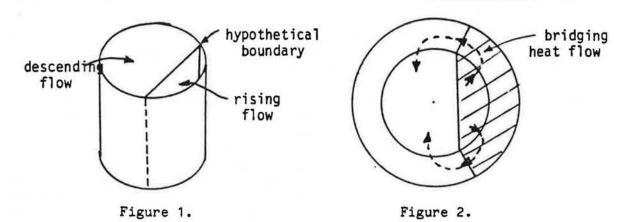
2. APPIAISAL OF THE PROBLEM

The Scanada FLUESIM computer model is an excellent first attempt at modelling flue behaviour in terms of the entire house "system". The model is necessarily limited at this stage of its development, though this will doubtless be remedied by the inclusion of new knowledge and refinements. One of the most important of these refinements will relate to bidirectional flow: a rising stream of hot flue gases coexistent with a descending stream of cold exterior air. There are indications that this situation exists in practice, and even a simple examination of the flow processes provides us with good reason for its existence. Accepting this, the bi-directional flow regime could be the dominant regime during furnace start-up, and it could also be influential in over-sized flues under steady-state conditions.

The main difficulty lies in modelling this flow regime. Fortunately, we are assisted in this by pseudo-secret theoretical developments in nuclear reactor heat transfer - developments in which the author of this proposal has had considerable experience.

In nuclear reactors the fluid flow and heat transfer processes are often complicated by a mixture of surfaces: for example some surfaces may be smooth while others may contain extended surfaces (fins) or turbulence promoters (surface roughness). When conducting research on these configurations it is not always possible to reproduce the channel geometries, and a research model may contain a mixture of rough and smooth surface effects that is quite different from the real-life mixture. As a result, the model may give a poor representation of the real-life situation. To overcome this problem a mathematical technique has been developed for separating the flow effects of rough and smooth surfaces by setting up hypothetical boundaries in the flow. This is now a well established and well proven technique, but unfortunately it has been developed and applied under conditions of commercial secrecy and has never been exposed to the open scientific literature.

Addressing the problem of bi-directional flow, it is proposed to model the flow using a hypothetical boundary between the two flow regimes. At this early stage, the most convenient form of the boundary would appear to be a flat surface dividing the channel into two distinct parts (figure 1). A model based on this approach will involve the following considerations:



- Development of a procedure for establishing the position of the hypothetical boundary.
- Establishing a reasonable model for momentum transfer across the boundary, as a basic first step in setting up the flow regimes.
- Establishing reasonable models of heat and mass transfer across the boundary. The heat exchange between the two flow regimes will have a considerable effect on temperature distributions, and this in turn will have a significant secondary effect on pressure distributions and position of the hypothetical boundary. The mass transfer across the boundary is perhaps the most important factor, since it determines the rate at which combustion gases are entrained in the downward air flow and carried back into the house environment.

It must be stated, at the outset, that the proposed model will be a considerable oversimplification of the actual state of affairs. It is unlikely that the boundary between the two regimes will be flat, let alone stable with time. It is more likely to be sinusoidal or randomly varying with time and space. Indirect evidence of this is provided by the Consumers Gas Study, conducted under the BETT program, in which a bouncing air column was observed in the flue under certain start-up conditions. Part of this may be explainable in terms of shifts in the flow regime in the flue. Another obvious weakness of the plane boundary can be seen by looking at the way in which the flue connector is joined to the vertical flue. This geometry will obviously lead to secondary flow patterns at high flow rates, giving strong coupling flows between the two flow regimes. But at low flow rates (ie. creeping laminar flows) the likelihood of secondary flows will be small.

The justification for the proposed model is that it will give us a manageable and achievable basis for modelling the bi-directional flow regime. Its limitations are necessary within the current state of the art, and may possibly be overcome by later refinements and developments.

It is proposed to develop the model in a series of stages, each stage representing an advance in complexity. This approach is preferred by the author as a way of keeping track of the legitimacy of the model. Thus, the first stage will consist of a simple zero heat transfer model (isothermal). The next stage will look at the effects of heat transfer between the two flow regimes and into the flue wall, using a simple model for the flue wall. The next stage will look at a more complicated wall model, in which heat can flow from one regime to another via the wall (figure 2). The next stage — difficult to foresee at this time — may consist of refinements such as a density-related acceleration term and changes in friction factor and heat transfer coefficient with distance (ie. non-fully-developed boundary layer effects). When the model has been refined to a reasonable level, including momentum and heat transfer mechanisms only, the final step will be to develop a matching mass transfer model.

Both in developing this model and in fitting it into the existing FLUESIM program, it will be necessary to have a detailed knowledge of the internal workings of FLUESIM: the algorithms, the assumptions, the built-in boundary conditions, the selected method of iteration, etc. It will be impossible to proceed without this knowledge. This is already clear from initial development work on the model: several criteria, defining different flow modes, have already presented themselves, but these criteria cannot be fitted into the FLUESIM model without knowing how FLUESIM deals with pressure loss coefficients at entrances and exits. Similarly, it is likely that the bi-directional flow model will involve modification of the finite element techniques currently used for modelling the flue.

All this suggests that there should be a strong liaison between SRC and Scanada at all stages of the work, to ensure that the new bi-directional model is fitted into FLUESIM as efficiently as possible, and to the satisfaction of the authors of FLUESIM.

APPENDIX "C"

OVERALL PROJECT SUMMARY

OVERALL PROJECT SUMMARY

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 supprojects 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
- post-1975 houses
- one storey houses
- exterior chimneys

- masonry chimneys with under-sized metal liners
- houses with three or more exhaust fans
- houses with two open masonry fireplaces
- 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 WOOD BURNING SIMULATOR, 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 -

- Review of current knowledge on pollutant generation due to improper venting of combustion appliances (literature review).
- Development of a computer program to predict levels of various pollutants under various combustion venting failure scenarios.
- 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 NO2, 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 fireplace.

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 depressurization 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 inves-

tigated 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 fluc 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.