MODIFICATIONS AND REFINEMENT OF THE
COMPUTER MODEL "WOOD BURNING SIMULATOR"

A Study Prepared for

CANADA MORTGAGE AND HOUSING CORPORATION

by

Scanada Consultants Limited

August 25, 1987

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

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

Under Part V of this Act, the Government of Canada provides funds to CMHC to conduct research into the social, economic and technical aspects of housing and related fields, and to undertake the publishing and distribution of the results of this research. CMHC therefore has 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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EXECUTIVE SUMMARY

The characteristics of wood burning and their relative fireplace designs were investigated by refining and calibrating the wood burning simulator model. The investigation included -

- *a literature review*
- *a review of applicable codes and standards*
- *modification of the WOOD BURNING SIMULATOR computer model to allow it to model fireplace wood burning for a number of fireplace configurations*
- *generation of field data on the performance of a fireplace*
- *calibration of the modifications to WOOD BURNING SIMULATOR using data generated in field tests on open fireplaces*
- *use of the WOOD BURNING SIMULATOR model to illustrate the capabilities of the model*
- *incorporation of user friendly features to improve the accessibility and utility of the program*

The model was successfully refined and calibrated such that the main characteristics of wood burning and the performance characteristics of various fireplace enclosures can be simulated with some confidence.

The work has highlighted some of the aerodynamics and thermal design concerns that arise from introducing doors and a dedicated combustion air intake to a fireplace. Although this combination can be a remedy to prevent house depressurization by the fireplace, it introduces several other ways in which the fireplace can be a hazard.

Difficulties in calibrating the model have highlighted the complexities involved simulating a wood fire.

INTRODUCTION

As part of its ongoing study of combustion venting problems in Canadian houses, Canada Mortgage and Housing Corporation engaged the Scanada Sheltair Consortium to conduct studies to assist in the design of wood burning devices - with emphasis on fireplace design - so that these can operate safely in the house environment.

The WOOD BURNING SIMULATOR model had already been developed by Scanada Consultants as part of a previous contract for CMHC. It was an outgrowth the FLUE SIMULATOR model developed for CMHC by Scanada. FLUE SIMULATOR is a detailed theoretical computer model of the combustion venting process of oil- and gas-fired appliances and the interaction of that process with the building envelope and the building ventilation system. 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 those mechanisms. WOOD BURNING SIMULATOR is an extension of FLUE SIMULATOR to allow the study of the combustion venting process of wood-fired appliances. It is necessarily more complex because, whereas the combustion process in oil- and gas-fired appliances is a steady state process, the combustion process in wood-fired appliances is highly variable and thus the model must include an extensive module just to model the combustion process.

Although Version 1.0 was developmental, it was able to model the combustion venting system well enough to predict start-up spillage and chimney flow characteristics throughout a burn cycle. However, several limitations of that version did not allow safety issues related to the operation of fireplaces and wood stoves to be properly simulated. The focus of this project was therefore on refining the model sufficiently such that the following phenomena could be investigated:

- air supply to a closed firebox (e.g. direct outdoor air intake to a fireplace with airtight glass doors)
- heat transfer to materials surrounding the firebox

The following tasks were performed as part of this project:

- Review of the existing model
- Review of codes and standards on fireplaces
- Refinement of the model
- Calibration of the model against field data

Each of these tasks is discussed in detail in the following sections.

REVIEW OF THE EXISTING MODEL

The WOOD BURNING SIMULATOR model, as presented at the completion of the project "Residential Combustion Venting Failure - A Systems Approach" (2), was a successful first stage in the development of a model of the wood burning process. However, the comments of users of the model and Scanada's own use of the model indicated that there was considerable room for refinement of the model in the following areas:

Wood Charge Configuration

The wood charge was not a user input but was built into the program code. Thus only one configuration could be used whether one was modelling a fireplace or a wood stove and the effect of charge configuration on performance could not be investigated easily.

Geometry and Radiation Shape Factors for the Firebox Enclosure

The model did not calculate radiation shape factors for the various sides of the firebox enclosure nor did it take into account the geometry of the enclosure. Thus the effects of firebox geometry on radiation from one side of the firebox to other sides and to the room could not be investigated.

Radiative Heat Loss From the Flame

The model did not account for radiative heat loss from the flame and thus may have predicted higher flue gas temperatures and lower heat transfer to the enclosure walls and room than would actually occur.

Heat Transfer From the Enclosure

The model did not account for the transfer of heat from the fireplace or stove enclosure to the surrounding room or structure. Thus it was unable to predict the effect of -

- the fire on the temperature of the enclosure walls,

- the temperature of the enclosure walls on the fire,

- the temperature of the enclosure walls on nearby combustibles, and

- all the above on the heating efficiency of the device.

Combustion and Dilution Air Supply

The model was able to model a variety of combustion and dilution air supply strategies only crudely or, in some cases, not at all. For instance, the combination of truly airtight doors with a separate exterior air supply was difficult to model.

User Interface

WOOD BURNING SIMULATOR did not make use of graphic input screens as used in FLUE SIMULATOR, nor did it allow as wide a range of input conditions.

REVIEW OF RELEVANT CODES AND STANDARDS

The following codes and standards were reviewed for this project:

- National Building Code, 1985 (NBC)
- proposed changes for the 1990 edition of the National Building Code
- Ontario Building Code, 1983 (OBC)
- CSA-A405 - Design and Construction of Masonry Chimneys and Fireplaces, Draft Standard.
- ULC-S610-83 - Standard for Factory-built Fireplaces
- ULC-S628-82 - Standard for Fireplace Inserts
- ULC-S638 - Standard for Glass Doors for Masonry Fireplaces, Draft, 1984.

The information gleaned from this review that is relevant to this project was as follows:

- The required clearances of combustible materials from site-built solid fuel burning devices are quite clearly spelled out in the NBC and OBC (identical). These are shown in Figure 1. Both codes currently reference ULC-S610 regarding requirements for factory-built fireplaces and ULC-S628 for fireplace inserts. The clearances for factory built fireplaces are the same as those for masonry fireplaces.

- The current edition of the NBC specifies minimum clearances for wood stoves. The proposed changes for the 1990 edition of the NBC indicate that all requirements for solid fuel burning appliances will be dealt with by reference to CAN/CSA-B365. Minimum clearances under the most recent edition of B365 are 300 mm greater than those stipulated by the NBC code. The NBC clearances are shown in Figure 2.

  While the codes have, in the past, included only "motherhood-type" statements on combustion air supply (e.g. "Compensation shall be made for air drawn by other appliances or exhaust equipment"), one recent standard, ULC-S610-M1983 recommended designing combustion air inlets as follows:

  > *5.12.1 Where a fireplace is provided with combustion air inlets, the ducting to the fireplace shall be at least as large in effective area as one half of the area of the flue.*

More recently, references to the design, construction and operation of wood burning appliances are becoming more specific, at least for fireplaces. For example, it is proposed to include the following in an Appendix to Part 9 of the 1990 NBC:

1) *The combustion air in Article 9.22.1.4 is supplied by a duct having a minimum diameter of 100 mm or equivalent area.*

2) *The air supply duct is noncombustible, corrosion-resistant and where exposed to room air shall be insulated for its entire length with thermal resistant insulation having a thermal resistance value of RSI 1.41*

3) *The air supply outlet is to be located as close to the fireplace opening as possible.*

4) *When the air supply outlet is placed inside the fire chamber, it is located at the front centre of the chamber hearth and is equipped with a non-combustible*

hood which when open will direct air away from the fire and shall be designed to prevent embers from entering the supply duct.

5) *The supply duct contains a tight fitting damper when in the closed position and such damper is located close to the outlet end.*

6) *The damper is operable from the room containing the fireplace and the control mechanism shall clearly indicate the actual position of the damper.*

7) *The air supply duct is installed with a minimum 50 mm clearance from combustibles for 1 m distance measured away from any outlet duct located in the fire chamber.*

8) *The exterior air supply duct is protected against the entry of rain and direct wind. The inlet opening shall have an insect screen of corrosion-resistant material.*

9) *The exterior air supply duct inlet is located to avoid being blocked by either snow or fallen leaves.*

Review of the draft ULC standard on glass doors for masonry fireplaces indicated that the glass in glass doors must be loose fitting (with allowance for vertical and horizontal movement of 3 mm and lateral movement of .1 mm) or be provided with resilient, heat resistant, gasketing materials of equivalent dimensions. This standard is also used by ULC for factory-built fireplaces.

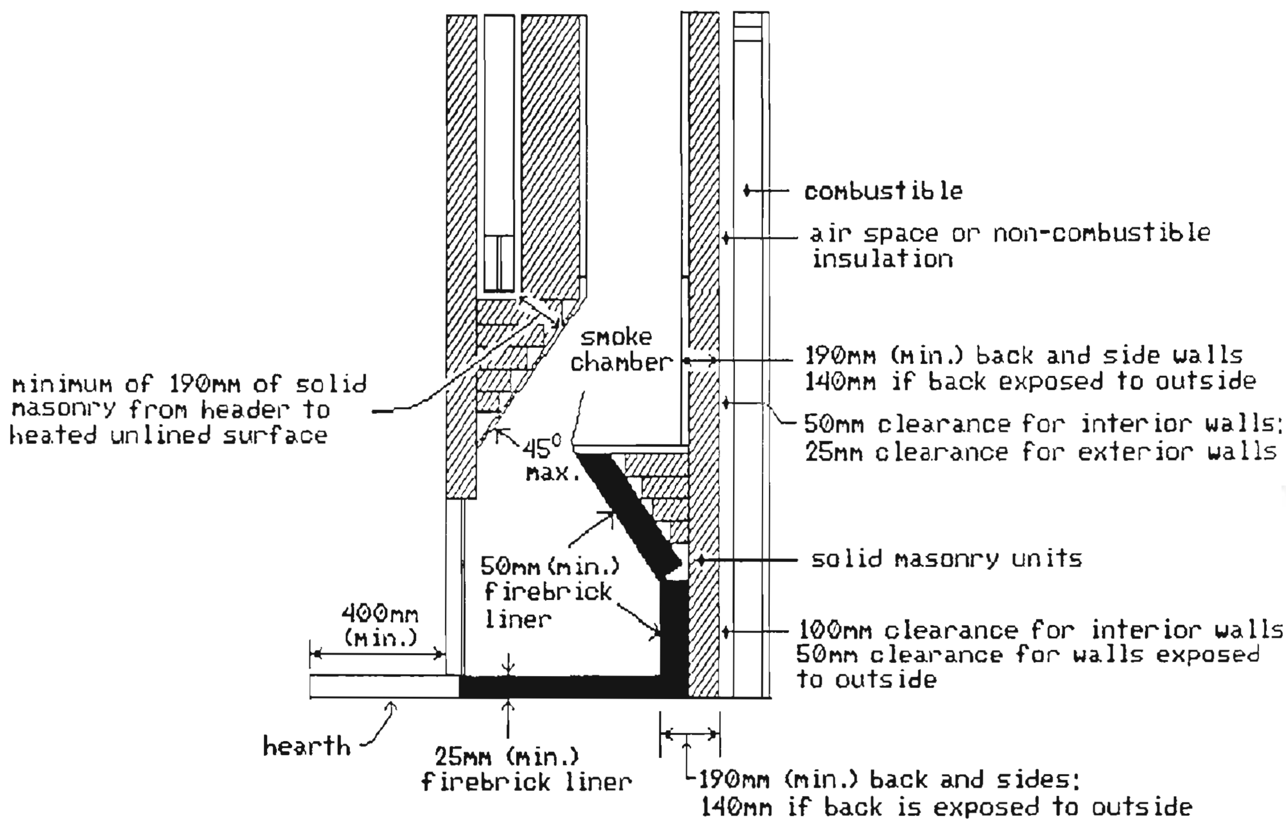
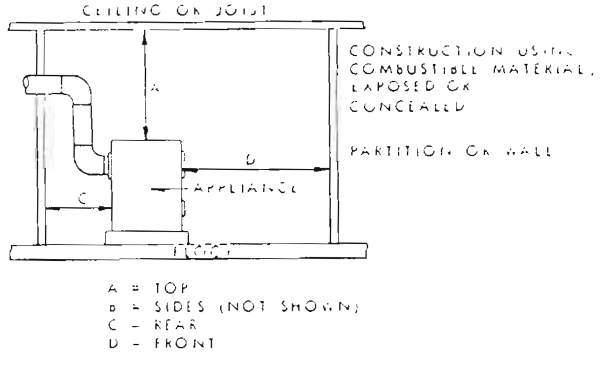


FIGURE 1: Minimum clearances to combustible materials for site-built solid fuel burning appliances

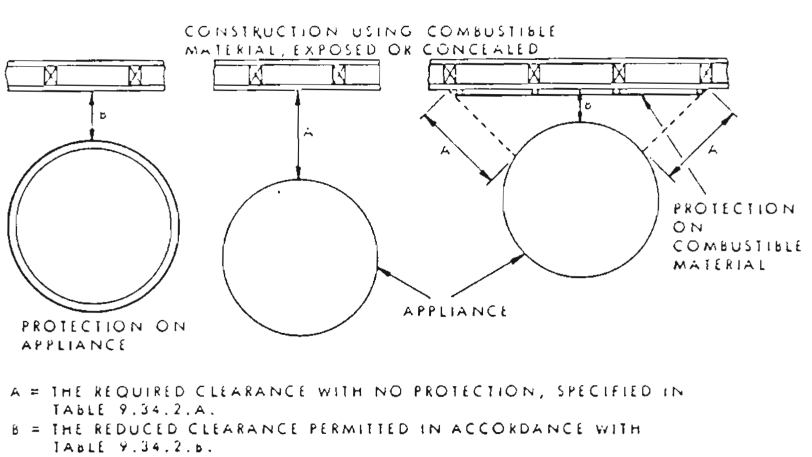
Table 9.34.2.A.
Forming Part of Article 9.34.2.4.

MINIMUM CLEARANCES TO COMBUSTIBLE MATERIAL FOR STOVES, RANGES AND SPACE HEATERS USING SOLID FUEL

Appliances	Minimum Clearance, mm			
	Top	Sides	Rear	Front
Stoves and *ranges* without refractory lining	1 200	—	900	1 200
fire box side	—	900	—	—
other side	—	450	—	—
Stoves and *ranges* with refractory lining	1 200	—	600	1 200
fire box side	—	600	—	—
other side	—	450	—	—
Space heaters with at least a 50 mm air space between the outside of the fire chamber and external casing to allow air circulation	1 200	600	600	1 200
Space heaters other than above	1 200	900	900	1 200
Column 1	2	3	4	5



(a) BASIC CLEARANCES (TABLE 9.34.2.A.)



(b) CLEARANCES WITH PROTECTION (TABLE 9.34.2.B.)

FIGURE 2: Minimum clearances to combustible materials for stoves, ranges and spaces heaters using solid fuels

REFINEMENTS TO WOOD BURNING SIMULATOR

New and Refined Algorithms

One objective of this phase of work was to refine the current WOOD BURNING SIMULATOR model sufficiently to allow investigation of the following key issues:

- The adequacy of current code requirements for clearances to combustibles especially with respect to fireplaces incorporating tight doors and dedicated combustion intakes.

- The effects of doors and dedicated intakes on the draft of fireplace chimney flues.

The following refinements were incorporated into the model to achieve the above objective:

1) **Flame radiation to surrounding firebox enclosure.** This algorithm was added in order to model the wood burning process more realistically, allowing proper distribution of the total heat of combustion into wall radiation and energy lost up the flue.

2) **Re-radiation from firebox walls to other surfaces.** The primary purpose of this modification was to account not only for radiation between the different surfaces of the firebox but also for radiation from the firebox wall surfaces to the room.

3) **Conductive/convective heat transfer through the firebox enclosure.**
The original WOOD BURNING SIMULATOR model did not model the heat transfer process through the firebox walls and surrounding structure. The incorporation of this algorithm would allow determination of temperatures within the firebox walls.

4) **Heat transfer and leakage effects of doors.**
This algorithm was designed to allow the investigation of the effects of fireplace doors with various leakage characteristics on the temperature gradients through the firebox walls and surrounding structure. The heat transfer algorithms of the fireplace doors are a subset of the generalized heat loss algorithms for the walls.

5) **Combustion air intakes for fireplaces.**
This algorithm was intended to accommodate the trend towards tight glass doors combined with dedicated combustion intakes both in newer fireplaces and retrofit applications.

Figure 3 depicts all the energy flows of interest.

The algorithms used are described in detail in Appendix A.

User Interface

A second objective was to make the model easier to use.
The input portion of the model was modified to allow the user to define the characteristics of the wood burning appliance (i.e. wall thickness, area, material properties, shape factors),

different woodpile configurations and the various influence indicators that describe the ignition sequence of each element of the woodpile.

Further refinements included the incorporation of most of the "user-friendliness" features of the latest version of FLUE SIMULATOR, such as graphic data input screens with help screens, error trapping and graphic outputs.

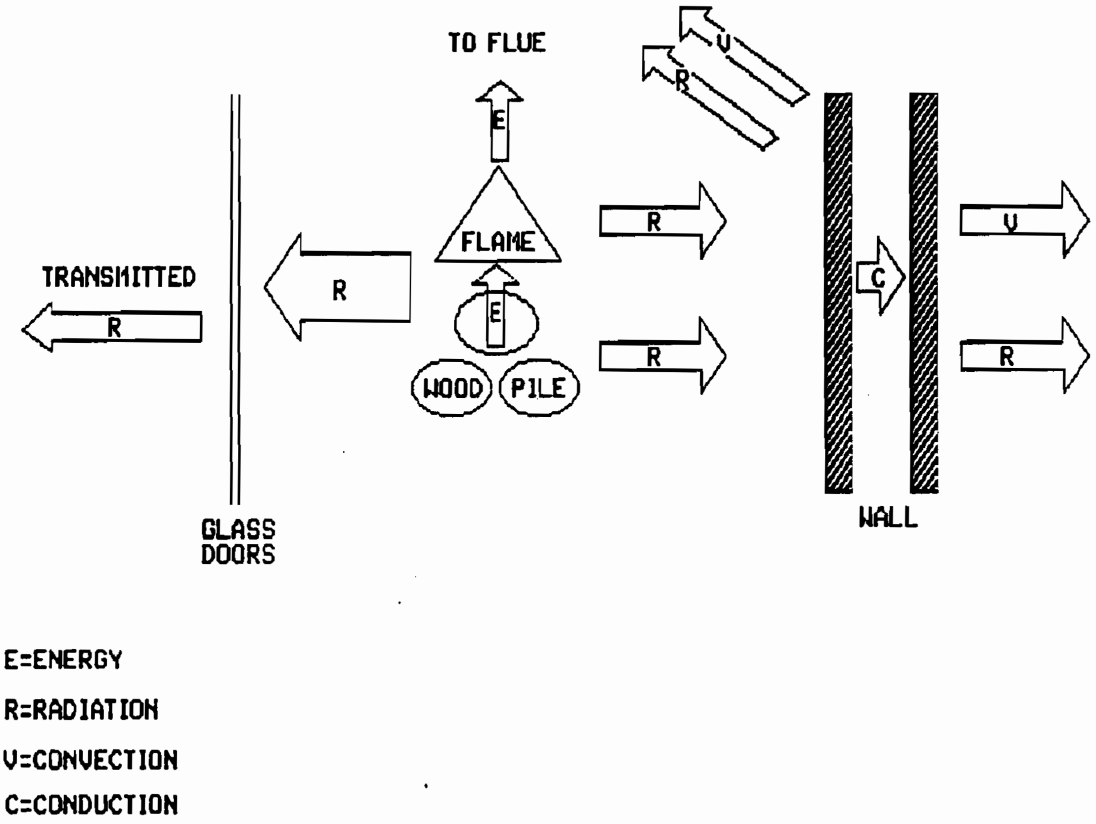


FIGURE 3: Schematic of the energy flows for the woodpile and firebox

CALIBRATION OF THE MODEL

Two sets of field data were available that were suitable for use in calibrating the model. The first came from tests carried out by Sheltair Scientific Inc. specifically for this purpose as part of this project. The second set of data came from an Underwriters Laboratories Inc. (UL) report on fireplace tests (4).

The tests conducted by Sheltair Scientific were heat-up/cool-down tests using wood charges chosen to closely match the standard configuration used in the existing version of the model. Test data collected by Sheltair included firebox wall surface temperatures, flue gas temperatures and chimney flow. Data was collected at selected intervals over an 80 minute period allowing the model to be calibrated dynamically. A full description of the calibration of the model to the Sheltair data is included in Appendix B.

Test data collected by UL differed from the Sheltair data in that the authors of the report were interested in worst case steady state conditions only. Steady state conditions were achieved by performing a "brand fire" test wherein the fire was replenished with an identical wood charge every 7-1/2 minutes until steady state conditions were achieved. The model was temporarily reconfigured to accommodate this test protocol. The report contains only two sensor measurements which the model could be calibrated against. These are the back firebox wall surface temperature and the flue gas temperature above the damper. A full description of the calibration of the model to the UL data is included in Appendix C.

Results of Calibration

The comparisons reported in Appendices B and C indicate that WOOD BURNING SIMULATOR predicts flue gas temperatures and flows reasonably well but significantly overpredicts temperatures of the firebox walls. This is not surprising since, in trying to match both flue gas and wall temperatures to field data, it was necessary to favour flue gas temperature since flue gas temperature determines draft, which controls flue flow, which controls the burn rate. If flue gas temperature were allowed to be too high, the fire would burn too quickly and the wood charge would be consumed in an unrealistically short time. However, in restricting the energy transfer to the flue gas, apparently too much energy was then given to radiation, thus leading to the over-prediction of firebox wall temperatures.

On the other hand, a possible alternative explanation is that the amount of energy the model currently has to deal with is unrealistically high since there are no algorithms to account for the moisture content of the wood. The presence of moisture in the wood has three effects not presently accounted for in the model:

- For a given log weight, there is less wood to burn.
- The sensible heat capacity of the water is a heat sink.
- The latent heat capacity of the water is also a heat sink.

The wood burning process and the response of the firebox enclosure to that process is very complex, incorporating numerous inter-related variables. Many of these were varied in different ways in order to optimize the calibration of the model to the field data. The calibration results reported in the appendices are final results of this optimization process. The process itself is discussed below and the rationales for the decisions currently reflected in the model are given.

Liner Convective Heat Transfer Coefficient

Convective heat transfer coefficients for the inside liner faces were varied from 8.33 $W/m^2 °C$ (conductance for surface air film in still air) to 33.33 $W/m^2 °C$ (conductance for surface air film in moving air). It was found that, for the Sheltair calibration, the effect of increasing the convective heat transfer coefficient was to increase and extend the overprediction of the flue gas temperatures during the cool-down portion of the burn cycle (i.e. higher heat transfer coefficients produced rounded peaks). In essence, more energy per unit time could be picked up by air by-passing the fire and passing over the firebox walls. This energy is transferred to the flue gas.

It was found that use of a heat transfer coefficient of 8.33 $W/m^2 °C$ would result in a flue gas temperature profile that best matched the profile observed in the field (i.e. a spike at the peak instead of a rounded profile). This value was fixed in the model for both the Sheltair and UL calibration.

No attempt was made to vary the heat transfer coefficient as a function of air temperature or velocity; however, this is a future refinement that should be considered.

Lighting Sequence

Two lighting sequences were investigated in the Sheltair calibration. The first was to let the model light only the middle kindling piece to initiate the wood burning process (see Appendix B.3 for a description of the woodpile used in the Sheltair fire). The second method was to let the model simultaneously light all three of the bottom kindling pieces. With the first method, the peak flue gas temperatures occurred at about 10 minutes whereas, when the second method was used, the peak temperatures occurred at about 7 minutes. The latter was more consistent with temperature profiles observed in the field. In addition, the second method resulted in a slightly faster drop in flue gas temperatures after the peak compared to the first method. This also helped improve the match between predicted and field data. As a result, the model now simultaneously lights all three kindling pieces to initiate the wood burning process. Allowing the initial lighting sequence of the woodpile to be user defined is another area for possible future refinement for the model.

Shape Factors

The fraction of energy leaving one body and falling on another is influenced by several factors control. These include:

- relative surface areas of one surface compared to another
- the distance between these surfaces
- the angle of one surface relative to another

All these factors combine to yield a unique factor which describes what fraction of the total radiation leaving one surface falls on another surface. This factor is called various names in various references, including "shape factor", "view factor" and "configuration factor". "Shape factor" will be used throughout this report.

The assignment of shape factor values is a difficult task. Although shape factors for re-radiation between surfaces of the firebox enclosure can be defined approximately using standard textbook data, such data is not available for the wood and the flame (i.e. the distribution of radiation from the wood and flame to all firebox surfaces). During the calibration of the model it was found that reasonable variations in the shape factors describing the re-radiation between firebox surfaces did not affect wall and flue gas temperature profiles to any great degree. Thus, simplifying obliquely angled firebox geometries to equivalent square geometries to facilitate use of standard shape factor graphs (see Figure A.1a and A.1b) was found not to affect the simulation significantly. However, the shape factors that define the flame and wood radiation distribution were found to affect wall and flue gas temperature profiles much more significantly. After trying a number of combinations, none of which resulted in good agreement with the test data, it was decided to allocate 20% of the flame and wood radiation to the sides, front and back of the firebox enclosure. Of the remaining 80%, 50% of the wood radiation is allocated to the floor (because of its proximity to the woodpile) and 30% is allocated to the top of the firebox. The distribution of the remaining flame radiation is 30% to the floor and 50% to the top of the firebox. These values were chosen simply because they resulted in wall temperatures for the Sheltair calibration under 200°C, a reasonable expectation for temperatures of these wall surfaces. The UL fireplace had a geometry similar to that of the Sheltair fireplace and so these same factors were applied to the UL calibration. Flame and wood shape factors represent the weakest components in the definition of the fireplace system. Clearly, more field data is required to substantiate or refine these inputs more accurately.

Burn Rate

The **burn rate** is the rate of combustion of wood expressed as the mass of wood above 204°C (kg) per unit surface area of log (m^2)

per litre of air flow into the pile. Multiplying the burn rate by the total surface area of the wood pile (m^2), the rate of air flow through the woodpile (L/s) and the heating value of the wood (J/kg) yields the **energy release rate** (J/s); i.e. the rate at which energy is released from the burning wood.

The flue gas temperature profiles were found to be very sensitive to variations in burn rate, as would be expected. Increases in burn rate consumed the wood charge too quickly, resulting in an early and high peak of the flue gas temperature profile; lower burn rates delayed and reduced the peak of the flue gas temperature. It was found that a burn rate of 0.0003 $kg/L \cdot m^2$ produced the best fit to the flue gas temperature profiles for the Sheltair field data. This value was also applied to the UL calibration and produced an energy release rate profile consistent with field observations for open masonry fireplaces.

Time Step/Time Constant

One of the concerns during the development and calibration of the model was whether the time steps used with the linear heat transfer algorithms would be appropriate for the fourth power radiative heat transfer algorithms. No authoritative source could be found (within the time frame of the project) that could provide guidance on determining time constants for radiation. However, a simple test was performed whereby two simulations were conducted with different time steps. In one simulation, the time step was fixed at 0.01 seconds. In the second simulation, the model was allowed to determine its own time step (approximately 0.2 seconds). Results from both simulations were compared and there were virtually no differences. This suggests that the time steps set by the model are sufficiently smaller than the fundamental time constants of radiative heat transfer. Future refinement of the model should include further research into radiative heat transfer time constants.

FINDINGS

Although this study did not include a parametric analysis of the thermal and flow performance of a fireplace having combustion air intake and doors, a number of important findings were brought to light as a result of modifying the WOOD BURNING SIMULATOR model to account for the intakes and doors.

Tight fireplace doors have the advantage of decoupling the woodburning process from the house pressure. However, the combination of doors and a combustion air intake introduces a number of additional modes of venting failure that require additional consideration.

- The firebox flow is now perfectly coupled to the chimney flow. This means that downdrafting in the chimney induced by wind patterns about the chimney and the exterior of the house results in downdrafting in the firebox and out of the combustion air intake - a potential hazard since hot coals or ashes can be drawn into the combustion air intake which may be in contact with combustible materials. The use of appropriate flue caps and the judicious placement of the combustion air intake is essential for the avoidance of downdrafting flows for this configuration.

- When air is flowing upward in the chimney, the perfect coupling of firebox and chimney results in the firebox flow and hence the energy release rate of the woodpile being a strongly dependent on net chimney draft. This represents a loss of control of the fire which must be regained by judicious design and regulation of the combustion air intake, or more specifically its stream away from the woodpile, as required by code, also helps to regain control of the combustion process.

- The venting system no longer has an adequate source of dilution air. This results in higher temperature gas entering the chimney. Control over the amount of intake air thus becomes doubly important since, for a given burn rate, the chimney will be hotter and the hotter chimney will induce more combustion air, thereby increasing the energy output of the woodpile.

- With no doors or combustion air intake, combustion gas spillage out the front of the fireplace under low draft conditions is driven by the buoyancy of the hot gases in the firebox. The presence of even loose doors should be enough to foil the weak convection loop that feeds this low-burn spillage mode and kill the fire (i.e. the fire either dies or builds enough to counter the low draft). On the other hand, with a combustion air intake, spillage is driven by the pressurization of the firebox due to the balance of pressures around the firebox/house flow loop (see Figure A.4). With this configuration, very tight doors are likely needed to avoid prolonged spillage since loose glass doors will not likely foil the higher driving pressures that can be developed in the firebox/house loop.

RECOMMENDATIONS FOR FUTURE REFINEMENTS TO THE MODEL

It is believed that the current version of WOOD BURNING SIMULATOR has most of the necessary algorithms to enable the model to be used as a valuable research and design tool. However, the model has only been calibrated with masonry fireplace test data and agreement with that data was not complete. The following is a brief summary of the areas in which further field testing is recommended in order to fully calibrate the model.

1) Measuring temperature profiles through different firebox enclosures such as factory-built fireplaces, masonry fireplaces with inserts, and wood stoves.

2) Measuring the effects of fireplace doors and combustion air inlets on the temperatures in firebox.

3) Establishing a wood charge configuration that is easily reproducible in field or laboratory testing.

4) Investigating the effects of sensor placement and shielding on measured firebox surface temperatures.

5) Measuring the radiative energy output from the flame and wood.

Incorporation of algorithms to account for the moisture content of the wood and an algorithm to automatically assign a fraction of leakage through fireplace doors to combustion air is also recommended.

CONCLUSIONS

The WOOD BURNING SIMULATOR was refined to allow modelling of the following phenomena:

- heat transfer through firebox enclosure
- flame radiation
- firebox re-radiation
- fireplace doors
- combustion air intakes into the firebox

The results of these refinements produced a model that is capable of simulating wall and flue gas temperatures for the following types of solid fuel burning appliances:

- standard site-built masonry fireplaces
- standard site-built masonry fireplaces with metal inserts
- factory-built fireplaces
- wood stoves

Calibration of the model was conducted using data from tests on masonry fireplaces. The model predicts flue gas temperatures reasonably well but seems to overpredict firebox wall temperatures.

Further field testing is recommended to allow complete calibration of the model in areas such as temperature gradients through different types of firebox enclosures and the effects of fireplace doors and combustion air intakes on these firebox enclosure temperatures. Incorporation of some additional algorithms is also recommended.

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A P P E N D I X   A

DESCRIPTION OF NEW ALGORITHMS INCORPORATED IN WOOD BURNING SIMULATOR VERSION 2.0

APPENDIX A

DESCRIPTION OF NEW ALGORITHMS INCORPORATED IN WOOD BURNING SIMULATOR VERSION 2.0

FLAME RADIATION

The initial course of action in modelling the flame radiation component as part of the total combustion process was to treat the flame as a free body with constant area and perform an energy balance, iterating on the flame temperature, until the energy balance equation was solved. The energy balance of the flame is made up of three components from which the flame temperature was solved:

- total heat of combustion released from the wood and converted to energy in the flame at any instant in time
- radiation heat loss from the flame to all surrounding surfaces
- residual energy in the gas emerging at the top of the flame

Although this approach produced an acceptable comparison with one set of field data, it was observed that the results of this particular approach to modelling the flame limited the models' application to more generalized woodpile configurations. These results included:

1) The model was relatively insensitive to burn rate, resulting in rounded flue gas temperature profiles when the woodpile reached its peak output, and significant overprediction of flue gas temperatures during the cool-down portion of the burn cycle.

2) There was a precarious balance between wall temperatures and flue gas temperatures; i.e. even small attempts at moderating the radiation to the wall resulted in large changes in flue gas temperatures. This is because the heat capacity of the firebox walls is so much greater than that of the flue gas - a small change in the wall temperature represents a relatively large transfer of energy to the flue gas.

The problems were traced to unrealistically high flame temperatures being generated using this free body approach. As a result, an alternative approach was adopted wherein the flame temperature was fixed at 1200°C (Reference 4). The flame **area** was then made a linear function of the energy release rate of the woodpile. The empirical constant relating flame area to energy release rate was determined by repeated simulations until reasonable agreement was achieved with measured flue gas temperature data. The energy balance between heat released by the flame, radiation heat transfer and residual heat in the flue gas was maintained in this formulation.

FIREBOX SURFACE RE-RADIATION

The re-radiation algorithms are designed to take into account radiation from each of the firebox wall surfaces to all other firebox surfaces and to the room.

The net radiation exchange between two grey surfaces can be expressed by equation 1 below. The equation is a simplification of the generalized series expression for radiative energy exchange between two grey bodies neglecting all terms after the first incidence of reflection.

$$Q_{ij} = \epsilon_i \cdot \epsilon_j \cdot SB \cdot (T_i^4 - T_j^4) \cdot A_i \cdot F_{ij} \qquad (1)$$

where:

ϵ_i = the emissivity of surface i

ϵ_j = the emissivity of surface j

SB = is the Stefan-Boltzmann constant equal to $5.669 \cdot 10^{-8}$ W/m$^2 \cdot$°K^4 (Reference 3)

T_i, T_j — are the absolute temperatures (°K) of the two bodies

A_i — is the area of body i

F_{ij} — shape factor for radiation leaving body i and falling on body j

Figure A.1a and A.1b are plots of shape factors for two parallel planes and two planes joined at right angles. Extension of these figures to a generalized fireplace configuration (i.e. obliquely angled firebox walls) can be achieved with reasonable accuracy by following two basic rules:

1) The sums of the fractions of radiation leaving a given surface must equal unity.

For example, consider a surface which can radiate to 3 other surfaces.

$$F_{12} + F_{13} + F_{14} = 1$$
$$F_{21} + F_{23} + F_{24} = 1$$
$$F_{31} + F_{32} + F_{34} = 1$$
$$F_{41} + F_{42} + F_{43} = 1$$

$F_{11} = 0$; $F_{22} = 0$; $F_{33} = 0$; $F_{44} = 0$ for all but concave surfaces.

2) The product of the area of Surface A times the fraction of energy leaving Surface A and falling on Surface B equals the product area of Surface B times the fraction of radiation leaving Surface B and falling on surface A.

Continuing with the above example:

$$A_1 \cdot F_{12} = A_2 \cdot F_{21} \qquad A_1 \cdot F_{13} = A_3 \cdot F_{31}$$

$$A_1 \cdot F_{14} = A_4 \cdot F_{41} \qquad A_2 \cdot F_{23} = A_3 \cdot F_{32}$$

$$A_2 \cdot F_{24} = A_4 \cdot F_{42} \qquad A_3 \cdot F_{34} = A_4 \cdot F_{43}$$

The relative dimensions (length and height) of A_1, A_2, A_3 and A_4 would determine the exact values of F_{12}, F_{13}, F_{14}, F_{23}, F_{24}, F_{34} extracted from Figures A.1a and A.1b.

The determination of these shape factors is not an easy task; however, applying the above rules combined with the two figures and good judgement should be sufficient to allow the user to derive reasonably accurate shape factors for most simple firepl-ace configurations. The reader is encouraged to refer to basic texts on radiation theory for a complete understanding of the determination of these shape factors for more complex configura-tions.

WOOD BURNING SIMULATOR allows users to input an emissivity for each surface of the firebox. Woodpile and flame emissivities are fixed at 0.85 and 1 respectively (i.e. the flame is treated as a black body).

Shape factors for each surface are also input by the user.

Length, widths and heights of each surface of the firebox enclosure are input by the user and are used to calculate the area of each surface.

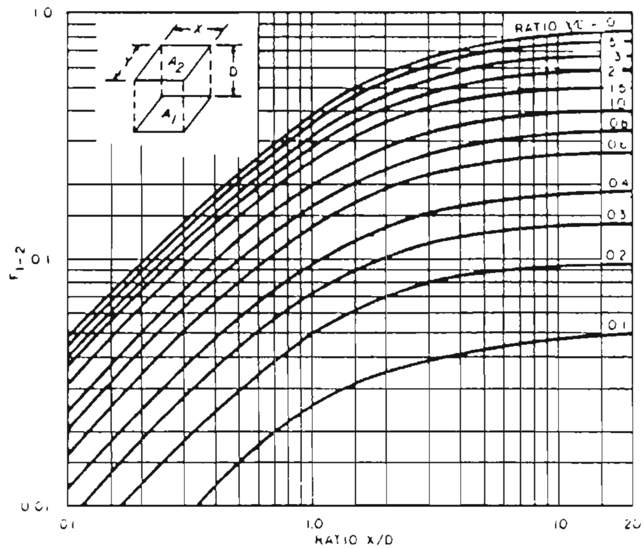


FIGURE A.1a: Radiation shape factor for radiation between parallel planes. (Reproduced from ASHRAE Handbook of Fundamentals, 1985)

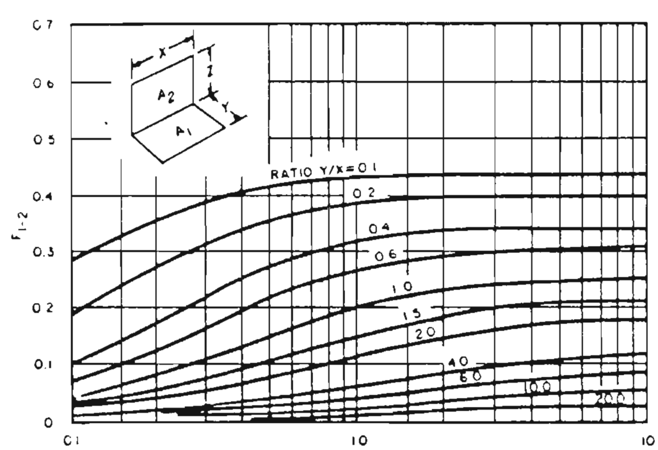


FIGURE A.1b: Radiation shape factor for radiation between perpendicular rectangles with common edge. (Reproduced from ASHRAE Handbook of Fundamentals, 1985)

HEAT TRANSFER THROUGH THE FIREBOX ENCLOSURE.

The model is designed to simulate three types of fireplaces and a wood stove. The three types of fireplaces include:

- a masonry fireplace
- a masonry fireplace with a steel liner
- a factory built fireplace surrounded by wood framed walls.

The wood stove is modelled in a manner similar to that used for the factory built fireplace (i.e. an appliance surrounded by walls).

The basic heat transfer algorithms incorporated in the model were made general enough that they could be applied to any one of the above appliance types. Each wall of each appliance was divided into 10 nodes. These nodes are identified in Figure A.2 for each type of appliance. The general energy balance equation is shown below for any given node.

$$Q_{stored} = Q_{condin} + Q_{radin} - Q_{convl} - Q_{condout} - Q_{convext} - Q_{radout} \quad (2)$$

where:

Q_{stored} is the net energy stored in the wall element.

Q_{condin} is the net energy transferred by conduction into the element

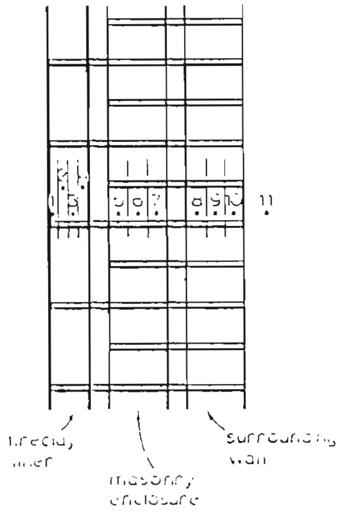
Q_{radin} is the net radiation energy transferred into the element (flame or wood radiation)

Q_{convl} is the net convective heat transfer off the inside face of the element

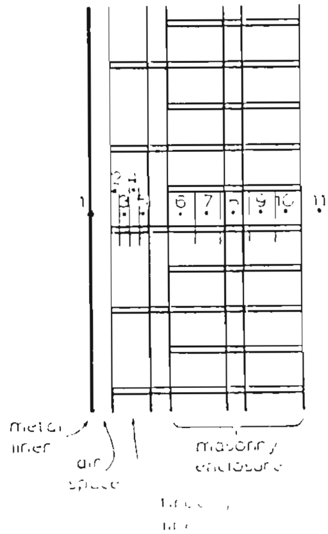
$Q_{condout}$ is the net heat transfer by conduction out of the element

$Q_{convext}$ is the net convective heat transfer on the exterior side of the element

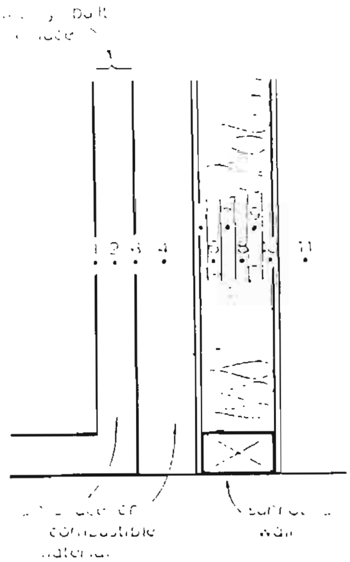
Q_{radout} is the net radiation energy out of the exterior surface of the element (night sky radiation)



Nodal points for
Masonry Fireplace



Nodal points for Masonry
Fireplace with Metal liner



Nodal points for Factory-Built Fireplace

FIGURE A.2: Assignment of nodal calculation points for the different types of wood burning appliances.

Not all heat transfer processes apply to each node. As a result the generalized equation can be simplified for some of the nodes.

For example:

For the first element in the liner, the equation (2) reduces to:

$$Q_{stored} = \Sigma(Q_{radin}) - Q_{conv1} - Q_{condout}$$

Re-writing this equation explicitly in terms of the properties of each node gives the following equation:

$$Q_{stored} = \Sigma[(\epsilon_i \cdot \epsilon_j \cdot SB \cdot (T_i^4 - T_j^4) \cdot A_j \cdot F_{ij})] - (h_c \cdot A_j \cdot (T_a - T_j)) - ((A_j/R_j) \cdot (T_j - T_{j+1}))$$

where:

ϵ_i is the emissivity of the various bodies emitting radiation to a given surface j. This would include all other firebox wall surfaces, the logs and the flame.

h_c is the convective heat transfer coefficient ($W/m^2 \cdot {}^\circ K$)

T_a is an average of the intake and stack temperatures and is used as a proxy for the temperature of the air passing over the wall surfaces

R_j is the thermal resistance between two adjacent nodes (i.e. node j and j+1)

The above equation applies equally well to wall surfaces separated by an air space such as the wall surrounding a factory-built fireplace.

For an interior node, Equation (2) reduces to:

$$Q_{stored} = Q_{condin} - Q_{condout}$$

Re-writing the equation explicitly in terms of the properties of each node gives the following equation:

$$Q_{stored} = [(A_{j-1})/(R_{j-1})] \cdot (T_{j-1} - T_j) - A_j/R_j \cdot (T_j - T_{j+1})$$

For the last or exterior element in the firebox, Equation (2) reduces to:

$$Q_{stored} = Q_{condin} - Q_{convext} - Q_{radout}$$

Re-writing this equation explicitly in terms of the properties of each node gives the following equation:

$$Q_{stored} = (A_{j-1})/(R_{j-1}) \cdot (T_{j-1} - T_j) - (h_c \cdot A_j \cdot (T_o - T_j)) - \epsilon_j \cdot SB \cdot (T_j^4 - T_o^4) \cdot A_j \cdot F_{io}$$

where:

T_o is the exterior temperature (°K)

F_{io} is the fraction of radiation leaving surface j and falling to the exterior (generally this value reduces to unity)

The above equation also applies to the exterior wall surface of a factory-built fireplace surrounded by a wall. For this case, it is assumed that no re-radiation occurs among the surrounding walls themselves; i.e. they re-radiate to the firebox but not diagonally to each other. The emissivity of the exterior wall surface has been assigned a value of 0.85.

The temperature rise associated with the stored energy in any node is determined according to the following expression:

$$\text{Temperature Rise} = \frac{Q_{stored}}{M_i \cdot C_p}$$

where:

M_i is the mass of the node (kg)

C_p is the heat capacity of the node (kJ/°K·kg)

The heat transfer algorithms are based on two dimensional analysis. Thus the heat transfer area remains constant throughout the depth of each surface. The area is multiplied by the thickness and density of each layer of the firebox enclosure to calculate the mass of each layer of the enclosure. The mass is then allocated to each of the nodes accordingly. The thermal resistance of each layer of the enclosure is allocated to each node accordingly.

Fireplace Doors

The heat transfer associated with fireplace doors is similar to Equation (2) above with the addition of transmission of energy.

$$Q_{stored} = Q_{radin} - Q_{transmitted} - Q_{convi} - Q_{convext} - Q_{radout}$$

where:

$Q_{transmitted}$ is the fraction of the total energy falling on the fireplace doors that is transmitted to the room.

Re-writing the equation in terms of the properties of the fireplace doors gives the following expression:

$$Q_{stored} = \Sigma[(\epsilon_i \cdot \epsilon_g \cdot SB \cdot (T_i^4 - T_g^4) \cdot A_g \cdot F_{ig})] + (\epsilon_r \cdot \epsilon_g \cdot SB \cdot (T_r^4 - T_g^4) \cdot A_g \cdot F_{ig}) - \Sigma[\tau \cdot \epsilon_i \cdot SB \cdot (T_i^4) - \tau \cdot \epsilon_r \cdot SB \cdot (T_r^4)] - (h_c \cdot A_g \cdot (T_i - T_g)) - (h_c \cdot A_g \cdot (T_r - T_g))$$

where:

ϵr is the emissivity of the room

ϵg is the emissivity of the door material

τ is the transmissivity of the door material

Figure A.3 summarizes the energy balances for each of these nodes.

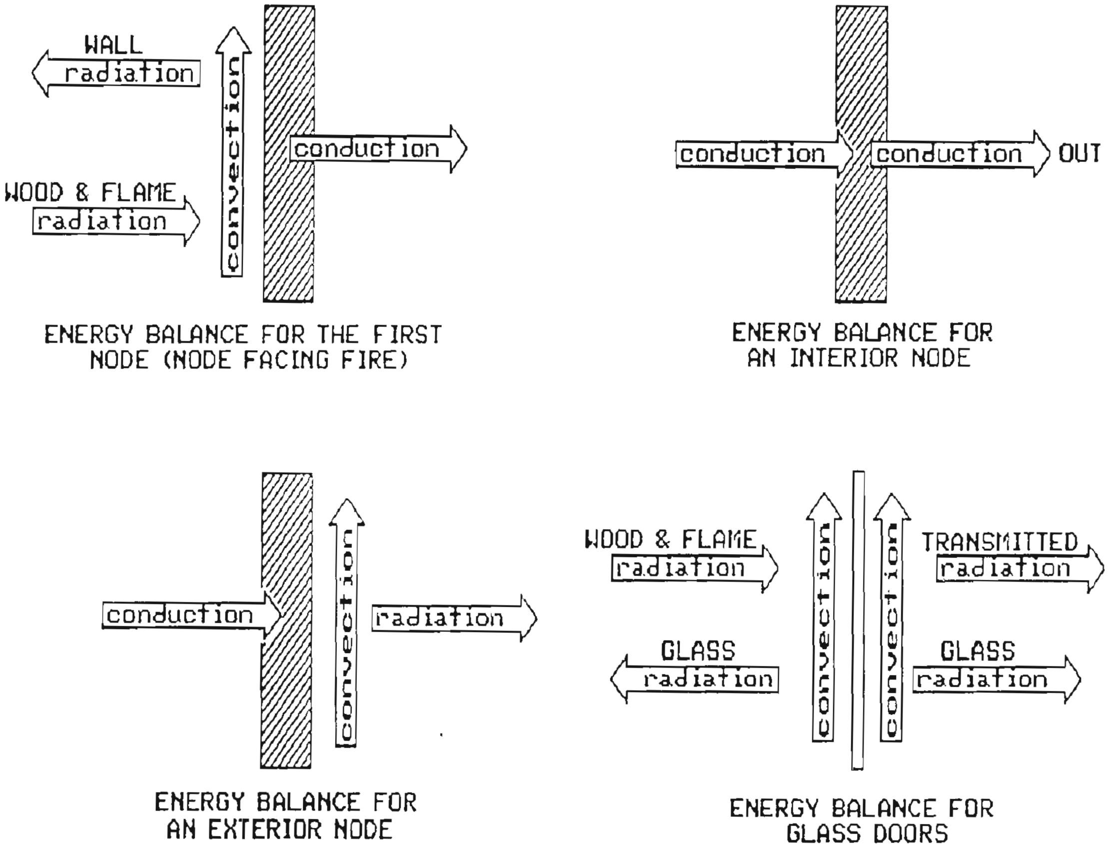


FIGURE A.3: Summary of the various energy balance equations for the firebox enclosure.

EFFECT OF COMBUSTION AIR INTAKE AND DOORS ON THE FLOWS THROUGH THE VENTING SYSTEM OF A FIREPLACE

Identification of Flow Paths

The flow module within the WOOD BURNING SIMULATOR model has consisted of two distinct flow paths along which pressures and mass flow rates were calculated to satisfy the laws of conservation of mass and energy (the energy equations are expressed in terms of pressure balances along the two closed calculation loops). Those flow paths are the chimney loop and the firebox loop. The chimney loop, illustrated in Figure A.4, remains unchanged by the addition of doors and combustion air intake to the firebox. However, the firebox loop is changed radically. The loop for the normal fireplace simply involves the parallel columns of hot gas over the fire and room air outside the fireplace. For the fireplace with doors and an intake, this loop includes the column of hot gas in the firebox, the column of room air from the centre of leakage of the fireplace doors up to the Vertical Centre of Leakage (VCL) of envelope, and the column of outdoor air from the VCL down to the opening of the combustion air intake. That flow path also includes the equivalent leakage areas (ELA's) of the fireplace doors and of the envelope and the equivalent flow area (EFA) of the combustion air intake. These elements of the firebox flow path are shown in Figure A.4.

The new firebox flow calculation loop can be used to immediately highlight several critical parameters in the operation of the fireplace and its venting system when doors and an intake are present.

The first is the **ELA of the fireplace doors.** As the ELA of the glass doors approaches zero, the flow though the doors approaches

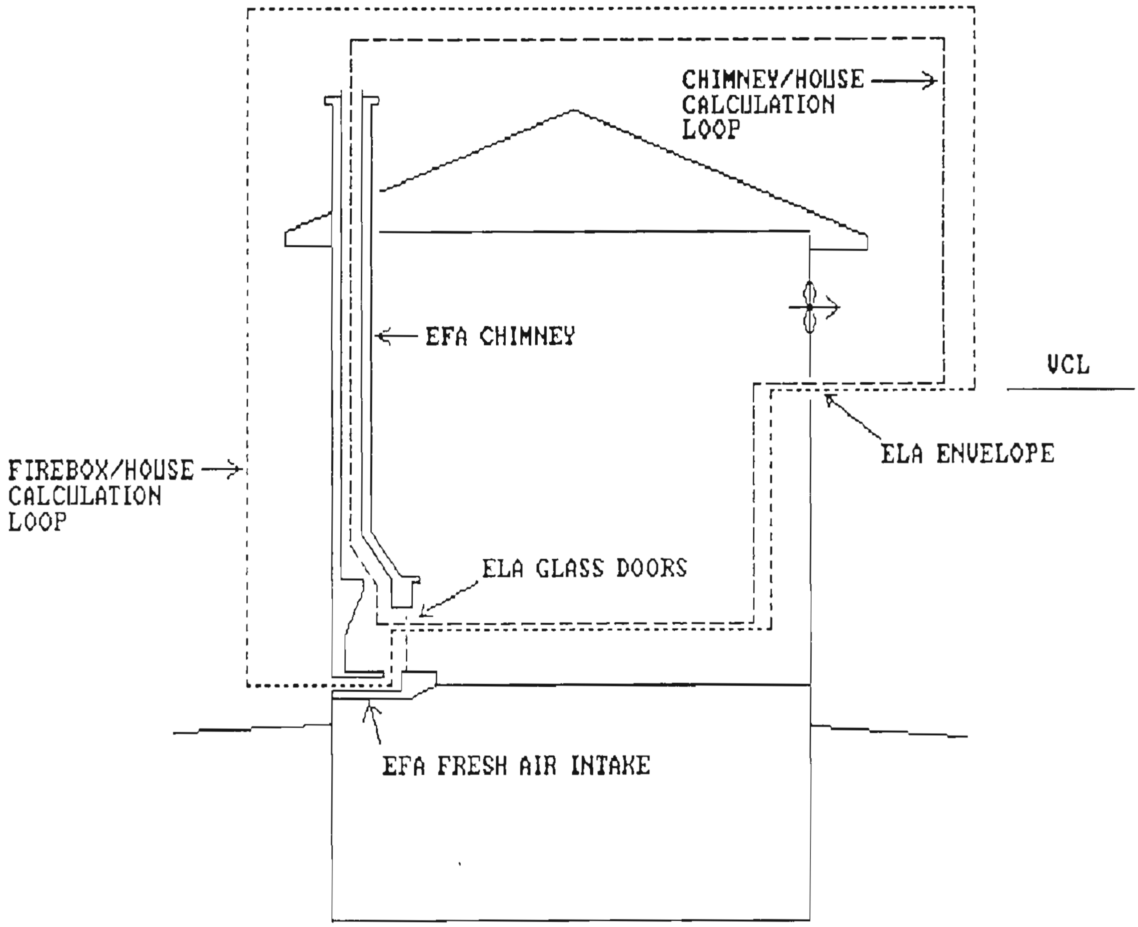


FIGURE A.4: The air flow/pressure calculation loops for a fireplace with glass doors.

zero, thereby decoupling the flow conditions in the firebox and chimney from the inside of the house. This results in an effective redirection of flows along the path which includes only the column of hot gas in the firebox and chimney and cold outside air. The house pressure no longer affects the combustion and venting process. To that extent, the combustion air intake and tight door combination have an advantage over the open fireplace in a house that is subject to considerable depressurization (e.g. 5 Pa or more). However three potential disadvantages can be identified:

- The firebox flow is now perfectly coupled to the chimney flow. This means that downdrafting in the chimney induced by wind patterns about the chimney and the exterior of the house results in downdrafting in the firebox and out of the combustion air intake - a potential hazard since hot coals or ashes can be drawn into the combustion air intake which may be in contact with combustible materials. The use of appropriate flue caps and the judicious placement of the combustion air intake is essential for the avoidance of downdrafting flows for this configuration.

- When air is flowing upward in the chimney, the perfect coupling of firebox and chimney results in the firebox flow and hence the energy release rate of the woodpile being a strongly dependent on net chimney draft. This represents a loss of control of the fire which must be regained by judicious design and regulation of the combustion air intake, or more specifically its **Equivalent Flow Area (EFA)**. Directing the intake air stream away from the woodpile, as required by code, also helps to regain control of the combustion process.

- The venting system no longer has a source of dilution air. This results in higher temperature gas entering the chimney. Control over the amount of intake air thus becomes doubly important since, for a given burn rate, the chimney will be hotter and the hotter chimney will induce more combustion air, thereby increasing the energy output of the woodpile. This is likely the reason why airtight wood stoves are designed as slow burning appliances - a fast burn would result in a loss of control of the energy release rate of the woodpile and of resulting enclosure temperatures.

  A possible design adjustment that would foil this unstable condition would be an air intake configuration that splits the incoming air into combustion air at the bottom of the firebox and dilution air at the top. This could help control chimney temperatures and decouple the flow of combustion air from the chimney draft thereby promoting a more stable energy release rate for the woodpile. This approach has not been investigated in this study; however, the general principle that the combustion air intake must also provide dilution air had to be followed in the modelling in order to generate reasonably low energy release rates when simulating this configuration.

The above discussion is based on the assumption of perfectly sealed fireplace doors (i.e. $ELA_{door} = 0$) which is not the case with real glass fireplace doors on the market. As fireplace doors do have a finite leakage area, house depressurization does affect the chimney flow to a greater or lesser extent - depending on the ELA of the fireplace doors and the EFA of the combustion air intake. The two flow loops are as shown in Figure A.4, and a key feature of the firebox loop is that it now includes the ELA of the envelope, the VCL of the envelope, the ELA of the doors and the EFA of the intake.

This means that the house buoyancy and the house depressurization not only have an effect on the venting process, as they do for an open fireplace, but they also have a much more direct effect on the combustion process. In situations where moderate house depressurization results in moderate spillage of combustion products from the fireplace, the smaller leakage area of the fireplace doors (compared to that of an open fireplace) helps to reduce the quantity of spillage to the house and may help to redirect hot gases up the chimney, thereby promoting faster increase of the draft. This is a clear advantage of having fireplace doors. However, in situations where house depressurization is high enough to cause the chimney flow to approach the stalled or backdraft condition, the two adverse pressures, house buoyancy and house depressurization, can produce an entirely different flow pattern. These adverse pressures can draw air through the intake, promote combustion, and draw the products of combustion through the fireplace doors into the house. Stated differently, pressure-induced venting problems with an open fireplace usually result in the fire dying down, thus reducing the quantity of combustion products spilled into the house; but pressure-induced venting problems with a fireplace with imperfectly-sealed doors and a combustion air intake can actually encourage the fire to flare up, thus increasing the amount of spillage. This is a failure mode that is introduced by the addition of the combustion air intake and loose fireplace doors.

A further failure mode has been identified. If the chimney is experiencing low draft or even backdraft due to down-drafting winds and the house is **pressurized** due to wind effects on the envelope or due to the effect of intake fans, then air would flow from the room, through leaks in the doors, over the combusting wood or coals and out of the combustion air intake.

The process of setting up the model to handle fireplace doors and combustion air intakes has therefore resulted in the identification of ways in which these measures can improve the venting of combustion products. However, the increased degrees of freedom identified have also uncovered various additional ways in which the venting system of a fireplace can fail. Some of these failure modes have been observed in the field. These various modes of venting - both good and bad - can now be investigated with the model.

Solution to the Flow Equations

The solution to the chimney flow equations is exactly as in WOOD BURNING SIMULATOR Version 1.0, as described in Reference 2. For the fireplace door/intake configuration, the dilution opening of the venting system is set equal to the total leakage area of the fireplace doors as opposed to the upper portion of the fireplace opening which is used for an open fireplace. This change in the way the leakage area of the doors is handled when there is a combustion air intake reflects the change in role of the doors in this configuration. A firebox with no combustion air intake can easily develop buoyant pressures in the firebox that result in spillage at the top of the box and inward air flow at the bottom. When the combustion air intake is introduced, larger pressures develop across the doors (either positive or negative) as a result of the balance of pressures around the new firebox/house flow loop. The order of magnitude of these pressures are almost always much larger than the local buoyancy pressure gradient across the doors so that the flow through the doors is likely to be all in the same direction. In other words, with no combustion air intake, combustion gas spillage under low draft conditions is driven by the buoyancy of the hot gases in the firebox, whereas with a combustion air intake, spillage is driven by the pressurization of the firebox due to the balance of pressures around the firebox/house flow loop. The treatment of the leakage area of the fireplace doors is therefore different for these two situations.

The firebox flow equations, which are based on the balance between driving pressures (the buoyancy of the hot combustion gases) and friction losses due to flows into and out of the firebox, are changed only in regard to what constitutes the new driving pressures and friction pressure drops. The driving pressure is now due to the buoyancy of hot combustion gases and room air up to the VCL, relative to a column of outdoor air of equal height. The friction losses include those due to the EFA of the combustion air intake, the ELA of the fireplace doors and the ELA of the house envelope. Again, the solution to these equations has not changed from Version 1.0.

One limitation of the model as it stands is that it can only solve for two modes of fireplace operation:

- open fireplace doors, firebox combustion air intake shut
- closed fireplace doors, firebox combustion air intake open

The case in which the fireplace doors are open and the firebox intake is also open cannot presently be modelled in that the firebox intake becomes just another opening in the envelope when the fireplace doors are open. The envelope leakage sites and other openings through the envelope are currently modelled as one "lumped leak" having one flow characteristic and one vertical location at the VCL. The model could be used to assess the effect of the dedicated combustion air intake on house pressure and total flow through the house, but there is no current technique for disaggregating the total flow through the envelope and intake. Therefore, for the condition with the fireplace doors open, the model would not be able to predict how much of the flow through the firebox is warm air from the house and how much is cold air from the combustion air intake.

The case in which the fireplace doors are closed and the combustion air intake is restricted can be modelled but may not be modelled accurately at present because the leakage through the doors is automatically assigned to dilution air rather than combustion air when a separate combustion air intake is present. As a result, the model would likely predict that the fire would die out, whereas, in reality, the leakage through the doors might be enough to supply sufficient combustion air. This could be modified in future versions of the model by the addition of an algorithm which would assign a fraction of the leakage through the doors to combustion air.

Impact of Fireplace Doors and Combustion Air Intake on the Thermal Model

The fact that the dedicated intake provides cold intake air to the fireplace rather than warm room air is the only thermodynamic difference between a dedicated intake into the firebox and a general combustion air intake into the house. When the fireplace doors are shut in a simulation, the thermal module specifies the temperature of the intake air to be the outdoor air temperature. If the fireplace doors are shut shortly after lighting, and the outdoor temperature is cold, the firebox and flue temperatures drop to well below room temperature until the energy release rate from the woodpile picks up. This temporary drop in chimney temperature does not result in negative net driving pressures since the chimney is decoupled from house air by the fireplace doors and remains warm compared to outdoors.

Figures A.5 to A.7 compare the thermal behaviour of a masonry fireplace with and without doors and a dedicated combustion air intake. The ELA of the doors was specified as 0.002 m^2 (i.e. relatively tight), and the size of the combustion air intake was specified as 0.008 m^2.

Energy Release Rate

Figure A.5 is a comparison of energy release rate from the woodpile. From the figure it can be seen that the installation of fireplace doors has affected the energy release rate in two ways:

a) The peak energy release rate from the woodpile is reduced.

b) The woodpile's energy release rate decreases more slowly following the peak (i.e. the fireplace doors have created a longer fire)

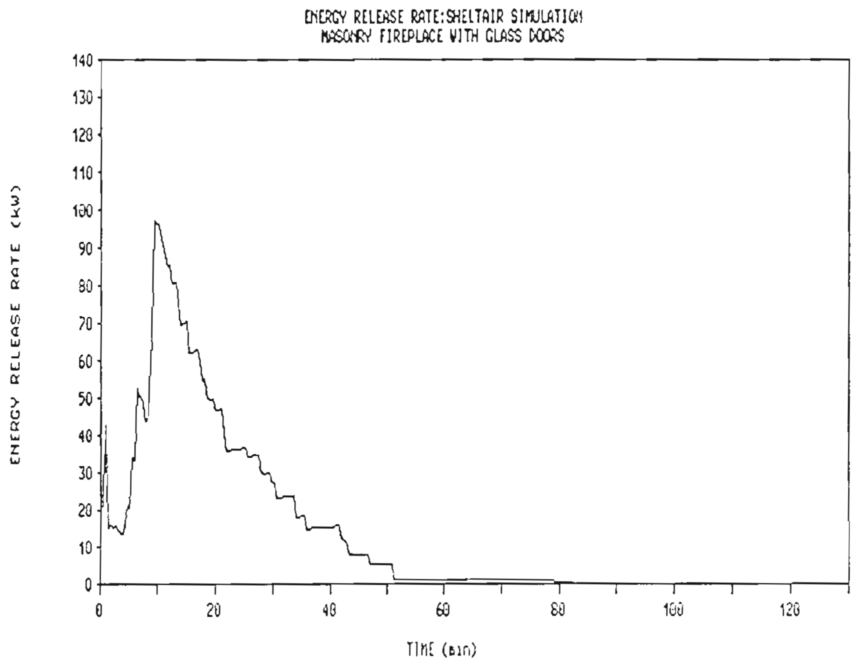
These two results are due to the fact that the fireplace doors eliminate the house as a primary but uncontrolled combustion air source for the fire. Instead, the combustion air intake to the firebox becomes the control valve for the wood burning process, a strategy used in airtight wood stoves to produce slower and longer burns.

Wall Surface Temperatures

Figure A.6 shows the effect fireplace doors have on firebox wall surface temperature profiles. With the fireplace doors installed, the surface temperatures are only slightly cooler than without glass doors despite the fact that with glass doors installed, the energy release rate is much lower throughout the burn cycle. This apparent insensitivity is due to three counteracting effects that cancel one another in this example. First, the presence of the fireplace doors reduces the walls' ability to re-radiate to the room since they now "see" a hot body - the fireplace door at 125°C instead of the room at 20°C. This drives the wall surface temperatures up compared to an open masonry fireplace with the same energy release rate. However, the lower energy release rate prevents this effect from being fully realized. In addition, convective heat transfer from the walls is higher when the fireplace doors are installed because part of the cold combustion air from outside is directed to the walls, which also prevents the wall surface temperatures from reaching the level they would in an open masonry fireplace. Thus, these factors, a lower energy release rate, reduced re-radiation and colder combustion air, offset each other, resulting in approximately the same wall temperature profile.

House Pressure

Figure A.7 shows the impact fireplace doors have on the house pressure. The fireplace doors have reduced the level of depressurization on the house by approximately 5 Pa. This will clearly have a significant impact on the behaviour of competing chimneys such as the furnace flue. This is not a full endorsement of fireplace doors for houses that suffer from spillage and backdrafting of furnace chimney flues due to fireplace operation. Other issues related to the temperatures of combustibles behind the firebox due to hotter fire have to be addressed as well. This is particularly important in older houses that have been tightened, since thickness of the firebox liner and walls and clearances to combustibles may be much less than in newer houses.



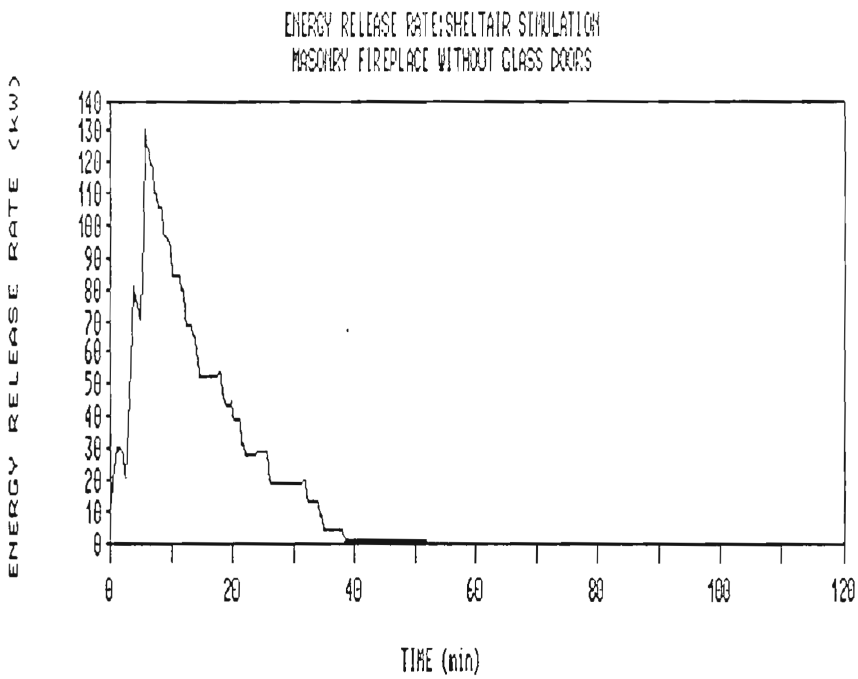


FIGURE A.5: Comparison of the woodpile energy release rate for a masonry fireplace with (top) and without (bottom) doors

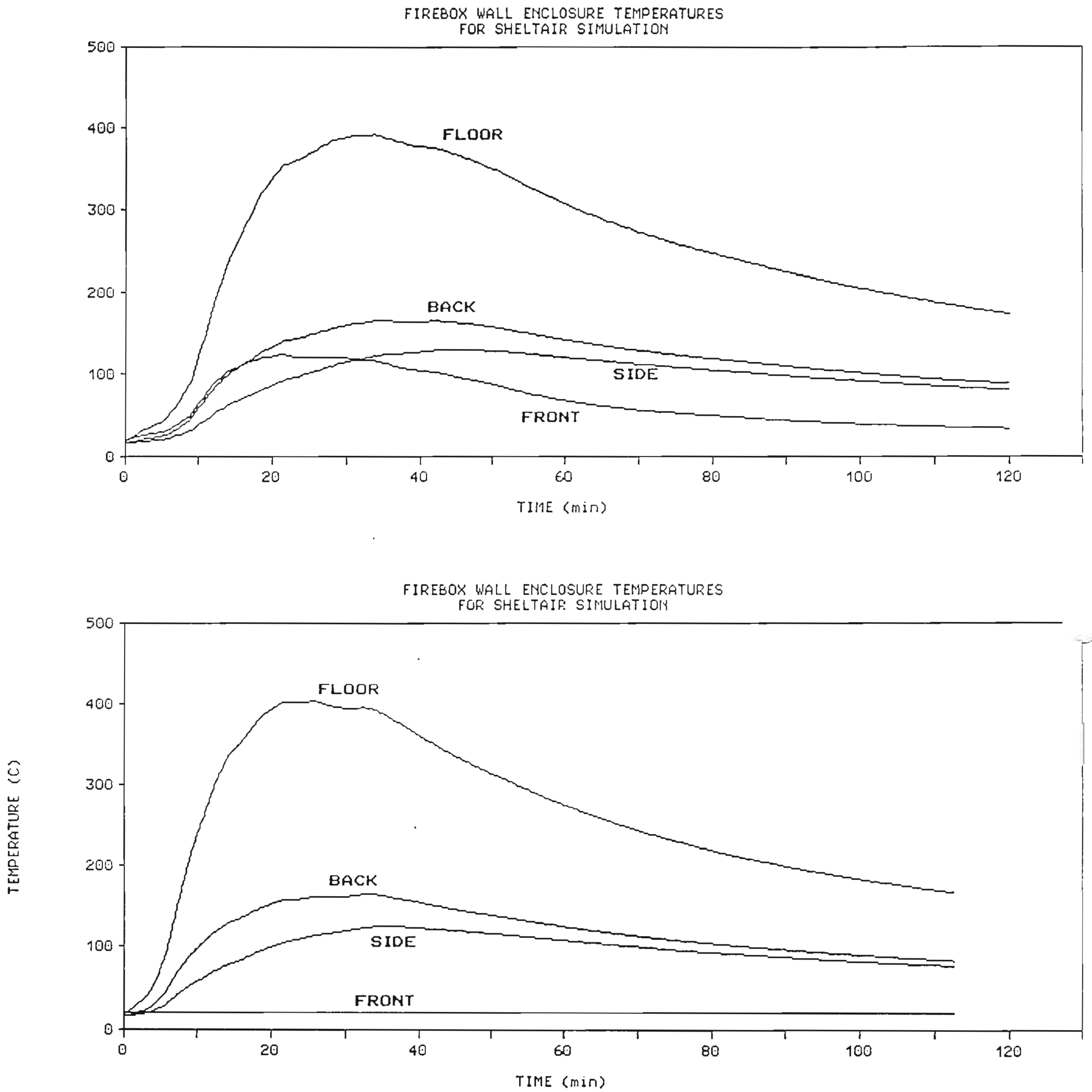


FIGURE A.6: Comparison of the wall surface temperatures for a masonry fireplace with (top) and without (bottom) doors

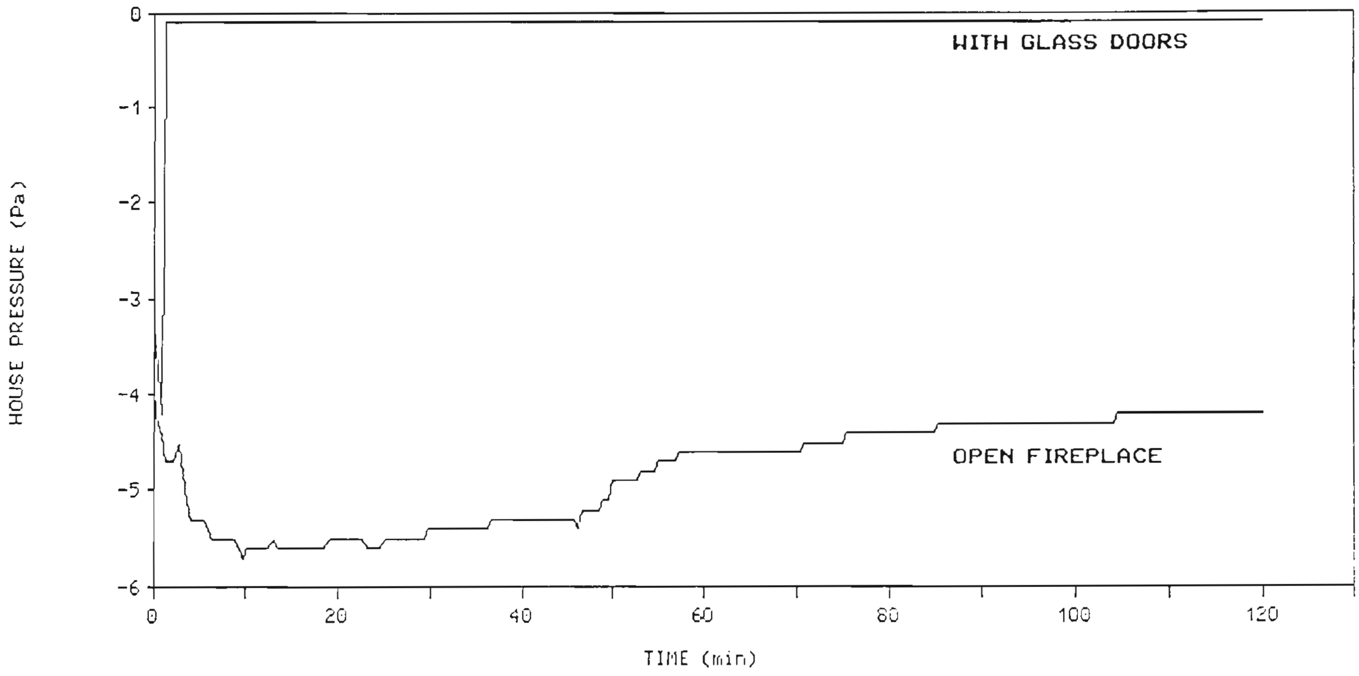


FIGURE A.7: Comparison of house pressures for a masonry fireplace with (top) and without (bottom) doors

WOODPILE CONFIGURATION AND INFLUENCE INDICATORS

The model defines the woodpile configuration as follows:

1) There are a total of 10 pieces of wood.
2) Each piece is made up of 5 concentric rings that are the same shape as the overall piece.

Figure A.8 depicts the default woodpile arrangement for the model showing 5 kindling pieces and 5 larger pieces. Also shown in the figure are examples of how the model defines the concentric rings for a round piece and a split piece.

Despite these restrictions, any woodpile can be approximated by replacing the actual woodpile with 10 pieces of equivalent mass (see discussion under UL calibration, Appendix C, for an example).

The stacking scheme influences how heat is transferred among the wood pieces during the burning process. The feature of the model that allows any woodpile configuration to be modelled is its ability to deal with the relationship between each wood piece in the woodpile and adjacent wood elements in terms of simple numbers called influence indicators. Each piece is assigned influence indicators which indicate which pieces receive energy from that piece as it burns. For example, if it were expected that the heat generated during the burning of Piece 1 would be transferred to Pieces 2, 4 and 5, Piece 1 would be assigned the influence indicators 2,4,5.

The number of pieces influenced by a given piece will depend on its position relative to the other pieces. For example, a piece may influence only its three nearest neighbours.

Influence indicators and sizes of the pieces are chosen to achieve a particular sequence of piece burning and to achieve an overall energy release rate profile. In general, modelling efforts to date, the influence indicators have been restricted to adjacent wood members only; i.e. each burning piece influences only wood members that it is in direct contact with (see Appendices B.2 and C.2 for examples of influence indicators for the two field calibrations). Although assigning influence indicators according to which pieces are in direct contact seems to result in realistic simulated fires, matching a specific burn rate profile may require a trial and error process of indicator selection and refinement.

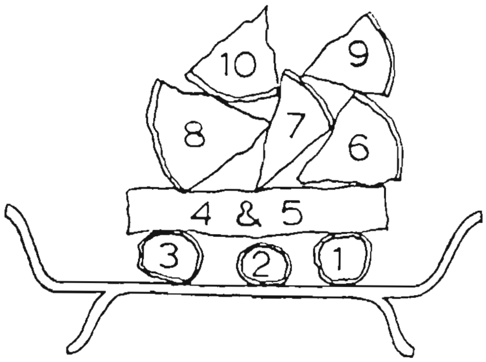


FIGURE A.8a: Default woodpile stacking scheme used by WOOD BURNING SIMULATOR

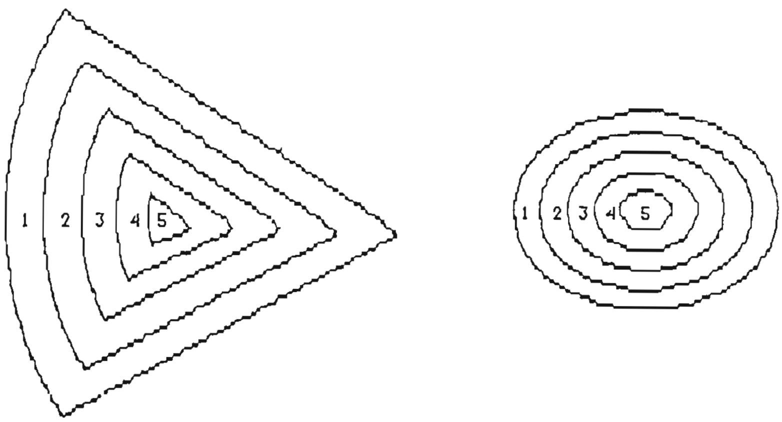


FIGURE A.8b: Example of how the model assigns the concentric rings to full and split pieces.

APPENDIX C.1

CALIBRATION OF WOOD BURNING SIMULATOR USING THE UNDERWRITERS LABORATORIES TEST DATA

The second calibration of the WOOD BURNING SIMULATOR model was based on research data collected by Underwriters Laboratories (U.L) for the National Bureau of Standards (NBS) (Reference 4). The authors of the report conducted a vast number of tests to investigate the fire hazards associated with fireplace inserts for factory-built and masonry fireplaces. The purpose of the research was to provide information on the temperature rise that occurs in and around wood burning fireplaces with fireplace inserts under specified firing conditions. Of importance to the validation of the current version of the WOOD BURNING SIMULATOR model was one particular test wherein an open masonry fireplace, without insert, was tested. (Note: Although the results of other tests presented in the report are also relevant to the complete calibration of the model, calibration of the model to that data was outside the scope of the present project.).

Detailed data describing the fireplace/chimney system used in the test is included in Appendix C.2.

The test protocol differed from that used by Sheltair in that steady state conditions were of principal interest to the authors. Steady state conditions were approximated by recharging the fire with a fixed wood charge at specific intervals until maximum temperature rises were reached. The UL report calls this the "brand fire" test. These tests lasted from 4 to 6 hours.

Temperature data for this test were much more limited than any other test presented in the report. As a result only two sensor locations could be used to validate the model. These were: