FIREPLACE AIR REQUIREMENTS

Prepared for:

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Policy Development and Research Sector
Canada Mortgage and Housing Corporation

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EXECUTIVE SUMMARY

Research at Canada Mortgage and Housing Corporation (CMHC) through the eighties showed that excessive house depressurization can cause the spillage of combustion products from fuel-burning appliances into the indoor air. Operating fireplaces (especially open masonry ones) can be major sources of air exhaust from houses, and can cause this excessive depressurization. Fireplaces also can be a source of indoor air pollution themselves when house depressurization causes them to spill. This project involved the investigation of factory-built fireplace air demands, pressure limits, and air supply strategies, as well as an effort to find ways to isolate house and fireplace air. The work was performed at the laboratories of **ORTECH** International.

In a test room at **ORTECH**, five factory-built fireplaces were taken through test burns to establish: their resistance to spillage under various room depressurizations, their chimney flow rates, and the flow rates in their specified fresh air intakes. Separate tests were carried out to determine the airtightness of the glass doors and fireboxes, and the flow characteristics of the air intakes and chimneys. Thermal characteristics of the fireplaces and chimneys can be calculated from the data.

The results show that most of the factory-built fireplaces tested would not act as major house exhausts nor would they be likely to spill, under normal operation. Chimney flow rates were relatively low when the fireplaces were operated with closed doors, but open door testing showed significantly higher flows. Fresh air intakes proved to be of variable utility, supplying close to all required air in some fireplaces and less than 25% in others. Those air intakes which were connected to the circulation air plenums were usually ineffective. Those directly connected to the **firebox** could match air requirements but could be dangerous in reverse flow incidents (when combustion products flow out through the intended intake). Note: the frequency of occurrence of such reversals has yet to be established. All fireplaces would spill, during fire **diedown**, if a room depressurization of roughly 10 **Pascals** was maintained. This is a rare level of depressurization in most existing houses, although it is attainable, especially in mechanically exhausted dwellings.

The study also describes the use of the fireplace simulation computer program, WOODSIM, to translate the laboratory results to other types of fireplaces. The report outlines some fireplace design guidelines, based on the study results.

DISCLAIMER

THIS PROJECT WAS FUNDED BY THE CANADA MORTGAGE AND HOUSING CORPORATION AND ENERGY MINES AND RESOURCES CANADA. THE VIEWS EXPRESSED ARE THE PERSONAL VIEWS OF THE AUTHORS. NEITHER THE CORPORATION NOR EMR ACCEPTS RESPONSIBILITY FOR THEM.

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1.0 INTRODUCTION

As part of its ongoing study of combustion venting in Canadian houses, Canada Mortgage and Housing Corporation engaged ORTECH International (formerly Ontario Research Foundation), along with Scanada Consultants and Sheltair Scientific, to conduct a project on performance requirements and design guidelines for prefabricated fireplaces and fireplace retrofit packages.

Extensive research into spillage from combustion appliances had been carried out by Sheltair Scientific Ltd. and Scanada Consultants Ltd. The problems that were identified with tireplaces include;

- spillage of flue products from the fireplace into the house;
- spillage of flue products from other combustion appliances caused by the fireplace depressurizing the house;
- fires resulting from overheating of combustible materials adjacent to the fireplace or fireplace chimney;
- reverse flow of flue products through air intakes connected directly to the firebox.

The first problem relates to nuisance spillage of smoke and potentially harmful spillage of carbon monoxide and carbon dioxide from the fireplace during operation, and odours from the fireplace when it is not in operation. Work done for CMHC has shown that a substantial number of fireplaces experience some degree of spillage during their operation. It was felt that the frequency and severity of spillage warranted further study of fireplace operation to determine how to reduce spillage.

The second concern was that fireplaces can act as large exhaust appliances which would depressurize a house to some extent, depending on the tightness of the house. This depressurization could lead to potentially harmful spillage from other combustion appliances located in the house.

It was felt that these problems could be reduced or eliminated by isolating the fireplace combustion process from the general house environment using a sealed combustion system. This has been attempted by putting glass doors onto fireplaces, and bringing combustion air supplies directly from outdoors into the firechamber. These actions may prompt the third and fourth problems mentioned above, namely ignition of combustible materials in the building structure, and reverse flow of flue products through air intakes.

CMHC defined a project to investigate the performance characteristics of fireplaces, and to develop design guidelines to assist in the isolation of fireplaces from the house environment. It was decided to use factory-built fireplaces in this project, since they are more suitable for laboratory testing than masonry fireplaces, (i.e. can be placed on scale for burn rate measurements) and it was believed that some manufacturers had already achieved a high degree of airtightness in their construction. It was also proposed to use the WOODSIM computer program to model fireplaces other than those being tested, after validation of the program against lab results from the factory-built fireplaces.

ORTECH was engaged by CMHC to carry out laboratory testing of the fireplaces. Sheltair Scientific and Scanada Consultants assisted in the development of facility design and test protocols. WOODSIM modelling, validation and improvement was assigned to Scanada Consultants. Sheltair Scientific also carried out field testing of the air-tightness of fireplaces.

The results of the tests were then used to develop the design guidelines for fireplaces in relation to spillage reduction.

In addition to the tests of fireplaces, a series of tests was undertaken on a variety of factory-built chimneys. The objective of this work was to compare the performance of three different chimney types when used in conjunction with a factory-built fireplace.

2.0 PROCEDURES

Laboratory testing of the fireplaces was carried out in a facility specially designed for this project. A test method was devised, and fireplaces were selected for testing. The following sections contain descriptions of these elements.

2.1 Description of Test Facility

The facility was constructed in general accordance with the specifications contained in Appendix A. The major parts of the facility, as shown in Figure 1, are as follows:

- The fireplace test room in which the fireplace is located. The interior dimensions of this room are approximately 3350 mm wide by 3350 mm long by 2450 mm high. This room has a forced air cooling system, and an exhaust system which vents to the chimney vent chamber.
- The exterior air intake chamber. This chamber is located at the side of the fireplace test room and shares a common wall with the test room. Air intakes for fireplaces under test will draw air from this chamber.
- The environmental chamber. This is an environmentally controlled chamber which supplies conditioned air to the exterior air intake chamber.
- The chimney vent chamber. This chamber is located at the top of the facility and is the chamber in which the fireplace chimney terminates. It has an exhaust fan system which draws the flue products from the chamber, through a dilution tunnel and to the outdoors through a roof stack. The vent chamber is connected to the exterior air intake chamber through a 900 mm x 900 mm duct which has a moveable partition to allow variation of pressure between the two chambers.
- The attic space. This is a partially enclosed area through which the chimney passes from the test room to the vent chamber.
- The crawl space. This is a 600 mm high space located under the test room. This space contains the weigh scale for the fireplace, and allows for use of combustion air supply ducts that are installed through the floor.

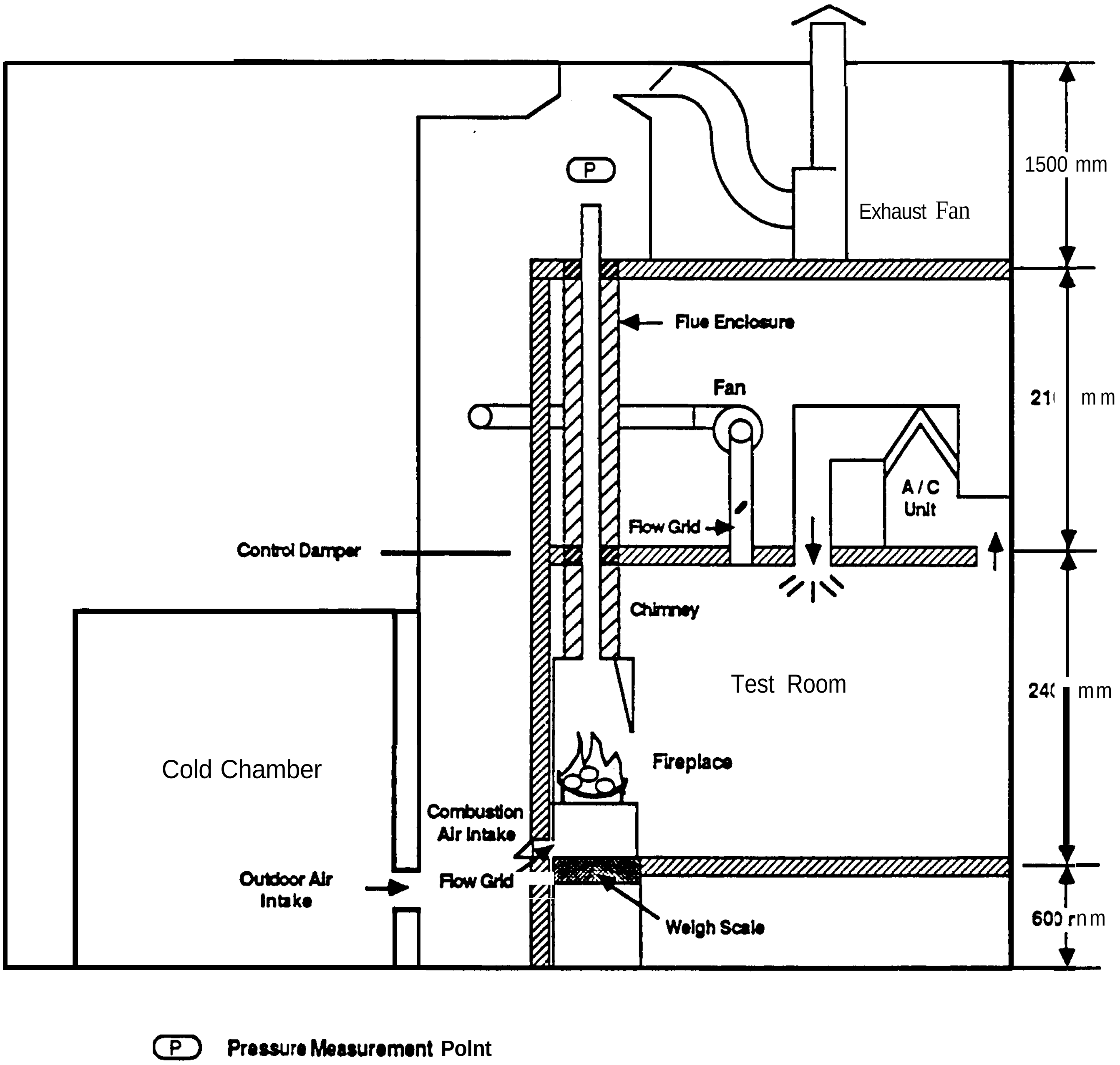


Figure 1: Cross Section of Fireplace Test Facility

The test room has a volume of about 27.5 m3. The ELA varied slightly with each fireplace installation, but was on the order of 0.03 m2 at 10 Pa. For the **fireplace** A installation the equation for flow **from** the room was Flow **(L/s)** = 17.7 x $p^{0.59}$ where p is the inside - outside pressure difference, in **pascals.** This ELA would be similar to that of a relatively tight house. The exhaust airflow required to produce a negative pressure of 5 **pascals** in the mom is in the range of 40 to **50** Us, with the fireplace sealed.

Instrumentation of the test facility, shown in Figures 2 and 3, consists of the following:

- approximately 80 Type J thermocouples for measurement of surface temperatures of materials in and around the test fireplace;
- approximately 8 Type K thermocouples for measuring flue gas, chimney surface and combustion chamber temperatures;
- CO, CO2 and 02 *analyzers* for flue gas analysis;
- **CO** and CO2 analyzers for spillage detection and measurement;
- airflow sensors for combustion air supply flow, room exhaust flow and dilution tunnel flow;
- electronic pressure sensors for measurement of differential pressure between the test room, outdoor air chamber and vent **chamber;** and draft at the base of the chimney relative to the room pressure;
- electronic weigh scale for measurement of fuel weight.

The instrumentation is connected to a data acquisition system which consists of an HP 3497A scanner with voltmeter, and an HP 9816 computer with floppy disc storage. The program was a modified version of the one developed by **CCRL** for testing to CSA Standard **B415-M1986,** Performance Testing of Solid Fuel Burning Appliances. Appendix A contains more detailed information on the instrumentation, and accuracy of measurements.

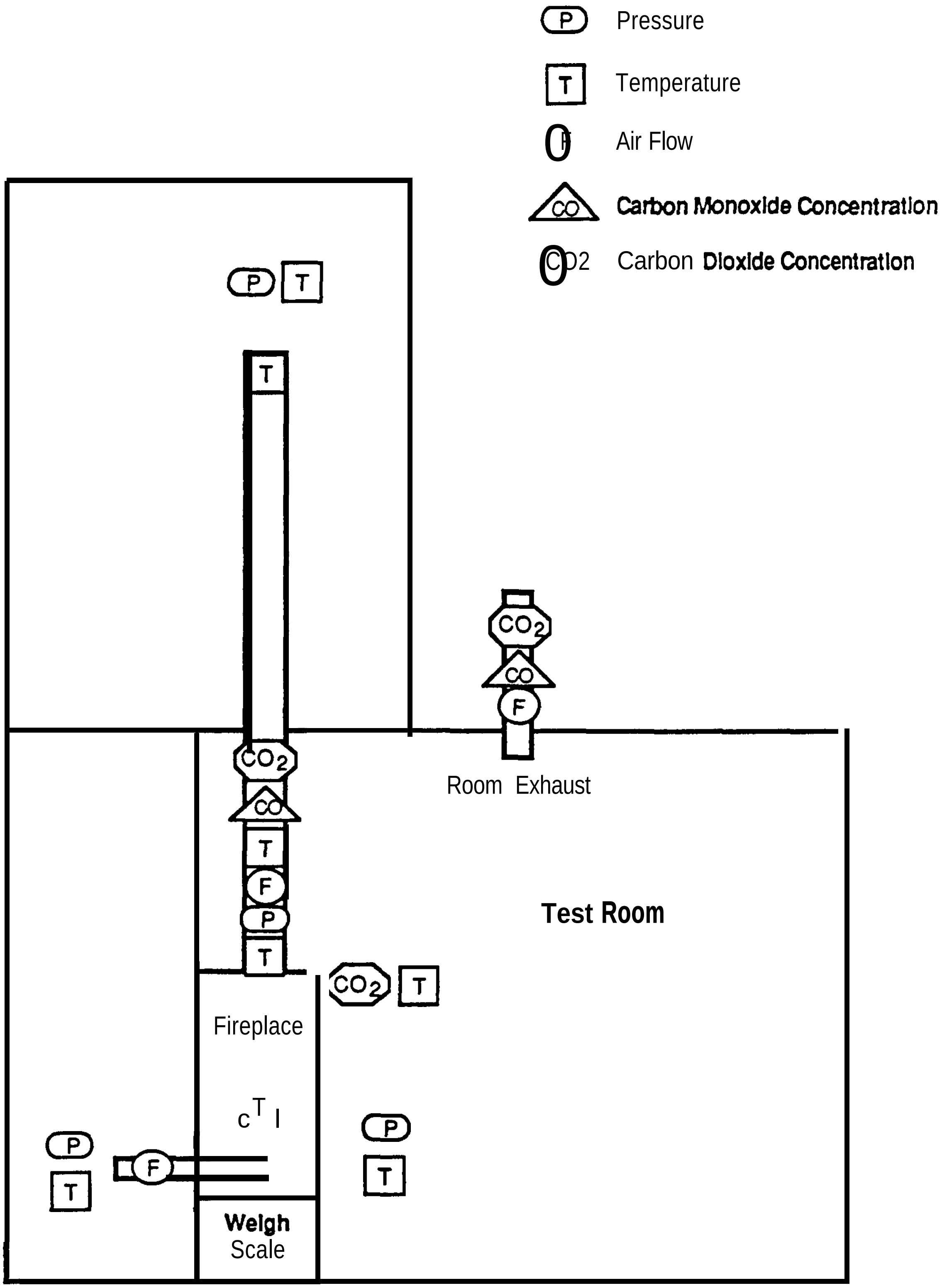
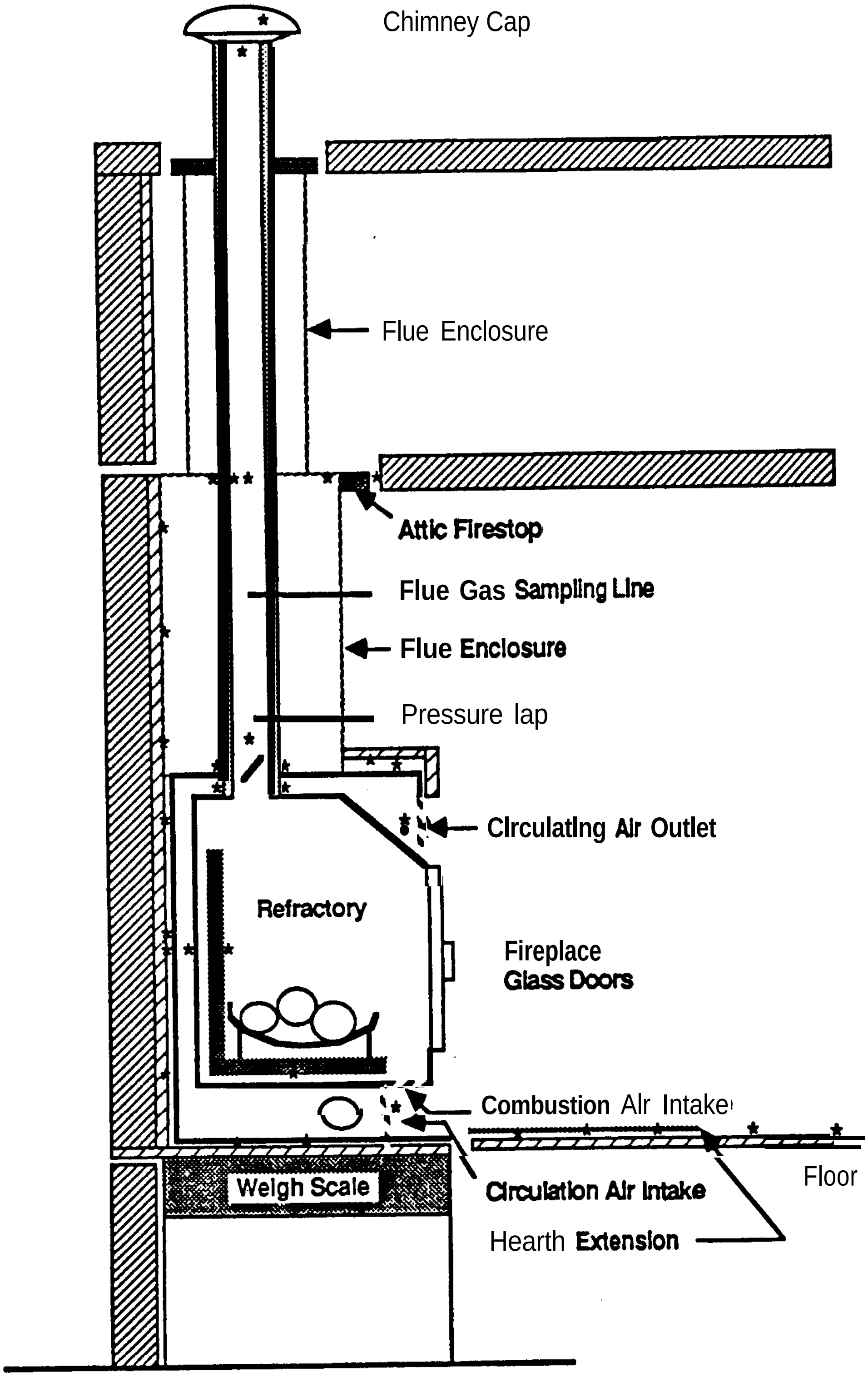


Figure 2: General Measurement Locations



• denotes thermocouple location

Figure 3. Fireplace Instrumentation

The facility is capable of accommodating chimney heights up to 5.5 metres above the floor of the test room. For all tests, a chimney length of 3.66 m was used, which gave an overall height of about 4.6 m from the floor of the test chamber. This is, in most cases, the minimum height recommended by the manufacturers. The minimum height was selected because it was anticipated that it would provide the minimum draft for the testing, and that spillage would be most critical with minimum draft..

2.2 Test Fireplaces

Five fireplaces were chosen for testing, to represent the broad range of units found on the market. Table 1 provides a general description of each unit.

Table 1: Description of Fireplaces Tested

Unit	Relative Tightness of Firebox & Doors	Outdoor Air Supply Termination	Outdoor Air Duct Size	Firechamber Lining	Other
A	Loose	Circulation Plenum	100mm diameter	Refractory	
B	Medium	Circulation Plenum	83 x 254 mm	Metal	Fan Forced Circulation & Combustion Air
C	Tight	Circulation Plenum	100mm diameter	Refractory	
D	Very Tight	Firebox	100mm diameter	Metal	
E	Loose	Firebox	100 mm diameter	Refractory	Air-cooled Chimney

For units A, B and C, the outdoor air supplies terminated in the plenum where air circulated to remove heat from the fireplace. Unit A had no connection between the circulation air plenum and the firebox. Units B and C had combustion air drawn from the circulation air plenum. Unit B had two fans which pressurized this plenum to a certain extent and assisted in the flow of combustion air. The fans were controlled by a thermostat in the fireplace which turned them on after the temperature in the fireplace exceeded the thermostat setting. In Unit B a damper system allowed the unit to draw all of the circulation and combustion air either from outdoors, or from the room in which the fireplace was located. Unit D had combustion air directly ducted to the firebox. Air for the circulation plenum comes exclusively from inside the house. Unit E had combustion air ducted through the firebox wall, behind the refractory liner.

Further details on the fireplaces are given in Appendix B.

2.3 Test Chimneys

The chimneys used in the testing of fireplaces A to D were type A prefabricated metal chimneys that had been approved for use with the fireplaces. Fireplaces A and B used the same chimney, as did fireplaces C and D. The chimneys were 7 inch internal diameter (179 mm) with a 1 inch (25 mm) thick insulated wall. Chimney sections were 36 inches long (914 mm). Four sections were used for the tests, with a standard cap at the top. See Section 3.2 for chimney performance characteristics.

Three chimneys were selected for additional testing with Fireplace E. Chimney A was an air-cooled chimney, with a 200 mm inside diameter and a 300 mm outside diameter. Chimney B was a type A chimney, with a 200 mm inside diameter and a 250 mm outside diameter. Chimney C was a 650°C chimney, with a 200 mm inside diameter and a 300 mm outside diameter. The chimneys were tested in conjunction with a standard factory-built fireplace designed for use with the air-cooled chimney.

2.4 Testin Procedures

Split, air-dried maple was used for all of the testing. The wood moisture content varied from about 9 to 12%. In contrast, the fuel used for ULC standard tests is made from 19 x 19 mm strips of Douglas fir or spruce, spaced 25 mm apart on centres. The CSA Standard B415, Performance Testing of Solid Fuel Burning Appliances, calls for Douglas fir of various sizes, depending on the firechamber volume.

The loading procedure was to start with a kindling charge made up of about 0.4 kg of newspaper and 0.7 kg of wood, split to about 25 x 25 mm. This was placed in the fireplace, and lit. After the fire was well established (about 5 minutes) a full charge was added. A full charge normally consisted of 3 pieces of split maple, totalling 6 to 8 kg in weight. In most cases, the wood was allowed to burn with no adjustments to the wood pile. Additional charges were added when about 1 kg of coals and ash were left in the fireplace, for runs where more than one charge was used. At the time of reloading, the coals were distributed evenly over the grate. Up to three charges were used in a day of testing. After the last charge was added, the fire was allowed to burn until it went out.

The fuel used would possibly not produce as severe conditions as that used in the ULC-S610M Standard for Factory-Built Fireplaces. In this standard, there is a brand fire in which racks made of 19 x 19 mm spruce or fir are added to the fire at 7-1/2 minute intervals, until temperatures in the fireplace and enclosure reach a maximum. A flash fire test is carried out with eight brands stacked in the fireplace. A radiant fire is carried out using charcoal briquettes, with fuel added at 7-1/2 minute intervals and the bed stirred to maintain maximum intensity, until maximum temperatures are reached in the fireplace and enclosure.

In our tests, we did not use the ULC fuelling, since it was not felt to be representative of typical fireplace use. Therefore, no correlation can be made between the maximum temperatures measured in the present study and those that might be measured in a ULC test.

During the testing, burn rates *were* characterized as high or low. High bum rates occurred when the fire was burning briskly, with visible flames in much of the firechamber. Low burn rates were when few flames were visible, usually toward the end of a burn cycle when over 75% of the fuel had been consumed. Diedown of the fire was after about 80 - 90% of the fuel had been consumed, and no further charges were added. This phase continued until the fire was out. In some cases, temperatures were monitored in the cooldown period, after the fire was out.

Baseline tests were carried out with no pressure differentials between the various sections of the test facility and combustion air controls fully open. Additional tests were carried out with negative pressures in the test room where the fireplaces were located (relative to the outdoor intake chamber), and with negative pressure in the chamber where outdoor air was drawn from (relative to the test room). Room negative pressures were set by varying the rate of exhaust of air from the room. Pressures were variable from 0 to -30 Pascals. Levels of -5, -10, and -17.5 Pascals were typical for much of the spillage testing. A level of -5 Pa is the maximum depressurization recommended for naturally aspirated appliances in the new CSA F326 Standard The -17.5 Pa tests are equivalent to the ULC and CSA tests for solid fuel burning equipment in mobile homes.

Spillage from the fireplaces was induced by lowering the pressure in the room until CO2 levels in the room began to rise, indicating the presence of flue gases. In some cases, the pressures were lowered until backdrafting occurred. Backdrafting was indicated by a sudden drop in flue gas temperatures, starting at the top of the flue.

Tests were also carried out with cold air (-20°C) at the outdoor air intake to see the effect on the operation of the fireplace.

A series of tests was carried out on each fireplace. Table 2 shows the tests that were undertaken for each fireplace.

In addition to the bum tests, measurements were also undertaken to characterize the leakage areas of the fireplaces and flow characteristics of the air intakes and chimneys.

A fan and flow meter were connected to the chimney connection. Tests were carried out at various flowrates, with static pressure measured at the outlet of the fireplace. To measure the leakage of various components, tests were done with and without those components sealed with plaster sheeting and tape. Flow rates through combustion air inlets were measured by measuring flow with the dampers opened and then closed.

2.5 Chimney Test Procedures

A standard factory-built fireplace designed for use with an air-cooled chimney was used for all of the chimney tests. The fireplace was installed in ORTECH's fireplace test facility shown in Figure 1. The fireplace was instrumented with thermocouples on the inside surface of the fire chamber, and on the inlet and outlet of the circulation air plenum.

Thermocouples were installed on each of the test chimneys at a number of points. The chimneys were constructed from 0.91 m sections. Sets of thermocouples were placed 0.1 m from the base of each section, at a height of 1.2 m, and 0.1 m from the top of the chimney. Each set of thermocouples consisted of one placed in the centre of the flue, one mounted on the inside surface of the flue, and one mounted on the outside surface of the flue. Chimney A was tested as an inside chimney, installed in a flue enclosure, and as an outside chimney without an enclosure. Chimney B was tested as an inside chimney only, and chimney C was tested as an outside chimney only. For the outside installation, a 30 degree elbow was installed on the fireplace outlet, followed by 1.2 metres of chimney to a second 30 degree elbow outside of the test room. From there, the chimney went straight up, along the outside of the test room, in the outdoor air plenum.

The standard fuelling procedures described in Section 2.4 were used for the tests.

Table 2: Tests Carried Out on Each Fireplace

Fireplace & Test	**Description of Run (See Table 1 for Description of Fireplaces A - E)**
A-l	Fireplace doors open, no pressure differences.
A-2	Fireplace doors closed, no pressure differences.
A-3	Fireplace doors sealed with tape, no pressure differences.
A-4	Room depressurized to induce spillage, sequential loads with doors open, doors closed & doors sealed.
A-5	Fireplace modified to have direct outdoor air connection to firebox, negative pressure in air inlet
A-6	Fireplace with direct outdoor air connection, outdoor air @ -20°C.
B-l	Makeup air from outside, no negative pressure in room, fans activated.
B-2	Same as B- 1 except fans not energized.
B-3	Circulation and combustion air from room, fans energized.
B-4	Same as B-3 except fans not energized.
B-5	Makeup air from outdoors, negative pressure in room. Fan on for first 2 loads and off for third load.
B-6	Circulation & combustion air from room, negative pressure in room. Fan on for first 2 loads and off for third load.
B-7	Combustion and makeup air duct reverse flow test.
B-g	Test with cold outdoor air.
C-l	Dampers fully open. (Problem with weight of wood.)
c-2	Damper closed to 40 mm point. (Problem with weight of wood.)
c-3	Dampers fully open - negative pressure in test room for spillage tests.
C-4	One load test - aborted because of facility problem.
C-5	Repeat of Test C-l.
C-6	One charge, damper partially closed, -10 Pa depressurization.
C-7	One charge, dampers fully open.
C-8	Repeat of Test C-l.
c-9	Test at minimum burn rate, dampers almost fully closed.
c-10	Test with cold outdoor air.
C-11	Makeup air supply. Reverse flow test.
D-l	Single charge - no negative pressures.
D-2	Repeat of D-l.
D-3	Two charges - no negative pressures.
D-4	First reverse flow test.
D-5	Spillage test.
D-6	Single charge - chimney - fireplace joint taped.
D-7	Three charges - with grate.
D-8	Test with cold outdoor air.
D-9	Reverse flow test - without backdraft damper.
D-10	Reverse flow test - with backdraft damper.
E-l	Chimney A - inside, conditioning test, no doors.
E-2	Chimney A - inside, no doors on fireplace.
E-3	Chimney A - inside, cold air outside, no doors on fireplace.
E-4	Chimney A - inside, doors closed on fireplace.
E-5	Chimney A - inside, doors closed on fireplace, cold air outside.
Ed	Chimney B - inside, fireplace doors open.
E-7	Chimney B - inside, fireplace doors closed.
E-8	Chimney A - outside, fireplace doors closed.
E-9	Chimney A - outside, fireplace doors closed, cold outside air.
E-10	Chimney A - outside, fireplace doors closed, chimney air inlet blocked.
E-11	Chimney C - outside, fireplace doors closed.
E-12	Chimney C - outside, fireplace doors closed, cold outside air.

3.0 RESULTS

3.1 <u>Results of Burn Tests</u>

Data from the tests was collected and stored on computer diskettes. Ninety-six channels of data, including fuel weight, airflow rates, sensor differential pressures, static pressures, gas analyses and temperatures were collected at one minute intervals during each test. Data was set up so that it could be analyzed using the CCRL Wood Stove Data Analysis Program, on an HP Series 200 computer. In addition, the data was also transferred to a ‘spreadsheet’ type program for further analysis on a Macintosh computer. Table 3 shows an excerpt of data from one test, at the one minute intervals. Values for calculated stack flow, combustion air requirements, and excess air % were calculated using equations from CSA Standard B415-M1986, as shown in Appendix C. It was found that, at the one minute intervals, the changes in wood weight were often less than the 0.1 pound resolution of the weighing system used, and therefore calculated values were inconsistent. In order to provide a better comparison between measured and calculated values, increased time steps were used. Table 4 shows data from the same test as shown in Table 3, with time steps increased to provide larger steps in wood weight.

Results for each fireplace, in terms of spillage characteristics, typical stack airflow rates, and high material temperatures are summarized in Table 5.

For Fireplace A, with doors open, spillage could be induced at high burn rates at a room pressure of -14 Pa, and at -11 Pa with a low burn rate. With the doors closed, these values changed to -25 and -20 Pa, respectively. As with the other units tested, it was noted that the tightness of the doors had little effect on the pressure at which spillage occurred. All units had spillage with room pressures around -25 to -27 Pa at high burn rates, and -16 to -20 Pa at low burn rates. Spillage appears to be linked to the draft at the base of the chimney, which is linked to the flue gas temperature in the chimney. Spillage occurs when the pressure at the base of the chimney is positive in relation to the room.

TABLE 3: Data from Test Run at One Minute Intervals

time	Wood Weight Kg	Flue gas Temp 1.2 m	Room Temp	Room Exh L/s	Stack CO ppm	Room CO ppm	Room CO2 ppm	Stack Flow L/s	Calc. Flow L/s	Character Height M	Draft At Stack Base	Combustion Air req. L/s	Excess Air %	Make-up Airflow	Flue liner Temp	Flue gas Damper	Flue gas Top	Refrac Left	D.P. Rm/Inlet
9.95	7.69	19.6	19.6	2	-6	2	513	44	-474	1.9	1.1	-439.7	17383	14.0	19.9	19.9	19.3	20.2	2.1
9.96	7.74	19.6	19.7	3	4	2	478	13	-261	1.5	4.2	-261.3	14727	0.0	20.0	19.7	19.3	20.2	-0.1
9.96	0.77	19.7	19.7	76	0	2	482	16	193651	3.1	0.2	160096.9	26490	1.9	19.9	19.7	19.4	20.1	-0.4
10.00	0.80	19.7	19.6	76	13	2	510	17	-677	2.0	0.2	-629.9	17708	2.2	20.0	19.7	19.3	20.2	-0.2
10.01	0.46	19.9	19.9	78	-5	2	497	26	5576	-0.7	0.3	5107.0	13613	2.5	20.0	20.0	36.9	20.2	-0.1
10.03	0.67	66.9	20.0	77	-6	2	519	46	-4065	-38.6	-5.2	-3779.9	17479	2.5	32.9	100.6	93.5	107.7	-0.1
10.04	0.49	117.9	20.0	75	-14	2	513	47	3476	19.6	-5.1	3232.7	14294	2.9	50.6	125.6	106.3	146.7	-0.3
10.06	7.43	120.4	20.1	76	2	3	500	43	-30906	6.1	-5.6	-26651.5	6516	2.9	61.8	130.1	66.9	141.3	-0.3
10.07	7.43	57.6	20.1	77	78	3	498	26	-3	26.1	-3.0	-3.2	3562	3.1	53.1	56.1	54.4	100.6	-0.2
10.09	7.36	54.6	20.1	77	200	2	466	31	46	107.4	-3.1	42.4	2249	3.2	40.6	56.1	54.0	64.6	-0.3
10.11	7.32	59.9	20.1	79	264	3	474	32	29	57.5	-3.3	26.6	1226	3.6	47.0	61.4	56.2	75.4	-0.4
10.12	7.24	70.6	20.1	75	191	3	459	36	-1531	170.6	-4.1	-1424.6	-45641	3.6	46.4	75.4	70.1	70.3	-0.3
10.14	7.15	94.6	20.2	77	79	2	455	35	-74	26.4	-5.7	-70.3	-1966	3.9	53.6	100.6	66.4	70.7	-0.4
10.16	7.05	106.4	20.2	76	336	3	450	46	-456	61.4	-5.4	-425.0	-11743	3.8	59.9	113.2	104.9	70.4	-0.2
10.16	6.97	119.5	20.2	74	610	3	447	44	30	34.6	-6.2	27.3	694	3.9	67.9	126.4	112.7	69.6	-0.4
10.19	6.03	152.6	20.3	76	1335	3	444	36	42	9.0	-0.7	37.9	560	4.0	79.7	161.6	121.2	97.4	-0.5
10.21	6.74	137.2	20.3	76	1725	2	444	51	30	37.3	-0.5	27.2	592	4.2	63.6	144.2	129.7	104.2	-0.5
10.23	6.65	137.5	20.4	77	1771	3	444	41	37	21.3	-9.0	33.0	676	4.4	09.0	144.5	124.7	104.4	-0.3
10.24	6.50	140.6	20.5	77	1622	2	447	44	53	29.1	-6.1	47.6	639	4.5	92.9	147.1	131.1	106.6	-0.4
10.26	6.42	141.5	20.5	76	1769	3	447	53	26	25.6	-7.9	25.5	562	4.5	94.6	146.2	130.3	113.1	-0.5
10.26	6.33	146.2	20.5	77	1722	3	446	46	32	27.6	-9.6	26.3	542	4.7	99.1	156.8	137.4	125.4	-0.5
10.29	6.19	146.6	20.6	74	1760	3	446	45	44	26.4	-6.4	39.1	463	5.0	101.0	152.6	136.2	142.1	-0.6
10.31	6.09	150.7	20.7	76	1646	2	446	51	26	36.4	-0.4	23.5	457	4.9	103.9	159.6	142.6	166.6	-0.3
10.33	5.96	156.6	20.6	76	1639	3	440	49	38	30.7	-10.9	33.5	423	5.1	106.5	169.7	146.0	195.0	-0.5
10.35	5.63	161.6	21.0	75	1964	2	450	49	36	26.6	-6.2	33.6	404	5.2	111.2	169.4	149.2	235.9	-0.6
10.36	5.69	162.3	20.9	75	1997	3	452	47	37	29.3	-11.1	32.6	377	5.4	115.3	177.6	151.0	260.5	-0.5
10.36	5.60	173.0	21.0	74	2005	2	453	52	27	27.3	-9.2	23.6	396	5.5	116.3	163.9	159.9	294.0	-0.6
10.40	5.46	172.2	21.1	77	2004	3	453	49	41	21.3	-6.6	36.6	369	5.6	120.6	177.3	155.7	305.2	-0.6
10.41	5.37	166.6	21.1	75	1772	4	455	47	26	26.6	-6.4	22.9	393	5.6	121.1	172.7	153.9	326.0	-0.6
10.43	5.26	167.4	21.0	75	1136	3	457	45	29	29.5	-8.9	25.6	431	6.0	122.2	174.8	155.7	347.0	-0.6
10.45	5.33	166.6	21.2	76	1034	4	457	46	-17	29.3	-10.1	-15.3	470	6.1	123.6	176.1	156.6	361.6	-0.6
10.47	5.15	246.7	21.3	74	993	3	456	30	64	13.1	-16.3	57.4	491	6.3	126.6	271.6	209.9	364.2	-0.6
10.46	5.06	261.2	21.4	73	1065	3	467	34	16	10.4	-16.4	15.6	225	6.3	144.5	306.6	226.6	361.7	-0.6
10.50	4.91	292.3	21.5	75	941	3	465	33	22	10.4	-17.6	19.2	139	6.7	155.6	321.6	235.6	369.5	-0.6
10.52	4.76	303.0	21.6	23	692	4	465	26	16	10.3	-16.5	13.5	99	6.6	167.4	332.5	243.2	377.5	-0.7
10.53	4.64	306.5	21.7	77	636	3	469	31	26	10.3	-17.4	22.5	209	6.7	177.0	331.6	246.4	362.2	-0.7
10.55	4.55	307.4	21.6	75	664	3	469	32	20	10.7	-17.7	17.4	257	6.9	163.6	332.8	249.1	364.2	-0.6
10.57	4.42	311.6	22.1	77	778	4	472	31	26	10.6	-16.0	24.1	222	7.1	190.1	337.9	252.6	390.5	-0.6
10.59	4.33	315.6	22.2	75	753	3	467	24	19	11.1	-16.9	16.5	240	7.2	196.1	340.3	257.6	397.7	-0.7
10.60	4.23	322.7	22.4	74	749	3	464	20	19	11.7	-16.6	17.1	221	1.6	201.9	340.5	265.9	402.9	-0.9
10.62	4.09	331.3	22.4	75	766	3	466	24	27	10.6	-17.6	23.5	199	2.7	208.9	353.6	267.5	407.9	-0.6
10.64	4.00	326.3	22.5	74	742	3	485	23	17	10.9	-16.1	15.0	191	3.1	213.4	351.6	267.0	412.0	-0.6
10.65	3.87	320.5	22.7	75	646	3	464	21	26	11.1	-16.6	22.5	200	3.6	216.7	349.5	268.0	416.8	-0.7
10.67	3.76	326.9	23.0	75	964	3	402	20	19	11.5	-16.6	16.3	229	4.0	219.5	350.1	270.3	421.6	-0.6
10.69	3.64	350.1	23.1	75	1033	4	462	27	30	10.3	-16.6	26.6	235	4.3	226.2	371.9	261.3	427.9	-0.9
10.71	3.56	345.0	23.3	74	769	3	402	29	17	10.6	-16.6	15.0	193	4.3	230.9	366.2	279.0	432.4	-1.0
10.72	3.46	340.5	23.1	74	770	3	482	23	16	11.2	-19.2	15.4	188	4.9	233.7	359.9	270.5	435.9	-0.7
10.74	3.31	336.1	21.7	75	735	4	482	25	30	11.6	-16.6	26.2	199	5.1	235.4	354.6	270.3	440.5	-1.1
10.76	3.23	336.9	22.0	73	986	4	466	16	19	11.7	-16.6	16.9	250	5.3	236.4	355.8	277.0	445.3	-0.9
10.77	3.15	337.4	22.8	74	994	3	521	23	21	11.7	-16.9	19.0	266	5.6	237.5	356.6	270.2	451.2	-0.9
10.79	3.06	336.4	23.2	75	542	3	512	25	22	11.7	-16.5	19.6	263	5.6	236.6	355.6	279.3	457.5	-0.9
10.61	2.96	339.2	23.3	75	624	3	504	26	27	11.6	-19.0	23.6	260	5.7	240.5	357.4	260.3	462.4	-0.6
10.83	2.66	340.4	23.6	75	663	3	500	20	22	11.7	-18.1	19.4	301	5.7	241.9	356.6	280.9	470.6	-0.9

TABLE 4: Example Test Data After Reduction

time	Wood Weight Kg	Flue gas Temp 1.2 m	Room Temp	Room Exh L/s	Stack CO ppm	Room CO ppm	Room CO2 ppm	Stack Flow Us	Calc. Flow L/s	Character Height M	Draft At Stack Base	Combustion Air req. L/s	Excess Air %	Make-up Airflow	Flue liner Temp	Flue gas Damper	Flue gas Top	Refrac Left	D.P. Rm/Inlet
10.06	7.43	120.4	20.1	76	2	3	500	43	127	6.1	-5.6	116.0	6516	2.9	61.6	130.1	86.9	141.3	-0.3
10.11	7.32	59.9	20.1	79	264	3	474	32	16	57.5	-3.3	16.6	1226	3.6	47.0	61.4	56.2	75.4	-0.4
10.14	7.15	94.6	20.2	77	79	2	455	35	-69	26.4	-5.1	-65.2	-1988	3.9	53.6	100.6	66.4	70.7	-0.4
10.18	6.97	119.5	20.2	74	610	3	447	44	32	34.6	-6.2	26.4	694	3.9	67.9	126.4	112.7	69.6	-0.4
10.19	6.83	152.6	20.3	76	1335	3	444	36	42	9.0	-6.7	37.9	560	4.0	79.7	161.6	121.2	97.4	-0.5
10.23	6.65	137.5	20.4	77	1771	3	444	41	35	21.3	-9.0	31.9	676	4.4	69.0	144.5	124.7	104.4	-0.3
10.24	6.50	140.6	20.5	77	1622	2	447	44	53	29.1	-6.1	47.6	639	4.5	92.9	147.1	131.1	106.6	-0.4
10.26	6.33	148.2	20.5	77	1722	3	446	46	29	27.6	-9.6	26.2	542	4.1	99.1	156.6	131.4	125.4	-0.5
10.29	6.19	146.6	20.6	74	1760	3	446	45	44	26.4	-6.4	39.1	463	5.0	101.0	152.6	136.2	142.7	-0.6
10.33	5.96	156.6	20.6	76	1639	3	446	49	31	30.7	-10.9	27.7	423	5.1	106.5	169.7	146.0	195.0	-0.5
10.35	5.63	161.6	21.0	75	1964	2	450	49	36	26.6	-6.2	33.6	404	5.2	111.2	169.4	149.2	235.9	-0.6
10.36	5.60	173.0	21.0	74	2005	2	453	52	32	27.3	-9.2	26.6	396	5.5	116.3	163.9	159.9	294.0	-0.6
10.41	5.37	166.6	21.1	75	1772	4	455	47	33	26.6	-6.4	29.6	393	5.6	121.1	172.7	153.9	326.0	-0.6
10.47	5.15	246.7	21.3	74	993	3	456	30	26	13.1	-16.3	23.4	491	6.3	126.6	271.6	209.9	364.2	-0.6
10.46	5.06	261.2	21.4	73	1065	3	467	34	16	10.4	-16.4	15.6	225	6.3	144.5	306.6	226.6	361.7	-0.6
10.52	4.70	303.0	21.6	23	692	4	465	26	17	10.3	-16.5	14.7	99	6.6	167.4	332.5	243.2	371.5	-0.7
10.55	4.55	307.4	21.8	75	664	3	469	32	25	10.7	-17.7	21.7	257	6.9	163.6	332.6	249.1	364.2	-0.6
10.59	4.33	315.6	22.2	75	753	3	467	24	24	11.1	-16.9	20.9	240	7.2	196.1	340.3	257.6	397.7	-0.7
10.62	4.09	331.3	22.4	75	766	3	488	24	23	10.6	-17.6	19.7	199	2.7	206.9	353.6	267.5	407.9	-0.6
10.65	3.67	326.5	22.7	75	646	3	464	21	22	11.1	-16.6	19.0	200	3.6	216.7	349.5	266.0	416.6	-0.7
10.69	3.64	350.1	23.1	75	1033	4	462	27	25	10.3	-16.6	21.7	235	4.3	226.2	371.9	261.3	427.9	-0.9
to.72	3.46	340.5	23.1	74	770	3	462	23	17	11.2	-19.2	15.1	166	4.9	233.7	359.9	276.5	435.9	-0.7
10.77	3.15	337.4	22.6	74	994	3	521	23	26	11.7	-16.9	23.0	266	5.6	237.5	356.6	216.2	451.2	-0.9
10.61	2.96	339.2	23.3	75	624	3	504	26	24	11.6	-19.0	21.7	260	5.7	240.5	357.4	260.3	462.4	-0.6
10.64	2.71	341.8	23.2	73	1036	3	496	29	24	11.6	-16.5	21.1	267	6.1	243.5	356.7	262.4	476.1	-0.8
10.66	2.59	345.1	22.3	73	369	4	497	25	-24	11.6	-16.9	-22.6	-476	6.5	246.4	362.3	265.4	491.3	-1.0
10.91	2.42	347.6	23.6	74	772	3	496	23	29	11.9	-16.7	25.6	365	6.4	249.9	369.2	267.9	507.3	-1.2
10.94	2.23	347.7	24.1	74	612	3	498	32	13	11.6	-16.9	10.6	70	6.6	253.8	360.5	267.3	513.5	-1.1
10.96	2.05	345.6	22.6	73	903	4	499	31	26	12.0	-19.6	25.1	315	7.3	255.6	357.2	266.7	510.0	-1.2
11.01	1.66	344.0	22.4	73	666	3	500	31	31	12.1	-19.0	27.6	336	7.6	257.0	355.6	266.1	510.9	-1.3
11.07	1.73	339.0	24.1	72	702	3	498	29	16	12.1	-16.6	16.6	366	7.1	257.4	347.1	261.6	510.4	-1.2
11.10	1.60	334.1	24.6	74	636	3	502	27	30	12.5	-16.6	27.3	423	7.6	256.0	339.1	260.1	509.6	-0.3
11.13	1.46	331.3	23.2	71	556	3	499	25	34	12.3	-16.9	30.7	436	a.5	254.4	337.6	276.6	514.2	0.0
11.17	1.36	323.3	22.6	72	524	3	496	29	23	12.6	-16.7	21.5	427	6.6	252.3	327.6	271.3	521.1	-0.1
11.20	1.26	316.3	22.6	72	676	3	499	26	22	12.6	-16.4	20.0	465	6.6	249.5	320.7	267.7	524.6	-0.3
11.25	1.14	314.4	24.7	73	961	3	496	29	25	12.6	-16.3	22.6	472	6.6	246.4	316.4	264.6	526.4	-0.3
11.31	1.04	313.3	24.0	72	1007	3	499	27	17	12.9	-16.5	15.9	434	9.0	244.4	317.1	264.2	532.2	-0.4
11.36	0.92	311.7	23.2	71	1099	3	500	32	24	12.6	-16.3	22.5	464	9.3	243.6	314.9	262.7	536.2	-0.3
11.41	0.62	312.1	23.3	72	1090	3	496	26	19	12.9	-16.6	17.4	432	9.3	243.5	313.1	263.3	540.9	-0.4
11.46	0.73	294.5	25.0	71	1264	3	500	30	19	13.4	-17.9	17.6	525	9.3	236.6	269.9	250.5	541.4	-0.5

Notes on Tables 3 and 4

Explanation of Column Headings

Time:	Time of day in hours
Wood Weight:	Weight of fuel - kg
Flue Gas Temp. 1.2 m:	Temperature in deg.C of flue gas 1.2 m above chimney connection to fireplace
Room Temp.:	Temperature in deg. C in test room
Room Exhaust - Us:	Flow through exhaust duct from test room, L/s
Stack CO - ppm:	Concentration of CO in stack gases - ppm
Room CO - ppm:	Concentration of CO in exhaust flow from room
Room CO2 - ppm:	Concentration of CO2 in exhaust flow from room
Stack Flow - Us:	Flue flow at standard density (21°C, 101.325 k pa) as measured by pitot tube in stack
Calc. Flow - L/s:	Flue flow at standard density as calculated from fuel usage and excess air level
Characteristic Height **M:**	Characteristic height, H* calculated from $H^* = - H/\ln (T_H - T_o) / T_{in} - T_o)$
where:	$H = 2.46$ m T_H = Flue gas temperature at top of stack, C T_o = Temn. of air in enclosure surrounding stack, C T_{in} = Temp. of flue gas at 1.2 m height, C
Draft at Stack Base:	Static pressure in Pascals measured with pitot tube at stack base
Combustion Air Req. L/s:	Quantity of air calculated going in combustion chamber from flue gas analysis and fuel use
Excess Air - %:	% of air above stoichometric as calculated from fuel gas analysis
Makeup Airflow L/s:	Flow through outdoor air intake, measured using flow grid
Flue Liner Temp.:	Temperature of flue lines, deg. C, at about 1.2 m above stack base
Flue Gas Damper:	Temperature of flue gas at base of stack
Flue Gas Top:	Temperature of flue gas at top of stack, deg. C
Refractory Left:	Temp. in deg. C on inside surface of firechamber at left side
D.P. Room/Inlet:	Differential pressure between test room and air intake chamber in Pascals. Negative value means room is at lower pressure than air intake chamber.

TABLE 5: SUMMARY OF RESULTS FOR **FIREPLACES TESTED**

FIREPLACE & DESCRIPTION	PRESSURE TO INDUCE SPILLAGE		DIE DOWN SPILLAGE @ 10 Pa ROOM DREPRESSURIZATION		FIREPLACE ELA ● 10 Pa M ^2	ROOM FAN FLOW RATE FOR 5 Pa DEPRESSURIZATION	FLUE FLOW RATE - L/s ● 22 C		AIR INTAKE FLOW @ 5 Pa L/s ● 22°C
	HIGH BURN	LOW BURN	DURATION . HOURS	CO OUTPUT . LITRES @ 22°C			HIGH BURN	LOW BURN	
A - Doors Open	14	11			0.031	40	47	40	8
A - Doors Closed	25	20			0.026	40	29	16	8
A - Doors Taped	27	20			0.024	40	23	18	8
A - With Retrofitted Outside Air Duct	25		Note 1	Note 1		40			
B - Outdoor Air/Fan Off	25	16			0.01	45	44	43	20
B - Outdoor Air/Fan On	25	16			0.01	45	40	35	36
B - Room Air/Fan Off			3.25	28.5	0.01	45	36	30	7
C	25	16	0.8	3.3	0.005	45	31	10	7
D	24		3.5	27.7	0.001	42	36*	5	3
E	Note 1	Note 1	Note 1	Note 1	0.027	Note 1	70	50	1

Note 1: This test was not performed for these fireplaces.

* Flow with Doors Ajar

Spillage is more likely to occur when the draft is lowest, and this happens at the beginning and end of the bum cycles. At the start of a fire it was found that it is best to heat up the flue as quickly as possible, in order to increase the draft quickly. Not unexpectedly, a starter fire with paper and kindling alone was found to be good for this. After the flue temperature is up (200°C), the full charge can be added. A trial run was carried out with the kindling and a full charge all together. This produced a smoky fire which was slow to start.

Fireplaces C and D had fixed baffles above the fire which forced the flue gases towards the front of the firebox before they entered the chimney. It was found that, when the fire was lit, there was a tendency for smoke to roll out the front of the fireplace when the doors were open. Closing of the doors, to within about a 20 mm of full closing, reduced or eliminated this problem With fireplaces B, C and D it was found that, if the fireplace doors were closed tightly right after lighting of the fire, the fire would go out. It appeared that there was not enough draft established to draw in sufficient air to sustain the fire. The solution to this problem was to leave the doors slightly ajar until the fire was going well and a good draft was established. The draft required for operation with doors closed tightly depended on the equivalent leakage (flow) area (ELA) of the combustion air intakes, that is, the smaller the ELA, the greater the draft required to induce adequate combustion air.

The connection of the outdoor combustion air supply directly to the firebox, as in fireplace D, did little to assist in the prevention of spillage during startup. The fueplace had to rely on room air for combustion until sufficient draft had been created to allow closing of the doors, and intake of combustion air through the direct connection. The only way to overcome this dependence on room air for startup would be to provide a forced or induced draft system for the fireplace. Fireplace B did have a fan assisted air supply, however the fan did not operate until the fireplace warmed up.

During diedown of the fire, spillage occurred when the pressure at the base of the chimney was higher than that in the room For a room pressure of -10 Pa, spillage began to occur from fveplaces A, B and C when the stack temperature dropped below about 100°C. This diedown phase often occurs when the traditional fireplace user is away from the fire, or asleep. Backdrafting took place when the room pressure was 3 Pa less than the pressure at the base of the stack. When room pressures were set to -5 Pa, no spillage was detected during diedown in any of the four fireplaces.

The flow rate of air up the chimney was determined for the fireplaces under test. The range of airflow rates was on the order of 10 to 50 L/s (standard air). The high flow rate would depressurize the test room by about 5 Pa.

Tests were also carried out to determine the effect of a negative pressure at the inlet of the outdoor air intake. For fireplaces A and C, with the air supply to the open circulation plenum, there was no problem with this operation. Air was drawn outwards through the air intake duct, but since it came from the inlet of the air circulation plenum it was close to room temperature. Reverse flow could be detected with pressures as low as 3 Pa. Fireplace A was modified to have an outdoor air connection directly to the front of the fuechamber. Under a negative pressure of 5 Pa at the air inlet., flue gases could be drawn through the air intake, producing temperatures above 100°C in the intake duct.

For fireplace B, all of the circulation air came through the air intake when the fireplace was set for outdoor operation. A negative pressure of 21 Pa at the air inlet reversed the flow through the circulation plenum, and drew heated air out through the air intake. With the fan off, a negative pressure of 3 Pa was sufficient to reverse the flow. Conditions with a duct surface temperature of 134°C and an air temperature of 120°C at the air inlet grille were measured in this test

Fireplace D was designed with a direct connection of the combustion air intake to the firechamber. A negative pressure of 20 Pa at the air inlet was sufficient to backdraft the fireplace through the air inlet, producing a peak duct surface temperature of 157°C.

No tests of reverse flow were carried out on Fireplace E.

Operation of the **fireplaces** with cold combustion air was not significantly different than operation at **22°C,** except for **fireplace** A with the modified duct air connection to the **firebox.** The first load in this test was slow to burn, with the cold air impinging on the wood pile. Once the fueplace was warmed up well, and a bed of coals created, second and third charges burned normally.

3.2 Air Intake and Chimney Flow Characteristics

The flow versus pressure characteristics of the air intakes and chimneys were measured during the tests. Figure 4 shows the characteristics of the air supplies connected to the circulation plenum The two 100 mm diameter intake ducts for fireplaces A and C showed similar flow characteristics. The much larger intake for fireplace B was able to provide a much greater flow of outdoor air at similar pressures.

Table 6 shows the flows through the air intake at a 5 Pa pressure differential, and the Equivalent Leakage Areas at 10 Pa

Table 6: Air Intake Flows and Areas

Fireplace	Flow at **5** Pa AP **L/s**	ELA at 10 Pa **m^2**
A	8	0.0050
B Fan On	**36**	
B Fan Off	**20**	0.0123
C		
D	73	0.0040 0.0015
E	1	0.0005

The chimney flue characteristics were also measured by connecting a fan and flow meter to the base of the chimney, and measuring the static pressure at the base of the chimney at various flow rates. Chimney I was used with fireplaces A and B, Chimney II was used with fireplaces C and D. The pressure drop was measured before and after’ the thermocouple grid for flue gas measurement was installed. Results are shown in Figure 5.

The characteristic length of the chimneys used was calculated for the test runs. The characteristic length is an indicator of heat transfer from the chimney. When gases flow through the chimney, they lose or gain heat to or from the ambient conditions that surround them. That heat flow is a function of the properties of the flowing gas and of the chimney. The equation that describes the temperature change along the chimney is:

$$TL = TO * EXP\,(-L/L^*)$$

where: TL = temperature at a distance L from the inlet
m = inlet temperature
EXP = exponential = e to the power in the brackets,
where e is the base for natural logarithms = 2.71828 . . .
L = distance from the entrance (where T = TO)
L^* = characteristic length of the heat loss process

The calculated length varied from 0 to about 60 metres depending on the flue flow rate. At high burn rates characteristic lengths up to 60 m were calculated. During spillage tests the effective length could be reduced to 0 when the flow up the chimney was stopped. In general, the lower the burn rate was, the lower the characteristic length.

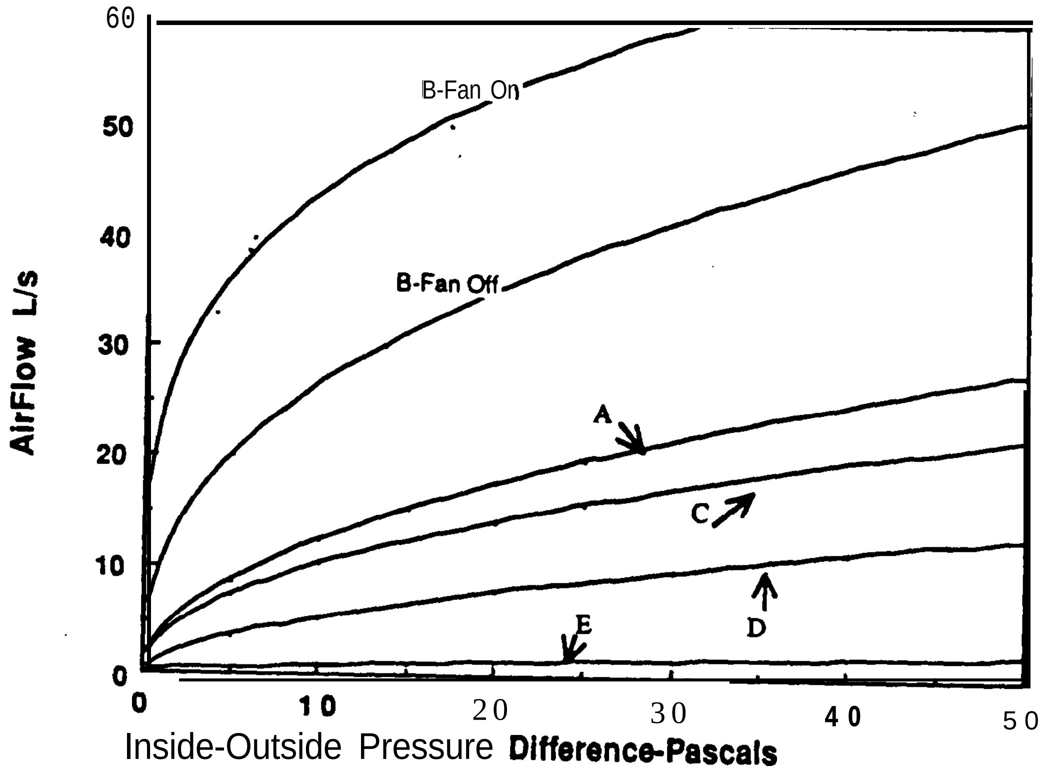
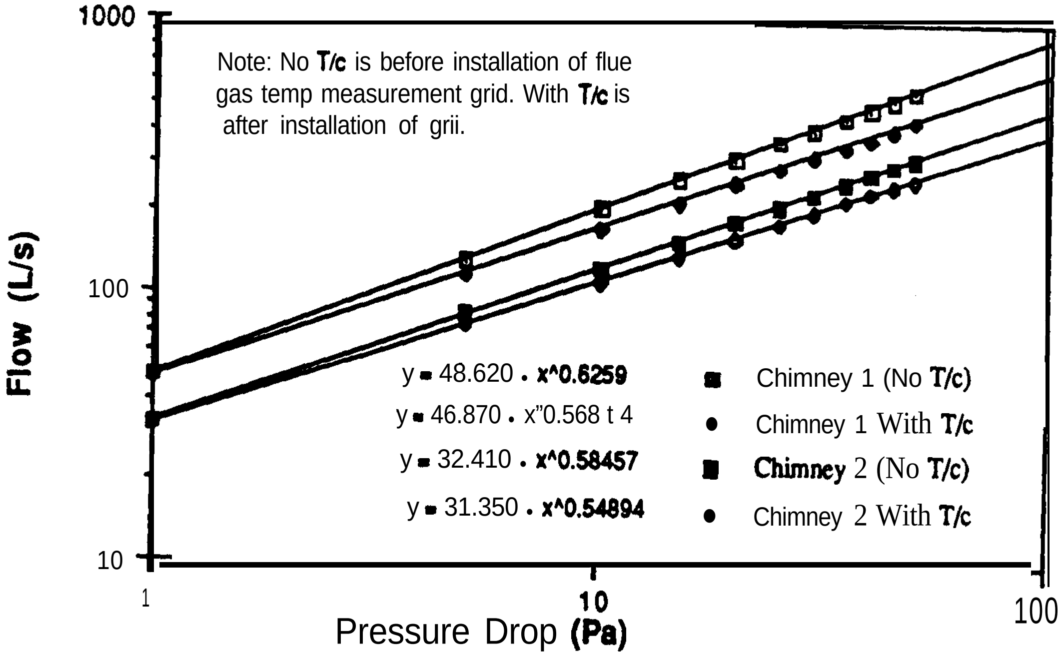


Figure:4 Fireplace Make-up Air Supply Flowrates



Note: No T/c is before installation of flue gas temp measurement grid. With T/c is after installation of grii.

Figure 5: Chimney Flow Characteristics

3.3 Results for the WOODSIM Model

As a first step in the validation of WOODSIM, Scanada prepared WOODSIM input files that described the test facility and fireplace A. They then performed simulations of the tests and compared simulation and test results.

These preliminary comparisons yielded encouraging results both from the point of view that the data collected at the facility appeared to be readily usable and reliable, and that the match between simulation burn rates and flue temperatures was showing similar trends to the test results. Figures 6 and 7 illustrate the results of initial comparisons. The figures show that, although the trends in performance were similar, the simulated burn rate was initially too high (the mass of the wood drops more quickly in the simulation, as shown in Figure 6). The simulated flue gas temperatures peaked too early and were too high initially (Figure 7). These two deviations from test results were consistent, however, a faster initial burn would produce warmer flue gas temperatures.

The following deficiencies were identified in the model:

- The model predicted too much spillage of combustion products throughout the burn cycle, when in fact CO_2 and CO readings from the test room indicated no spillage. The problem was traced to an outdated flue friction factor algorithm in WOODSIM - the friction factor was independent of length, which for a short straight chimney, such as that of the facility, resulted in a large overprediction of flue friction. The sensitivity to flue length had already been updated in FLUESIM and this updated flue friction algorithm was transferred directly to WOODSIM from FLUESIM.
- There was no provision for modelling the circulation air moving through the air space between the firebox and the outer shell of the fireplace; thus, the simulated firebox wall temperatures were too high. As an interim measure, it was decided to model the air space as if all of the mass of the air in the room were available to be heated in the jacket; i.e. the room air heat capacity was modelled as a concentrated mass having, in this case, the effective density of steel. This remains a poor approximation of reality.

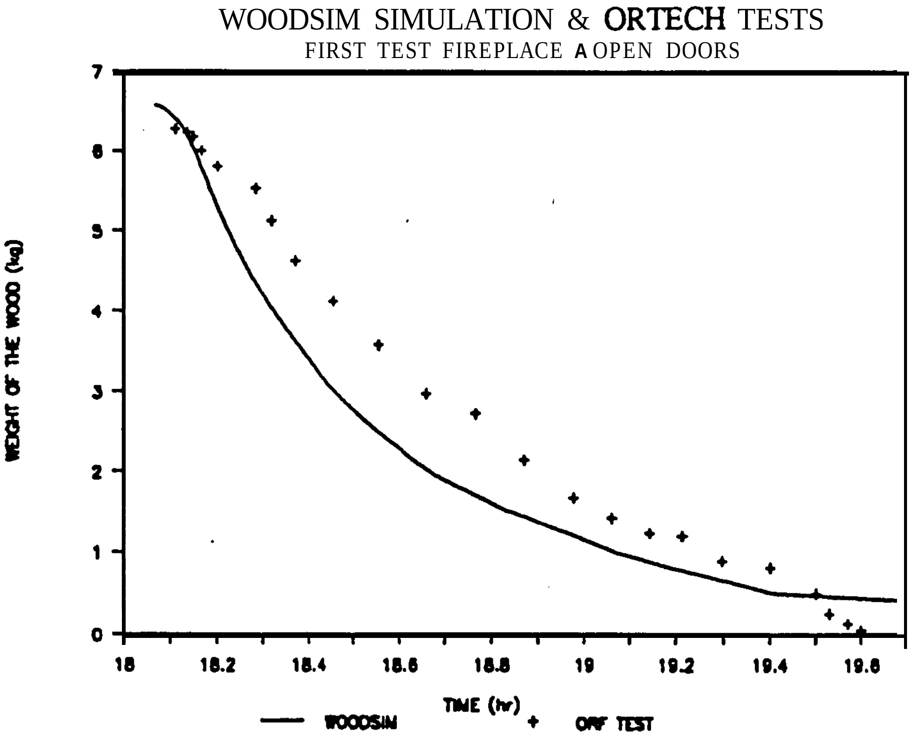


FIGURE 6. FIRST COMPARISON BETWEEN WOODSIM SIMULATION & ORTECH TEST RATE OF BURNING OF THE WOOD PILE

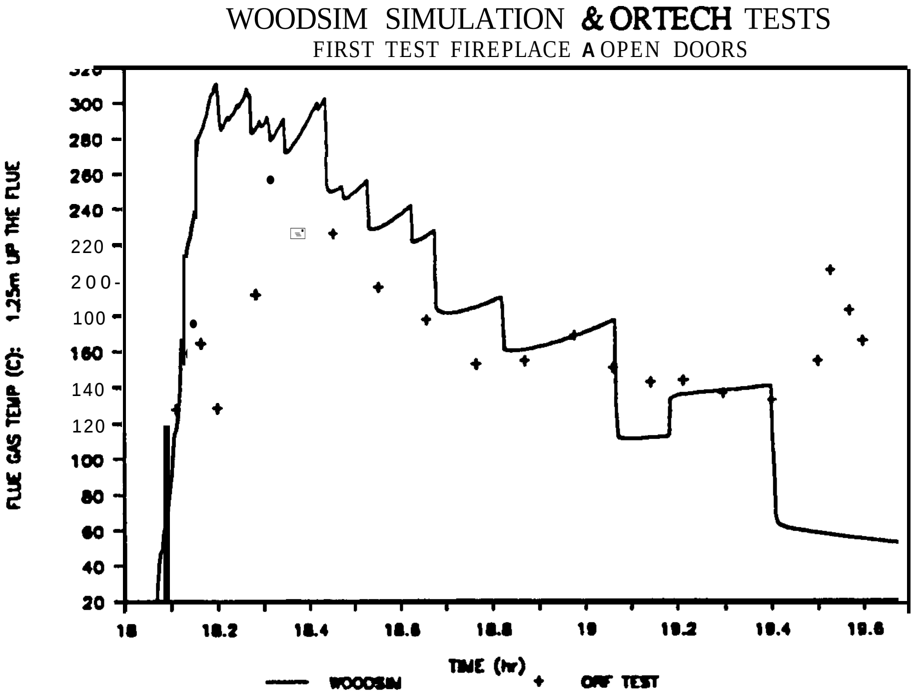


FIGURE 7. FIRST COMPARISON BETWEEN WOODSIM SIMULATION & ORTECH TEST FLUE GAS AND FLUE LINER TEMPERATURES

The overprediction of the rate of bum at the early stages of the fire was attributed to:

- a lack of accounting by the model for moisture content of the wood;
- an overestimation of the amount of surface area available to bum for a log at any one time.

To correct the deficiency in accounting for wood moisture content, the wood moisture content algorithm developed by CCRL for the Standard CSA B-415, Ref. 1, was used. This algorithm was adapted to the model by applying the algorithm to each wood piece in the wood pile. The initial moisture content of each piece is now an input to the model. In this way, dry kindling pieces can ignite and give off heat more quickly, and the larger, wetter main logs take longer to heat up and give off less heat per gross unit weight, forestalling the faster burn rates.

Finally, the total area of log surface available to burn at any one time was reduced from 100% to 75%.

When these changes were implemented, the refined WOODSIM model was rerun and the simulation results were compared to a number of test results generated at the ORTECH test facility. The problem of overpredicting spillage was eliminated. As well, the predicted burn rates fell into line with the tested rates.

Figures 8 and 9 show comparisons between the refined model results and the ORTECH test results for fireplace A, operating under normal circumstances, i.e. doors closed and no room depressurization. Two wood piles were burned successively. Figure 8 indicates that the simulated wood pile burned at correct rates throughout the first cycle. However, the simulated fire lagged slightly in the second cycle. Figure 9 indicates that the program quite closely matches the test for flue gas and liner temperatures in the first cycle. These temperatures were underpredicted in the second cycle, due in part to the lag in the burn rate.

The revised WOODSIM model was used in a parametric study to highlight features of the fireplace, fresh air intake, doors and chimney that help reduce the risk of combustion gas spillage into the house.

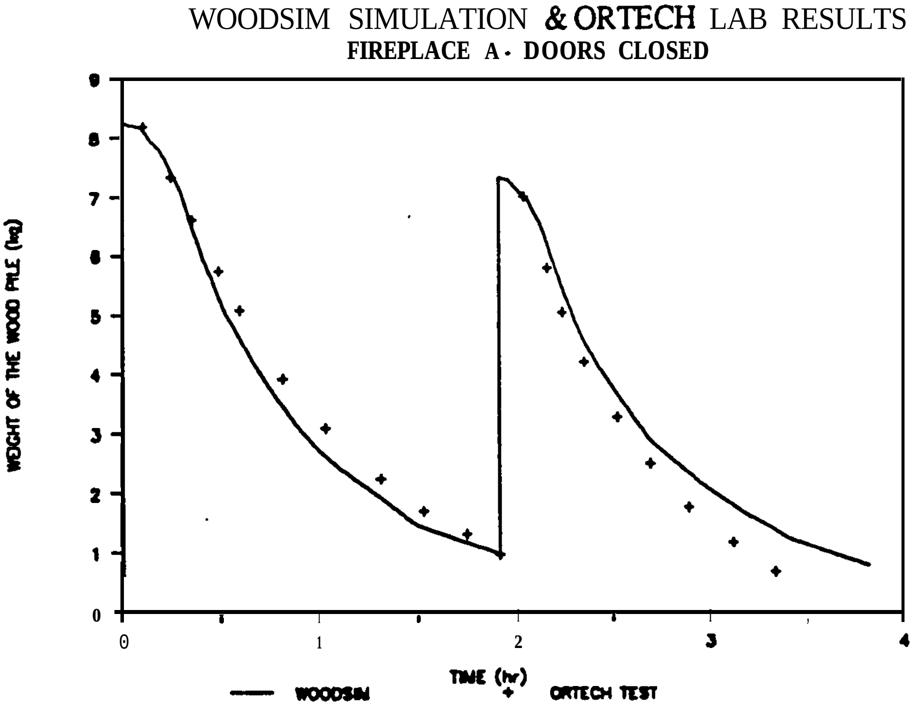


FIGURE 8. REFINED WOODSIM SIMULATION VS ORTECH TEST RATE OF BURNING OF THE WOOD PILE

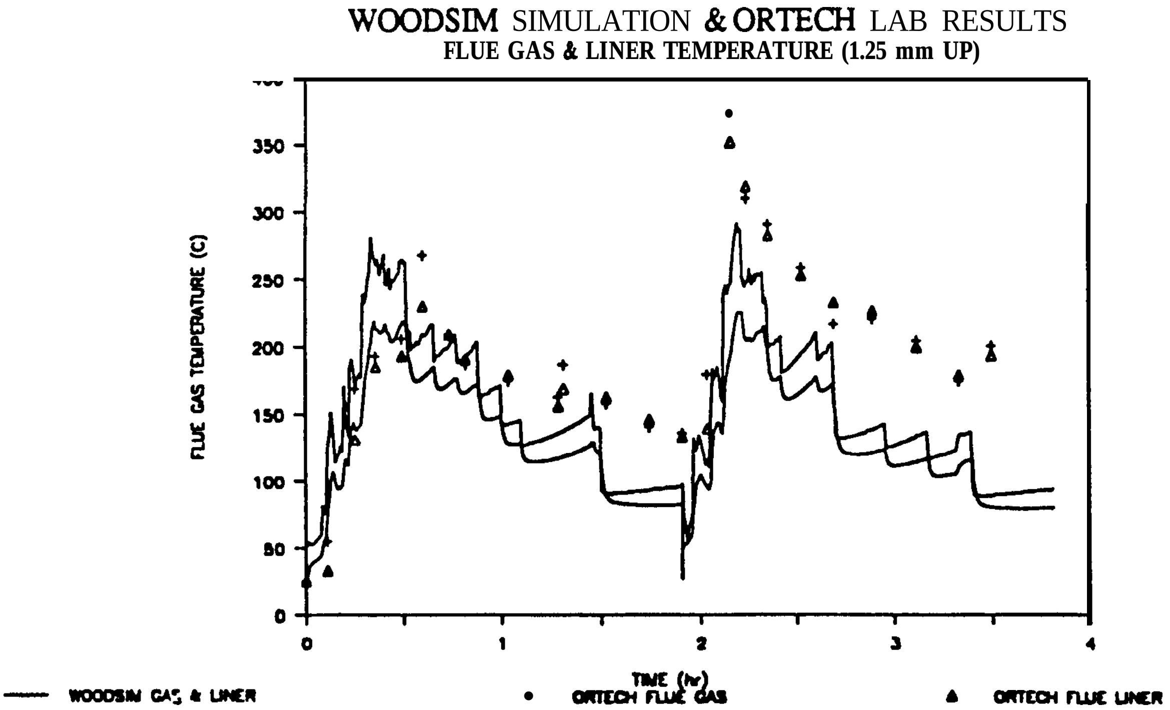


FIGURE 9. REFINED WOODSIM SIMULATION VS ORTECH TEST FLUE GAS AND FLUE LINER TEMPERATURES

The parametric study indicated that:

- Simulated factory-built fireplaces did not spill at 5 Pa house depressurization for the conditions tested
- Fireplace doors have the effect of distributing the draft throughout the firebox leaks, preventing some low draft spillage that might occur in open face fireplaces. The size of the leakage area of the doors appears not to be important for this effect to occur.
- Chimney height appears to have the strongest influence on spillage prevention, provided that the chimney is properly insulated. With a well insulated chimney, the taller the better.
- Energizing the fire at startup and cool down appears to be a key element in preventing spillage. Tight designs, that control the burn rate by closing down the combustion air intake and minimizing leaks, tend to de-energize the flue towards the end of the burn and make these units more susceptible to spillage in a severely-depressurized house. However, tight designs have less potential to depressurize a house at full burn, if operated with the doors closed.

3.4 Results of Chimney Tests

The air-cooled chimney had some operating characteristics which were different from the type A and 650 chimneys. In general, the outside surface temperature of the type A and 650 chimneys decreases with height, as shown in Figure 10. With the air-cooled chimney, there was an initial increase in outside temperature with height, as shown in Figure 11. This increase was partially attributed to an increase in the temperature of the cooling air inside the chimney as it travelled up through the chimney.

The cooling airflow up the air-cooled chimney appeared to be in the range of 5 to 9 L/s for most cases. This would give an average velocity of 0.12 to 0.2 m/s compared to flue gas velocities in the order of 2 to 3 m/s. When the fire is burning, the mass flow rate of the cooling air is about 0.1 of the flue gas flow rate. Therefore, the heat given up from the flue gas by a temperature drop of 1°C would raise the temperature of the cooling air by 10°C. Figure 12 shows temperature in the air-cooled chimney calculated for various cooling air temperatures, outdoor temperatures and flue flow rate, based on a simple model described in ORTECH Report ESC-89-61. Going from a cooling air inlet temperature of 20°C, down to a temperature of -40°C results in about a 4°C lower flue gas temperature. With the air-cooled chimney, the outside surface temperature at the base of the chimney is lower than that of the insulated chimneys. Therefore, heat loss from the chimney to the surroundings is lower for the air-cooled chimney. The cooling air entering the chimney is partially heated by energy that is conducted out through the wall of an insulated chimney. Figure 13 shows the projected energy flows for the insulated and air-cooled chimneys.

The overall heat transfer coefficient (U-value) was estimated for each of the chimneys by use of a simplified heat loss model, described in ORTECH Report ESC-89-61. The heat loss was calculated using the equation:

$$Q=UAAT$$

where Q is heat loss in watts
U is heat transfer coefficient $W/(m^2C)$
A is area m^2
AT is temperature difference between two points

Values of U were estimated from information in the ASHRAE Handbook of Fundamentals. Temperatures of flue surfaces, outside surfaces, cooling air and temperature drop of the flue gas due to heat loss were then calculated, and values compared with the experimental results. Using this method, it was estimated that the overall U-values for the 3 chimneys, based on inside surface area, are as follows:

Air-cooled	$U = 6.5\ W/(m^2C)$
Type A	$U = 4\ W/(m^2C)$
650	$U = 2.7\ W/(m^2C)$

These values are approximate, and could easily vary from actual values by ± 0.5 $W/(m^2C)$ or more, due to the fluctuating flue gas temperatures and flow rates encountered in the testing.

For the insulated chimneys, the heat loss will depend on flue gas flow rate. For the air-cooled chimney, heat loss rate will depend on flue flow rate, cooling airflow rate and cooling air temperature. The interior surface temperatures of the flue in the air-cooled chimney appeared to respond to fluctuations in the flue gas temperature more quickly than the type A or 650 chimneys. The 650 chimney showed the least response of flue surface temperature to flue gas fluctuations.

Figure 10: Type A Chimney Temperatures

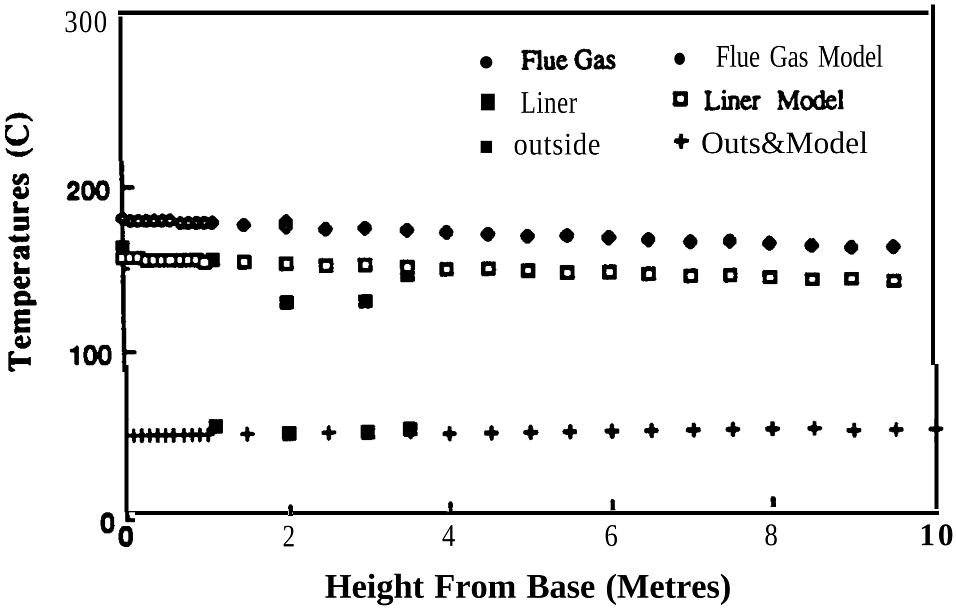
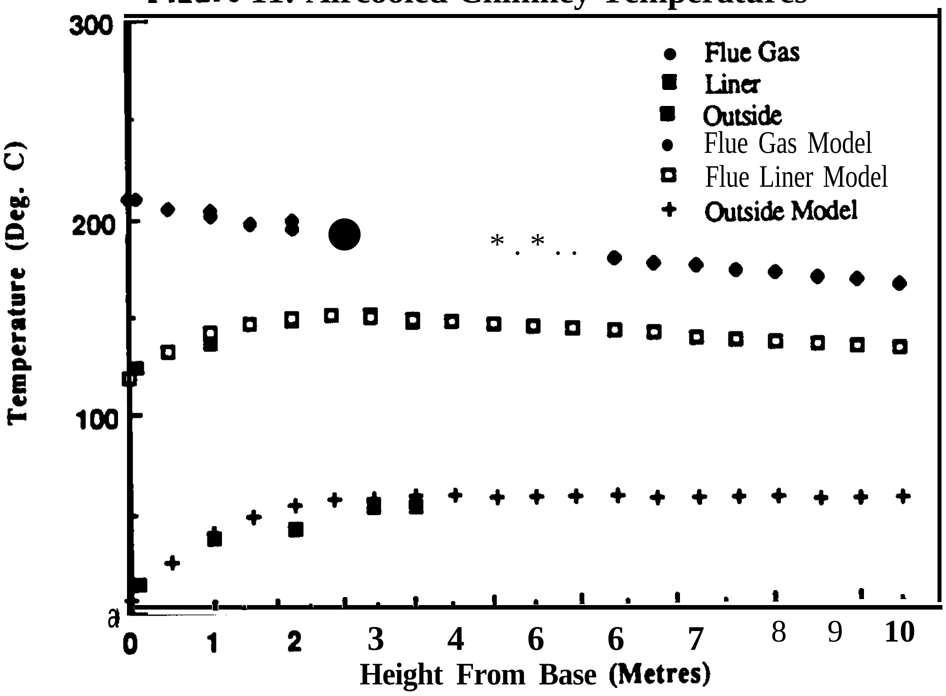
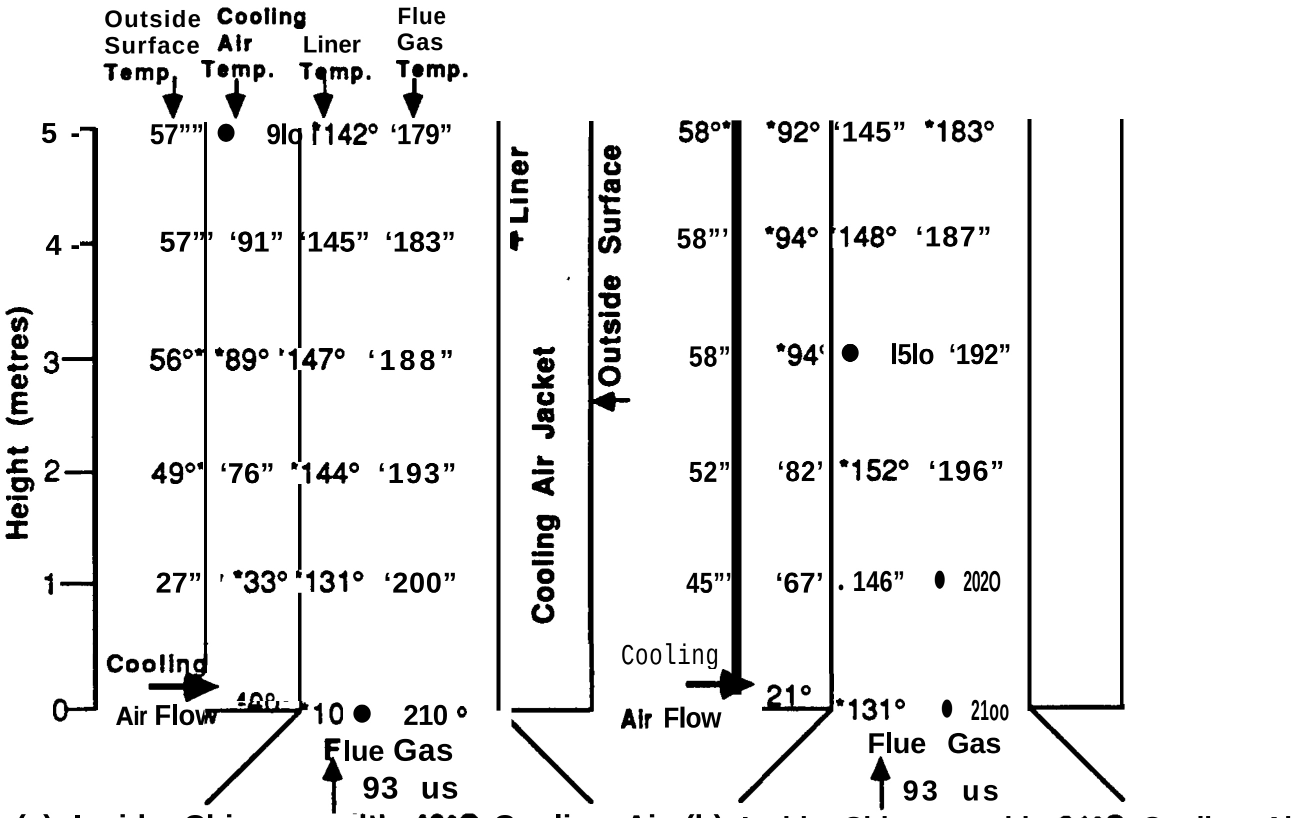
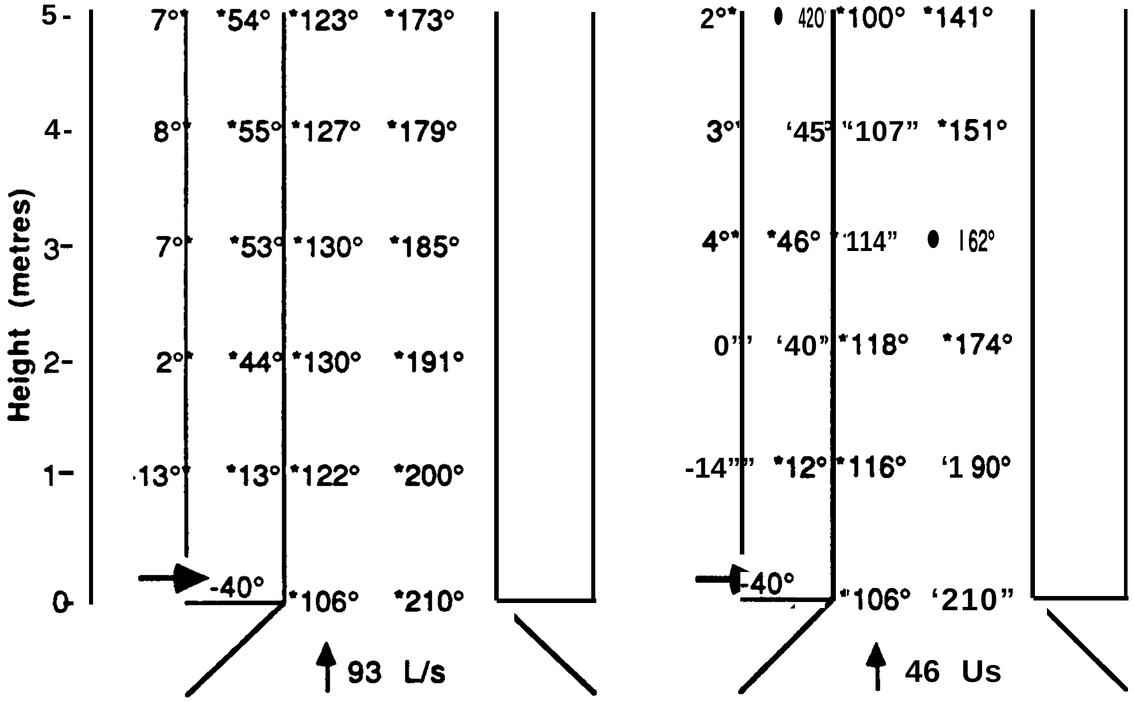


Figure 11: Aircooled Chimney Temperatures



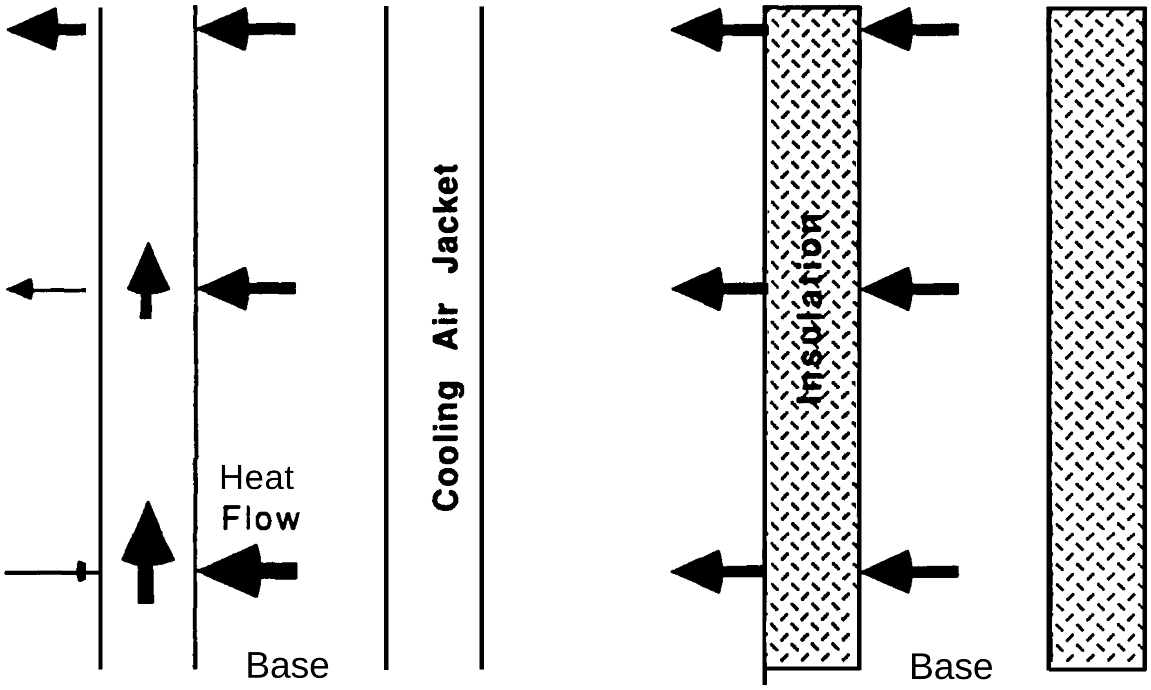


(a) Inside Chimney with -40°C Cooling Air (b) Inside Chimney with 21°C Cooling Air



(c) Outside Chimney with -40°C Cooling Air (d) Outside Chimney at Lower Flue Flow

Figure 12: Temperatures in Air Cooled Chimney (from Model)



(a) Air Cooled Chimney (b) Insulated Chimney

Figure 13: Comparison of Heat Flows In **Air-Cooled** and Insulated Chimneys

During cool down, the flue surface temperature of the air-cooled chimney stayed below the flue gas **temperature** in most cases. In the type A and 650 chimneys, heat stored in the chimneys allowed the flue surface temperature to stay above the flue gas temperature during part of the cool down period.

4.0 DISCUSSION

There are some limitations on the scope of the testing which may affect the widespread application of the results to all fireplaces. The fireplaces that were used for the testing were all factory-built models that had been tested and certified to ULC requirements. They are required to be installed with prefabricated metal chimneys that are tested with the fireplace.

Most of the testing was done with fireplace doors closed, as this was found to be the condition most resistant to spillage.

The information from the testing may not be directly applicable to masonry built fireplaces, or to fireplaces that are operated without doors. The results may also not be applicable where fuel other than dry split hardwood is used.

It should be noted that tests were done with charges of at least 6 kg of wood. Small short fires might be more susceptible to spillage during diedown due to less storage of heat in the fireplace and chimney for maintenance of draft during diedown.

The results show that the fireplaces tested were more resistant to spillage than had previously been expected. As was expected, it is difficult to start a fire without spillage when the room is under a negative pressure and there is a flow down the flue. However, if the negative pressure is removed (eg. by opening a window in the fireplace room), draft can usually be readily established. Once a good draft is established, the fireplaces were relatively resistant to spillage as long as the fire is burning well. One condition where draft might be difficult to establish is the case where a chimney has been backdrafting for an extended period of time in cold weather. If the stack is cooled significantly below the house temperature, it may act as an opening below the neutral pressure plane of the house. This condition was not included in the tests because of the difficulty in maintaining the chimney exhaust chamber at cold temperatures for long periods.

After the chimneys were drafting well, no problems with spillage were noted, even when the room was depressurized to a constant -5 Pa. Room depressurizations of - 10

Pa did result in spillage from the fireplaces towards the end of the fire when coals were burning. This is a potentially hazardous situation, since the spillage flow is usually high in CO concentration, which is odourless and does not contain any smoke particles. It was found that an ionization smoke detector would respond to spillage during startup of a fire, however it would not respond to spillage during diedown of a fire.

These fireplaces do not appear to have a high potential for depressurization of a house during their operation. They operate well with a supply flow rate of about 20 L/s, and appear to have a maximum flow rate on the order of 50 L/s for the sizes tested. Larger models with higher burn rates may draw higher amounts of air.

The 100 mm diameter combustion air ducts connected to the circulation air plenum do not supply the total air requirements of the fireplace at a house pressure of -5 Pa during the medium to high burn rates. They do provide some measure of protection against excessive depressurization in a tight house, however their ELA is about 0.005 m^2 as compared to an estimated ELA of 0.020 to 0.030 m^2 for tight houses. To supply 20 L/s at a 5 Pa differential pressure, an ELA of 0.012 m^2 would be required. This indicates that combustion air inlets have to be roughly 2-3 times as large in order to match the fireplace exhaust rate at low burn. The ELA of the fireboxes in the units tested ranged from 0.001 m^2 for the tightest unit to 0.027 m^2 for a unit with loose fitting glass doors. The ELA of the chimneys used was about 0.044 m^2.

The 83 x 254 mm rectangular air intake on Unit B was much more capable of providing the combustion air requirements of the fireplace, especially when assisted with a circulation fan. The only problem encountered with this intake was reverse flow of heated air through the intake duct. A fan forced air supply, with a capacity of 20 to 40 L/s connected to the air circulation plenum, would appear to have potential as a combustion air supply.

The 100 mm combustion air duct connected directly to the firechamber can supply the total air requirements for a low burn fire, once a draft of 15 to 20 Pa has been established, and if the firebox can be sealed tightly from the room. Once operating, this type of fireplace is relatively insensitive to house pressures, and would work well in houses where intermittent high depressurization occurs. The major problem with this type of intake is the potential for reverse flow of hot gases through the air intake when a large negative pressure is applied to the air intake. This condition could occur in a strong wind if the intake were in a leeward area. The pressure in the firebox (15 to 20 Pa) must be overcome in order to produce reverse flow. In comparison, air intakes connected to the circulation plenum will show reverse flow at pressures as low as 3 Pa. Therefore circulation plenum intakes are far more likely to reverse but without major repercussions. If a direct coupled intake is to be used, it must be treated as a flue gas duct, and be appropriately isolated from combustible materials.

One possible method to reduce potential hazards from reverse flow of hot gases through the air intake would be to install a backflow prevention damper in the intake duct. A test, using a draft control damper of the type normally used on oil furnaces, showed that reverse flow could be kept to a minimum using this strategy. The long-term reliability of this approach would need to be investigated before it could be relied on to provide complete protection against reverse flow.

A combined air intake was briefly studied as a potential solution to some problems. This intake consists of a central duct connected directly to the combustion chamber, surrounded by a larger duct connected to the circulation air plenum Figure 14 shows how this could be set up. This combined duct would allow the fireplace to draw air directly from outdoors for most of the time during operation, and would also help to maintain the pressure in the room in which the fireplace is located closed to the outdoor pressure. If a negative pressure occurred at the air inlet, and flow reversal took place, the air space surrounding the combustion air intake duct would act as an insulator to keep the outer surface of the air intake duct cool. It may be possible to design an intake system so that the fireplace would draw air from the house at times when the air intake was under negative pressure.

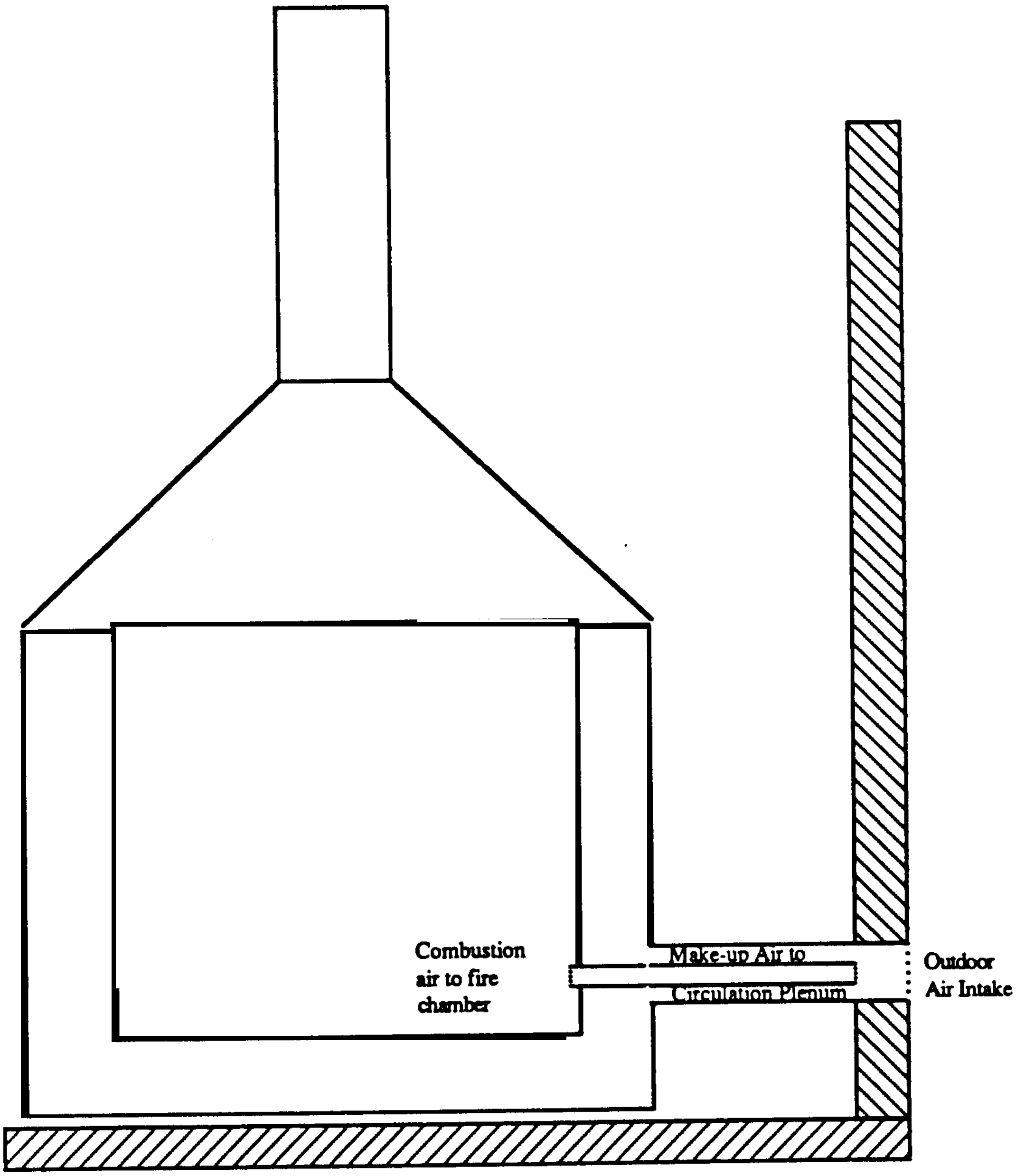


Figure 14: Dual Air Intake

Masonry Fireplaces

In order to extrapolate this test work to determine possible applications on masonry fireplaces, simulation runs were carried out using **WOODSIM.** From the testing and the modelling, some observations were made which should apply to both factory-built and masonry fireplaces.

Fireplace doors have the effect of distributing the draft throughout the **firebox** leaks, preventing some low draft **spillage.** The leakage area of the doors does not appear to be **important** for this effect to occur.

Energizing the **fire** at startup and cool down appears to be a **key** element in preventing spillage. Designs that control the bum rate by closing down the combustion air intake and minimizing leaks tend to de-energize the flue towards the end of the bum and make these units more susceptible to spillage in a severely depressurized house. However, when looking at the opposite problem of fireplaces depressurizing other house combustion appliances, tight designs do not **depressurize** the house significantly, even at full burn.

Design Principles That Will Help Avoid Spillage

In order of importance, the following principles have emerged from modelling, testing, and consultation with project team members, CMHC advisors and steering committee members:

Principle #1: Create Energy Momentum

Establish and maintain draft in the chimney by promoting “energy **momentum" -** get the **fire** to bum quickly when low draft conditions prevail at startup and cool down, thereby energizing the chimney and storing heat in its structure. **ORTECH** has developed stacking and lighting procedures that promote “energy momentum” quickly at startup.

Avoid controlling the bum rate at startup and cool down. On the other hand, the mid portion of the burn is not susceptible to spillage, and energy conserving techniques of controlling the burn rate by closing down the intake area can be implemented without fear of combustion gas spillage during this portion of the burn. Effective chimney height appears to be a key in developing and retaining draft, thereby promoting “energy momentum” in the system The taller the chimney the better, provided that it is adequately insulated. The taller chimney also presents more mass in the form of more liner material, thereby storing more heat. **Increased** chimney liner mass may have a role but the “mass effect” on its own does not appear to be a key approach to conserving “energy momentum”.

Principle #2: Produce Pressure Drop at Face of Fireplace

Ensure that the available draft, developed by the chimney, is transferred down through **all** of the **firebox** openings, from top to bottom. Closed fireplace doors appear to be all that is needed to achieve this, regardless of door tightness. The Equivalent Flow Area of most doors is much less than that of the open face of a fireplace.

To elaborate, the chimney/fireplace/house envelope flow systems are connected in series. The total available draft of the chimney is entirely converted to friction losses as a result of air or gas flow through each part of the total flow system. The total friction pressure drop through all of the components will always add up to the total theoretical draft. The greater the friction pressure drop in one component, the less there will be in the others. The objective is to minimize the chimney friction and envelope friction such that the maximum friction (i.e. pressure drop between the room and the chimney base, measured as “draft”) occurs at the doors and intake, hence minimizing the probability of spillage. Conversely, if most of the friction drops occur in the chimney and/or envelope, there will be little pressure drop across the face of the fireplace (e.g. an open fireplace), thereby opening the possibility of neutral pressure zones forming in the face of the fireplace, with room air flowing into the **firebox** through one zone and combustion gases flowing into the room in the other - see Principle **#3.**

Once a distributed draft across the **firebox** is achieved with doors, a careful balance in the split between combustion air from the intake, and by-pass or dilution air through the doors or secondary air supply has to be achieved to retain control of the burn rate. Concentrating **all** of the draft on the intake, and directing the intake air to the woodpile creates an uncontrolled “blow torch” effect, seen both in the lab tests and WOODSIM simulations. Doors with leakage near the top, and air discharges on the sides of top of the **firebox** can be used to distribute the air for better control. Figure 15 shows the effects of various air distribution patterns on the **fire.**

Principle #3: Matching the Plume Shape

Match the damper opening shape to the shape of the streamlines emerging from the fire, or vice versa. At startup, when doors may have to be left opened to establish a good burn rate, and the draft is low, a number of factors appear to come into play - the shape of the **firebox,** fire location, grate design, and opening at the top - none of which are **modelled** explicitly in WOODSIM. In the model it is assumed that these factors are optimized, such that, when the chimney is venting, as much gas as being produced by the fire is being vented, so there is no spillage. In **reality,** a poor **firebox** venting design can manage to spill combustion products into the mom in spite of the fact that there is enough flow up the chimney to capture all combustion products. With a poor **firebox** venting design, spillage will occur in circumstances where the WOODSIM model predicts no spillage. An example of this low draft spillage mechanism is seen in open masonry fireplaces with a wide (rectangular) damper opening. Moderate draft in the chimney will draw from the edges of the wide damper as well as the middle. However, if the smoke plume is cylindrical in shape (buoyant action tends to draw the flame and smoke toward the **centre),** the plume will concentrate at the mid portion of the damper opening. The edges of the opening draw cool room air. The flow rate in the centre portion of the damper is then not sufficient to capture all of the cylindrical smoke plume. Spillage is observed at or near the top centre of the **fireplace** opening, while the room air is flowing inward at the edges. Furthermore, the chimney is being partially served by cool room air instead of the spilled warm smoke, Thus the establishment of sufficient draft is delayed, prolonging the occurrence of spillage.

The circular firebox openings that accommodate A-vents on factory-built fireplaces appear to be appropriate to effectively capture the cylindrical plumes at low draft, thereby avoiding unnecessary spillage. Masonry fireplaces that get progressively shallower towards the damper opening have the effect of flattening out the plume to the shape of the damper opening, thereby venting a rectangular plume with a rectangular opening. Such a design is recognized to be effective in spillage control.

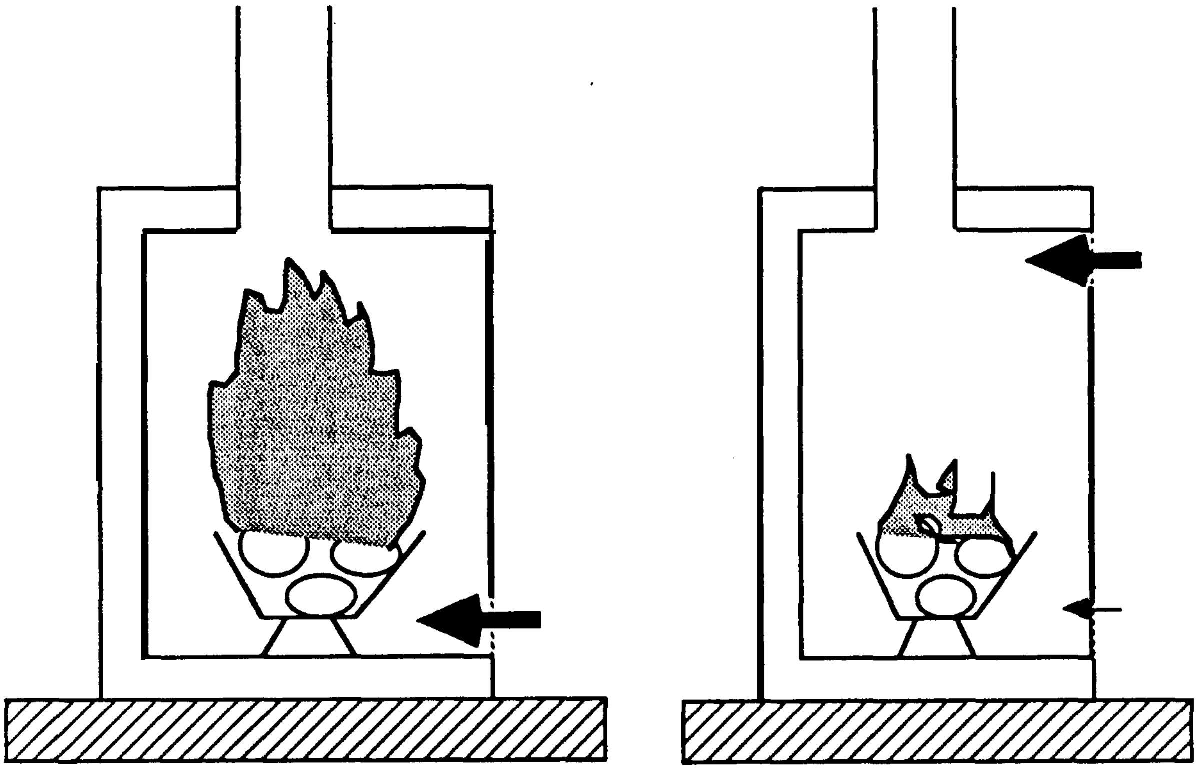
As an example of how all three principles can be used to solve a spillage problem, consider the startup spillage problems encountered by ORTECH while testing of the fireplaces. A fixed baffle in the firebox changes the shape of the plume, thereby contravening Principle #3 and resulting in startup spillage under low draft conditions. Closing the door (Principle #2) kills the fire, contravening Principle #1. (This premature burnout was predicted by WOODSIM.) Modulating the door opening was a solution to help avoid startup spillage problems. This door modulation serves all three principles:

- it directs more air through the fire area, promoting higher bum rates than with closed doors, thereby creating “energy momentum” (Principle #1);
- it distributes whatever draft there is to the openings around the doors that are left slightly open, thereby eliminating neutral pressure zones in the open face (Principle #2);
- it reshapes the streamlines of the plumes, thereby compensating for the problem created by the baffle (Principle #3).

Fresh Air Intake Location

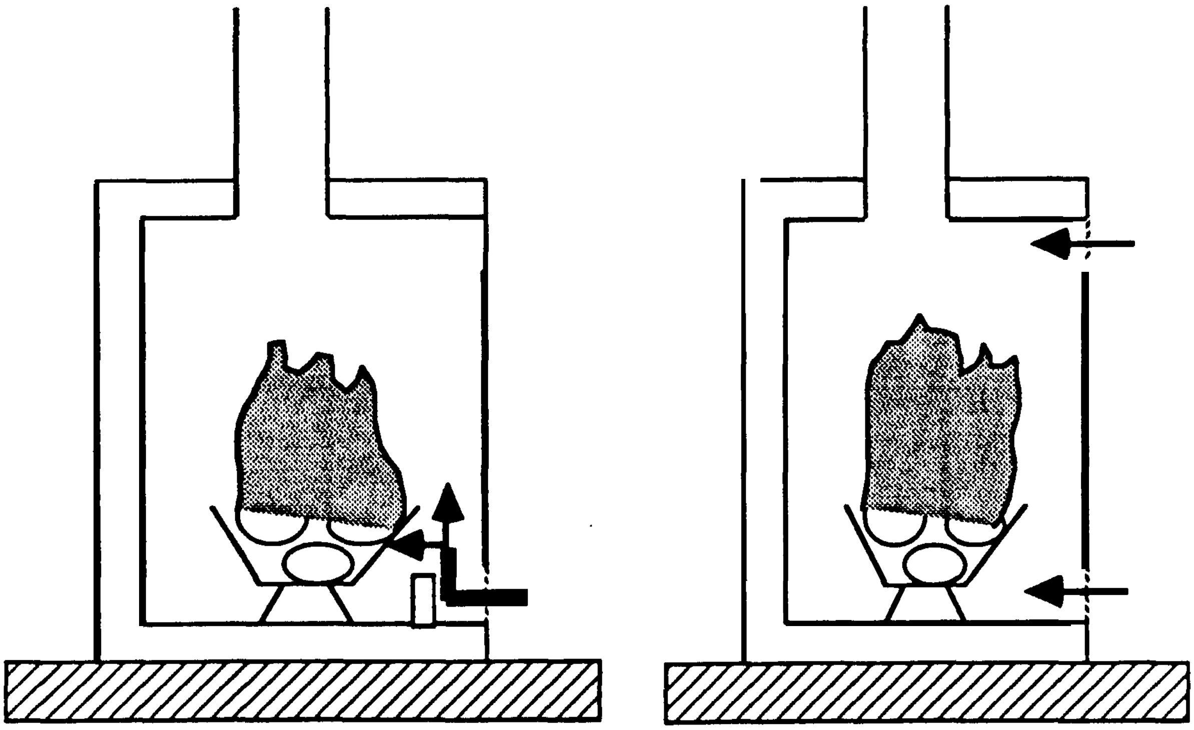
The fresh air intake to the room or to the air circulation plenum in the fireplace jacket both have the effect of reducing envelope friction pressure drop - following Principle #2, outlined above. Since the plenum in the fireplace jacket is connected to the room, with generous openings between plenum and room, connecting the intake to the plenum, rather than to the room, makes no difference on the room pressure. The plenum connection has the advantage of preheating outdoor air before entering the room, when the fireplace is operating.

FIGURE 15: Effects of Air Distribution on Fire



(a) Air concentrated at bottom and directed at grate.

(b) Air concentrated at top.



(c) Air concentrated at bottom and distributed in firechamber.

(d) Air distributed through top and bottom intakes.

The fresh air intake that is connected directly to the firebox has a very different effect: it tends to decouple the firebox and chimney flow systems from the house system, so that the house air flow system is no longer acting in series with the firebox and chimney flow systems. Although the “decoupling route" appears, at first, to be the best approach, it actually has four disadvantages when compared to the plenum connection:

- since the intake is not connected to the room, the room depressurization caused by other exhaust devices is greater than if the intake were connected directly to the room (To visualize this effect, consider a very powerful exhaust fan depressurizing a house, and a very large fresh air intake. A room-connected intake relieves the room depressurization, whereas a firebox intake behind reasonably tight doors will not. The firebox intake will "try" to relieve the severe room depressurization through firebox leaks in the doors, joints, and leaks in the vent connections, until draft is established.)
- the room is put in a series flow path with the fresh air intake, while involving the combustion area of the firebox in its flow path, as shown in Figure 16. The direct firebox intake flow system thus has two added degrees of freedom of flow, both of which are undesirable:
    - flow of intake air through the firebox and into the room, which can entrain combustion products via the mechanism described above;
    - flow of room air and/or chimney air through the combustion area and out the intake, due to intake depressurization by wind effects and/or room pressurization, resulting in a potential fire hazard.
- by physically connecting the intake to the firebox walls, radiant, convective and conductive heat transfer can occur along the intake passage at low drafts at the end of the fire.
- by virtue of the fact that all of the draft acts on the fresh air intake, control of the burn rate can be more difficult Improperly directed intakes can result in very fast, hot fires (the “blow torch” effect) or sluggish fires at startup, with most of the intake air bypassing the fire area

If the fresh air intake is ducted to the plenum in the firebox jacket, a fourth principle will apply. It relates to the impact of fireplaces on the venting of other combustion appliances in tight houses.

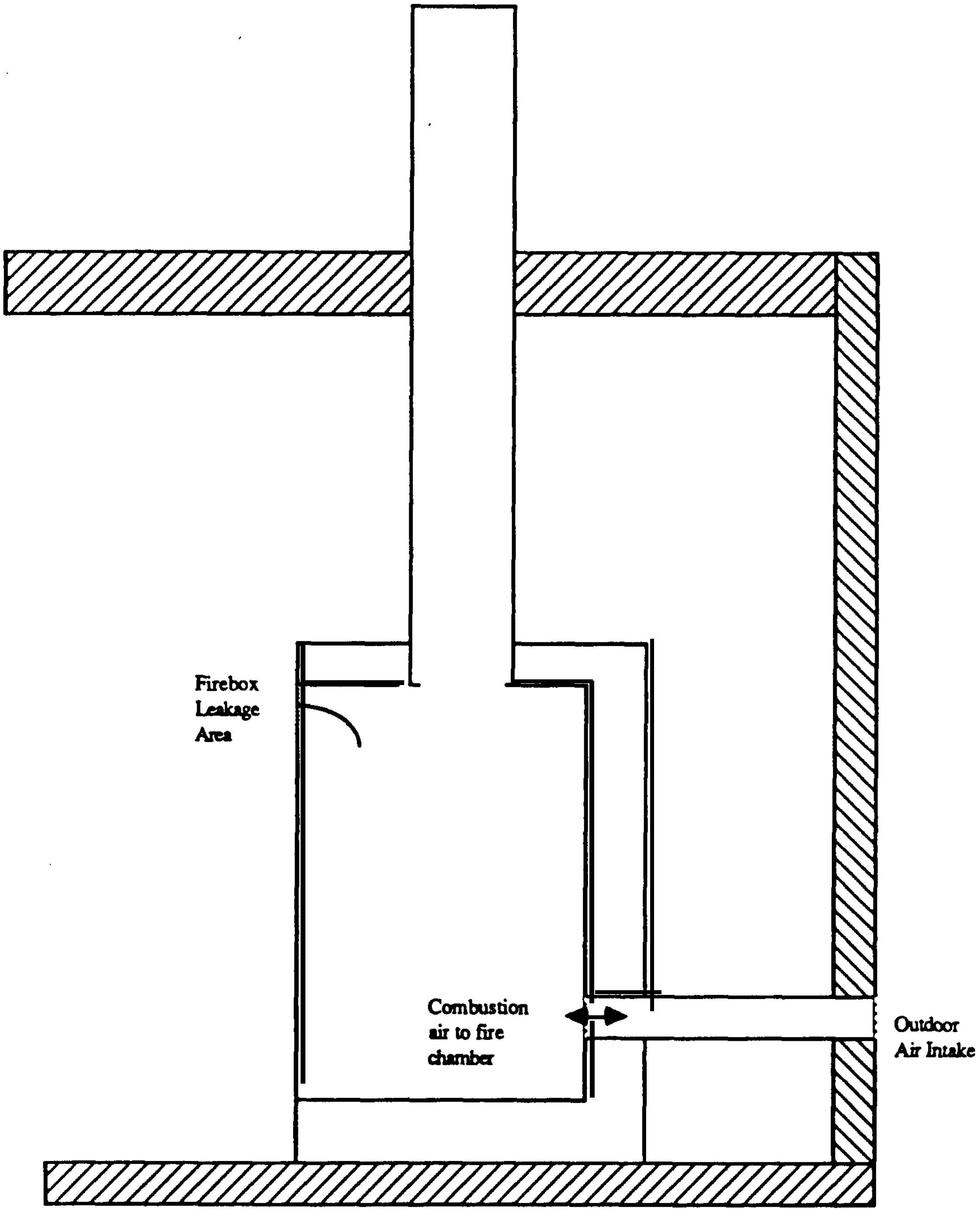


Figure 16: Air Flow In Direct Outdoor Connected Fireplace

Principle #4: Control of Air Intake and Firebox ELA

Provide the fireplace with control for combustion air intake size, and firebox ELA during the mid portion of the burn, when Principle #1 is satisfied - which is most of the duration of the fire. Reducing the combustion intake size and firebox ELA (including doors) reduces the amount of house depressurization and, at the same time, gives some control over the bum rate. Principle #4 appears to have been met by the factory-built fireplaces, since none of the ones tested and simulated appear to draw excessive quantities of room air when their doors are closed.

It should be noted that none of the above principles are new, they are merely an attempt to put order into commonly known design approaches and intuitive practices, based on lab and simulation modelling results.

A number of design features and guidelines were developed as a result of this project. Promising avenues of spillage control and prevention should be further researched and validated by both testing and modelling.

Proposed further WOODSIM refinements include:

- modelling the thermal and airflow performance of the air space in the jacket around the firebox of factory-built fireplaces, using ORTECH test data to guide and validate the model;
- modelling air-cooled chimneys.

A promising direction for future R & D in this field would be the testing and development of an integrated air intake system that uses the glass doors and intake plenum combination, with thermally controlled vanes on the firebox side of the plenum at the bottom of the doors which direct a mixture of house air and outside air:

- towards the fire under low burn conditions, thereby encouraging faster lighting, establishing draft at startup, and promoting effective burn out of the remaining combustible material under sustained draft at cool down;
- towards the inside face of the glass doors under high burn rate conditions, thereby controlling the burn rate and cooling the doors;
- and shutting off under conditions of plenum air overheating, i.e. backdrafting.

This concept, if successful, could represent an improvement to factory-built fireplaces as well as being a potential retrofit option for open masonry fireplaces.

5 .O CONCLUSIONS

The factory-built fireplaces were found to be relatively resistant to spillage. Fireplace doors increase spillage resistance, even if they are not tight.

Standard 100 mm air intake ducts, when connected to the fireplace circulation plenum, do not supply all of the combustion air requirements under normal operating conditions.

When fireplaces are quipped with tight doors and controllable combustion air supplies; their air consumption is relatively low, and probably would not cause large depressurization of houses.

When combustion air supplies are controlled, and dilution air is reduced, increased fireplace temperatures can result. This could create a problem in masonry fireplaces where doors are retrofitted.

Air intakes which are connected directly to fireboxes can experience reverse flow of hot gases through the duct. Therefore these ducts should be isolated from combustible materials. Directconnected air intakes are not recommended unless the firechamber is relatively tight and isolated from the house when the doors are closed. Backflow prevention dampers may provide a solution to the reverse flow problem.

The results producted from the tests in the ORTECH fireplace test facility were useful for validation and refinement of the WOODSIM model.

The refined WOODSIM model simulated the heat and flow performance of the fire and chimney rather well, resulting in a significant level of confidence in the findings of the parametric study.