IMPLEMENTATION OF THE AIM-2 INFILTRATION MODEL IN HOT2000

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INTÉGRATION DU MODÈLE DE PRÉVISION D'INFILTRATION DE L'AIR AIM-2
AU LOGICIEL HOT2000

1.0   INTRODUCTION

Le logiciel HOT2000 a utilisé le modèle Shaw « original » (Shaw, 1981) de 1985 environ jusqu'en septembre 1989, date de la mise sur le marché de sa version 5.07, dernière de la génération 5. Dans la version 6.02, le modèle de prévision de l'infiltration de l'air s'appuie sur les travaux plus récents de Shaw (Shaw, 1987). Des changements y ont été apportés pour tenir compte, par exemple, de plus nombreux types de systèmes de ventilation, et on a modélisé l'effet de l'utilisation de calorifères aux carburants fossiles (par ex., l'effet de l'utilisation des calorifères sur les taux d'infiltration).

Toutefois, on a constaté que le modèle de prévision des taux d'infiltration exploité par HOT2000 comportait des lacunes, notamment en ce qui concerne l'interaction entre le taux calculé d'infiltration naturelle et le taux compensé de ventilation forcée. De ce fait, on a adopté un modèle plus récent, connu sous le sigle AIM-2 (Wilson et Walker, 1990).

Le modèle AIM-2 (Air Infiltration Model) est un modèle de prévision de l'infiltration de l'air dans une seule zone. Il tient compte de l'effet du vent et de l'effet de convection ainsi que de leur interaction, de la répartition des points de fuites d'air entre les plafonds, les murs et les planchers, de même que des points de fuites distincts que représentent les tubes de fumée de calorifères et de cheminées. La vitesse du vent aux stations météorologiques et aux endroits où sont situés les bâtiments est corrigée pour tenir compte des effets du terrain calculés selon les paramètres de Davenport. Le modèle tient également compte de l'interaction entre la ventilation naturelle et la ventilation forcée.

Implementation of the AIM-2 Infiltration Model in HOT2000

1.0 INTRODUCTION

The "original" Shaw model (Shaw, 1981) had been used in HOT2000 from about 1985 to the last release of Version 5, 5.07 in September 1989. In HOT2000 Version 6.02, the infiltration model is based on later work by Shaw (Shaw, 1987). In the implementation of this model, some changes were made to accommodate other types of ventilation systems, as well as to model the effect of fossil furnace operation (eg. the effect of furnace operation on infiltration rates).

A number of problems have been noted with the infiltration model used in HOT2000, including the interaction between the calculated natural infiltration rate and the balanced forced ventilation rate. This has lead to adoption of a more recently developed model, known as AIM-2 (Wilson and Walker, 1990).

The AIM-2 (Alberta Air Infiltration) model is a single zone air infiltration model. This model accounts for stack and wind effects and their interaction, the distribution of leakage sites in ceilings, walls and floors, as well as separate leakage sites for furnace and fireplace flues. Wind speed at the weather station and at the building site is adjusted for terrain effects based on the Davenport parameters. The interaction between natural and forced ventilation is also accounted for.

2.0 AIM-2 MODEL VERSION 1

2.1 Introduction

The model implemented here is generally based on "The Alberta Air Infiltration Model AIM-2", I.S. Walker and D.J. Wilson, University of Alberta Dept. of Mechanical Engineering Technical Report 71, January 1990. Modifications have been made to include the effects of both balanced and unbalanced mechanical ventilation, and to make use of the Davenport shielding parameters. This version takes flues into account in an approximate manner, i.e. a constant flue diameter is assumed. In later sections, a flue model which accounts for operation of a flue damper in some space heating and DHW systems will be discussed.

The following is an exposition of the model equations as implemented in HOT2000, generally arranged to correspond to the actual computer code. Refer to the Walker and Wilson paper for a more complete discussion and development of the model.

The total air flow due to natural infiltration is given by

$$Q = C \, (\Delta P)^n \tag{1}$$

where C and n may be determined by blower door tests. Alternatively, the "Air Tightness Type" defined for the building is used to choose these values from a table provided in HOT2000 (see Section 3.0).

In the AIM-2 model, air leakage sites are identified as ceilings, floors, walls, and the flue.

C_{flue} = leakage of flue at H_f above floor level
C_c = leakage of ceiling at H above floor level
C_f = leakage of floor level leaks
C_w = leakage of walls

It is assumed that the exponent n is the same for all leakage sites, so the total leakage coefficient C is

$$C = C_c + C_f + C_w + C_{flue} \tag{2}$$

The flue flow coefficient is estimated from

$$C_{flue} = 0.5 \, A_{flue} \left(\frac{\rho}{2 \, \Delta P_{ref}} \right)^{(n-0.5)} \tag{3}$$

where A_{flue} is the total cross-sectional area of all flues, ρ is the air density, and ΔP_{ref} is the typical pressure difference on the envelope (4.0 is the accepted LBL standard).

It is assumed that the blower door tests (or assigned airtightness type) applies to the house with the flues sealed, i.e.

$$C_0 = C_c + C_f + C_w \tag{4}$$

The total leakage coefficient is then given by

$$C = C_0 + C_{flue} \tag{5}$$

Leakage distribution parameters are assigned as follows.

$$R = \frac{C_c + C_f}{C} \qquad \text{"ceiling-floor sum"} \tag{6}$$

$$X = \frac{C_c - C_f}{C} \qquad \text{"ceiling-floor difference"} \tag{7}$$

$$Y = \frac{C_{flue}}{C} \qquad \text{"flue fraction"} \tag{8}$$

One set of inputs to the model are the fractions of leakage for the ceilings, floors, and walls,

$$\alpha_1 = \frac{C_c}{C_0} \; ; \; \alpha_2 = \frac{C_f}{C_0} \; ; \; \alpha_3 = \frac{C_w}{C_0} \tag{9}$$
$$\alpha_1 + \alpha_2 + \alpha_3 \equiv 1$$

With these assumptions, it may be seen that

$$R = (\alpha_1 + \alpha_2)(1 - Y) \tag{10}$$
$$X = (\alpha_1 - \alpha_2)(1 - Y) \tag{11}$$

A superposition technique is used to add the effects of stack and wind induced flows, and introduces an additional term to account for the interaction of the wind and stack effects. The total natural air flow Q_{nat} is given by

$$Q_{nat} = (\, Q_s^{\frac{1}{n}} + Q_w^{\frac{1}{n}} + B_1 \, (Q_s * Q_w)^{\frac{1}{2n}} \,)^n \tag{12}$$

where

Q_s = Flow due to stack effect

Q_w = Flow due to wind effect

B = Interaction coefficient, assumed constant, $B \sim 1/3$

2.2 Infiltration with no Flue

In the absence of a flue, the stack effect is assumed to have the following form

$$Q_s = C \, f_s \, P_s{}^n \tag{13}$$

The stack effect reference pressure is given by

$$P_s = \rho_0 \, g \, H \left(\frac{T_i - T_o}{T_i}\right) \tag{14}$$

where g is acceleration due to gravity (9.8 m/s^2), ρ_0 is the outdoor air density, H is the building eave height, T_i is the indoor temperature, and T_o is the outdoor air temperature.

The stack flow factor f_s is determined by the distribution of leaks, and has the following functional form.

$$f_s = \left(\frac{1 + nR}{n+1}\right) \left(\frac{1}{2} - \frac{1}{2}\left(\frac{X^2}{2-R}\right)^{\frac{5}{4}}\right)^{n+1} \tag{15}$$

Similarly, the wind induced infiltration rate Q_w is defined in terms of the wind factor f_w by

$$Q_w = C \, f_w \, P_w{}^n \tag{16}$$

The reference wind pressure is

$$P_w = \rho_0 \, \frac{(S_w \, U_e)^2}{2} \tag{17}$$

where U_e is the unobstructed wind speed (with no local shelter) at eaves height at the building site, and S_w is the local wind shelter coefficient.

The approximating function f_w developed for AIM-2 is given by

$$f_w = 0.19 \, (2-n) \left(1 - \left(\frac{X + R}{2}\right)^{\frac{3}{2}}\right) \tag{18}$$

2.3 Infiltration with a Flue

In AIM-2, the flue is considered to be an additional leakage site, located at a normalized height β_f,

$$\beta_f = \frac{H_f}{H} \tag{19}$$

where H_f is the height of the flue top, and H is the building eave height.

The approximating functions developed for AIM-2 assume that the flue is filled with air at indoor room temperature. The air flow induced during combustion when the flue is hot is neglected. The stack factor developed on the basis of these assumptions is given by

$$f_{fs} = \left(\frac{1 + nR}{n+1}\right)\left(\frac{1}{2} - \frac{1}{2}M^{\frac{5}{4}}\right)^{n+1} + F \tag{20}$$

where

$$M = \frac{(X + (2n + 1)\ Y)^2}{2 - R}\ ;\ M \le 1 \tag{21}$$

The additive flue function F is,

$$F = n\ Y\ (\beta_f - 1)^{\frac{3n-1}{3}}\left(1 - \frac{3\ (X_c - X)^2\ R^{1-n}}{2\ (\beta_f + 1)}\right) \tag{22}$$

where

$$X_c = R + \frac{2\ (1 - R - Y)}{n + 1} - 2\ Y\ (\beta_f - 1)^n \tag{23}$$

The variable X_c is the critical value of the ceiling floor difference fraction X at which the neutral level (pressure plane) passes through the ceiling. For $X > X_c$ the neutral pressure plane will be above the ceiling, and attic air will flow in through the ceiling.

The approximating function for the wind factor in a house with a flue is given by

$$f_{fw} = 0.19 \ (2 - n) \ (1 - (\frac{X + R}{2})^{\frac{3}{2} - Y}) - \frac{Y}{4} \ (S - 2 \ Y \ S^4) \qquad (24)$$

where

$$S = \frac{X + R + 2 \ Y}{2} \qquad (25)$$

A more complete description of the development of the above equations, and the implications of relationships between the various parameters is given in the report by Walker and Wilson.

2.4 Adjustments for Wind Speed

Wind speed at the building site is considered to be influenced by two main factors, local shielding, and overall terrain roughness which extends several kilometres upwind of the building site.

Local obstructions caused by trees and neighbouring structures located within two house heights provide direct shielding. The effect of this shielding is accounted for by the use of a shelter coefficient. In AIM-2, the shelter coefficient S_{wo} for the building walls is combined with S_{wflue} for the top of the flue stack as follows.

$$S_w = S_{wo} \ (1 + Y) \ + S_{wflue} \ (1.5 \ Y) \qquad (26)$$

where the factor 1.5 is an empirical adjustment.

Shelter coefficients are selected from the following list (Wilson and Walker, 1990).

Table 1. Estimates of Shelter Coefficient S_{wo} for No Flue

Shelter Coefficient S_{wo}	Description
1.0	No obstructions or local shielding
0.9	Light local shielding with few obstructions within two house heights
0.7	Heavy shielding, many large obstructions within two house heights
0.5	Very heavy shielding, many large obstructions within one house height
0.3	Complete shielding, with large buildings immediately adjacent

Wilson and Walker note that shielding is directionally dependant, and that an appropriate value be selected based on the average shielding in all directions.

The original AIM-2 model used a power law profile (Irwin, 1979) to account for the effects of terrain roughness on the local wind speed. The model implemented in HOT2000 uses a log profile based on the Davenport model (Wieringa, 1986, and Yuill and Assoc., 1990). For this model, the following parameters are defined.

H = building eaves height

H_{met} = height of anemometer at weather station (generally 10 m)

Z_{met} = surface roughness length (Z_0) at weather station

Z_{site} = surface roughness length (Z_0) at building site

U_{met} = wind speed measured at weather station

The roughness length Z_0 defined in the Davenport model is based on the terrain class for the location, as presented in Table 2 (Wieringa, 1986). In the table, x is a typical upwind obstacle distance, and h is the height of major obstacles. An arbitrary value of $Z_0 = 2$ for city centre has been assumed in HOT2000.

Table 2. Davenport Roughness Classification

Class	Terrain Description	Z_0 (m)
1	Open sea, fetch at least 5 km	0.0002
2	Mud flats; no vegetation, no obstacles	0.005
3	Open flat terrain; grass, few isolated obstacles	0.003
4	Low crops; occasional large obstacles, x/H > 20	0.10
5	High crops; scattered obstacles 15 < x/H < 20	0.25
6	Parkland, bushes; numerous obstacles, x/H ~ 10	0.5
7	Regular large obstacle coverage (suburb, forest)	1.0
8	City centre with high and low rise buildings	?

With these definitions, the correction factor for wind speed is given as

$$C_T = \frac{Ln\left(\frac{60}{Z_{met}}\right) Ln\left(\frac{H}{Z_{site}}\right)}{Ln\left(\frac{H_{met}}{Z_{met}}\right) Ln\left(\frac{60}{Z_{site}}\right)} \qquad (27)$$

and the wind speed at the site is

$$U_e = C_T U_{met} \qquad (28)$$

2.5 Effects of Mechanical Ventilation

The method adopted to account for the interaction between natural infiltration and mechanical ventilation was developed by Kiel and Wilson (1987), and updated by Wilson (Lubun, Private Communication, 1990). Minor changes were also made for implementation in HOT2000, where it is possible to have more than one type of ventilation system in operation.

In HOT2000, the following parameters are defined.

Q_{sup}	=	central ventilation system supply rate
Q_{exh}	=	central ventilation system exhaust rate
Q_{exo}	=	total of exhaust only fans
Q_{bal}	=	total balanced ventilation rate
Q_{unbal}	=	total unbalanced ventilation rate

If the house includes a Heat Recovery Ventilator, the central ventilation system is assumed to be balanced, i.e. $Q_{sup}=Q_{exh}$, and we have

$$Q_{bal} = Q_{sup}$$
$$Q_{unbal} = Q_{exo}$$

(29)

In all other systems, we have

$$Q_{ext} = Q_{exh} + Q_{exo}$$
$$Q_{bal} = Minimum\ (\ Q_{sup}\ ,\ Q_{ext}\ )$$
$$Q_{unbal} = |\ Q_{sup} - Q_{ext}|$$

(30)

With these definitions, the total infiltration rate is given by

$$Q_{total} = Q_{bal} + (Q_{nat}^{\frac{1}{n}} + (\frac{Q_{unbal}}{2})^{\frac{1}{n}})n + \frac{Q_{unbal}}{2}$$

(31)

where Q_{nat} is the natural infiltration rate calculated by AIM-2, Eq. 12.

3.0 DEVELOPMENT OF STANDARD AIRTIGHTNESS COEFFICIENTS

The HOT2000 program offers 4 sets of default C and n values, as shown in the table below. Inspection of Table 4-A, "Default Values for Air Tightness Tests", in the HOT2000 Version 6 Technical Manual (this table has not changed since Version 5), revealed some internal inconsistencies.

The equation for ELA which appears in this table is as follows.

(32)

$$ELA = 11570 * \sqrt{1.205} * C *10^{(n-0.5)}$$

(Note the square root was omitted in the table.)

When the values for C and N from the table are substituted in this equation, it is seen the ELA's obtained do not agree with those shown in the table (e.g. 1108.6, 729.3, 631.0, 342.2 instead of 1078, 709, 612, 330).

A decision was made to assume that the published values of C, n, and N_{50} (air change rate @50 Pa) were exactly correct. However, the air change rate for Energy tight houses was rounded to 1.50, and the flow exponent for "present" houses was changed from 0.7175 to 0.7125. Using these values, it is possible to calculate the volume of the house for which these apply. For use in HOT2000, a set of C' are defined by dividing the C for each tightness type

by the corresponding house volume. In other words, we develop a flow coefficient that is normalized with respect to house volume. In HOT2000, the value of C used is obtained by multiplying the C' by the actual volume of the house.

The following have been extracted from CAN/CGSB-149.10-M85 (11), "Determination of the Air Tightness of Building Envelopes by the Fan Depressurization Method". It is assumed that the flow coefficient of the orifice is exactly 0.611. At standard reference conditions, the density of air is given by

$$\rho = \frac{101.325}{0.287055 * 293.15} = 1.204097 \qquad (33)$$

The ELA is given by

$$ELA\ (m^2) = \frac{0.001 * C * (\Delta P)^{n-0.5}}{C_{orifice} * \sqrt{\dfrac{2}{\rho}}} \qquad (34)$$

After substituting for the constants, and converting to square centimetres, the ELA at 10 Pascals may be written as

$$(35)$$

$$ELA\ (cm^2) = 12699.148 * C * 10^{(n-0.5)}$$

In general, the flow rate for a given C, n, and pressure drop is given by

$$(36)$$

$$Q\ (m^3/sec) = C * (\Delta P)^n$$

Since

$$Q_{50} = \frac{N_{50} * Vol}{3600} \qquad (37)$$

where Vol is the house volume, it is seen that the house volume may be written as follows

$$Vol(m^3) = \frac{3600 * C * (50)^n}{N_{50}} \qquad (38)$$

Using these equations, the following table may be developed.

Table 3. Default Values for House Airtightness

	C (m3/(Pa-s)^n)	n	N_{50} (ACH @ 50 Pa)	ELA @ 10 Pa (cm^2)	House Volume (m^3)	Normalized C
Loose pre 1945	0.052	0.725	10.35	1108.6	308.4	16.86105e-5
Average	0.0364	0.698	4.55	729.2	441.8	8.23811e-5
Present	0.03046	0.7125	3.57	631.0	499.0	6.10730e-5
Energy Tight	0.0169	0.7028	1.50	342.3	634.1	2.66534e-5

In HOT2000 (versions 6.02 and 6.03), provision has been made to calculate a default ELA when only the air change rate at 50 pascals is entered, and assuming that the exponent "n" is 0.68 (Technical manual, p. 4-2). Combining equations (36) and (37), solving for C, and substituting in Eq. (35), the ELA (at 10 pascals) is

$$(39)$$

$$ELA \ (cm^2) = \alpha * N_{50} * V$$

where

$$\alpha = \frac{12699.148 * 10^{(0.68-0.5)}}{3600 * 50^{0.68}} = 0.373398 \qquad (40)$$

It may be verified that HOT2000 is indeed calculating the ELA as presented in the preceding calculations. To do this, start up HOT2000, go to the preferences menu and select "Diagnostics Output" to Yes. This will cause a number of messages to be printed out, just press <Enter> to proceed as required. In House editing mode, select "Natural Infiltration", enter a volume of 500 m³, select "Blower Door", enter a value for the air change rate

at 50 Pascals, set the ELA to 0.0, and select <Done>. A message at the bottom of the screen will show the calculated value of C and n. Note the value printed for n is not quite exactly 0.68 due to round-off errors. Select "Natural Infiltration" again, and notice the value for ELA has been changed from 0.0 to the calculated value. (Remember to set "Diagnostics Output" to "No" after completing these tests.)

The following values were obtained from several tests.

Air Change Rate at 50 Pascals	C	n	ELA
1.0	0.00972	0.6799	186.72
2.0	0.01943	0.6799	373.44
5.0	0.04858	0.6799	933.61

4.0 SENSITIVITY OF NATURAL INFILTRATION RATES TO THE AIM-2 PARAMETERS

A series of HOT2000 runs were prepared to investigate the sensitivity of the average annual natural infiltration rate to values assigned to the model parameters.

The first set, Figure 1, varies the Terrain description and Shielding class parameters for the same house at three locations, and for two airtightness types (Average and Energy Tight). In each figure, the x-axis is a 4 digit code to define the parameters used, as follows

Digit 1 - Terrain class at weather station
Digit 2 - Terrain class at building site
Digit 3 - Local shielding class for walls
Digit 4 - Local shielding class for flue

The values of the digits correspond to the entries in Tables 1 and 2.

Figures 1a and 1b show the variation in natural infiltration rate as the terrain class of the weather station is varied from open sea to city centre, for building shielding class 1 (S1111, S21111, ...), and for building shielding class 7 (S1711, S2711, ...). The infiltration rate increases by approximately 50% as weather station shielding class varies from 1 to 8. Heavier shielding at the building site decreases the sensitivity to weather station shielding. Figure 1c shows that the natural infiltration rate is very

sensitive to shielding at the building site. Natural infiltration decreases by a factor of approximately 2.5 as the building shielding class is varied from 1 to 8. Figure 2 shows that the infiltration rate is much less sensitive to changes in the local shielding class.

The sensitivity to relative leakage rates is shown in Figures 3a (linear scale) and 3b (logarithmic scale). In this series, it was assumed that the ceiling and floor leakage fractions are equal, and the infiltration rate is calculated for different values of the ratio of ceiling to walls leakage fraction (when the ratio is 2.0, the ceiling fraction is 0.2 and the walls fraction is 0.4). The infiltration rate is not very sensitive to this parameter. This is fortunate, since the relative leakage of ceilings, walls, and floors is not easily estimated.

The interaction between natural infiltration and mechanical exhaust fan flow rate for two airtightness types at 3 locations is shown in Figure 4. These results show that the tight house in Vancouver is most sensitive, and the average tightness house in Resolute is least sensitive to exhaust ventilation. In all cases, the effective natural infiltration rate decreases as the mechanical ventilation rate increases.

The effect of flue diameter on infiltration rates is presented in Figure 5. In all cases, the infiltration rate increases only slightly with flue diameter, up to a critical flue size which roughly corresponds (in area) to the ELA for the house. As the flue size is increased above the critical size, the calculated natural infiltration rate increases rapidly. This will be discussed in more detail in Section 6. It should be noted that the results shown in Figure 5 are for an unheated flue.

5.0 COMPARISON OF NATURAL INFILTRATION RATES : AIM-2 VS HOT2000 6.02

For comparison purposes, a series of runs were carried out for a house located in Regina, as shown in Figure 6. A total of 8 runs were done to include all combinations of airtightness type for both sheltered and exposed locations. The results designated as "6.02" refer to HOT2000 Version 6.02 which uses a modified Shaw model for infiltration calculations. For the AIM-2 runs (designated 6.03), "sheltered" and "unsheltered" were defined by terrain descriptions as follows.

Terrain Description	Sheltered	Unsheltered
@ Weather Station	High Crops (#5)	High Crops (#5)
@ Building site	Suburban, Forest	High Crops (#5)
Local Shielding	Heavy	Light

On an annual basis, Figure 6a, the AIM-2 model (and the set of shielding parameters selected here) estimates lower infiltration rates for loose houses, and higher infiltration rates for tight houses. For houses of Average and Present day tightness, the annual average rates are essentially the same, with slight variations depending upon shelter effects.

The monthly infiltration rates, Figures 6b and 6c, indicate that the AIM-2 model is more sensitive to air temperature variations, since the ratio of winter to summer infiltration rate is larger. These results also show that for houses of Average and Present day tightness, AIM-2 predicts higher winter, and lower summer infiltration rates than the Shaw model. For these houses, even though the annual average infiltration rates are approximately the same for both models, the estimated air infiltration heat loss rate will be higher using the AIM-2 model.

Another set of runs for the same house description, Figure 7, show the effect of exhaust only ventilation for HOT2000 6.02 and 6.03. In the top graph, it is seen that as the exhaust ventilation rate is increased, the effective natural air change rate decreases. For the energy tight house, the natural air change rate calculated by HOT2000 6.02 decreased to zero for ventilation rates above 0.17 ACH. In the AIM-2 model, the decrease in natural infiltration rate is much less.

6.0 FURNACE FLUE FLOWS

6.1 Introduction

In the previous version of HOT2000 (6.02), leakage sites for flues were not explicitly included in the Shaw model, or in any of the program inputs. Allowance was made for chimney air flows (9, pp. 10) by adapting the equations developed by Ferguson and Sullivan (10), and applying these equations in an iterative manner to the space heating system model. The resulting model accounts for both furnace off and on-cycle flows, as well as the effects of

vent dampers. Default flue diameters were selected based on fuel and furnace type.

The AIM-2 model does not account for flue flows when the furnace is operating (1, pp. 11). The approach taken here was to calculate the on-cycle flue flow using the Ferguson-Sullivan model, and treat it as an extra exhaust only flow. In the following sections, the method is presented, and compared with results of the previous model.

6.2 Estimation of Furnace Chimney Air Flows

The basic equations for chimney air flows developed by Ferguson and Sullivan, as quoted by Barringer for each fuel and furnace type, were adapted for use in the AIM-2 model. In this case, the off-cycle flows are obtained using the AIM-2 model, but with a flue diameter, D_s adjusted for furnace type. Only two equations are needed, with different coefficients, to describe all cases, as follows.

$$I_{on} = \frac{\alpha\, D_s^{\eta}\, C_f\, (\, 0.908 - E_f\,)\, L_f}{V} \qquad (41)$$

where

I_{on} = on cycle air flow, ACH
α = conversion factor for each fuel and furnace type
η = exponent for each fuel type
C_f = Furnace capacity, watts
E_f = Furnace efficiency (≤ 0.908)
L_f = Furnace load factor

Equation (41) applies to all furnaces except for the mid and high efficiency systems (types 4,5). For these furnace types, the following equation is used.

$$I_{on} = \frac{\alpha\, C_f\, L_f}{V} \qquad (42)$$

The following table summarizes the values of the coefficients used for each fuel and furnace type, and the default flue diameter used in HOT2000. Note that the adjustments made to the actual flue diameters, D_{flue} (mm), account for the vent damper efficiency, or for the fact that the furnace does

not have any dilution air.

Table 4. Furnace Air Flow Coefficients

Fuel/Furnace	Off-Cycle D_s	On-Cycle D_s	a	η	Default Diam. (mm)
Natural Gas/Propane					
Continuous pilot, Spark ignition	D_{flue}	D_{flue}	$1.61457e^{-6}$	1.7	152.4 127.0
Spark ign., Vnt Damp.	$D_{flue}/2$	D_{flue}	$1.61457e^{-6}$	1.7	101.6
Induced draft fan, Condensing or pulse	0	0	$1.28189e^{-3}$	N/A	0.
Oil					
Conventional	D_{flue}	D_{flue}	$2.72731e^{-6}$	1.6	152.4
Flue vent damper, Flame ret. head	$0.742*D_{flue}$	D_{flue}	$2.72731e^{-6}$	1.6	127.0 127.0
Mid-efficiency, Condensing	0	0	$1.15254e^{-3}$	N/A	0.
Wood					
Advanced, Catalytic, Conv. Furnace	D_{flue}	D_{flue}	$7.81647e^{-7}$	1.6	127.0 101.6 203.2

6.3 Iterative Annual Calculations

The need to account for furnace off- and on-cycle flows complicates the calculation of the space heating load, since this part of the load is unknown, and not easy to estimate until the furnace load factor is known, particularly when the heating system includes a heat pump.

In the previous version of HOT2000, this was accomplished by an iterative loop within the space heating system model. The disadvantage of this approach was that it did not allow for interaction between the chimney flows and the natural and forced ventilation rates calculated in the Shaw model. It did have the advantage of speed.

Planned changes in other models (basement heat balance, ventilation and furnace duct heat transfer) will require an iterative solution of the heat balance equations for the whole house. This will be necessary because the interactions between the various components of the heat loss equations will be too complex to solve directly.

It was decided, on this basis, to introduce an iterative solution to the ventilation and space heating system calculations. In this case, it has been found that fewer than 5 iterations are needed to converge to within 0.25 % of the heating load in any particular month. Thus, the convergence criteria have been set internally. Future versions may allow the user to specify the maximum number of iterations and the minimum difference between successive iterations. The method adopted is as follows.

On the first iteration each month, the furnace load factor is assumed to be zero. The AIM-2 model is run to obtain a first estimate of the net air heat loss rate in each temperature bin. Based on this estimate, the contribution of internal and solar gains is calculated, and the space heating system model is run to estimate the space heating energy consumption and the furnace load factor.

In subsequent iterations, the AIM-2 model splits the bins into furnace off- and on-cycle times based on the estimated furnace load factor. The air change rate for these bin segments are calculated using the flue diameters and coefficients shown in Table 4. These are then combined, weighted by the fraction of time in each mode, to obtain the average ventilation rate, and net air heat loss rate for the bin. The iterations are continued until the calculated auxiliary heat loss rate has converged, or the maximum number of iterations has been reached.

6.4 Comparison with HOT2000 6.02

Several sets of runs were done in order to compare the air change heat loss, and space heating loads calculated by the previous and present versions. These runs were done using the same house description with different heating systems. All heating systems included a fan operating in "Auto" mode.

For the first set of runs, Table 5, a furnace efficiency of 80 % was defined for all heating systems. This was done so that differences in space heating loads between system types would be more indicative of operating

modes.

Table 5. Comparison of 6.02 and 6.03 (Furnace Efficiency = 80%)

Fuel/Furnace	Air Change Rate ACH		Air Heat Loss (MJ)		Heating Load (MJ)	
	6.02	6.03	6.02	6.03	6.02	6.03
Electric	0.06	0.072	7139	8637	32252	35977
Natural Gas/Propane						
Continuous pilot	0.17	0.078	17539	9086	66751	57975
Spark ignition	0.17	0.080	17539	9419	50983	42568
Spark ign., Vnt Damp.	0.07	0.078	7923	9342	40175	42505
Induced draft fan, Condensing or pulse	0.06	0.072	7139	8637	32903	35977
Oil						
Conventional	0.20	0.078	21332	9087	52369	39647
Flue vent damper, Flame ret. head	0.09	0.081	9541	9563	39792	40163
Mid-efficiency	0.06	0.072	7139	8637	36336	39221
Condensing	0.06	0.072	7139	8637	32889	35977
Wood						
Advanced	0.26	0.080	27299	9470	63365	42626
Catalytic	"	0.079	"	9462	"	42626
Conv. Furnace	"	0.072	"	8233	"	41307

For the electric furnace, differences between the two versions are mainly due to the infiltration models. The house was considered to be "Sheltered" for 6.02, and in City centre with walls heavily sheltered for AIM-2. Differences for the other cases are due to modelling of the chimney air flows. Overall, the AIM-2 flue model predicts considerably less flue flow than the Ferguson-Sullivan model. The calculated air heat losses sometimes vary in a way which seems counter-intuitive. For example, the conventional natural gas furnace has a lower air heat loss than either the spark ignition (type 2) or the spark ignition, vent damper equipped furnace. Similar results are obtained for oil furnaces.

The decrease in air heat loss rate shown for some cases in Table 5 were

further investigated, for the same house description except that the airtightness used was "Average". In this instance, changing from conventional oil to vent damper resulted in an increase in heat loss rate.

The run set was then repeated, this time using the default efficiencies provided by HOT2000 for each furnace type, Table 6. These results are more representative of cases that will actually be run by users. In this set, it is seen that the calculated heat loss for the more conventional equipment has been reduced, while the heat loss of the advanced systems has been increased relative to HOT2000 6.02. This set also shows the modified AIM-2 air heat losses for a conventional system is greater than for a more advanced system.

Table 6. Comparison of 6.02 and 6.03 (Using Default Furnace Efficiencies)

Fuel/Furnace	Air Change Rate ACH		Air Heat Loss (MJ)		Heating Load (MJ)	
	6.02	6.03	6.02	6.03	6.02	6.03
Electric	0.06	0.072	7139	8637	26018	28781
Natural Gas/Propane						
Continuous pilot	0.17	0.078	22066	9116	68252	59065
Spark ignition	0.17	0.080	17655	9424	52484	43664
Spark ign., Vnt Damp.	0.07	0.078	7929	9345	41222	43598
Induced draft fan	0.06	0.072	7139	8637	32903	35977
Condensing or pulse	0.06	0.072	7139	8637	28002	30614
Oil						
Conventional	0.21	0.078	22066	9116	60416	44711
Flue vent damper	0.09	0.081	9687	9585	45528	45282
Flame ret. head	0.09	0.081	9496	9556	38214	38703
Mid-efficiency	0.06	0.072	7139	8637	34198	36914
Condensing	0.06	0.072	7139	8637	28291	30948
Wood						
Advanced	0.27	0.080	27925	9516	70689	46139
Catalytic	0.26	0.079	27508	9472	65670	43731
Conv. Furnace	0.29	0.074	30429	8809	119187	67144

6.5 Flue size Effects in AIM-2

The variation in air heat loss for different types of furnaces, discussed in the previous section, is caused by changes in the flue diameter used in the respective cases. This fact was determined from HOT2000 run sets in which only the flue diameter is changed, Figure 8. For both the very tight (1.07 ACH @50 Pa.) and the average tightness (4.55 ACH @50 Pa.) case, the air change rate initially increases with flue diameter, then decreases to a minimum, and subsequently increases again. The diameter at which the first maximum occurs is larger for the case which has a larger leakage area (ELA).

A more fundamental examination of this phenomena was carried out using a spreadsheet model of the AIM-2 equations presented in Section 2. This approach was used to avoid any possible "bugs" in the implementation of AIM-2 in the HOT2000 program. Selected parameters from this calculation are presented in Figure 9 for an energy tight (1.5 ACH @50 Pa.) house, and for a house of average tightness (4.55 ACH @50 Pa.). These results generally confirm those obtained from HOT2000.

In Figure 9, as the flue diameter increases, the flue fraction Y increases, the stack effect factor, Ff_s slowly increases, but the wind factor, Ff_w decreases to a minimum and then again begins to increase. The minimum in Ff_w occurs approximately at Y=0.5, so that for the house of average airtightness (and larger ELA), this occurs at a larger flue diameter than for the "Energy Tight" house.

The most interesting parameter (Wilson, 1993) is X_c, "the critical value of the ceiling-floor difference fraction at which the neutral level passes through the ceiling" (Ref. 1, pp 12). For $X > X_c$, the neutral level will be above the ceiling, and attic air will flow in through the ceiling.

The flue diameter effects noted above may be explained phenomenologically as the increasing resistance to infiltration of outside air through the ceiling and upper walls against the forces of buoyancy and of gravity.

[The reason for the second minimum seen for the very tight house shown in Figure 8 is not known at this time, and will be investigated further.]

7.0 CONCLUSION

The Alberta Air Infiltration Model, AIM-2, developed by I.S. Walker and D.J. Wilson, has been implemented in the HOT2000 computer program. This implementation includes several changes to the original model.

This version of AIM-2 uses the Davenport terrain classification scheme, and a logarithmic wind profile to adjust the wind speed at the weather station to conditions at the building site.

The flue model has been modified to account for varying flue diameters during off- and on-cycle furnace operation, and to account for increased flue flows during furnace operation. This has resulted in a requirement to iterate the annual heat loss calculations in HOT2000.

In general, the AIM-2 model predicts lower (~25%) infiltration rates for very "leaky" houses, and higher (~20%) infiltration rates for very "tight" houses, compared to the Shaw model previously used in HOT2000. The calculated natural infiltration rates in AIM-2 are not affected by balanced ventilation systems, and vary in a more reasonable manner for unbalanced systems as the ventilation rate is increased.

The flue model in AIM-2 has reduced the annual space heating load estimated for the more "conventional" systems, including Natural gas systems with a pilot or spark ignition, Oil fired conventional systems, and all wood fired systems. The reduction in space heating loads are considerable for houses that are "very tight", and somewhat less for houses which are of average airtightness.

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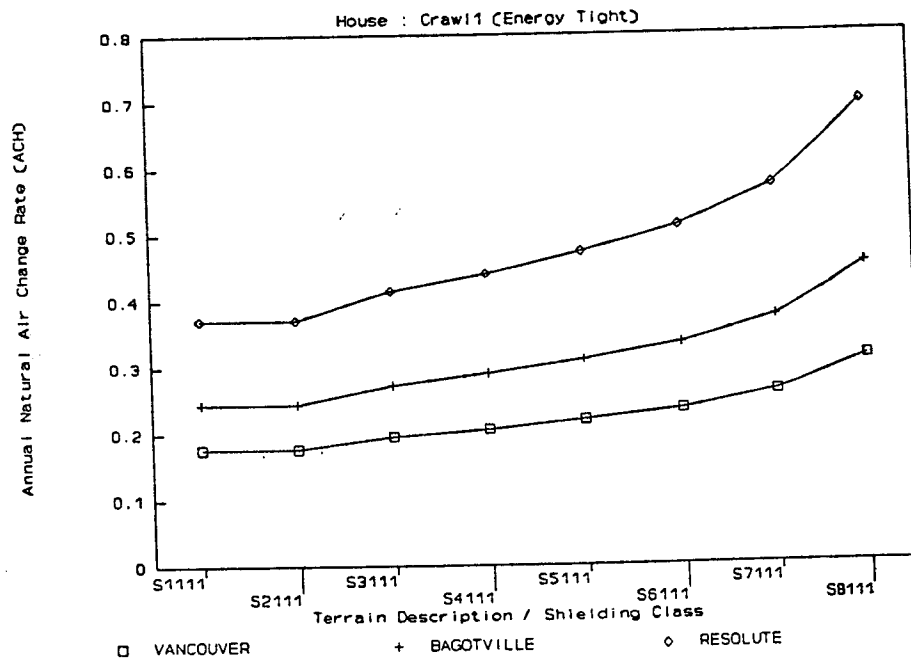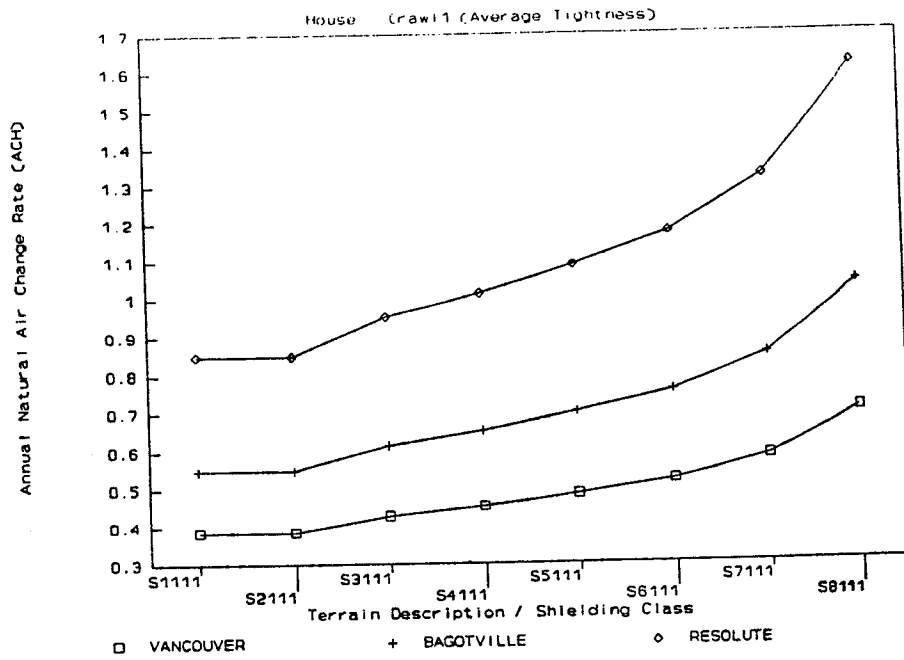
Figure 1a. Sensitivity to Terrain Description

House : Crawl1 (Average Tightness)

□ VANCOUVER   + BAGOTVILLE   ◇ RESOLUTE

House : Crawl1 (Energy Tight)

□ VANCOUVER   + BAGOTVILLE   ◇ RESOLUTE
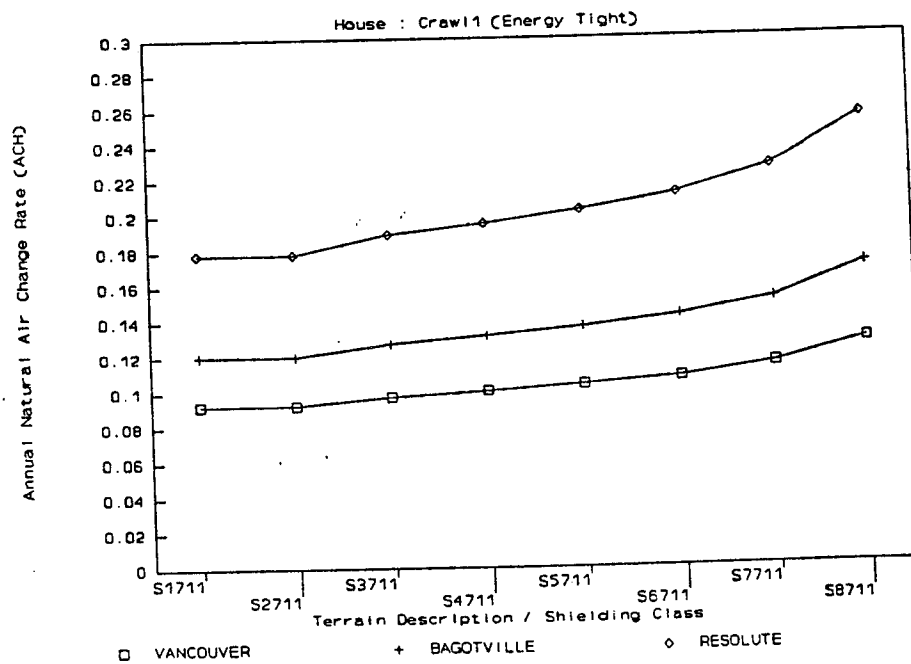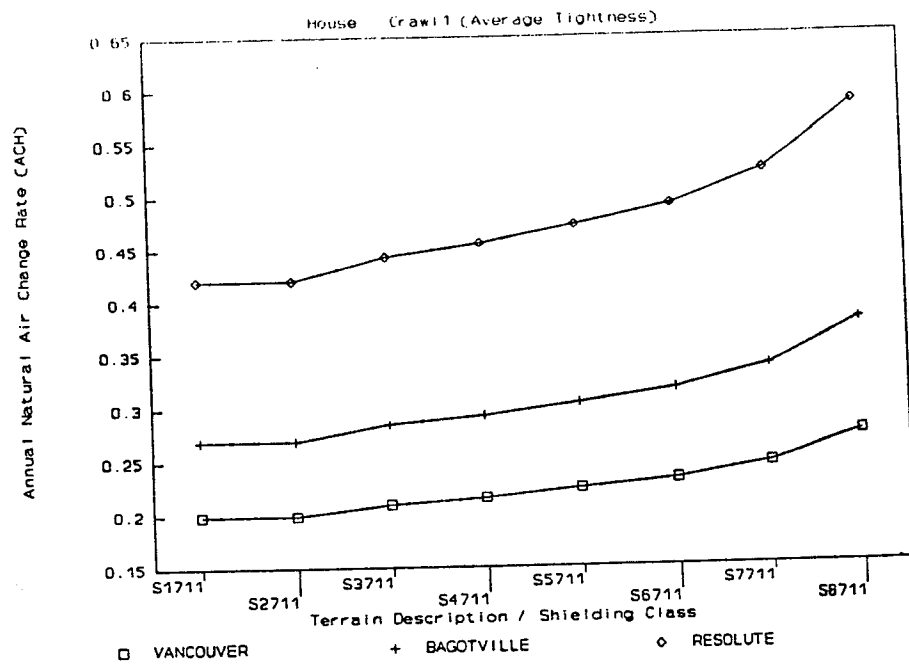
Figure 1b. Sensitivity to Terrain Description
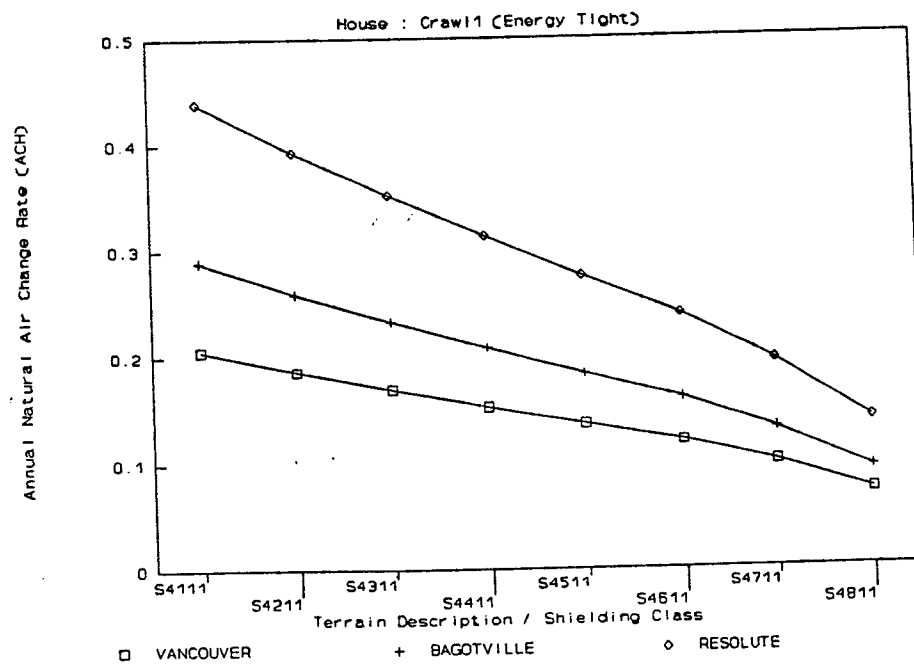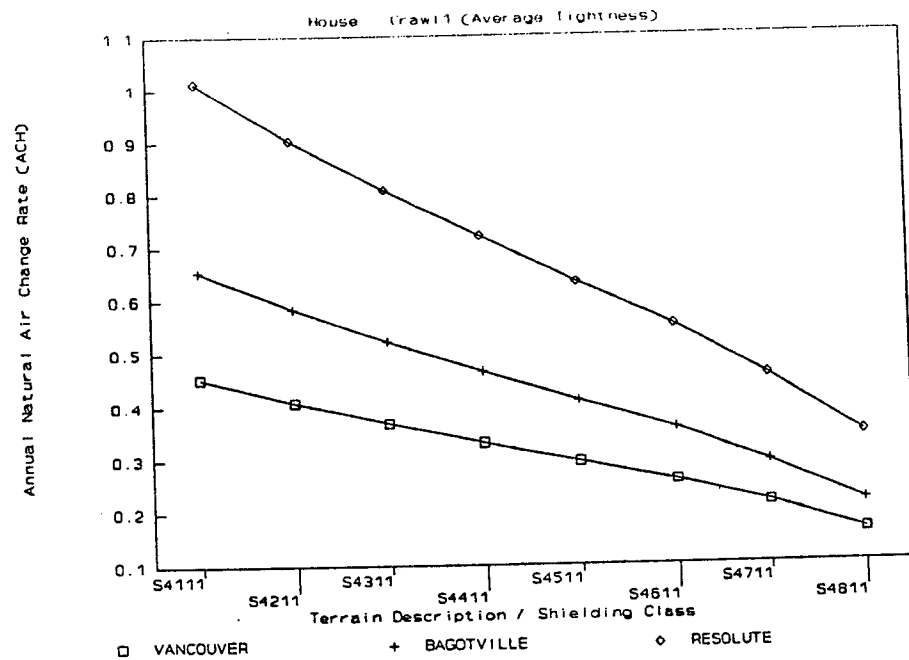
Figure 1c. Sensitivity to Terrain Description
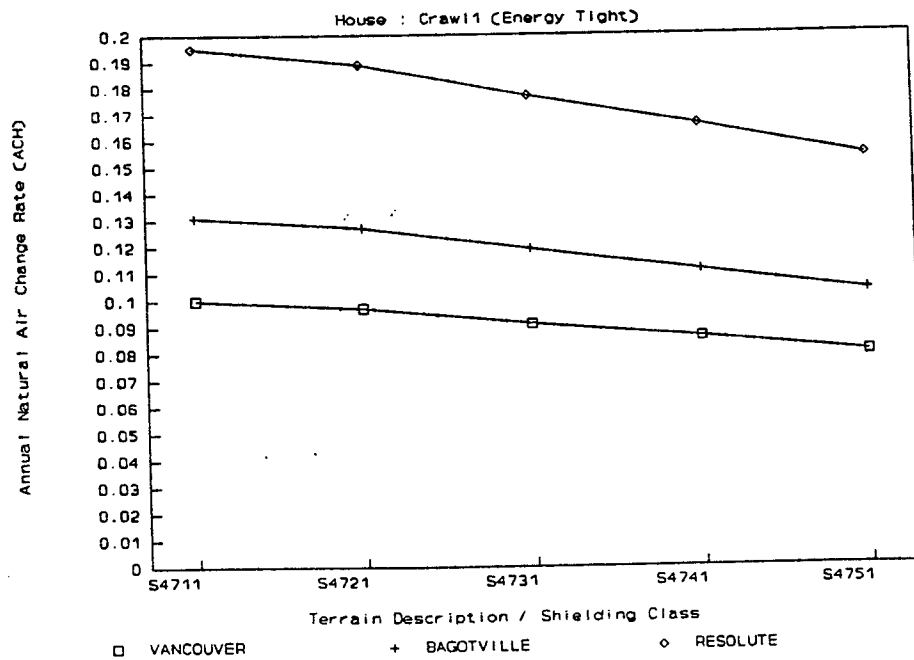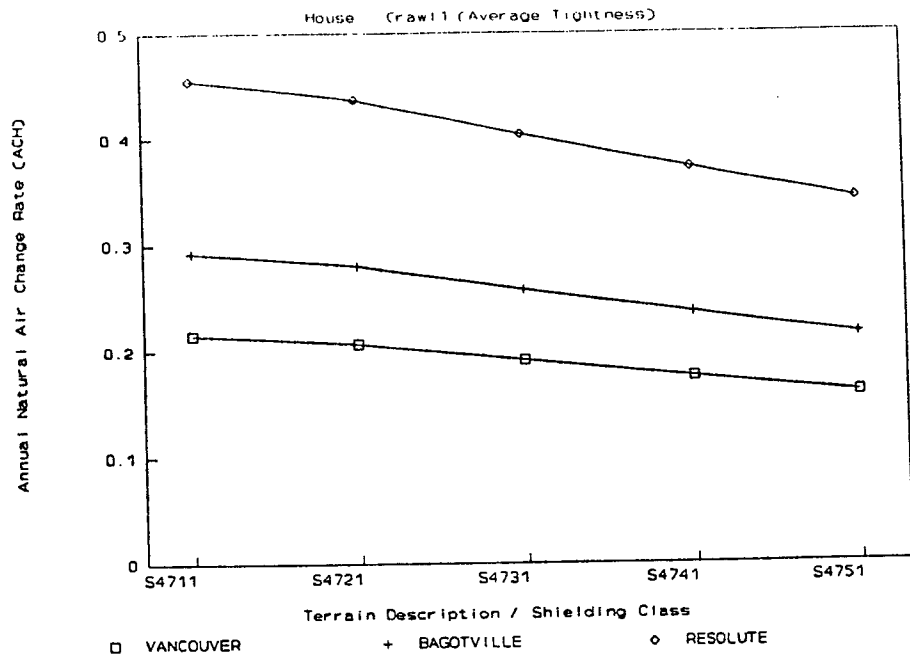
Figure 2. Sensitivity to Local Shielding Class

House   Crawl (Average Tightness)

□ VANCOUVER   + BAGOTVILLE   ◇ RESOLUTE

House : Crawl (Energy Tight)

□ VANCOUVER   + BAGOTVILLE   ◇ RESOLUTE
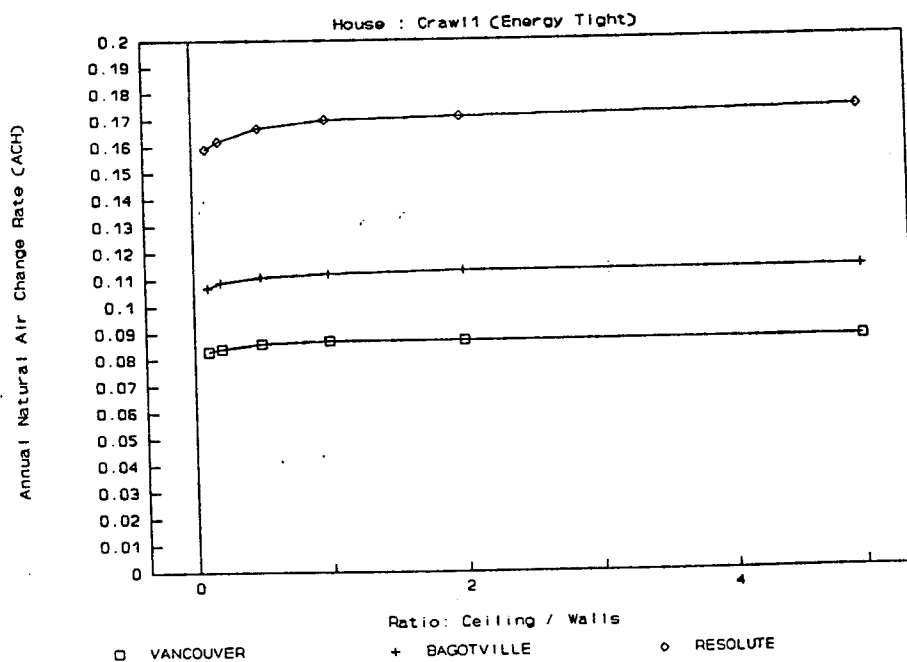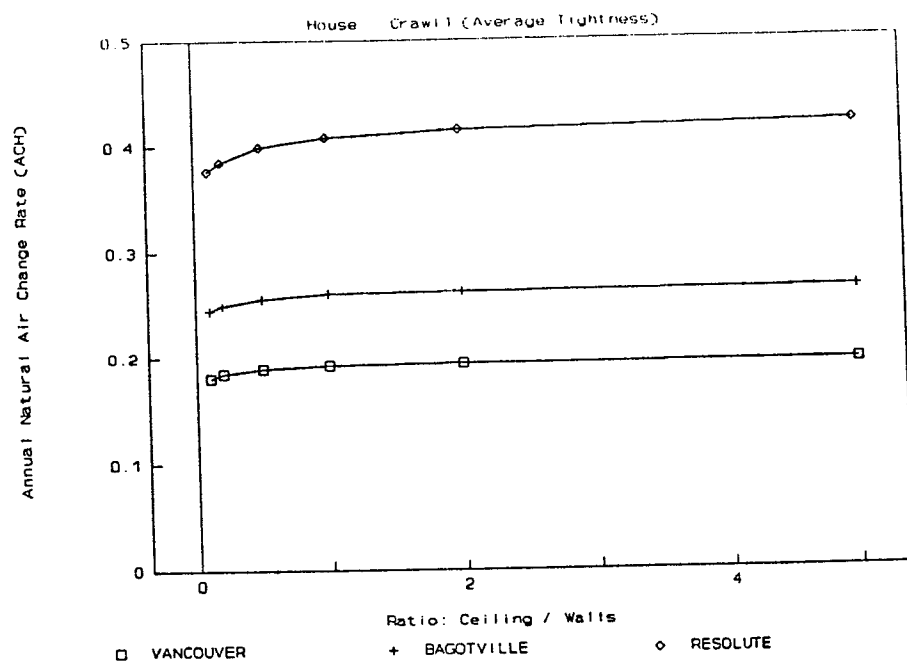
Figure 3a.   Sensitivity to Leakage Distribution
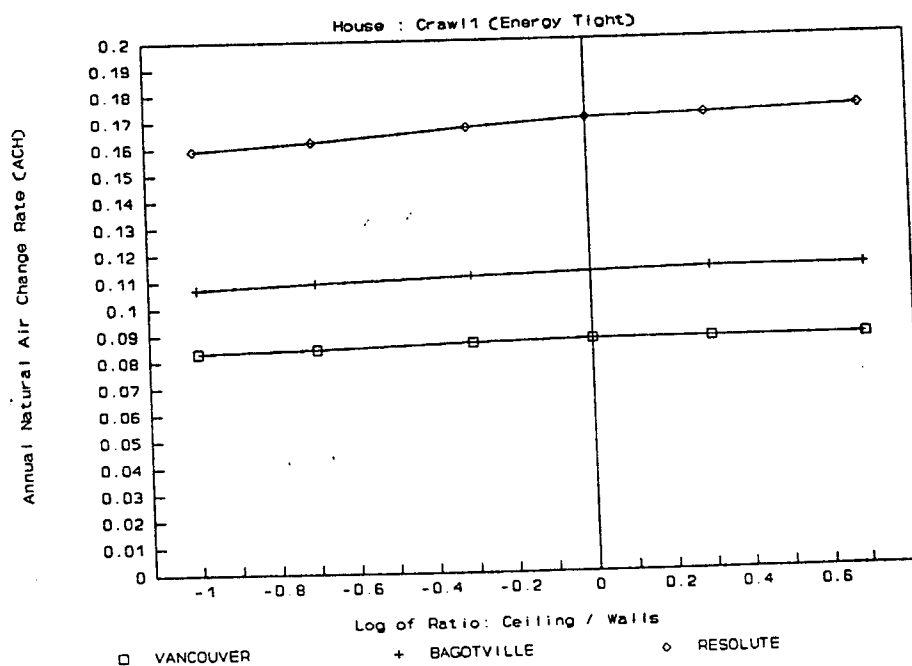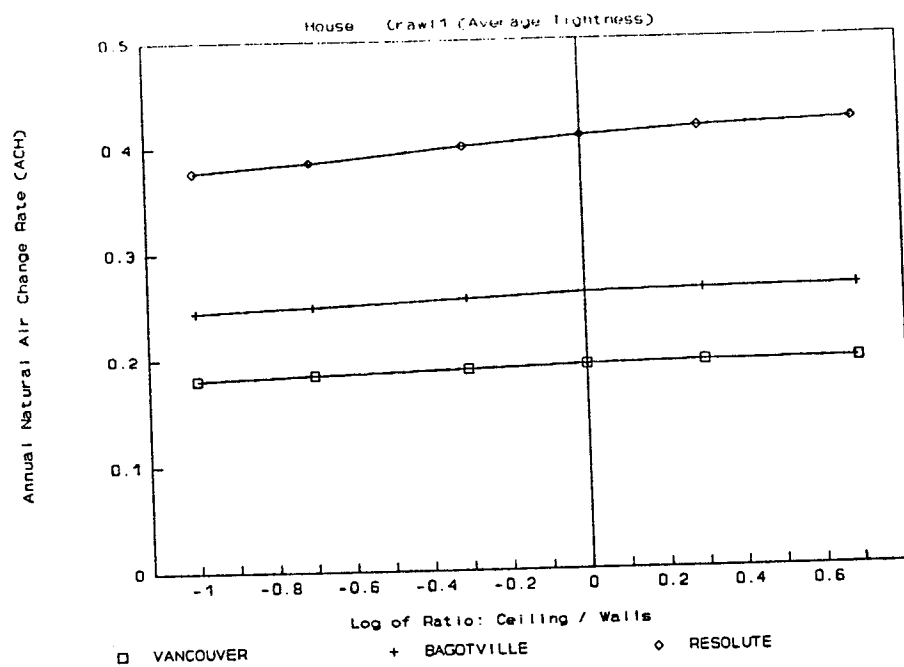
Figure 3b. Sensitivity to Leakage Distribution
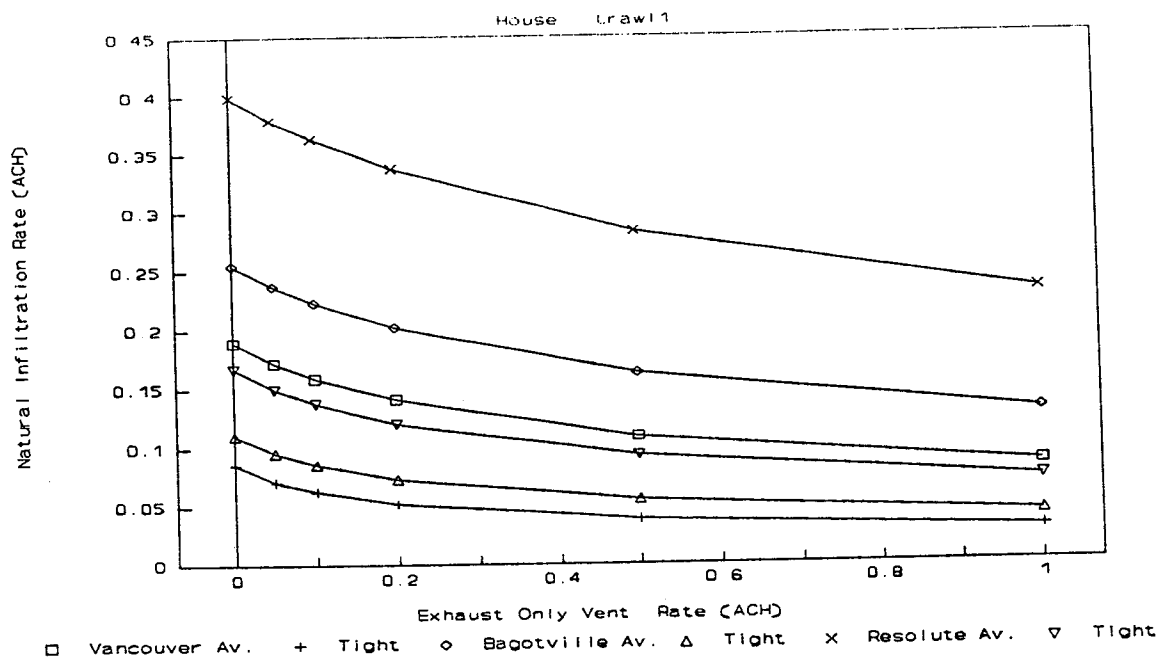
Figure 4. Sensitivity to Exhaust Flow Rate
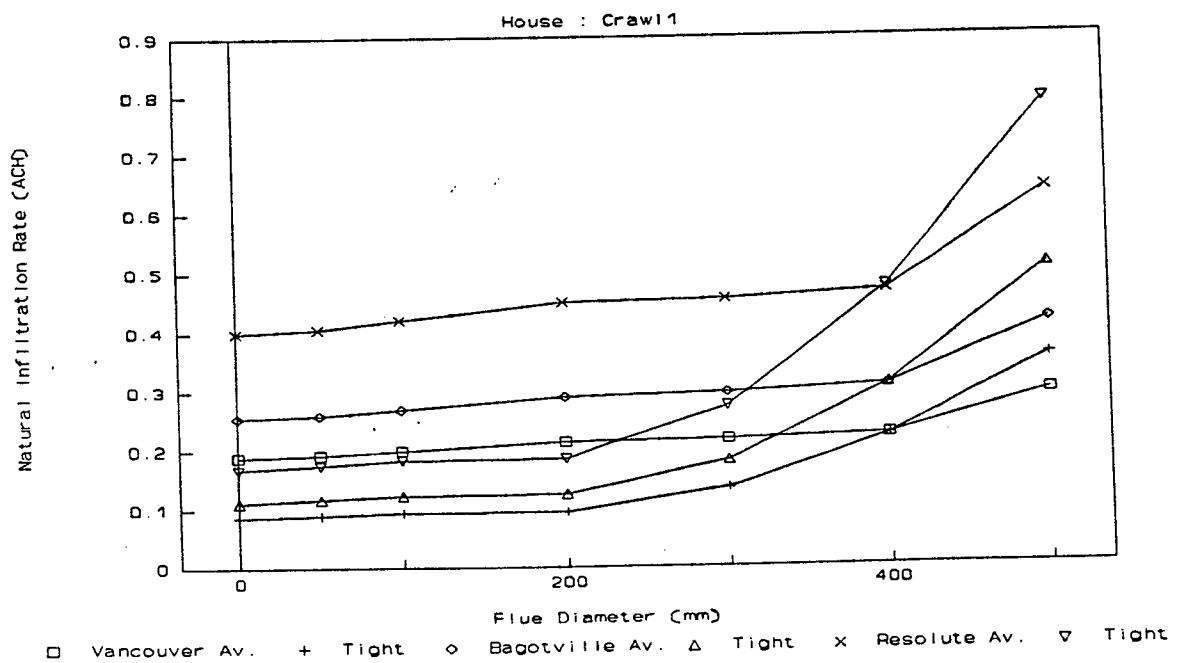
Figure 5. Sensitivity to Flue Diameter
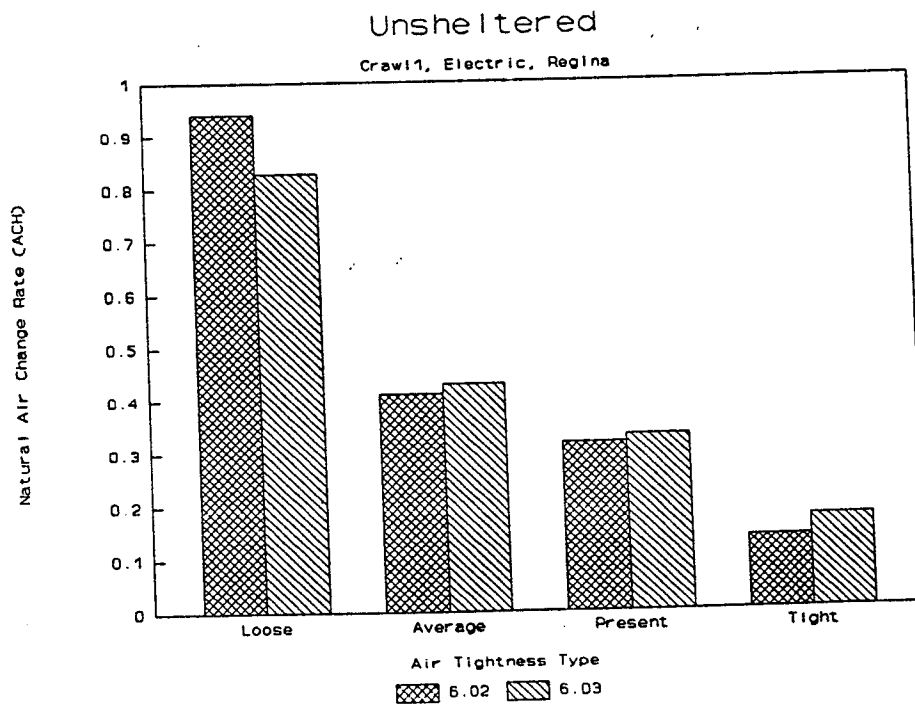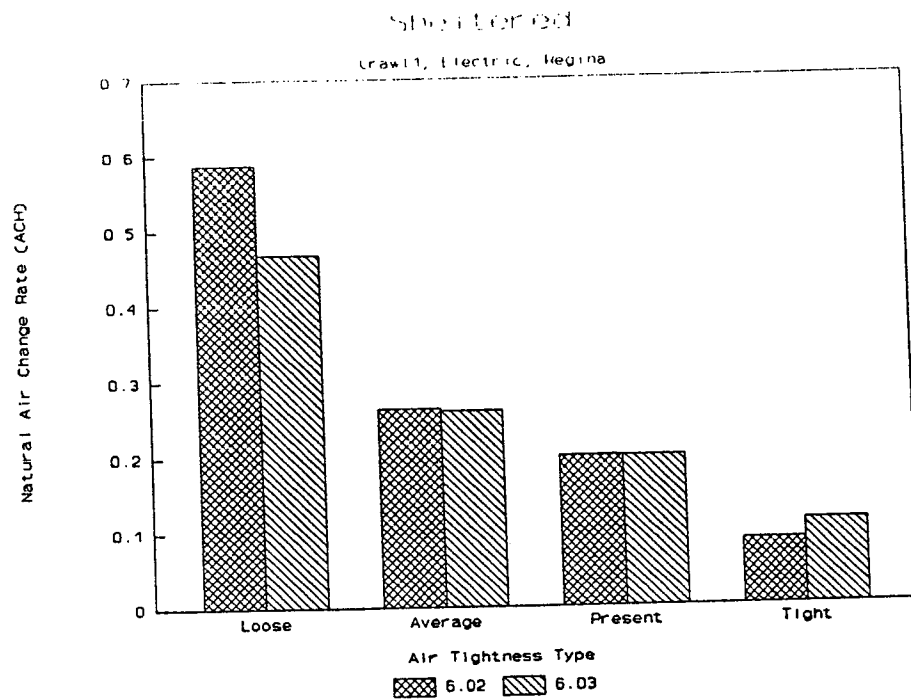
Figure 6a. Comparison of AIM-2 (6.03) with Version 6.02

Unsheltered
Crawl, Electric, Regina
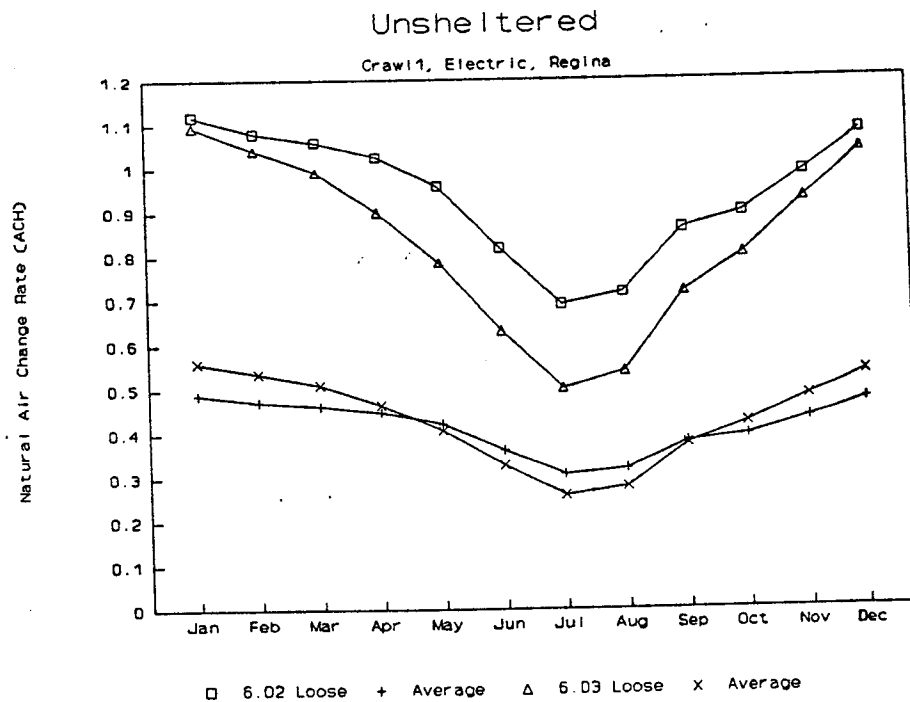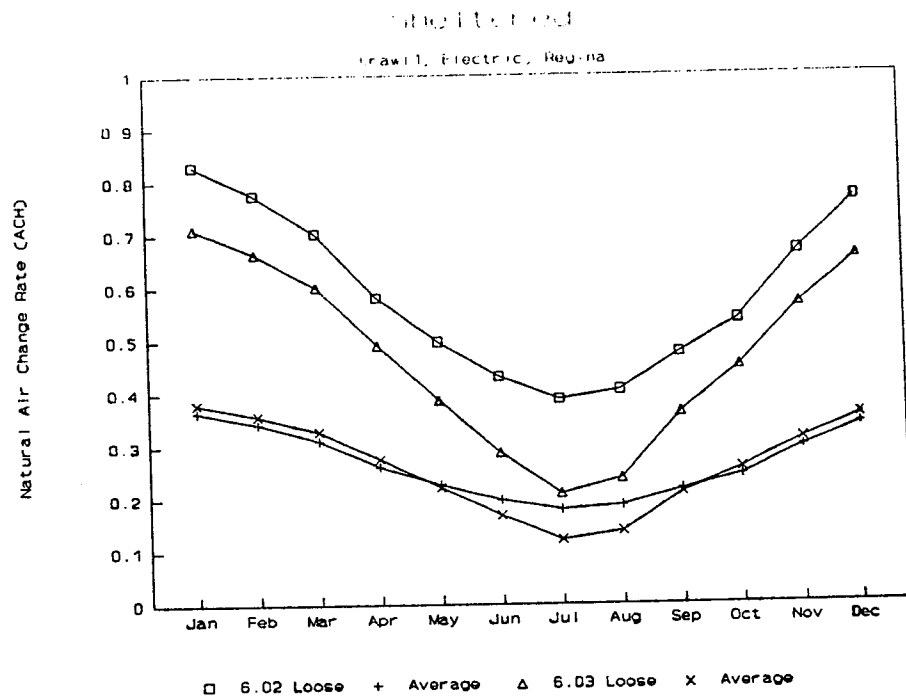
Figure 6b.   Comparison of AIM-2 (6.03) with Version 6.02

Sheltered
Crawl, Electric, Regina

Unsheltered
Crawl, Electric, Regina
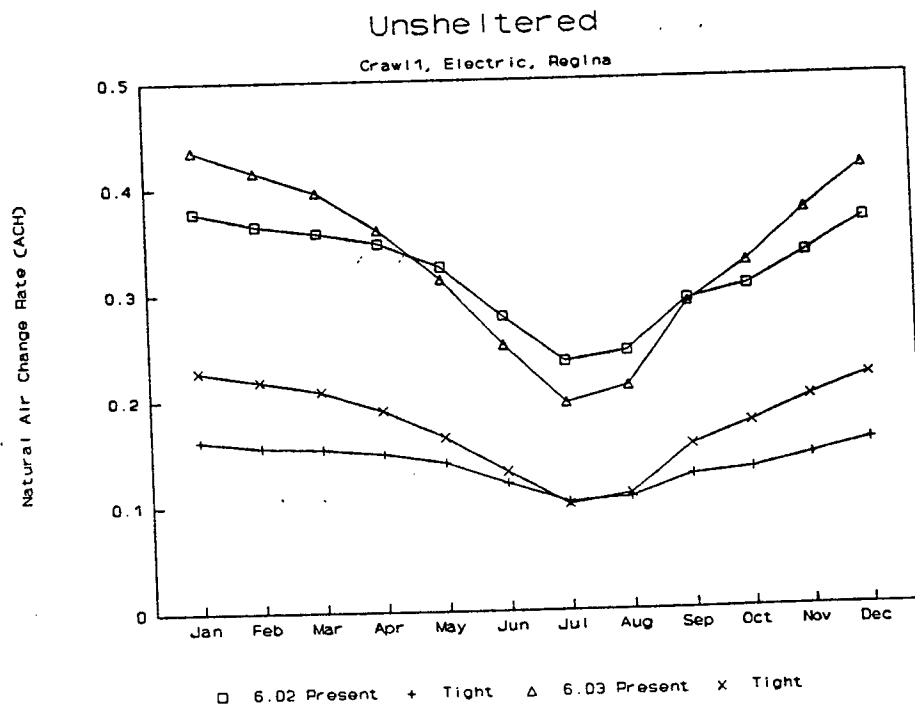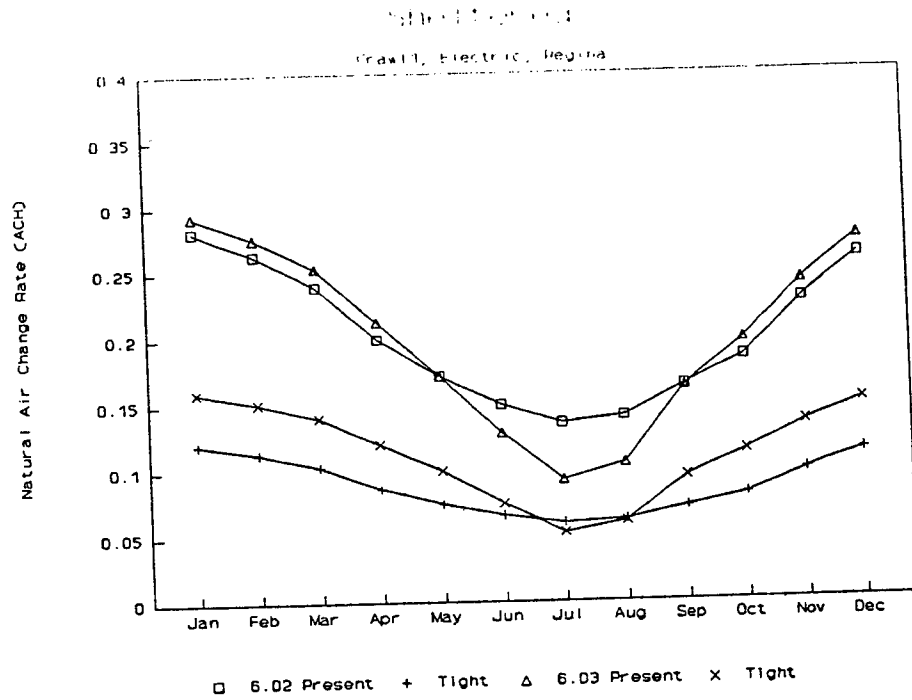
Figure 6c. Comparison of AIM-2 (6.03) with Version 6.02

Exhaust Only Ventilation

Crawl1, Electric, Regina

Exhaust Only Ventilation

Crawl1, Electric, Regina
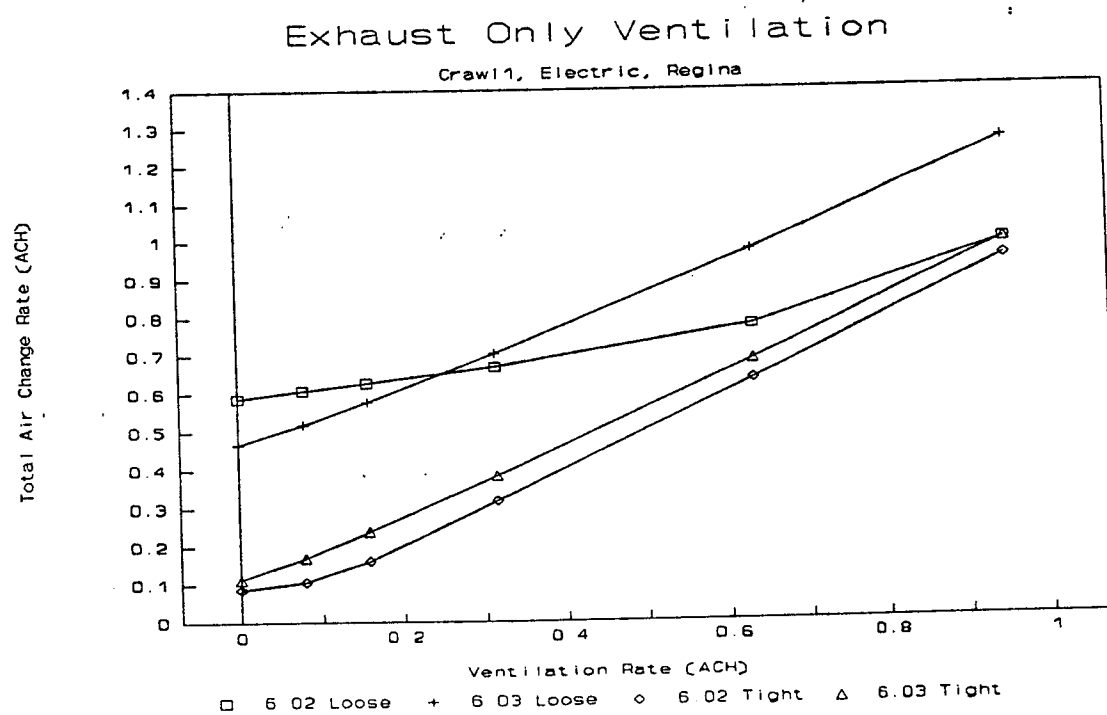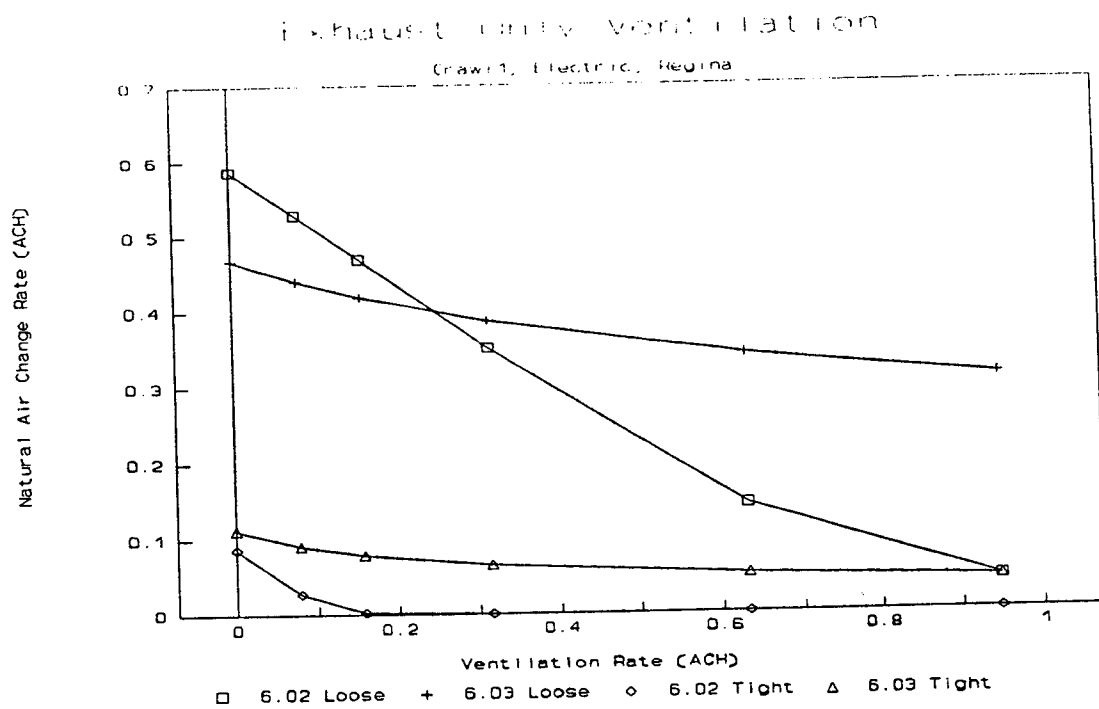
Figure 7. Effect of Exhaust Flow Rate : 6.02 vs 6.03
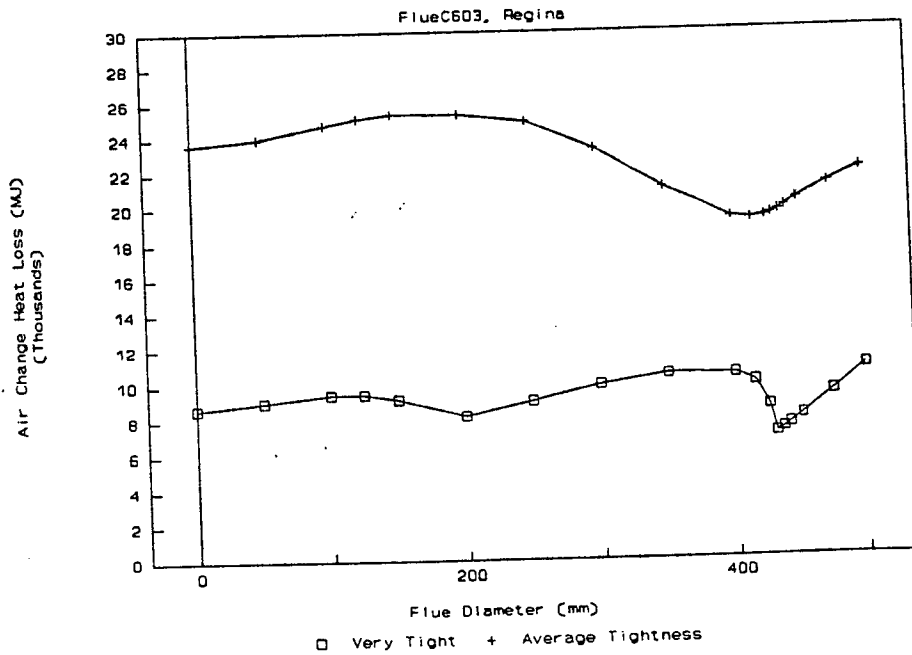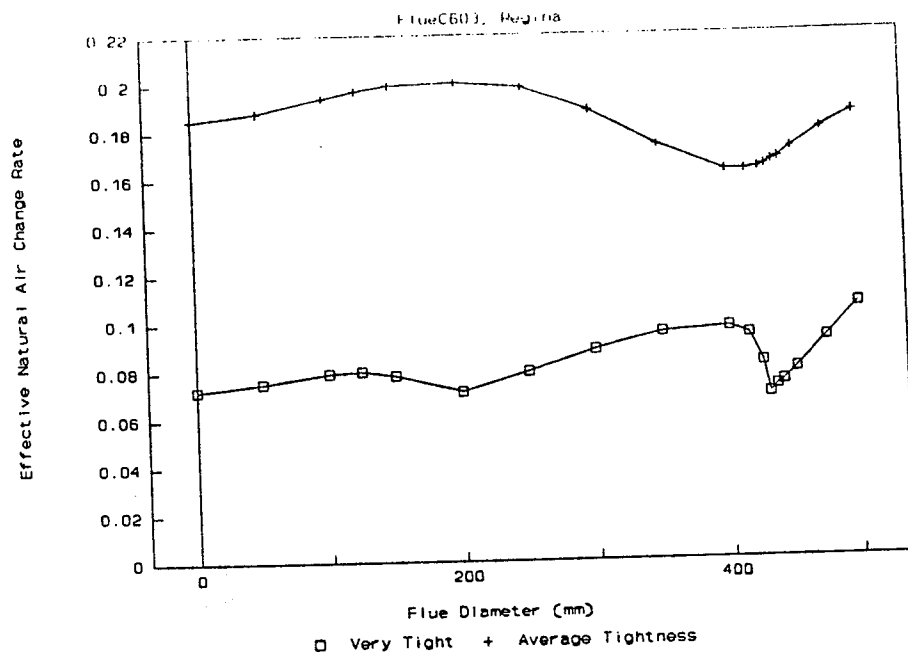
Figure 8. Variation of Air Flow and Heat Loss with Flue Diameter

House: Crawl1 - Energy Tight

□ Ffs + Ffw ◇ Y △ R × M ▽ Xc

Flue Parameters
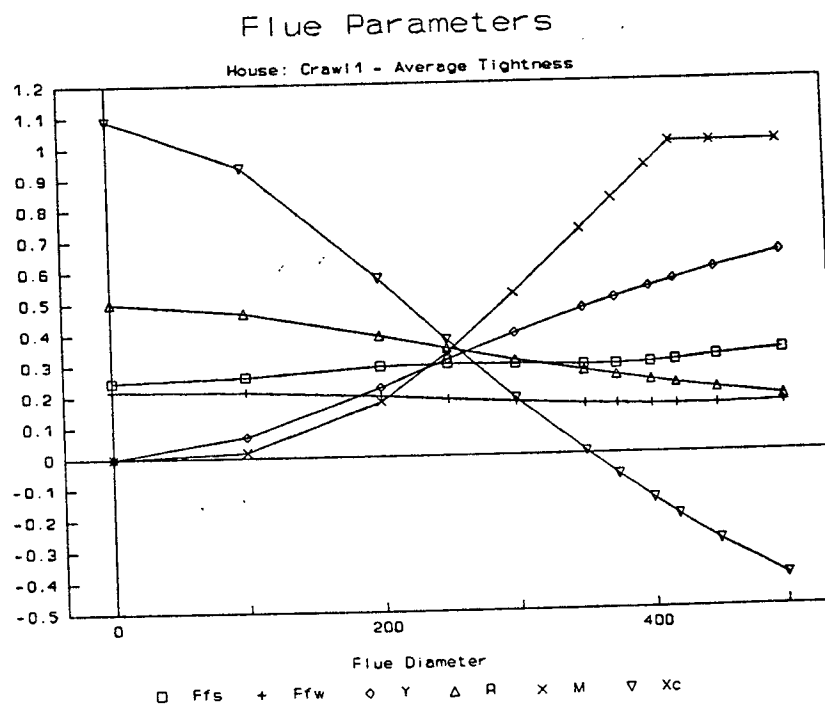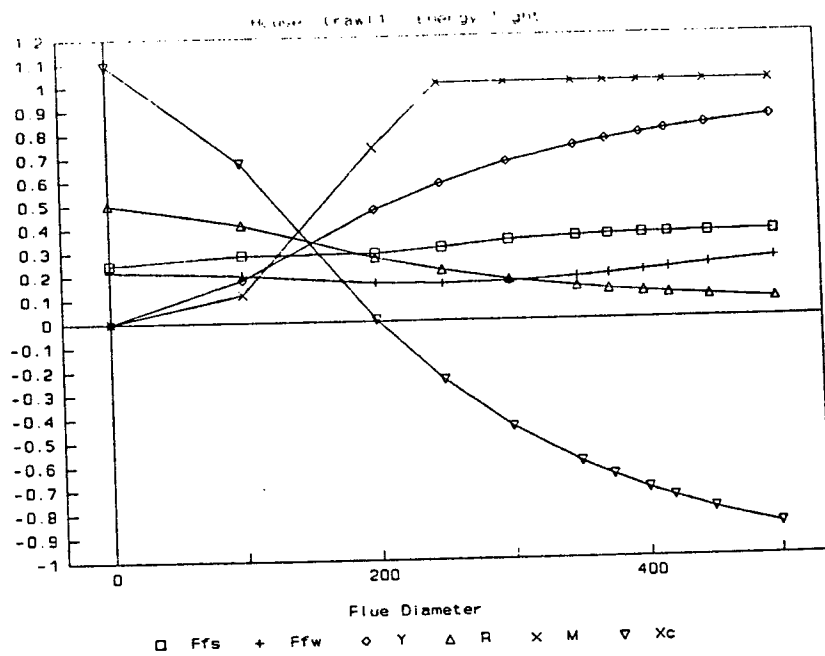
House: Crawl1 - Average Tightness

□ Ffs + Ffw ◇ Y △ R × M ▽ Xc

Figure 9. Variation of AIM-2 Parameters with Flue Diameter