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Fall, 1994

Dear Readers:

The sixth issue of the *Building Research Journal* is in your hands. The papers included in this issue represent applied research related to several of the following focus areas of the *Journal*.

1. Building Design

2. Construction Technology and Management

3. Building Operation and Performance

4. Stabilization, preservation, and Reuse

5. Policy and Consumer Issues

The paper by G.R. Newsham, D.M. Sander, and A. Moreau deals with the development of a correlation method to predict the consumption of monthly cooling energy. It also investigates the effect of thermal mass and manual venting on the cooling energy requirements. Within the Building Operations and Performance focus area, another paper by M.N.A. Said and S.A. Barakat analyzes the interzonal natural convective heat and mass transfer through door-way aperture using a three dimensional computation.

On the Policy and Consumer Issues focus area, A.L. Sweaney and C.B. Meeks present the evaluation of the impact of an energy education program. This paper looks at the long-term impact on consumers who are at risk for high energy costs and poor quality housing structures, mainly limited income, elderly individuals. The design and development of an automated system for purchase-related inspection of a single family home in Canada is presented in the paper by A. Sawhney, T.J. Toth and S.M. AbouRizk. This automated knowledge-based system is meant to speed up and enhance the work of a professional inspector.

The *Journal* contains two papers related to Construction Technology and Management focus area. The paper by M.A. Mullens, R.L. Armacost, and W.W. Swart proposes a framework for benchmarking construction costs for innovative homebuilding technologies. The paper by P.L. Watler, M.S. Malone, and J.D. Lutz deals with the productivity and performance of a repetitive construction operation. It presents the application of methods improvement techniques using data collected from a concrete placement operation.

We would like to thank the Building Research Council staff, the contributors, the reviewers, and the members of the editorial board for their efforts and input. Any comments and suggestions from our readers are welcome.

Matt G. Syal, Editor
Director, Housing Research Center
Colorado State University
October 1994

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A Correlation Method to Determine Monthly Sensible Cooling Energy Consumption in Canadian Homes

Guy R. Newsham, Dan M. Sander, and Alain Moreau

ABSTRACT

Building on the development of a correlation method to determine seasonal residential cooling energy in Canada, we developed a similar correlation method to predict delivered sensible cooling energy on a monthly basis. Further, we investigated the effect of thermal mass and manual venting on the sensible cooling energy requirement. The predictions using the monthly method were compared to those from an hourly simulation model and found to be satisfactory given the method's simplicity. Mean differences, over all climates and building parameters considered, were 6.5 percent in the light mass, no manual venting case. An example calculation using the method is presented, and the method's limitations are discussed.

Guy R. Newsham is a Research Associate, Institute for Research in Construction, National Research Council of Canada, Ottawa, Ontario. Dan M. Sander is a Senior Research Officer, Institute for Research in Construction, National Research Council of Canada, Ottawa, Ontario. Alain Moreau is a Research Engineer, LTEE, Hydro-Québec, Shawinigan Québec.

INTRODUCTION

Many Canadian utilities have supported programs to encourage the adoption of energy efficient electrical appliances in the home. Efficient appliances will not only affect the energy consumption of the home directly, through their own reduced electricity consumption, but also indirectly, through their reduced heat output (internal gains). Reduced internal gains mean an increased load on the heating system, and a decreased load on the cooling system; any assessment of the total energy impact of efficient appliances must account for these thermal effects. It is only recently, with an explosion of residential air conditioning ownership (Ontario Hydro 1990), that cooling effects have become potentially significant in Canada. This perhaps explains the lack of any existing simple method to accurately determine the impact of internal gains on residential cooling energy consumption.

In a previous paper (Newsham, Sander and Moreau 1993) we described the development of a correlation method to determine seasonal residential cooling energy consumption in Canada. Although this seasonal correlation was relatively accurate, it did assume that residences were cooled throughout the five month summer period from May to September. For many Canadian homes the cooling season is shorter than this, and, therefore, we extended the method to determine sensible cooling for individual summer months. This paper describes the extension of the method to monthly calculations.

METHODS AND PROCEDURES

We used the EASI hourly simulation model to calculate the sensible cooling requirements from which we derived the correlations. EASI employs the ASHRAE Transfer Function Method (ASHRAE 1993), and was originally developed by Public Works Canada. The hourly simulation runs were exactly the same as those described in Newsham, Sander and Moreau (1993). However, for the monthly correlations, the cooling energy requirement was summed monthly rather than seasonally.

In summary, the modeled house was of floor area (A_f) 160 m^2, external wall area (A_w) 184 m^2 and volume (V) 604 m^3. Cooling setpoint for the summer months was 24 °C, and the maximum ventilation rate, with windows open due to manual venting, was 0.2 m^3s^{-1}. The following parameters were varied between runs:

- Internal gains per unit floor area (including occupants): 0 to 12.5 W/m^2, constant schedule.
- Glazing (fraction of wall area glazed × shading coefficient): 0 to 0.5.
- Heat loss factor, HLF ([sum of u-value × area, for walls, roofs, and windows, and including infiltration] / A_f): 0 to 2.89 $W/m^2{\cdot}°C$
- Venting strategy: windows shut (non-vented) or manually openable windows (vented).
- Thermal mass per unit floor area: 60 $kJ/m^2{\cdot}°C$ (light) or 150 $kJ/m^2{\cdot}°C$ (medium).

The vented strategy attempted to account for residents' efforts to cool a house through increased ventilation before resorting to mechanical cooling. We modeled this action in the following way: If the cooling load could be met by increased ventilation then infiltration was considered to be increased to the rate necessary to satisfy the cooling setpoint (up to the given maximum air flow rate); if the maximum air flow rate was inadequate to meet the cooling load, then the infiltration rate remained at the minimum rate (i.e., the windows were considered shut) and mechanical cooling took over.

There are many strategies that occupants can adopt with respect to air conditioner use (Newsham, Sander and Moreau 1993), and the strategy described above is just one of them. Nevertheless, our assumptions represent an occupant gaining reasonable maximum ventilative free cooling, and, thus, form a lower boundary to the cooling energy requirements.

A total of 1848 parameter combinations for each of eight Canadian cities were considered. Monthly cooling requirements were simply the sum of the calculated hourly cooling requirements of that month. Only the months May to September were considered; we assume that, irrespective of the parameter values, mechanical cooling would not be engaged in Canadian residences outside of these months.

HOURLY COOLING CORRELATION

Non-vented Case, Low Mass

The correlation equation for monthly sensible cooling energy in the non-vented case is of the same form as that previously derived for seasonal cooling energy (Newsham, Sander and Moreau 1993), except that coefficients appropriate for a monthly rather than a seasonal calculation must be used:

$$
\begin{aligned}
C_f/G_{tot} = {} & e_1 + f_1 \cdot [\, G_{tot}/G_s \,] + e_2 \cdot [\, ln(\, 1/G_{tot}\,)\,] \\
& + f_2 \cdot [\, G_{tot}/G_s \,] \cdot [ln(1/G_{tot})] + e_3 \cdot [ln\,(G_{tot}/L_t)] \\
& + f_3 \cdot [\, G_{tot}/G_s \,] \cdot [ln\,(G_{tot}/L_t)] + e_4 \cdot [ln(1/G_{tot})] \cdot [ln\,(G_{tot}/L_t)] \\
& + f_4 \cdot [\, G_{tot}/G_s \,] \cdot [ln\,(1/G_{tot})] \cdot [ln\,(G_{tot}/L_t)]
\end{aligned} \tag{1}
$$

where

C_f = sensible cooling energy for month per unit floor area, kWh/m^2;

G_i = total of internal gains for month per unit floor area, kWh/m^2;

G_s = total of solar gains for month per unit floor area, kWh/m^2;

$G_{tot} = G_s + G_i$, kWh/m^2;

L_t = maximum contribution transmission loss can make to reducing the cooling load for month per unit floor area, kWh/m^2; and

e_i, f_i are climate dependent coefficients.

C_f/G_{tot} is, therefore, the fraction of solar plus internal gains which must be removed by the

Table 1. Correlation coefficients for Ottawa for the law mass case

	MAY	JUN	JUL	AUG	SEP
H_m	744	720	744	744	720
k_t	7.40	3.99	2.73	2.87	6.75
e_1	0.0248	0.2198	0.9065	0.5558	0.1596
e_2	-0.1944	-0.1546	-0.0147	-0.0862	-0.1669
e_3	0.2741	0.2040	-0.0431	0.0830	0.2256
e_4	0.0500	0.0359	-0.0141	0.0114	0.0402
f_1	0.0562	-0.1377	-0.3022	-0.2018	0.0084
f_2	0.0725	0.0030	-0.0560	-0.0200	0.0554
f_3	0.1420	0.1552	0.1388	0.1408	0.1505
f_4	0.0253	0.0292	0.0243	0.0249	0.0278
			Applies to All Months		
vm_1			0.8743		
vm_2			-0.4678		
vm_3			-0.0099		
vm_4			0.0024		

mechanical cooling system. Note that C_f is the delivered sensible cooling energy; to convert C_f to the billed energy one must divide by the appropriate COP of the air conditioner. **Table 1** gives values for the coefficients e_i and f_i which were determined for Ottawa. Appendix A describes a method for determining these coefficients from monthly climate statistics.

Parameter G_i depends only on the occupancy and the internal gains. In developing the correlation we assumed a constant internal gain schedule; therefore:

$$G_i = (H_m \cdot I)/(A_f \cdot 1000) \quad (2)$$

where

H_m = hours in the month;

I = average total internal gains (including occupants) for month, W; and

A_f = floor area, m^2.

Parameters G_s, and L_t are building and climate dependent. G_s is described by the following equation:

$$G_s = 0.32 \cdot (A_{gn} \cdot SC_n \cdot VSN + A_{gs} \cdot SC_s \cdot VSS + A_{ge} \cdot SC_e \cdot VSE + A_{gw} \cdot SC_w \cdot VSW \cdot (H_m/24)/A_f \quad (3)$$

where

A_{gi} = area of glass facing orientation i (where, i=n is north; i=s is south; i=e is east; and i=w is west);

SC_i = shading coefficient of windows facing orientation i;

VSS = mean daily solar radiation on south vertical, for the month, MJ/m^2;

VSN = mean daily solar radiation on north vertical, for the month, MJ/m^2;

VSW = mean daily solar radiation on west vertical, for the month, MJ/m^2; and

VSE = mean daily solar radiation on east vertical, for the month, MJ/m^2.

VSS, VSN, and VSW can be found in **Table 2**, which shows all relevant monthly climate data for the 8 cities studied; note, for this climate data, VSE = VSW.

Parameter L_t is described by the following equation:

$$L_t = k_t \cdot HLF \quad (4)$$

where HLF is the heat loss factor, given by:

$$HLF = (A_w \cdot U_w + A_r \cdot U_r + A_g \cdot U_g + 0.329 \cdot V \cdot ACH)/A_f \quad (5)$$

where

A_w = total area of opaque walls, m^2;

U_w = average U-value of opaque walls, $W/m^2 \cdot {}^oC$;

A_r = total area of roof, m^2;

U_r = average U-value of roof, $W/m^2 \cdot {}^oC$;

A_g = total area of windows, m^2;

U_g = average U-value of windows, $W/m^2 \cdot {}^oC$;

V = volume, m^3;

ACH = average infiltration, ac/h; and

k_t is a climate dependent coefficient.

Values of k_t for Ottawa are given in **Table 1**. Appendix B describes a method for determining the coefficient k_t from monthly climate statistics.

Manual Window Opening (Vented Case), Low Mass

The monthly sensible cooling energy requirement in the vented case is expressed in terms of the appropriate monthly cooling energy requirement for the non-vented case. Plotting the cooling energy consumption from the hourly model for the vented case versus that for the non-vented case for various months and parameter combinations (examples are shown in **Figure 1**) suggested the following relationship:

$$C_{f(vent)}(L_t, G_s, G_i) = C_{f(non-vent)}(L_t, G_s, 0) - vm_1 - vm_2 \cdot G_i - vm_3 \cdot G_s \cdot G_i - vm_4 \cdot L_t \cdot G_i \quad (6)$$

where

vm_1, vm_2, vm_3, and vm_4 are climate dependent coefficients.

Values of vm_i for Ottawa are given in **Table 1**. Appendix C describes a method for determining these coefficients from monthly climate statistics.

$C_{f(vent)}$ is also bound by the condition:

$$0 < C_{f(vent)} < C_{f(non-vent)} \quad (7)$$

Effect of Mass

The above results were all derived for a low mass house construction (60 $kJ/m^2 \cdot {}^oC$). This construction is representative of the majority of residences built in Canada. However, there are residences with higher internal mass, and we repeated the derivation process for a medium mass case (150 $kJ/m^2 \cdot {}^oC$) to determine the effect of mass on cooling energy. Example building constructions conforming to the above two mass types are shown in **Table 3**.

The form of the correlation equations in the medium mass case is exactly the same as for the low mass case; however, the correlation coefficients are changed. **Table 4** gives values of coefficients e_i, f_i, k_t, and vm_i for the medium mass case for Ottawa. Appendix A describes a method for determining the coefficients e_i and f_i from monthly climate statistics. Appendices B and C describe a method for determining the coefficients k_t and vm_i, respectively, from monthly climate statistics.

We also assume that the following condition applies(the assumption appears to be confirmed by our analysis):

$$C_{f(mass = medium)} < C_{f(mass = light)} \quad (8)$$

Table 2. Climate parameters for 8 Canadian cities, monthly. EDM = Edmonton; FRD = Fredericton; MTL = Montreal; OTT = Ottawa; TOR = Toronto; VAN = Vancouver; WIN = Windsor; WPG = Winnipeg

City	Month	HDD2	VSN	VSW	VSS	CDD1	CDD2	CDH1	DRNG
EDM	MAY	236.91	4.78	8.97	10.04	65.59	2.65	14.4	14.2
FRD	MAY	222.67	3.92	6.73	7.06	68.56	0.44	2.5	12.7
MTL	MAY	162.77	3.88	7.14	7.66	117.18	9.36	12.0	11.1
OTT	MAY	164.29	3.97	7.15	7.34	120.46	11.25	16.7	11.7
TOR	MAY	172.83	3.94	6.99	7.05	116.31	13.62	24.9	12.3
VAN	MAY	180.07	4.51	7.51	9.04	80.84	0.54	1.3	8.6
WIN	MAY	118.88	4.12	7.69	7.23	174.25	29.59	73.2	11.4
WPG	MAY	190.46	4.17	8.21	9.27	126.28	16.94	66.7	13.5
EDM	JUN	117.01	5.73	9.25	8.81	137.94	3.60	5.9	13.5
FRD	JUN	89.44	4.91	7.63	6.97	176.58	15.82	55.1	13.1
MTL	JUN	52.01	4.65	7.48	7.23	234.18	36.77	65.5	10.7
OTT	JUN	47.42	4.69	7.74	6.78	243.84	41.98	111.1	11.4
TOR	JUN	56.15	4.70	7.70	6.63	233.85	40.72	112.4	12.4
VAN	JUN	89.44	5.53	8.06	8.06	163.48	3.92	0.7	8.3
WIN	JUN	21.83	4.99	8.27	6.46	305.96	78.79	201.5	11.2
WPG	JUN	69.29	5.55	9.24	8.22	219.64	37.85	114.4	12.6
EDM	JUL	71.99	5.16	9.16	9.71	197.21	11.81	19.4	13.2
FRD	JUL	24.94	4.40	7.28	7.31	284.43	52.07	122.7	12.7
MTL	JUL	9.54	4.54	7.63	7.73	345.48	97.72	180.3	10.5
OTT	JUL	6.78	4.28	7.70	7.15	353.32	102.80	217.4	11.4
TOR	JUL	7.54	4.25	7.83	7.11	350.85	101.09	268.4	12.6
VAN	JUL	37.41	4.52	8.12	9.00	233.69	13.80	3.9	9.3
WIN	JUL	1.69	4.59	8.48	6.89	405.11	49.49	421.6	11.0
WPG	JUL	13.60	4.8	59.01	8.98	316.25	72.55	153.7	12.6
EDM	AUG	103.00	3.02	7.33	11.45	170.26	12.71	27.4	13.4
FRD	AUG	46.32	3.38	6.76	8.83	256.84	45.62	89.6	12.7
MTL	AUG	27.00	3.48	6.70	8.78	300.46	70.05	94.3	10.5
OTT	AUG	28.14	3.14	6.69	8.64	297.95	68.66	108.2	11.1
TOR	AUG	21.12	3.09	6.85	8.71	307.96	71.78	133.1	12.2
VAN	AUG	32.17	3.15	6.45	9.86	239.99	14.86	3.7	8.9
WIN	AUG	7.04	3.06	7.25	8.78	364.91	114.65	210.6	10.6
WPG	AUG	40.62	2.99	7.48	10.55	285.60	68.44	249.4	12.9
EDM	SEP	250.74	1.96	5.38	12.13	53.64	0.60	3.9	13.4
FRD	SEP	164.06	2.07	4.79	9.56	102.48	5.74	14.8	12.6
MTL	SEP	121.51	2.29	5.07	9.70	147.42	13.54	13.0	10.3
OTT	SEP	125.83	1.92	4.78	9.51	143.14	12.58	15.3	10.6
TOR	SEP	107.28	1.92	4.99	9.83	167.02	20.35	26.5	11.7
VAN	SEP	112.86	1.79	4.91	11.74	138.53	2.14	0.8	8.2
WIN	SEP	66.79	2.15	5.62	10.35	225.24	41.78	55.9	10.6
WPG	SEP	186.60	1.89	5.38	11.56	99.17	8.26	29.3	12.1

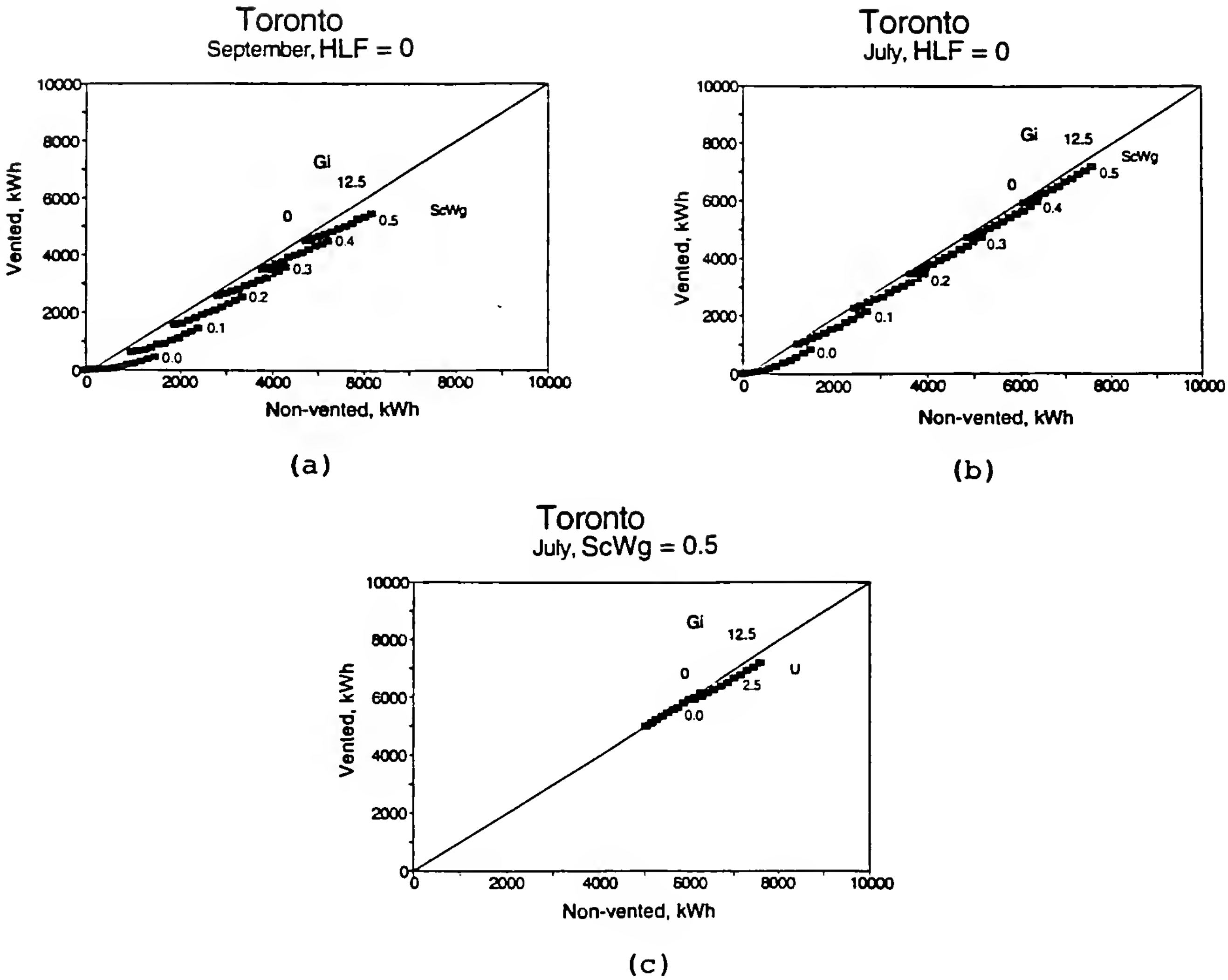

Figure 1. The relationship between sensible cooling energy requirement in the vented and non-vented cases, for various months and parameter combinations (W_g = fraction of wall area glazed). In panels (a) and (b) there are six sets of curves, one for each of six different values of the parameter ScW_g. The eleven points within each set show eleven different values of G_i. In panel (c) there are two sets of curves, one for each of two different values of U. The eleven points within each set show eleven different values of G_i.

Table 3. House constructions and associated thermal mass

Type	Mass (kJ/m^2·^{o}C)	Construction
light	60	wood frame construction 13 mm gypsum interior finish on walls and ceilings, carpets over wooden floors.
medium	150	as above, but 50 mm gypsum interior finish on walls, and 25 mm gypsum interior finish on ceiling

Table 4. Correlation coefficients for Ottawa for the medium mass case

	MAY	JUN	JUL	AUG	SEP
H_m	744	720	744	744	720
k_t	6.21	3.99	2.77	2.86	6.74
e_1	0.0445	0.1037	0.6308	0.4048	0.2257
e_2	-0.1495	-0.1392	-0.0470	-0.0865	-0.1178
e_3	0.2975	0.2766	0.0910	0.1706	0.2337
e_4	0.0430	0.0395	0.0090	0.0221	0.0325
f_1	-0.0520	-0.2266	-0.2561	-0.2410	-0.0880
f_2	0.0226	-0.0452	-0.0566	-0.0507	0.0086
f_3	0.1760	0.1778	0.1051	0.1375	0.2026
f_4	0.0408	0.0413	0.0233	0.0313	0.0474

	Applies To All Months
vm_1	1.2146
vm_2	-0.4707
vm_3	-0.0102
vm_4	-0.0045

DISCUSSION: GOODNESS OF FIT

Figure 2 shows, for the low mass, non-vented case, the monthly sensible cooling energy consumption calculated using the correlation vs. EASI monthly cooling energy consumption, for Ottawa. In a large majority of cases, the differences are less than 10 percent. Newsham and Sander (1994) contains similar plots for all eight cities studied, for both the vented and non-vented cases. **Table 5** summarizes the mean percentage differences for all eight cities for both the vented and non-vented cases. Mean percentage differences are less than 10 percent in three-quarters of the cases. However, the percentage differences in May, and in some cases September, are higher; one might expect this since the absolute cooling requirements in these two months tend to be small. Hence, in May and September, the mean percentage differences can be misleading and tend to overestimate the importance of small absolute differences in small cooling energy requirements.

Table 6 shows the mean percentage differences between the seasonal cooling energy requirement calculated by the hourly model and that calculated from a sum of the appropriate monthly correlations. By comparing **Table 5** with the results reported in Newsham, Sander and Moreau (1993) one can see that, in most cases, a sum of monthly correlations is slightly worse at predicting the seasonal sensible cooling energy consumption than the seasonal correlation described by Newsham, Sander and Moreau (1993). However, summing the monthly correlations to obtain a seasonal cooling energy requirement is by no means unacceptable because mean percentage differences are lower than 8 percent in all cases.

Figure 3 shows, in the non-vented case, the ratio of cooling energy requirement in the medium and low mass cases versus the cooling energy requirement in the low mass case, for sensible cooling calculated using the hourly model and the correlation. Only the values covering a range of typical house parameters are shown, and only plots for July and September

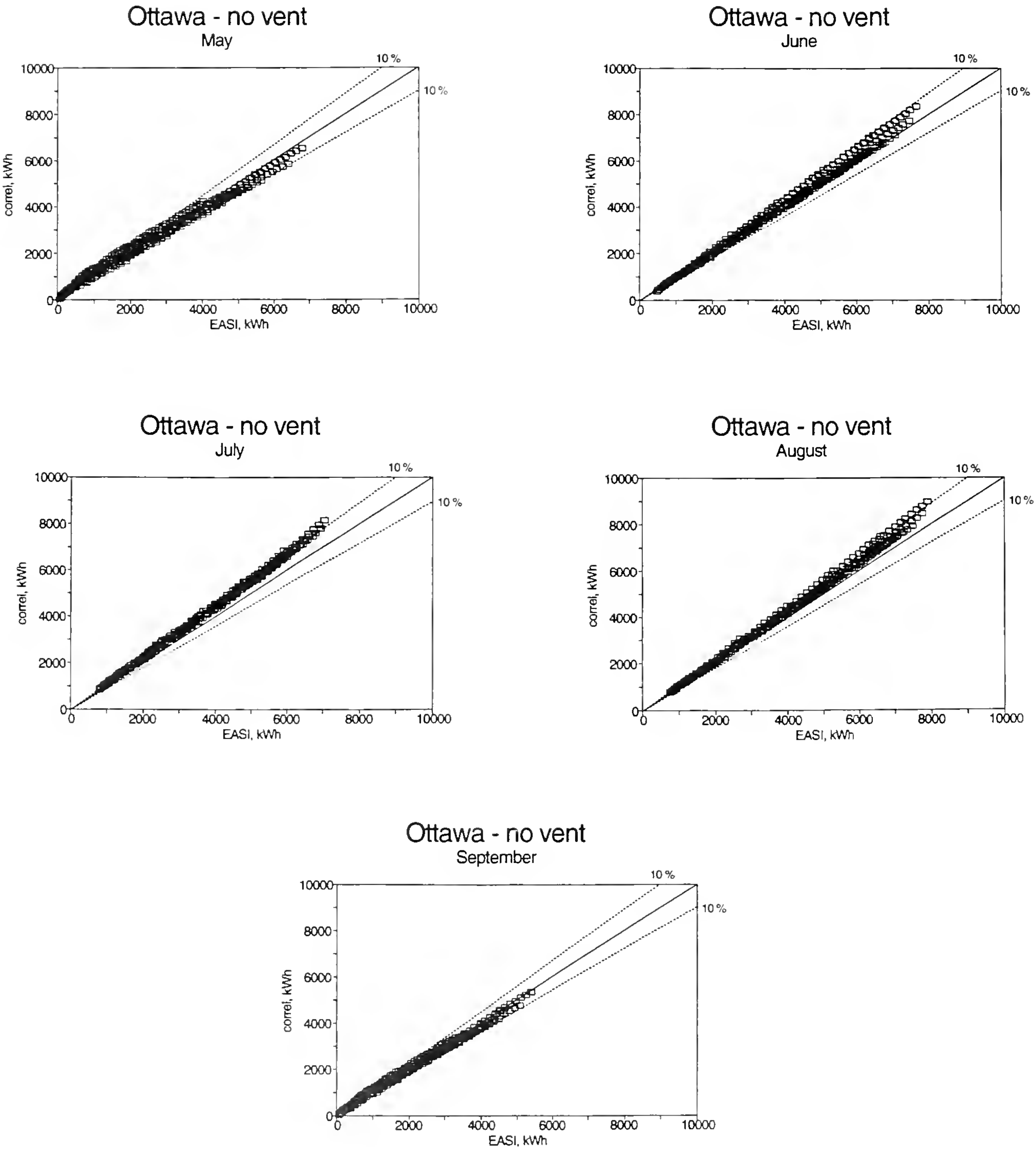

Figure 2. Monthly sensible cooling energy consumption for Ottawa calculated using the correlation versus that calculated using the hourly model, for all building parameter variations, for the non-vented case, for the light mass house. Ten percent difference levels are indicated.

Table 5. Mean percentage differences between the monthly sensible cooling energy consumption calculated by an hourly model and that calculated by the correlation, for all building parameter variations; low mass house.

City	Month	Mean Differences, percent non-vented	vented
Edmonton	MAY	11.4	12.3
Fredericton	MAY	14.1	19.5
Montreal	MAY	5.8	26.5
Ottawa	MAY	11.9	15.8
Toronto	MAY	9.3	12.2
Vancouver	MAY	9.9	11.8
Windsor	MAY	10.4	19.2
Winnipeg	MAY	10.3	10.9
Edmonton	JUN	4.6	8.2
Fredericton	JUN	2.0	4.9
Montreal	JUN	3.5	5.6
Ottawa	JUN	3.2	6.9
Toronto	JUN	2.5	4.6
Vancouver	JUN	7.1	8.3
Windsor	JUN	4.7	4.5
Winnipeg	JUN	4.7	5.9
Edmonton	JUL	3.9	7.0
Fredericton	JUL	7.9	7.2
Montreal	JUL	6.0	7.2
Ottawa	JUL	10.0	5.8
Toronto	JUL	4.3	6.2
Vancouver	JUL	3.0	7.3
Windsor	JUL	7.7	6.3
Winnipeg	JUL	3.5	7.9
Edmonton	AUG	4.9	11.1
Fredericton	AUG	3.0	7.8
Montreal	AUG	7.1	4.6
Ottawa	AUG	6.0	5.5
Toronto	AUG	4.0	5.4
Vancouver	AUG	3.4	10.0
Windsor	AUG	8.3	5.9
Winnipeg	AUG	5.2	5.6
Edmonton	SEP	10.8	13.8
Fredericton	SEP	7.8	11.5
Montreal	SEP	4.3	5.4
Ottawa	SEP	6.4	9.8
Toronto	SEP	3.7	5.3
Vancouver	SEP	14.3	11.2
Windsor	SEP	3.3	3.3
Winnipeg	SEP	7.2	8.3

Table 6. Mean percentage differences between the seasonal sensible cooling energy consumption calculated by an hourly model and that calculated using the sum of the monthly correlations, for all building parameter variations, for a low mass house.

City	Mean Differences, percent	
	non-vented	vented
Fredericton	3.6	4.4
Montreal	3.6	4.3
Ottawa	4.7	4.0
Toronto	2.5	4.0
Windsor	5.4	3.9
Winnipeg	3.1	5.2
Edmonton	4.9	7.4
Vancouver	4.2	6.1

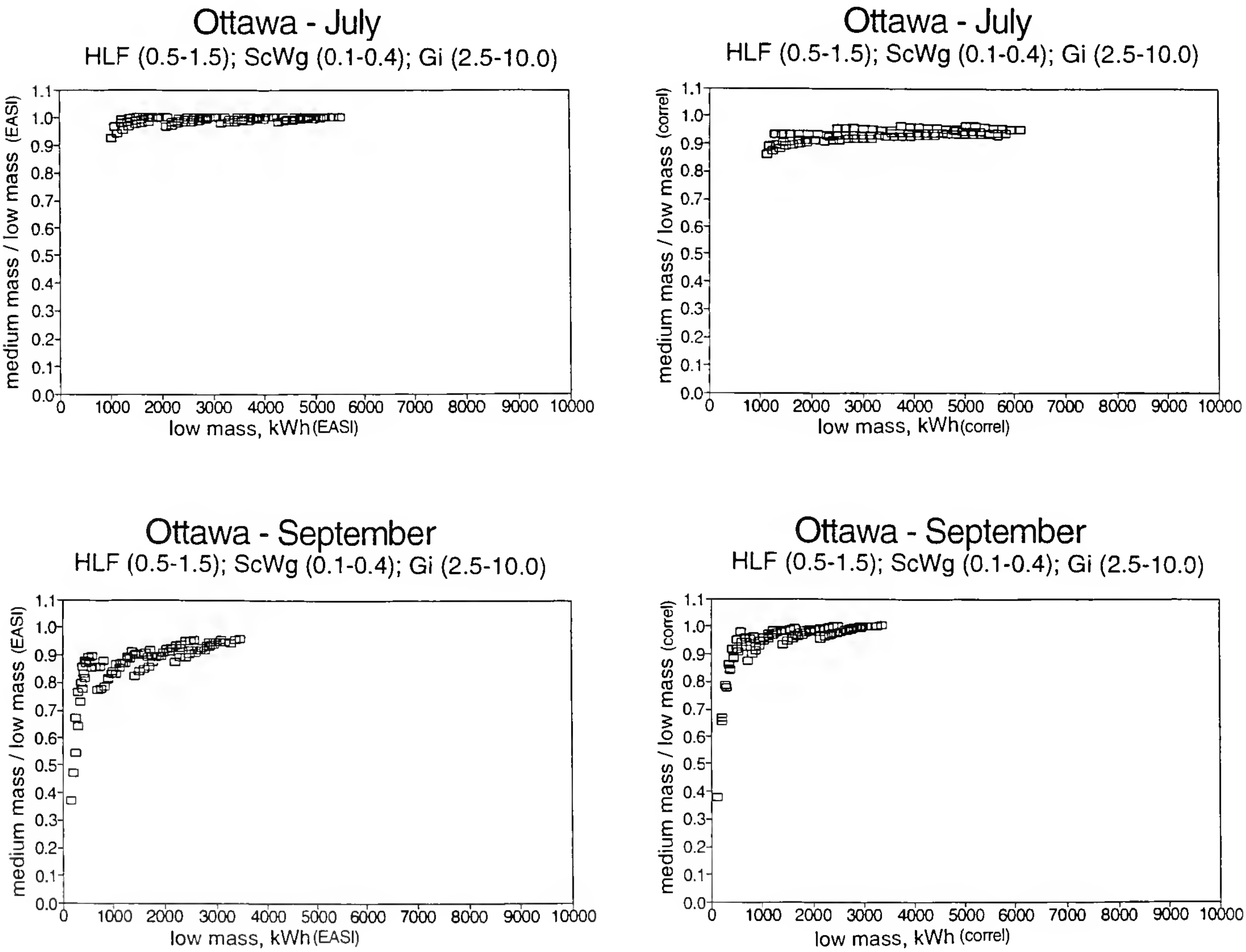

Figure 3. The ratio of the sensible cooling energy requirement in the medium mass house to that in the low mass house vs. the sensible cooling energy requirement in the low mass house, calculated using both the hourly model and the correlation, for various parameter combinations (W_g = fraction of wall area glazed).

in Ottawa are shown as examples. The effect of mass is small for all but the very lowest cooling loads, reducing sensible cooling load by less than 20 percent in most cases. The correlation performs adequately, reproducing the trends exhibited by the hourly model output. Since the mass effect is small, calculating the cooling energy consumption for thermal masses within the range 60 to 150 kJ/ $m^2 \cdot {}^\circ C$ can be done by linear interpolation.

Table 7 shows the mean percentage differences for all eight cities for both the vented and non-vented cases, in the medium mass case. In general, the differences for the medium mass correlation are a little higher than those for the low mass case. Nevertheless, mean percentage differences are less than 10 percent in most cases, though the percentage differences particularly in May and September are higher. However, to reiterate, the mean percentage differences can be misleading and tend to overestimate the importance of small absolute differences in small cooling energy requirements. Newsham and Sander (1994) contains plots similar to **Figure 2** for all eight cities studied, for both the vented and non-vented cases, for a medium mass house.

LIMITATIONS

The applicability of the simple monthly calculation method presented here is limited by some of the assumptions used in deriving the correlations:

- We assumed a constant internal gain schedule for simplicity. During the development of complementary seasonal cooling correlations (Newsham, Sander and Moreau 1993) we compared correlations developed from a more realistic schedule with those developed from a constant schedule and found no significant difference. However, the correlations described in this paper might prove more unreliable for internal gain schedules very different from constant. Remember, we expected the method to be applied to large populations of houses in which the mean internal gain schedule would lack dramatic peaks.

- Heat loss to the basement was not considered. In the majority of Canadian houses the basement is not directly conditioned, and therefore in summer would be at a lower temperature than the rest of the house. Thus, there is the possibility of free cooling to the basement. However, in most cases, due to basement air stratification and poor coupling between the basement and the rest of the house, the effect of summertime heat loss to the basement would be small. If consideration of basement heat loss is required, it could be calculated separately and included in the correlation as a reduction in internal gains. Basement heat loss can be treated in this manner because it will be close to constant over a 24 hour period, which matches our assumption for the internal gains profile.

- A single zone model was assumed for the house. Therefore, it applies only to the case in which the entire house (excepting the basment) is conditioned to the same temperature, and there is good mixing of the indoor air.

- Attic temperature was not simulated by the hourly model from which the correlation was derived; heat transfer through the roof was modeled as though the attic was at outdoor temperature. This results in an underestimate of cooling requirements. In Canada, where it is normal for the ceiling to be highly insulated and the attic to be well ventilated, this is not a serious inaccuracy. However, it may be significant when this is not the case.

- Glazing was assumed to be equally distributed in the four cardinal directions. Again, this assumption was made with the expectation that the method would be applied to large populations of houses, where the mean glazing distribution would be close to equal. However, we anticipate that the method can be

Table 7. Mean percentage differences between the monthly sensible cooling energy consumption calculated by an hourly model and that calculated by the correlation, for all building parameter variations; medium mass house.

City	Month	Mean Differences, percent non-vented	vented
Edmonton	MAY	19.4	22.1
Fredericton	MAY	30.1	37.4
Montreal	MAY	10.2	15.7
Ottawa	MAY	23.4	32.0
Toronto	MAY	17.4	28.5
Vancouver	MAY	23.8	26.4
Windsor	MAY	22.5	38.6
Winnipeg	MAY	17.2	24.7
Edmonton	JUN	6.9	12.9
Fredericton	JUN	2.5	6.6
Montreal	JUN	5.4	7.8
Ottawa	JUN	5.2	9.8
Toronto	JUN	3.6	7.1
Vancouver	JUN	17.0	17.7
Windsor	JUN	6.4	6.4
Winnipeg	JUN	6.2	10.7
Edmonton	JUL	8.0	10.9
Fredericton	JUL	6.6	9.9
Montreal	JUL	5.7	10.3
Ottawa	JUL	4.3	7.3
Toronto	JUL	4.3	10.8
Vancouver	JUL	4.8	10.5
Windsor	JUL	1.4	6.0
Winnipeg	JUL	5.3	12.6
Edmonton	AUG	5.9	14.9
Fredericton	AUG	8.1	8.6
Montreal	AUG	4.8	6.1
Ottawa	AUG	4.7	7.0
Toronto	AUG	4.7	8.0
Vancouver	AUG	5.9	13.1
Windsor	AUG	4.4	8.0
Winnipeg	AUG	4.3	9.4
Edmonton	SEP	20.3	26.4
Fredericton	SEP	20.5	22.0
Montreal	SEP	10.1	8.7
Ottawa	SEP	20.8	27.7
Toronto	SEP	5.9	9.4
Vancouver	SEP	17.8	25.1
Windsor	SEP	4.7	4.8
Winnipeg	SEP	12.4	15.0

used with other glazing distributions provided that the resulting solar gain profile is not very different from that produced by an equal distribution (see example below).

- Only two thermal masses were studied. The effect of mass was found to be small, so a linear interpolation is probably adequate for masses in between these two.
- The correlation calculates sensible cooling load only and not latent loads; thus, the correlation will always underestimate the total load. The ratio of total load to sensible load will vary hourly depending, in part, on the system characteristics. Since EASI does not model system performance we did not address latent loads in this study.
- The correlations were developed for the climates of only eight Canadian cities. At this point the method should only be used for the cities and climate data noted in this paper. Future work could expand the applicability of the method to other climates.
- The equations give the cooling required by the space (delivered energy); they do not include the cooling equipment efficiency characteristics. They are intended to be used with an assumed coefficient of performance for the air conditioning unit.

APPLICATION - AN EXAMPLE

The following is a step-by-step example of applying the method to calculate the sensible cooling energy for a typical single-family detached house in Ottawa in July, for the non-vented case. **Table 8** shows the house input parameters. **Figure 4** is a flow diagram outlining the

Table 8. Building parameters for a typical single-family detached house

Building Parameter	Value
Floor Area, A_f (m2)	192
Volume, V (m3)	604
Wall Area, A_w (m2)	
North	72
South	72
East	48
West	48
Roof Area, A_r (m^2)	96
Internal Gain, I (W)	800
U-value (W/m2·°C)	
Wall	0.32
Roof	0.10
Glazing	2.20
Shading Coefficient, SC0.7	
Glazing Area, A_g (m^2)	
North	10.8
South	10.8
East	4.8
West	4.8
Infiltration, ACH (ac/h)	0.25
Mass (kJ/m^2·°C)	60

procedure to be followed when calculating the cooling energy consumption using the monthly correlation.

From Equation 2:

$$G_i = (744 \cdot 800)/(192 \cdot 1000) = 3.10$$

From Equation 3:

$$G_s = 0.32 \cdot (0.15 \cdot 72 \cdot 0.7 \cdot 4.28 + 0.15 \cdot 72 \cdot 0.7 \cdot 7.15 + 0.1 \cdot 48 \cdot 0.7 \cdot 7.7 + 0.1 \cdot 48 \cdot 0.7 \cdot 7.7) \cdot (744/24)/192 = 7.13$$

and therefore:

$$G_{tot} = 3.10 + 7.13 = 10.23$$

From Equation 5:

$$HLF = (208.8 \cdot 0.32 + 96 \cdot 0.1 + 31.2 \cdot 2.2 + 0.329 \cdot 604 \cdot 0.25)/192 = 1.01$$

From Equation 4, and using the relevant value of k_t from **Table 2**:

$$L_t = 2.73 \cdot 1.01 = 2.77$$

Now, from Equation 1, and using the relevant values of e_i and f_i from **Table 2**:

$$\begin{aligned} C_f/G_{tot} = {} & 0.9065 - 0.3022 \cdot [\,10.23/7.13\,] \\ & - 0.0147 \cdot [ln\,(1/10.23)\,] \\ & - 0.0560 \cdot [10.23/7.13] \cdot [ln/10.23)\,] \\ & - 0.0431 \cdot [ln\,(10.23/2.77)\,] \\ & + 0.1388 \cdot [\,10.23/7.13\,] \cdot [ln\,(10.23/2.77)\,] \\ & - 0.0141 \cdot [ln\,(1/10.23)\,] \cdot [ln\,(10.23/2.77)\,] \\ & + 0.0243 \cdot [\,10.23/7.13\,] \cdot [ln\,(1/10.23)\,] \\ & \cdot [ln\,(10.23/2.77)\,] \\ = {} & 0.834 \end{aligned}$$

In other words, 83.4 percent of the total solar and internal gains in July need to be removed by the cooling system.

Therefore, the delivered sensible cooling energy per unit floor area is:

$$C_f = 0.834 \cdot 10.23 = 8.53\ kWh/m^2$$

and the total delivered sensible cooling energy is:

$$8.53 \cdot 192 = 1638\ kWh$$

(assuming a COP of 3, the billed cooling energy is 1638/3 = 546 kWh).

The EASI hourly model predicts a July delivered sensible cooling energy for the same building of 1462 kWh, for a difference between the correlation and EASI of 12 percent, which is acceptable. Repeating this process for the five months of the cooling season (May to September), and summing the predictions for each of the months yields a predicted seasonal delivered cooling energy consumption from the correlation of 5756 kWh. EASI predicts a seasonal value of 5727 kWh, remarkably close to the value predicted by the correlation. Note that the glazing in the example house was far from equally distributed in each of the four cardinal directions; equal distribution of glazing was the assumption on which the correlation was based. The level of agreement in the predictions between the correlation and EASI suggests that the method can indeed be successfully applied to other glazing distributions.

We compared the predictions of the correlation and EASI for seven variations on the example house shown in **Table 8**. **Table 9** details the variations, and **Figures 5** and **6** show the comparisons for July and for the cooling season, respectively. Although the correlation consistently overestimates the sensible cooling in July (when compared to EASI), the differences are acceptable for a simple method such as this one. The only difference greater than 12 percent is for variation F, where the glazing distribution is very unequal. The seasonal comparison shows all differences less than 9 percent. The greatest difference occurs for variation H. In this case the majority of the glazing faces east and west rather than north and south, as in the initial example house (variation A). Whereas the hourly solar gain distribution for variation A will be similar to that given by an equal glazing distribution (noon peak), variation H will likely yield a distribution with peaks in morning and afternoon, significantly different from the equal glazing

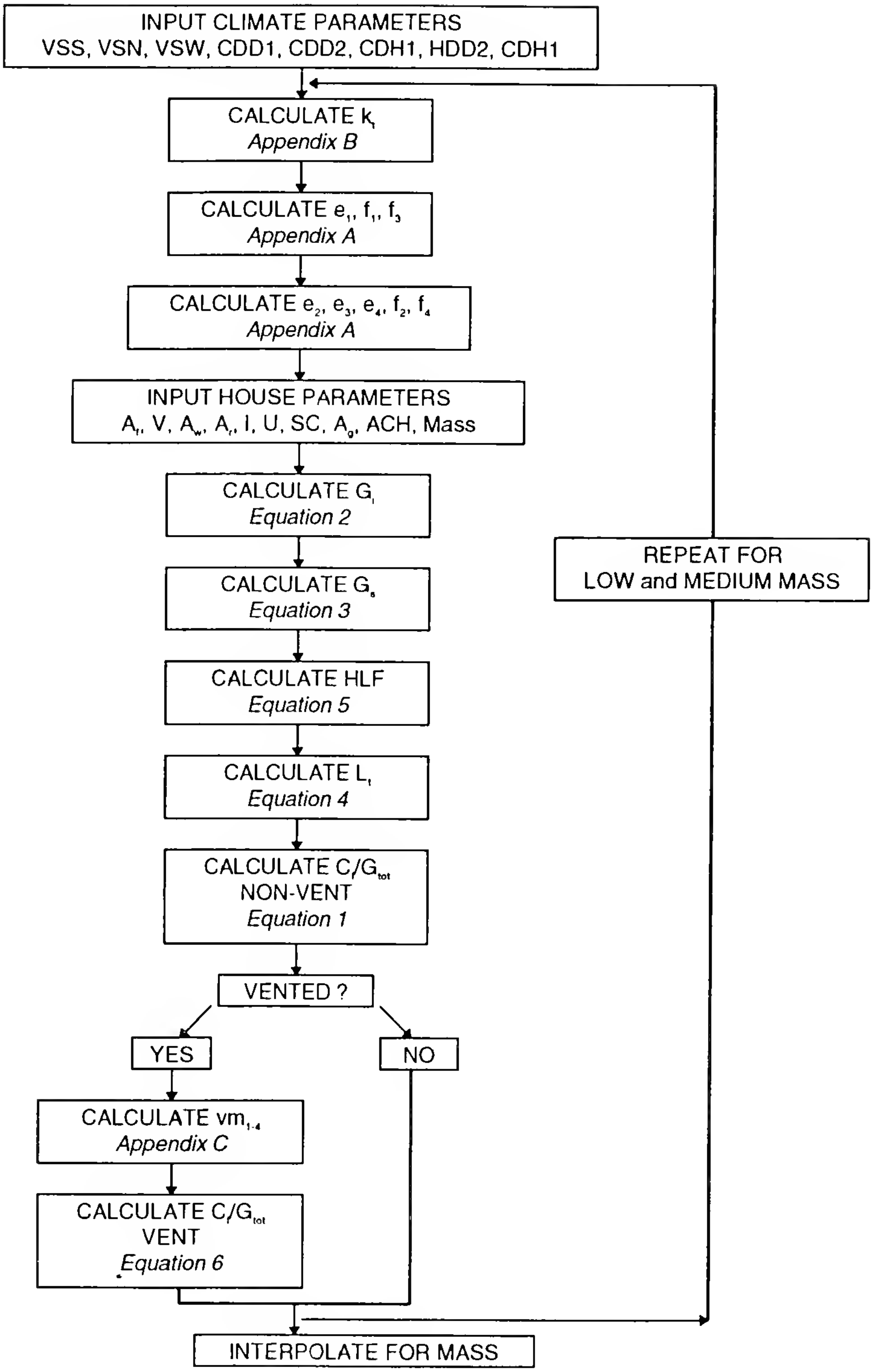

Figure 4. Calculation procedure for the monthly cooling energy consumption correlation method.

Table 9. Variations on the example house described in Table 8

Variation	Description
A	House, as described in Table 8
B	Internal Gains, I = 1200 W
C	Internal Gains, I = 400 W
D	Mass = 150 kJ/m^2.°C
E	Infiltrtion Rate, ACH = 0.75 ac/h
F	A_{gn} = 7.2 m^2, A_{gs}= 25.2 m^2, A_{ge} = 9.6 m^2, A_{gw} = 4.8 m^2
G	A_w (all walls) = 60 m^2; A_g (all walls) = 7.8 m^2
H	Rotate Variation A 90 °

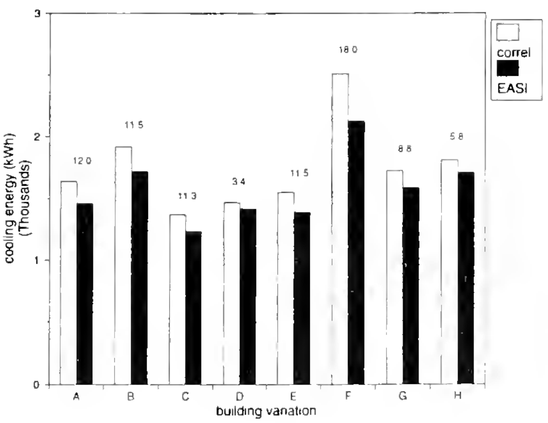

Figure 5. Comparison of the sensible cooling energy for July predicted by the correlation and the hourly model; for 8 building parameter variations in Ottawa.

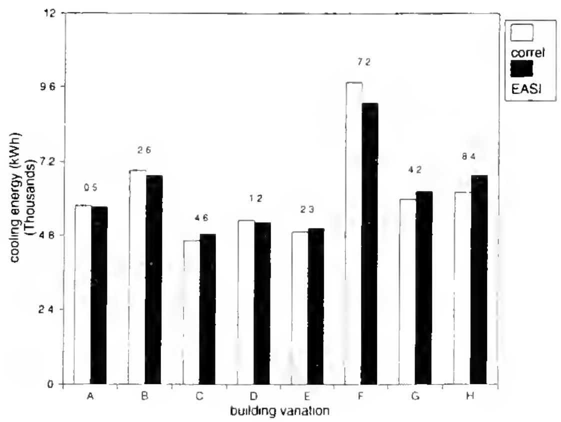

Figure 6. Comparison of the sensible cooling energy for the 5 month cooling season predicted by the correlation and the hourly model; for 8 building parameter variations in Ottawa.

distribution assumption on which the correlation was based.

CONCLUSIONS

A simple correlation equation to determine monthly residential sensible cooling energy consumption in Canada has been developed. It allows the quick determination of the change in residential cooling energy consumption with changes in internal gain, envelope U-value, glazing area, shading coefficient, and thermal mass.

As the correlation was developed for a Canadian house with equal glazing on all facades and thermal masses of 60 and 150 kJ/°C·m^2, the correlation will be most accurate when applied to houses of this construction and form. However, other constructions and forms can be accommodated with appropriate care.

Considering its simplicity, the correlation is relatively accurate. The mean percentage difference compared to the output of an hourly model, over a wide range of building parameters and climates, ranged from 6.5 percent in a low mass house with no manual venting, to 14.9 percent in a medium mass house where manual venting was considered.

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APPENDIX A

Determination of Coefficients e_i and f_i from Climate Statistics; Non-Vented Case.

As with the seasonal correlation equations described in Newsham, Sander and Moreau (1993), the climate coefficients of Equation 1 appropriate for a monthly calculation were found to be linearly related. For the low mass, non-vented case:

$$e_2 = -0.199457 + 0.203834 \cdot e_1 \quad \text{(A-1)}$$

$$e_3 = 0.28305 - 0.359833 \cdot e_1 \quad \text{(A-2)}$$

$$e_4 = 0.051848 - 0.072774 \cdot e_1 \quad \text{(A-3)}$$

$$f_2 = 0.052369 + 0.358601 \cdot f_1 \quad \text{(A-4)}$$

$$f_4 = -0.017041 + 0.298164 \cdot f_3 \quad \text{(A-5)}$$

These relationships are illustrated in Newsham and Sander (1994).

Therefore, climate dependence for only three of the coefficients (e_1, f_1, f_3), need be derived. e_1, f_1, f_3 can be correlated to monthly climate parameters:

$$e_1, f_1, f_3, = a_0 + a_1 \cdot VS + a_2 \cdot VSS + a_3 \cdot CDD1 + a_4 \cdot CDD2 + a_5 \cdot CDH1 + a_6 \cdot DRNG \quad \text{(A-6)}$$

where

VS = VSS + VSN + 0.5 (VSE + VSW);

CDD1 = monthly Cooling Degree Days (base 10 °C);

CDD2 = monthly Cooling Degree Days (base 18.3 °C);

CDH1 = monthly Cooling Degree Hours (base 26.7 °C);

DRNG = mean Daily temperature RaNGe for the month (°C); and

a_0 to a_6 are coefficients given in **Table A-1**.

Figures in Newsham and Sander (1994) illustrate the relationship between e_1, f_1, f_3 derived from the individual regressions for each location, and the e_1, f_1, f_3 derived from the climate correlations of Equation A-6, for all eight cities and five months.

It is important to note that the above correlation to climate was derived only for the eight cities and specific climate data noted in this paper. While future work considering more cities promises a universal climate correlation, we would not at present recommend its use beyond the climate data noted in this paper.

In the medium mass case:

$$e_2 = -0.15728 + 0.17475 \cdot e_1 \quad \text{(A-7)}$$

$$e_3 = 0.313123 - 0.35211 \cdot e_1 \quad \text{(A-8)}$$

$$e_4 = 0.045556 - 0.05797 \cdot e_1 \quad \text{(A-9)}$$

$$f_2 = 0.042722 + 0.387759 \cdot f_1 \quad \text{(A-10)}$$

$$f_4 = -0.00275 + 0.247787 \cdot f_3 \quad \text{(A-11)}$$

These relationships are illustrated in Newsham and Sander (1994).

Again:

$$e_1, f_1, f_3 = a_0 + a_1 \cdot VS + a_2 \cdot VSS + a_3 \cdot CDD1 + a_4 \cdot CDD2 + a_5 \cdot CDH1 + a_6 \cdot DRNG \quad \text{(A-12)}$$

The coefficients a_0 to a_6 for the medium mass case are given in **Table A-2.**

Figures in Newsham and Sander (1994) illustrate the relationship between e_1, f_1, f_3 derived from the individual regressions for each location, and the e_1, f_1, f_3 derived from the climate correlations of Equation A-12, for all eight cities and five months.

Table A-1. Coefficients necessary to determine e_1, f_1, f_3 from the climate correlations; low mass case

	MAY	JUN	JUL	AUG	SEP
			e_1		
a_0	-1.39541	13.15385	1.78257	6.402761	-0.70549
a_1	0.296447	-0.97771	1.492269	-0.13341	0.150486
a_2	-0.66077	2.062468	-3.7051	-0.06433	-0.17138
a_3	0.012591	-0.04664	0.004475	-0.01051	-1.4e-05
a_4	-0.0839	0.060232	-0.00354	0.014375	0.01261
a_5	0.010402	0.021536	-0.01011	0.002957	-0.00561
a_6	0.004698	-0.14801	-0.17113	-0.09032	-0.00146
			f_1		
a_0	0.293972	-0.9157	-0.7205	-1.65304	0.958032
a_1	-0.06345	0.157542	-0.23948	0.032763	-0.20992
a_2	0.127003	-0.41656	0.634356	0.014746	0.26714
a_3	-0.00317	0.003431	-0.00058	0.001893	-0.00222
a_4	0.015237	-0.00415	-0.00155	-0.00198	0.008331
a_5	-0.00134	-0.00369	0.002573	-0.00096	-0.00072
a_6	0.01996	0.028396	0.023578	0.035538	0.012869
			f_3		
a_0	0.306439	-0.2966	0.19518	-0.44132	-0.21076
a_1	0.000715	0.028915	-0.02661	0.033069	0.070312
a_2	0.003143	-0.03287	0.062417	-0.03012	-0.09102
a_3	-0.00053	0.001417	-0.00032	0.001043	0.001604
a_4	0.003678	-0.00228	0.000651	-0.00197	-0.00971
a_5	-0.0003	-0.00027	-9.9e-05	-5.4e-05	0.002505
a_6	-0.01482	-0.00882	0.006494	0.005578	-0.00551

Table A-2. Coefficients necessary to determine e_1, f_1, f_3 from the climate correlations; medium mass case

	MAY	JUN	JUL	AUG	SEP
			e_1		
a_0	1.525311	3.90778	0.774683	5.846196	0.676635
a_1	0.364147	-0.90353	1.394302	-0.03328	0.047836
a_2	-0.80666	1.862019	-3.38367	-0.22363	-0.07224
a_3	0.014173	-0.04935	0.005036	-0.0102	-0.0025
a_4	-0.09772	0.064825	-0.00663	0.010229	0.018419
a_5	0.012713	0.020568	-0.00863	0.002956	-0.00528
a_6	-0.00405	-0.17965	-0.16185	-0.07906	-0.03141
			f_1		
a_0	0.196194	-0.62047	-0.25574	-0.84882	0.160245
a_1	0.04247	0.108252	-0.09499	-0.01719	-0.17782
a_2	0.078267	-0.29899	0.250371	0.079434	0.255015
a_3	-0.00428	0.00157	-0.00084	1.24e-05	-0.00086
a_4	0.015275	-0.00126	0.001049	0.002758	0.003546
a_5	-0.00049	-0.00267	0.000878	-0.00083	-0.00067
a_6	0.026722	0.02704	0.002168	0.012216	0.028077
			f_3		
a_0	0.568372	-0.91094	-0.07323	-0.73152	0.808987
a_1	-0.05366	0.103803	-0.05073	0.052554	0.025018
a_2	0.114884	-0.20423	0.150215	-0.05242	-0.06664
a_3	-0.00151	0.003896	-0.00037	0.001477	-0.00022
a_4	0.012402	-0.00509	-0.00015	-0.00323	-0.00467
a_5	-0.00158	-0.00196	0.000402	-0.00018	0.002953
a_6	-0.01512	-0.00342	0.011707	0.013734	-0.03142

APPENDIX B

Determination of Coefficient k_t from Climate Statistics; Non-Vented Case.

k_t is the value that the term {[C_f(U-value, G_s, G_i) - C_f(0, G_s, G_i)] / HLF} tends to over the given period, calculated by the hourly model, as G_s and G_i tend to their upper limits. The term {[C_f(U-value, G_s, G_i) - C_f(0, G_s, G_i)] / HLF} is the contribution of the transmission loss in reducing the cooling load, its value as G_s and G_i tend to their upper limits indicates the transmission loss's maximum contribution. After trying many parameter combinations, k_t was found to be accurately correlated to monthly climate parameters:

$$k_t = a_0 + a_1 \cdot HDD2 + a_2 \cdot VS + a_3 \cdot VSS + a_4 \cdot CDD1 + a_5 \cdot CDD2 + a_6 \cdot DRNG \quad \text{(B-1)}$$

where

HDD2 = monthly Heating Degree Days (base 18.3 °C); and

coefficients a_0 to a_6 are given in **Table B-1**.

Figures in Newsham and Sander (1994) compare k_t derived from the hourly model and k_t derived from the climate correlation of Equation B-1, for all eight locations, and all five months.

In the medium mass case:

$$k_t = a_0 + a_1 \cdot HDD2 + a_2 \cdot VS + a_3 \cdot VSS + a_4 \cdot CDD1 + a_5 \cdot CDD2 + a_6 \cdot DRNG \quad \text{(B-2)}$$

The coefficients a_0 to a_6 in the medium mass case are given in **Table B-2**.

Table B-1. Coefficients necessary to determine k_t from the climate correlations; low mass case

	MAY	JUN	JUL	AUG	SEP
a_0	3.036601	332.5413	-25924.2	-402.18	17.22645
a_1	0.023506	-1.31738	100.5315	1.456179	0.024881
a_2	-0.08896	0.209174	1.333325	1.708286	-2.8231
a_3	0.265454	0.654212	-1.81128	-2.03485	3.532247
a_4	-0.00905	-1.37387	100.7769	1.533788	-0.00769
a_5	0.084042	1.394898	-100.879	-1.60275	0.053997
a_6	0.028848	0.157998	-0.2942	0.288399	-0.09609

Table B-2. Coefficients necessary to determine k_t from the climate correlations; medium mass case

	MAY	JUN	JUL	AUG	SEP
a_0	2.07735	335.0168	-25976.2	-404.218	17.28512
a_1	0.022945	-1.32752	100.7332	1.463149	0.02451
a_2	-0.10594	0.203216	1.344585	1.720076	-2.81628
a_3	0.297673	0.674291	-1.83491	-2.04599	3.525458
a_4	-0.01021	-1.38409	100.979	1.541272	-0.00818
a_5	0.086852	1.405381	-101.081	-1.61041	0.054387
a_6	0.032787	0.161463	-0.29585	0.289251	-0.09582

Figures in Newsham and Sander (1994) compare k_t derived from the hourly model and k_t derived from the climate correlation of Equation B-2, for all eight locations, and all five months.

Only for the month of May is there a significant change in the value of k_t with mass. This may be due to the influence of heating in early May.

APPENDIX C

Determination of Coefficients vm_i from Climate Statistics.

We found that a good result could be achieved with the simplification that vm_1, vm_2, vm_3, and vm_4 are correlated to appropriate anua,l rather than monthly, climate parameters. Such that:

$$vm_{1\text{-}4} = b_0 + b_1 \cdot VS_a + b_2 \cdot VSS_a + b_3 \cdot CDD1_a + b_4 \cdot CDD2_a + b_5 \cdot CDH1_a + b_6 \cdot DRNG_a \quad \text{(C-1)}$$

where

$VS_a = VSS_a + VSN_a + 0.5\,(VSE_a + VSW_a)$;

VSS_a= mean daily solar radiation on south vertical, MJ/m^2;

VSN_a= mean daily solar radiation on north vertical, MJ/m^2;

VSW_a= mean daily solar radiation on west vertical, MJ/m^2;

VSE_a= mean daily solar radiation on east vertical, MJ/m^2;

$CDD1_a$= annual Cooling Degree Days (base 10 °C);

$CDD2_a$= annual Cooling Degree Days (base 18.3 °C);

$CDH1_a$= annual Cooling Degree Hours (base 26.7 °C);

$DRNG_a$= mean Daily temperature RaNGe for July (°C); and

b_0 to b_6 are coefficients given in **Table C-1.**

Appropriate annual climate parameters may be found in **Table C-2** (from Tsi-Chih 1991). Note, for this climate data, $VSE_a = VSW_a$.

Table C-1. Coefficients necessary to determine $vm_{1\text{-}4}$ from the climate correlations; low mass case

	b_0	b_1	b_2	b_3	b_4	b_5	b_6
vm_1	-3.88719	0.123579	0.018138	0.001987	-0.000581	-0.002386	0.098205
vm_2	-3.19051	0.120353	-0.116823	0.001521	-0.003760	-0.000323	0.065662
vm_3	0.026307	-0.000425	-0.000092	-0.000030	0.000079	-8e-07	-0.000795
vm_4	0.187758	-0.006591	0.005453	-0.000096	0.000183	0.000035	-0.004898

Table C-2. Climate parameters appropriate for the seasonal correlation of $vm_{1\text{-}4}$ for 8 Canadian cities.

City	$HDD2_a$	VS_a	VSS_a	$CDD1_a$	$CDD2_a$	$CDH1_a$	$DRNG_a$
Fredericton	4840	18.21	9.20	928	124	319	12.7
Montreal	4615	17.65	8.67	1201	226	315	10.6
Ottawa	4758	18.27	9.13	1164	212	407	11.4
Toronto	4218	17.37	8.34	1201	224	510	12.5
Windsor	3687	18.82	8.86	1535	371	781	10.9
Winnipeg	5965	21.11	10.99	1000	169	479	12.5
Edmonton	5938	21.06	10.97	592	27	88	13.1
Vancouver	3112	17.12	8.25	859	30	8	9.1

Figures in Newsham and Sander (1994) illustrate the relationship between vm_{1-4} derived from the individual regressions for each location, and vm_{1-4} derived from the climate correlations of Equation C-1, for all eight cities.

For the medium mass case:

$$vm_{1-4} = b_0 + b_1 \cdot VS_a + b_2 \cdot VSS_a + b_3 \cdot CDD1_a + b_4 \cdot CDD2_a + b_5 \cdot CDH1_a + b_6 \cdot DRNG_a \quad \text{(C-2)}$$

The coefficients b_0 to b_6 for the medium mass case are given in **Table C-3**.

Figures in Newsham and Sander (1994) illustrate the relationship between vm_{1-4} derived from the individual regressions for each location, and vm_{1-4} derived from the climate correlations of Equation C-2, for all eight cities.

Table C-3. Coefficients necessary to determine vm_{1-4} from the climate correlations; medium mass case

	b_0	b_1	b_2	b_3	b_4	b_5	b_6
vm_1	-17.42494	0.671511	-0.468594	0.009234	-0.015321	-0.003958	0.417536
vm_2	-3.93434	0.140368	-0.132056	0.001870	-0.003925	-0.000653	0.090006
vm_3	0.0224138	0.000737	-0.001803	-0.000032	0.000061	0.0000070	-0.000713
vm_4	0.243836	-0.009126	0.008270	-0.000124	0.000218	0.000047	-0.006855

Analysis of Interzonal Natural Convective Heat and Mass Flow—Benchmark Evaluation

M.N.A. Saïd and S.A. Barakat

ABSTRACT

This paper presents an analysis of interzonal natural convective heat and mass transfer through doorway apertures using a three-dimensional computation. The main objectives of the study were to benchmark evaluate a public domain Computational Fluid Dynamics (CFD) computer program in predicting interzonal convective heat and mass transfer, and also to analyze the interzonal convective air flow patterns in a two-zone enclosure in order to better understand the effect of the aperture size on the natural convective interzonal heat and air mass flow.

Computational results are compared to measurements from full scale experiments in a two zone realistic building. The experiments involved natural convective interzonal heat and mass transfer through various doorway-like aperture configurations between two zones in a building. The air flow through the aperture was driven primarily by a small zone-to-zone temperature differential in the range 1°C to 2.5°C. Computations are reported for air (Pr = 0.71), aperture height relative to the enclosure height in the range 0.75 to 1, and aperture width relative to the enclosure width in the range 0.29 to 0.79. Computed temperature and velocity of the indoor air agree reasonably well with the measured data. Computed coefficient of discharge and Nusselt number for natural convective interzonal air mass and heat flow also agree quite well with those measured and with theoretically derived coefficients in the literature.

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NOMENCLATURE

C	constant in correlations
C_d	volumetric coefficient of discharge
C_p	specific heat of air (J/kg·K)
F	volumetric air flow rate (m^3/s)
F_c	computed volumetric air flow rate (m^3/s)
F_t	theoretical volumetric air flow rate (m^3/s)
g	gravitational acceleration, 9.81 (m/s^2)
g_i	gravitational acceleration in xi direction (m/s^2)
Gr_H	Grashof number, $g\beta H^3 \Delta T/v2$ (dimensionless)
h	convective heat transfer coefficient, $\rho F_c C_p/HW$ (W/m^2·K)
H	aperture height (m)
H_r	room (enclosure) height (m)
k	turbulent kinetic energy (J/kg or m^2/s^2)
K	thermal conductivity of air (W/m·K)
Nu_H	Nusselt number, hH/K (dimensionless)
P	pressure (Pa)
P_r	Prandtl number (dimensionless)
q	volumetric heat generation rate (W/m^3)
R_h	aperture height ratio, H/H_r
R_w	aperture width ratio, W/W_r
t	time (sec.)
U_i	mean velocity component in x_i direction (m/s)
U_n	velocity component normal to wall surface (m/s)
U_t	velocity component parallel to wall surface (m/s)
W	aperture width (m)
W_r	partition width (m)
x	vertical distance (m) from the floor level

x_i Cartesian coordinate
α thermal diffusivity of air (m^2/s)
β coefficient of thermal expansion (1/K)
ΔT_a difference between average air temperatures in each zone at a level of half the enclosure height (K)
ΔT_m difference between air temperatures at the center of each zone at a level of half the enclosure height (K)
ΔT_v difference between average air temperatures of a vertical grid of nodes at the centre of each zone (K)
ε dissipation rate of turbulent kinetic energy (J/kg·s)
v kinematic viscosity (m^2/s)
θ temperature difference between local temperature and a reference one (K)
ρ air density (kg/m^3)

INTRODUCTION

Natural convective interzonal heat and air mass transfer through doorway-like apertures in vertical partitions is an important process by which thermal energy and indoor contaminants are transported from one zone (room) to another in buildings. Computational Fluid Dynamics (CFD) numerical techniques are now viable tools for the analysis of interzonal heat and air flow in buildings. The main objectives of this study were to benchmark evaluate a public domain CFD computer program in predicting interzonal convective heat and mass transfer, and also to analyze the air flow pattern in a two-zone enclosure. The results assisted in better understanding the effect of the aperture size on the natural convective interzonal heat and air mass flow and air distribution in a two zone enclosure.

Three-dimensional computational results are compared to measurements from full scale experiments in a two-zone realistic building. The experiments (Saïd, Barakat, and Whidden 1993) involved natural convective interzonal heat and mass transfer through various doorway-like aperture configurations under small zone-to-zone temperature differentials. The enclosure aspect ratio (the ratio of enclosure height to enclosure length) of the test building is 0.26. The aperture configurations included aperture height ratio (R_h) in the range 0.75 to 1, and aperture width ratio (R_w) in the range 0.29 to 0.79. The partition thickness was in the range 0.021 to 0.028 of the aperture height. The natural convective air flow through the aperture was driven primarily by a small zone-to-zone temperature differential in the range 1°C to 2.5°C.

Computation studies that have examined interzonal natural convection are limited. Slavko and Hanjalic (1989) computed laminar and turbulent natural convective air flow patterns and temperature distribution in a two-dimensional rectangular enclosure with and without partition simulating solar or heated buildings. Slavko and Hanjalic compared computed results to measurements by Nansteel and Greif (1981) involving a two-dimensional laminar free convective in a water filled scale model rectangular enclosure with an aspect ratio of 0.5, aperture height ratio in the range 0.25 to 0.75, and partition thickness in the range 0.083 to 0.25 of the aperture height (note that for the 2-D enclosure, the aperture width ratio is 1.0). For the turbulent flow cases, they used a low-Re-number k-ε turbulence model to simulate a two-zone enclosure with an aspect ratio of 0.37 that mimics a solar heated building. Haghighat et al. (1989) used a high-Re-number k-ε turbulence model to study the effect of door height and its location in the partition on natural convection and air flow pattern in a three-dimensional partitioned rectangular enclosure dimensioned 10 × 4 × 3m. The interzonal convective air flow through the aperture was under the influence of the hot and cold temperatures of the two opposite end walls that are parallel to the partition. These walls were assumed to be isothermal. The other walls were assumed to be adiabatic. Haghighat et al. evaluated their numerical scheme by comparing computed Nusselt numbers to those measured by Nansteel and Greif (1984) in a water filled scale model rectangular enclosure (aspect ratio of 0.5) and aperture configurations of $R_h = 0.75$ and $R_w = 0.093$ which is rather a narrow opening. In the present study, computed air temperature, velocity, vertical temperature stratification, coefficient of discharge, and Nusselt number are compared to measured data from experiments conducted in a realistic building.

EXPERIMENTS

This section, briefly, describes the interzonal experiments. The experiments (Saïd, Barakat, and Whidden 1993) were performed in a full scale test house facility. **Figure 1** shows the floor plan and the aperture configuration of the test facility used in the experiments and the numerical simulations. The partition wall separating the two zones was constructed of 0.0508 m (2 in) polystyrene. The aperture was situated in the middle of the partition and did not have a sill. **Table 1** lists the aperture configurations.

All interior surfaces of the test house were practically isothermal. Direct solar radiation was blocked from entering the two test zones. Three baseboard heaters were located at the back wall of each test cell (one in the hot zone and two in the cold zone, **Figure 1**). The heaters were used to maintain nominal zone-to-zone temperature differences between 1°C and 2.5°C. Power consumption of each heater (**Table 1**) was measured with a kWh pulse meter.

The velocity and temperature distributions of the air at the aperture were measured with a vertical grid of 7 to 10[1] omnidirectional anemometers (with velocity and temperature measuring sensors). The accuracy of the omnidirectional anemometers was estimated to be ±2.5 percent for the velocity range 0.05-1.0 m/s and the absolute accuracy of temperature measurements was ±0.5°C. Trees consisting of nine copper-constantan thermocouples were located at the centre of each zone along the centre line of the aperture (**Figure 1**). The air temperature in surrounding rooms and outdoors were also monitored in the experiments. The maximum uncertainty in measured temperatures by the copper-constantan type thermocouples was estimated to be ±0.1°C. Measurements were collected continuously over at least a 24 hour period. Steady-state conditions were designated when there was negligible change in room air temperatures for at least 4 hours. The results were then averaged over a 12 hour steady-state period.

SIMULATION METHOD

The public domain CFD computer program EXACT3 was used in this study. Kurabuchi, Fang, and Grot (1990) describes EXACT3 in detail. EXACT3 is a three-dimensional finite difference computer program for simulating buoyant turbulent air flow within buildings. The buoyancy effect is accounted for by Boussinesq approximation. The program solves the conservation equations for continuity, momentum, and energy as well as the equations for the turbulent kinetic energy and its dissipation rate. The high-Reynolds-number k-e turbulence closure is used in EXACT3. The governing equations can be written in the general elliptic form for an incompressible fluid as:

$$\partial\Phi/\partial t + \partial (U_j \Phi)/\partial x_j - \partial (\Gamma_\Phi \; \partial \Phi/\partial x_j)/\partial x_j = S_\Phi \quad (1)$$

Table 1. Tests (Saïd, Barakat, and Whidden 1993) Configuration

Test	Aperture				DT_a	Heater Power (Watt)		
	W (m)	H (m)	R_w	R_h	(°C)	H1	H2	H3
A	1.49	2.41	0.49	1.00	1.8	1300.5		
B	1.49	2.11	0.49	0.88	2.2	1294.2		
C	1.49	1.81	0.49	0.75	2.0	570.6		
D	0.88	2.41	0.29	1.00	2.2	886.0		
E	0.88	2.11	0.29	0.88	2.3	711.0		
F	0.88	1.81	0.29	0.75	2.5	665.1		
G	0.88	2.41	0.29	1.00	1.1	368.2	196.3	207.0
H	0.88	2.11	0.29	0.88	1.1	388.6	190.5	199.2
I	1.49	1.81	0.49	0.75	1.2	315.9	160.1	168.8
J	2.41	2.11	0.79	0.88	1.2	739.3	154.6	164.6

[1]depending on the aperture height

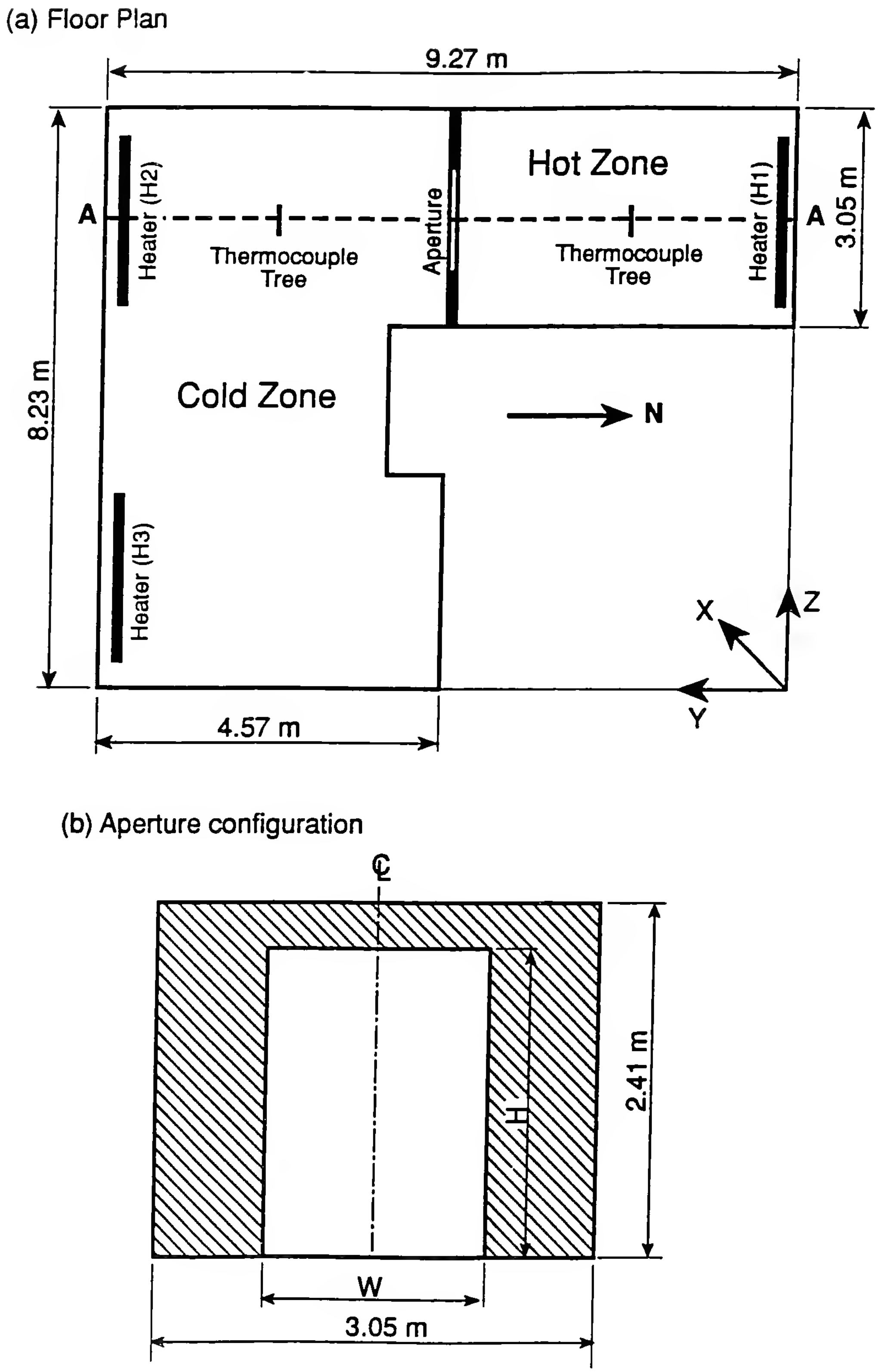


Figure 1. Geometry and coordinate system

where the parameters ϕ, Γ_ϕ and S_ϕ are identified for each equation in **Table 2**. Wall boundary conditions used by EXACT3 are also listed in **Table 2**.

A pressure relaxation method is used to satisfy the Poisson equation for mass conservation. The governing equations are solved by an explicit time marching technique using the marker and cell method by Harlow and Welch (1965). A staggered grid and a hybrid upwind/central differencing combination scheme are used in EXACT3.

In the simulation, measured power consumption of the baseboard heaters (see **Table 1**) was simulated as nodal heat sources. Thus, the heat input into the flow domain was assumed

Table 2. Values of ϕ, G_ϕ and S_ϕ associated with equation (1)

ϕ	Γ_ϕ	S_ϕ
1	0	0 (Continuity)
U_i	$\nu + \nu_t$	$(-1/\rho)\ \partial P/\partial x_i - \beta\ g_i\ \theta$
θ	$\alpha + \nu_t/\sigma_\theta$	$q\ /\rho\ C_p$
k	$\nu + \nu_t/\sigma_k$	$\nu_t + G - \varepsilon$
ε	$\nu + \nu_t/\sigma_\varepsilon$	$(C_1 \nu_t\ S - C_2\ \varepsilon + C_3\ G)\ \varepsilon\ /\ k$

$\nu_t = C_\mu\ k^2\ /\ \varepsilon$, eddy viscosity

$S = (\partial U_i/\partial x_j - \partial U_j/\partial x_i)\ \partial U_i/\partial x_j$

$G = \beta\ g_i\ (\nu_t/\sigma_\theta)\partial\theta/\partial x_i$

Empirical coefficients:

$C_\mu = 0.09$, $C_1 = 1.44$, $C_2 = 1.92$, $C_3 = 1.0$,

$\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3$, $\sigma_\theta = 0.9$

Wall Boundary Conditions:

$U_n = 0.0$
$\partial U_t/\partial y = U_{t1}\ 2m/y$
$\partial k/\partial n = 0.0$
$\varepsilon = C_\mu^{3/4}\ k^{3/2}\ /\ y$,

where:
m = 1/7, is the exponent of the velocity 1/7th power-law relation,
y is the length from wall surface to centre of the fluid cell immediately adjacent to wall, and
U_{t1} is the velocity component parallel to wall surface at the centre of the fluid cell immediately adjacent to wall

to be transmitted immediately to the fluid cells adjacent to the heaters. All walls, except the floor, were assumed to be isothermal. The floor was assumed to be adiabatic because it was very well insulated, and the space below was heated to 20°C. The temperature of the wall surfaces was estimated from known thermal resistance of the walls and measured ambient air temperatures. Wall surface temperatures (average for all tests) for the floor, ceiling, north wall, east wall, south wall, and west wall were respectively 25.6, 25.2, 24.6, 25.2, 25.6 and 24.6°C for the hot zone, and 24, 23.5, 24, 23, 23.3 and 23°C for the cold zone. The wall surface conductance was taken from ASHRAE(1989) as 9.26 and 8.29 W/m^2 K for the ceiling and vertical walls respectively. These values account for the convective as well as radiative heat transfer from the surfaces, and were chosen because EXACT3 does not calculate radiative heat transfer. The chosen values assume non-reflective surfaces with a surface emittance of 0.9 (ASHRAE 1989). It is noted that recent correlations by Khalifa and Marshall (1990) suggest that the surface convective heat transfer coefficient, for a temperature difference between the surface and ambient air of 2 to 3°C, would be about 3.1 and 2.8 W/m^2 K for the ceiling and vertical walls respectively. These correlations are based on measurements in a 2.95 × 2.35 × 2.08m (length × width × height) indoor test cell facility.

Computations were performed using a non-uniform grid, **Figure 2**, of 19 × 40 × 36 (a total of 27,360 nodes) for the two-zone enclosure (**Figure 1**) and the aperture configurations listed in **Table 1**. To check grid independence of computed results, computations were conducted using a non-uniform grid of 19 × 51× 56 (a total of 54,264 nodes) and found no significant differences in computed air temperatures and velocities (see **Figure 3**). Computation time, on an IBM-3090 main frame computer, was about 6

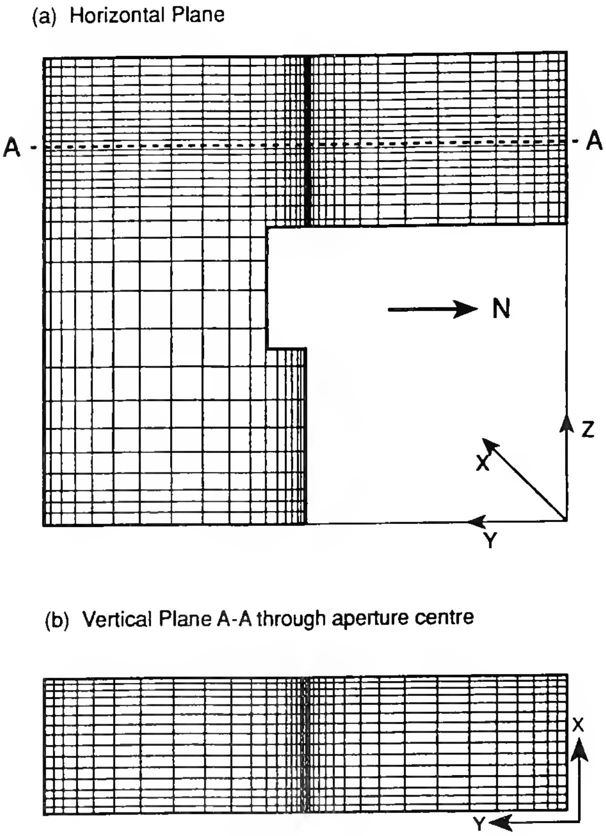


Figure 2. Grid (19 × 40 × 36) distribution

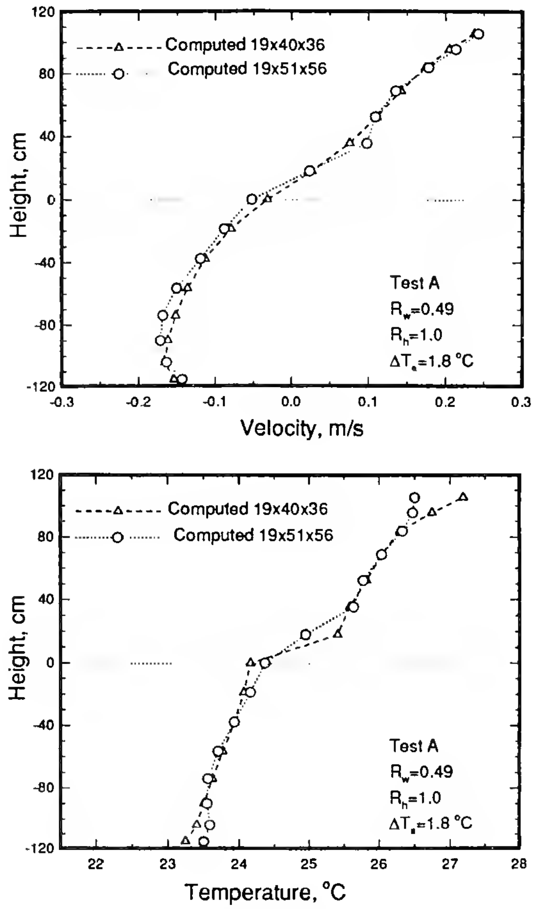


Figure 3. Grid effect on computed velocity and temperature at aperature

hours for the fine grid (19 × 51 × 56) as compared to 2.5 hours for the 19× 40 × 36 grid. It is noted that a much coarser grid has been used in the literature, e.g., Haghighat et al. (1989) used a uniform grid of 16 × 10 × 10.

RESULTS AND DISCUSSION

Temperature and Velocity Distributions

Figure 4 compares computed and measured (Saïd, Barakat, and Whidden 1993) vertical distributions of the air temperature at the thermocouple tree location (**Figure 1**) of each of the hot and cold zones. Predicted air temperatures are generally in good agreement with those measured. The air temperature is essentially stratified (**Figure 5**). Linear regression was used to evaluate computed temperature stratification in each zone. Temperature stratification, **Table 3**, was between 0.43 and 1.21°C/m at the cold zone centre, and between 0.63 and 1.93°C/m at the hot zone centre. The lower level of temperature stratification being for the tests with the lower zone-to-zone temperature

Table 3. Temperature stratification, S, °C/m

Test	Cold Zone		Hot Zone	
	Computed (Expt. [1])		Computed (Expt. [1])	
	S (°C/m)	R^2	S (°C/m)	R^2
A	1.21 (1.17)	0.90 (0.97)	1.93 (1.42)	0.97 (0.96)
B	1.18 (1.03)	0.93 (0.96)	1.86 (1.38)	0.99 (0.94)
C	0.68 (1.02)	0.90 (0.97)	1.30 (1.44)	0.98 (0.91)
D	0.88 (0.97)	0.86 (0.95)	1.42 (1.28)	0.99 (0.95)
E	0.73 (0.86)	0.87 (0.90)	1.35 (1.23)	0.98 (0.90)
F	0.64 (0.83)	0.89 (0.92)	1.39 (1.28)	0.94 (0.89)
G	0.54 (0.50)	0.90 (0.93)	0.63 (0.62)	0.98 (0.88)
H	0.43 (0.46)	0.88 (0.91)	0.66 (0.65)	0.98 (0.88)
I	0.48 (0.46)	0.92 (0.92)	0.70 (0.69)	0.97 (0.89)
J	0.81 (0.65)	0.99 (0.95)	1.06 (1.10)	0.95 (0.95)

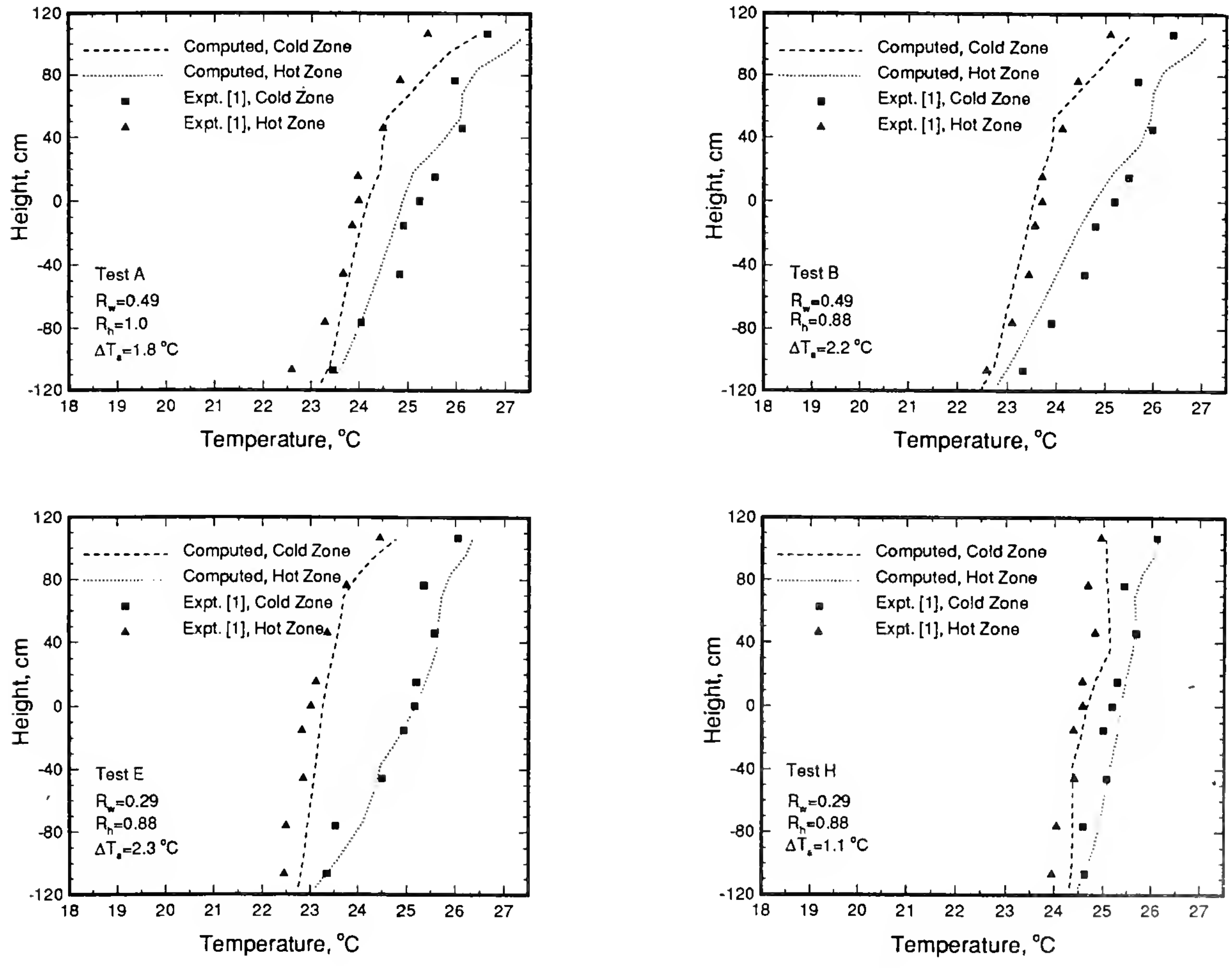


Figure 4. Vertical temperature distribution at centre of each zone

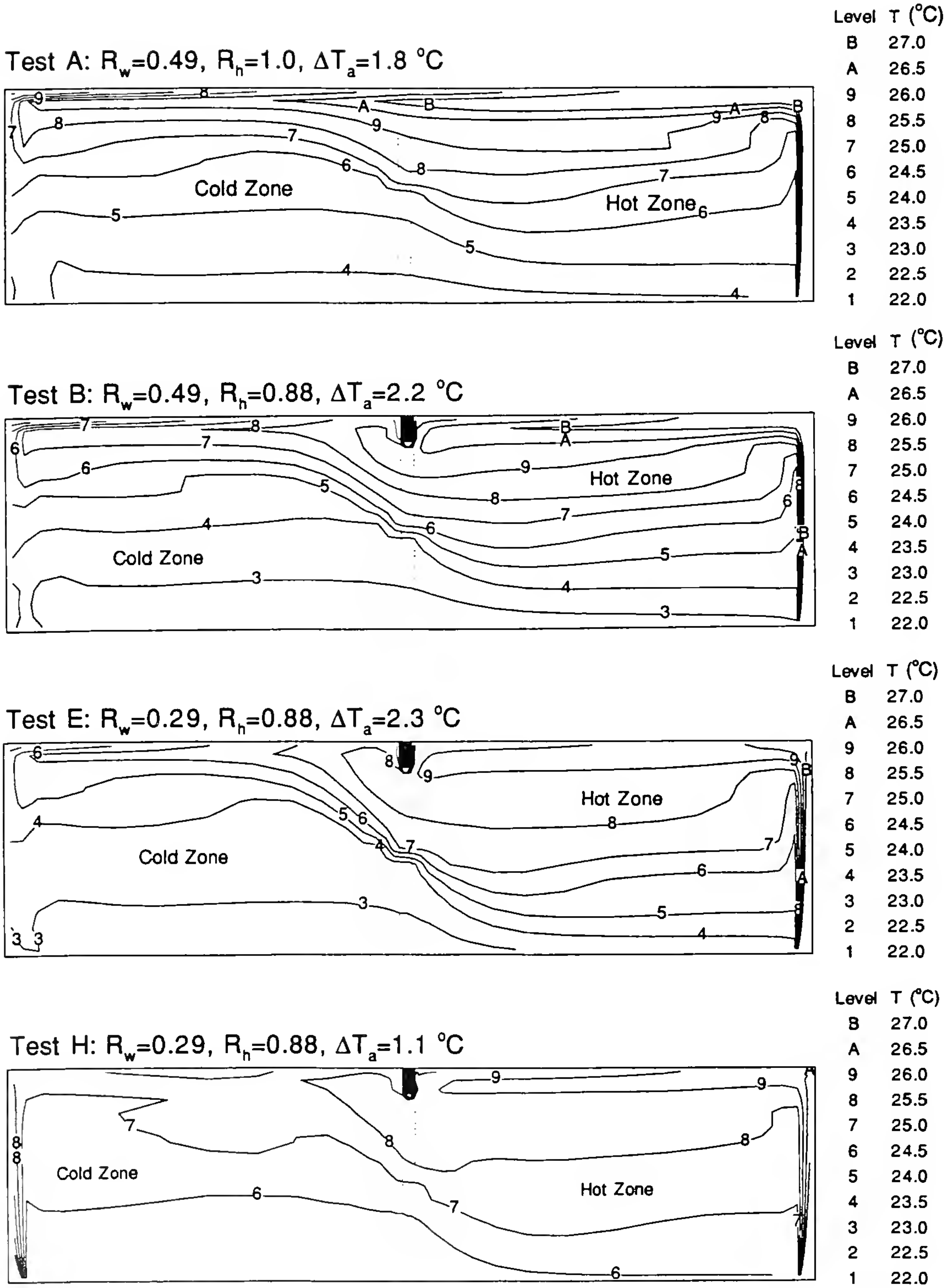


Figure 5. Temperature distribution in plane A-A through aperature centre

difference (ΔT_a = 1.0°C). Predicted temperature stratification values agree reasonably well with measured data, **Table 3**. Measured stratification was between 0.46 and 1.17°C/min. in the cold zone, and between 0.62 and 1.44°C/min. in the hot zone. Computed results suggest that for the tests with ΔT_a = 1.8 to 2.5°C, stratification decreased with decreasing aperture height. For the tests with ΔT_a = 1°C, aperture height appears to have little effect on stratification. Predicted stratification values are also consistent with those measured by Balcomb and Jones (1985). They reported temperature stratification levels in the range 0.91 to 2.19°C/m (0.5 to 1.2°F/ft) in passive solar buildings.

Computed air temperatures along the centre line of the aperture, **Figure 6**, are within 1°C of measured data. The discrepancy between computed and measured temperature profiles is probably due to the difficulty in duplicating the actual thermal boundary conditions of the experiments at the aperture. However, computed profiles of the horizontal component of the air velocity along the centre line of the aperture agree very well with measured data, **Figure 7**. The neutral plane (the plane of no horizontal flow) is nearly at the aperture mid-height (height = 0, **Figures 4** and **6**). It is noted that the vertical distributions of the horizontal velocity component are symmetric with respect to the neutral plane, and are similar to the theoretical velocity profile based on the Bernoulli equation by Brown and Solvason (1962).

Air Flow Pattern

Figure 8 shows typical air flow patterns in a vertical plane through the centre of the aperture (Plane A-A, **Figure 1**). A counterclockwise air circulation cell dominates the hot zone. The upward boundary layer flow by the north wall in the hot zone reaches the top of the enclosure where it turns horizontally and moves toward the aperture to the cold zone. The air flow accelerates as it moves through the aperture. After entering the cold zone, the air, along with entrained cooler air, move upward to the enclosure top then horizontally toward the south wall in the cold zone. This air flow pattern in the hot zone indicates that the interzonal natural convective flows were primarily under the influence of the so-called bulk-density flow regime in which the air flow through the aperture is driven by the zone-to-zone temperature difference.

The air flow pattern in the cold zone depended on the status of the heaters H2 and H3 by the south wall (**Figure 1**). For Tests A, B and E, shown in **Figure 8**, heaters H2 and H3 were off (see **Table 1**). One circulation cell occupies the top half of the enclosure. The air descends along the south wall to the floor. Then immediately turns up to about mid-height of the enclosure where it moves horizontally toward the aperture to the hot zone. This is believed to be due to the asymmetry caused by the irregular extension of the cold zone. It is worth noting that this L-shaped arrangement of the two zones is typical in Canadian doweling. As can be seen from **Figures 9** and **10**, unlike the hot zone, a counter-clockwise air circulation cell dominates the cold zone. This air circulation cell is fed from the relatively high momentum of the air accelerating out of the aperture (Plane x/H_r = 0.786, **Figure 9** and Plane x/H_r = 0.718, **Figure 10**). This relatively high momentum area across the aperture in the cold zone induces air entrainment upwards from the bottom where some air turns towards the aperture, and others follow the main air circulation cell.

For Test H, **Figure 8**, where heaters H2 and H3 were on (**Table 1**), the air ascends along the south wall up to the enclosure top where it moves horizontally until it is deflected downward by the warmer air stream from the hot zone. This results in two circulation cells in the cold zone. **Figure 11** shows the effect of the heat supplied by heaters H2 and H3 on the air flow pattern in the cold zone. The counter-clockwise air circulation cell noted earlier in the cold zone (**Figures 9** and **10**) is not present when heaters H2 and H3 are on.

For the aperture/enclosure configurations studied, the natural convective interzonal air flow through the aperture appears to be three-dimensional, **Figure 12**. This is consistent with the finding of Mahajan (1987). Above the neutral plane, two airflow circulation cells appear at the top of the aperture. Below the neutral plane, the convective air flows appear to be biased towards the bottom right corner of the aperture. This difference in the airflow pattern above and below the neutral plane at the aperture is clearly due to the fact that the hot and

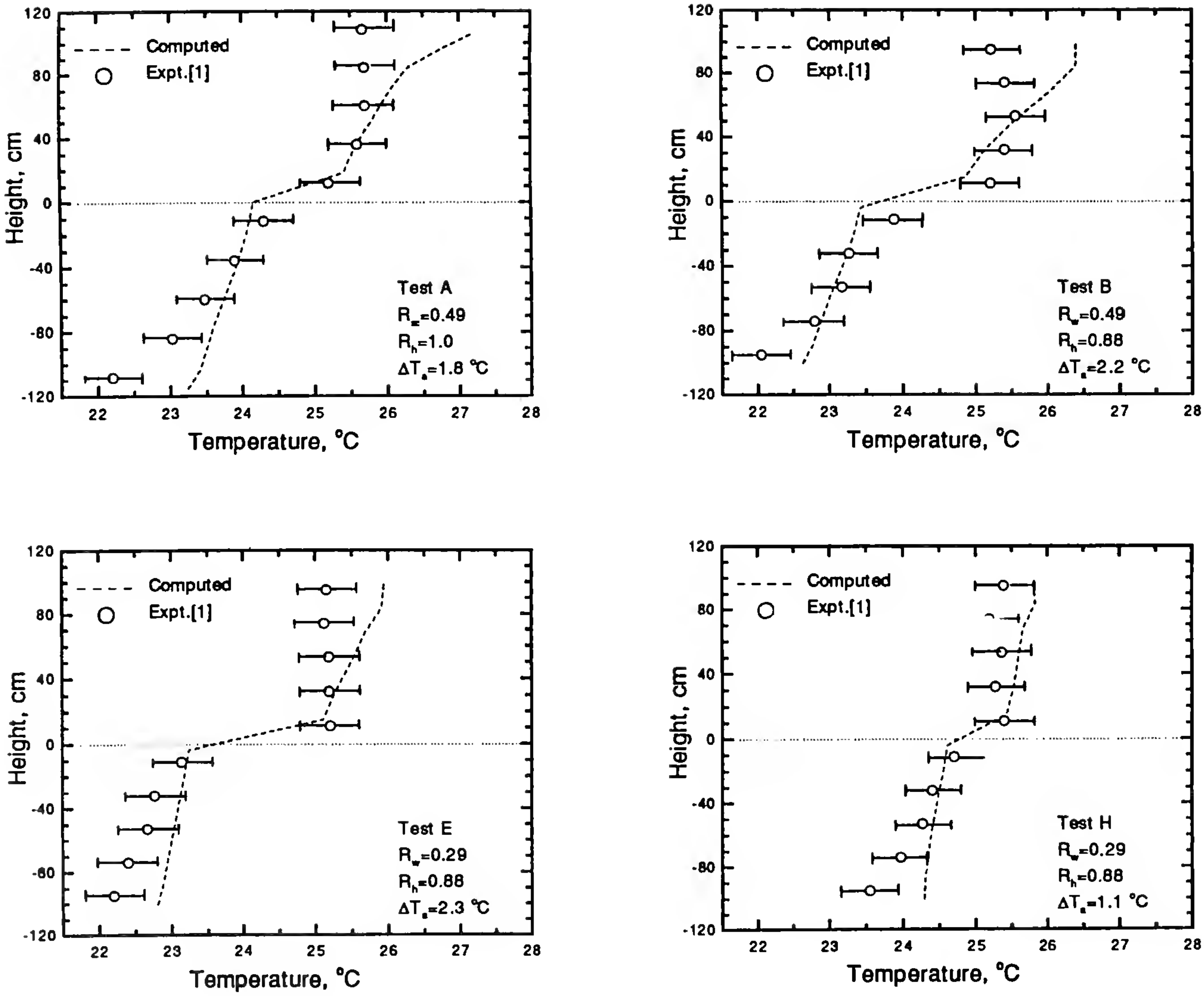


Figure 6. Vertical temperature distributions at aperture centre line

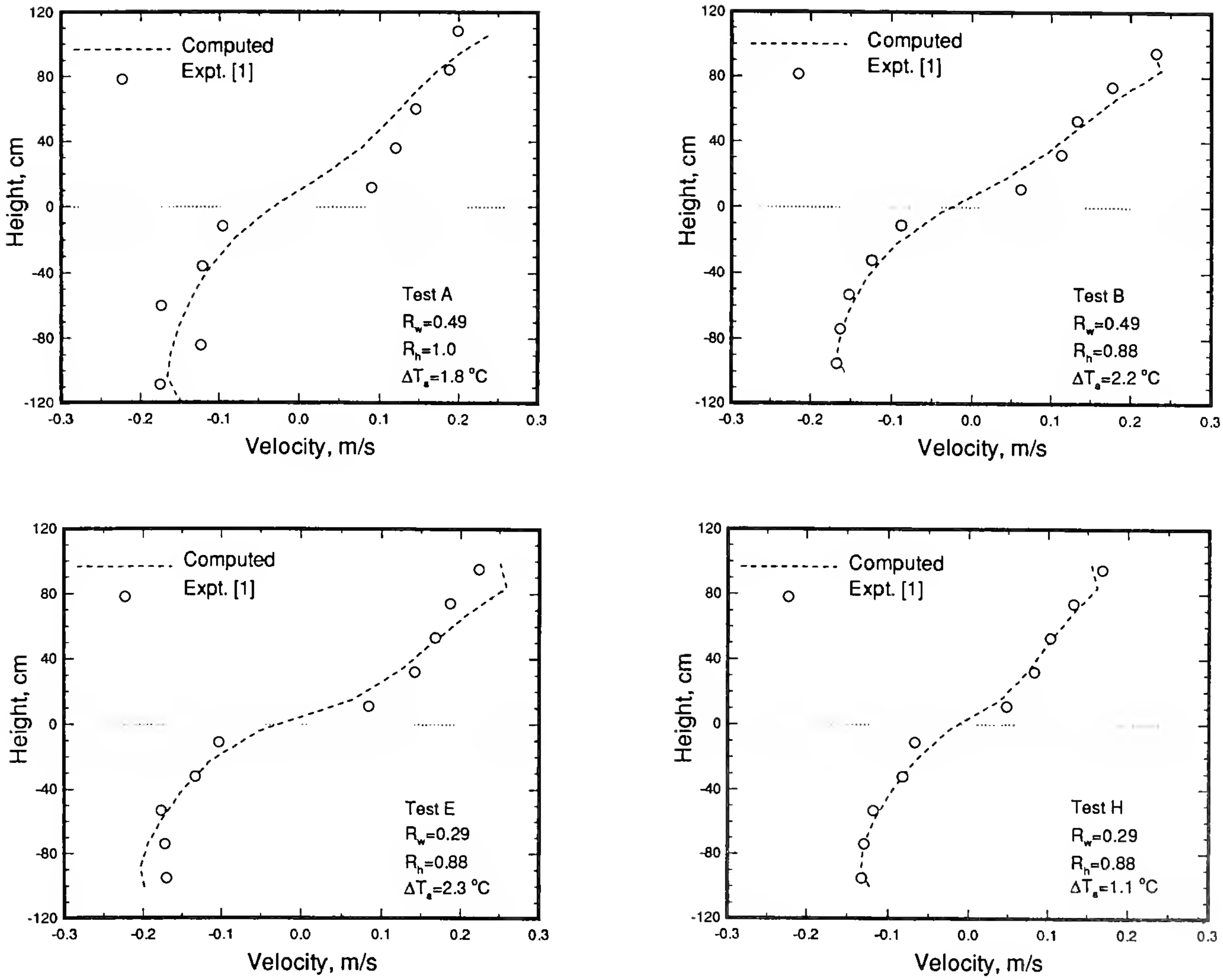


Figure 7. Vertical distribution of horizontal velocity component, V, at aperature centerline

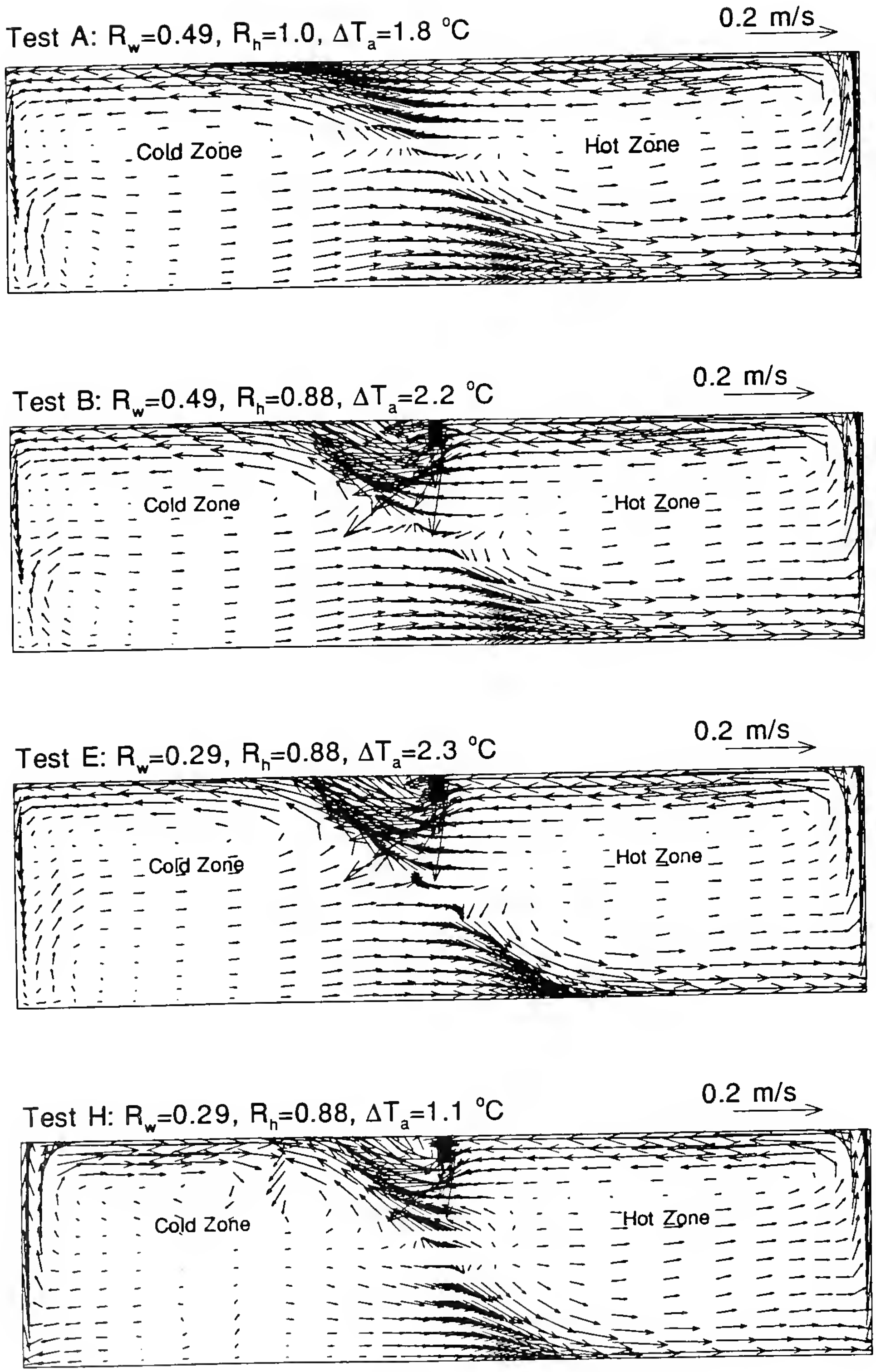
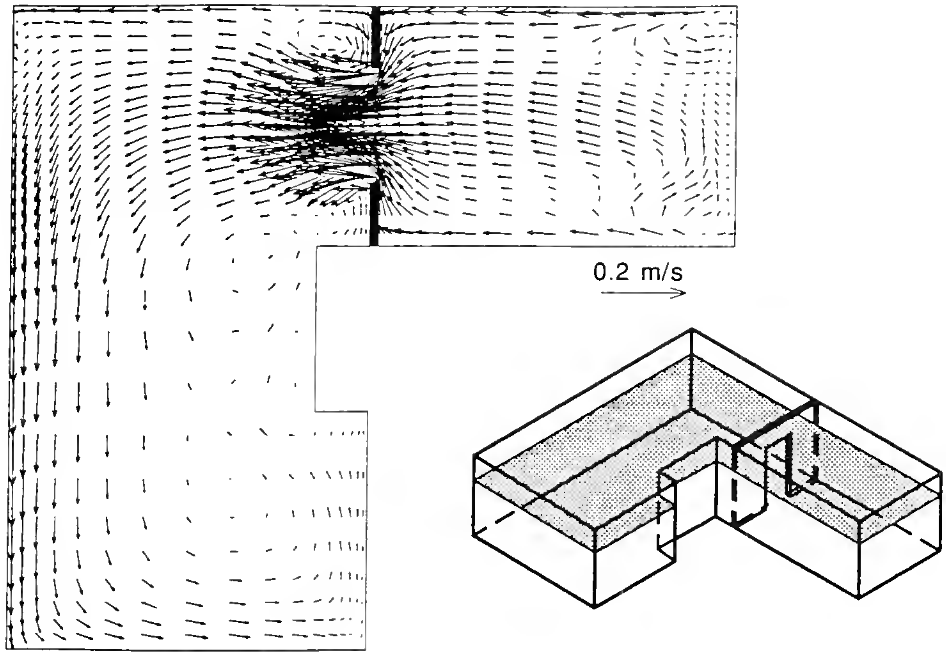
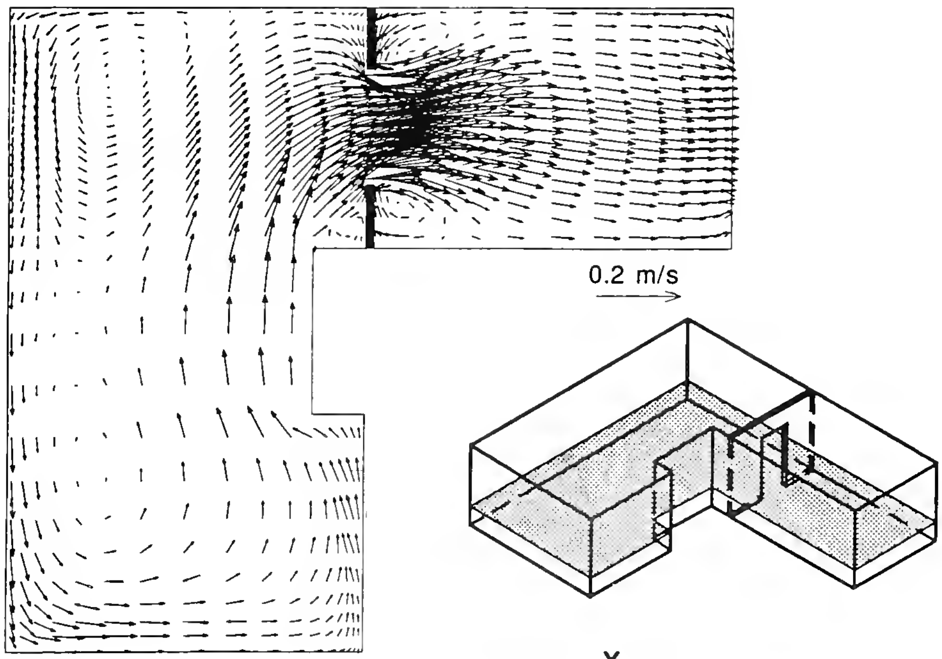


Figure 8. Velocity distribution in plane through aperature centre



Plane $\frac{x}{H_r} = 0.786$



Plane $\frac{x}{H_r} = 0.193$

Figure 9. Velocity distribution in horizontal planes $\frac{x}{H_r} = 0.786$ and 0.193

Test A, $R_w = 0.49$, $R_h = 1.0$, $\Delta T_a = 1.8°C$

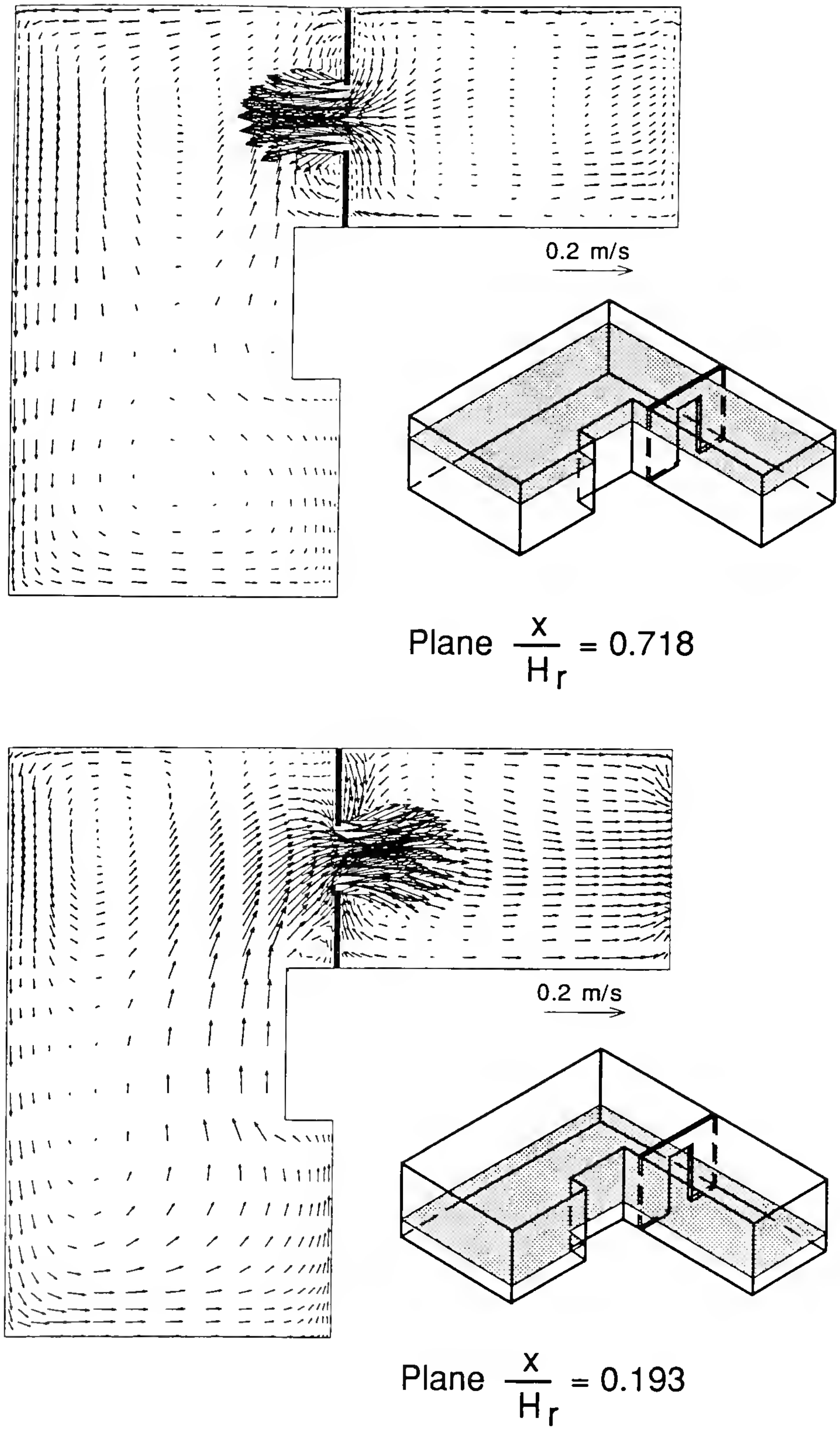


Figure 10. Velocity distribution in horizontal planes $\frac{x}{H_r}$ = 0.718 and 0.193
Test E, R_w = 0.29, R_h = 0.88, ΔT_a = 2.3°C

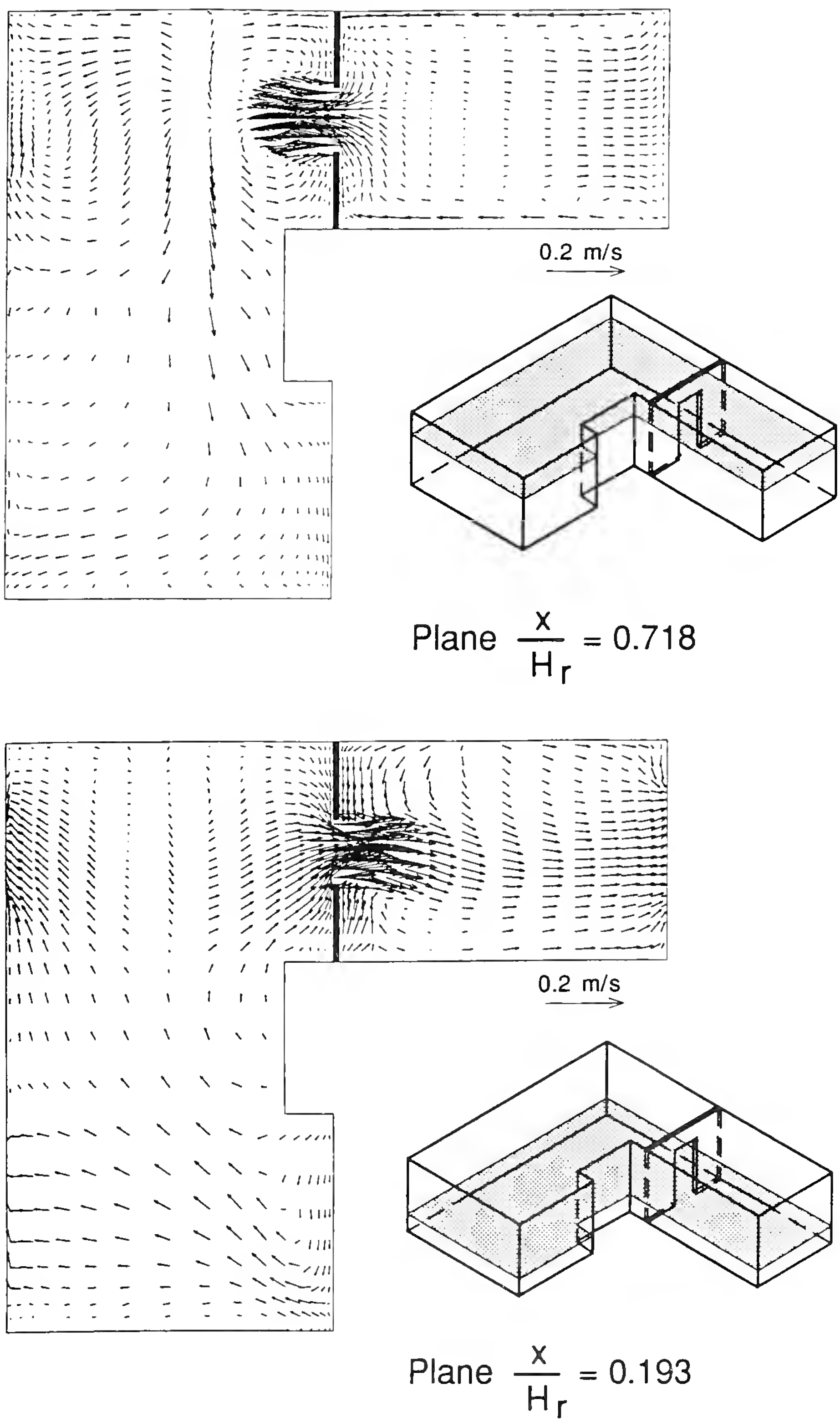


Figure 11. Velocity distribution in horizontal planes $\frac{x}{H_r}$ = 0.718 and 0.193

Test H, R_w = 0.29, R_h = 0.88, ΔT_a = 1.1°C

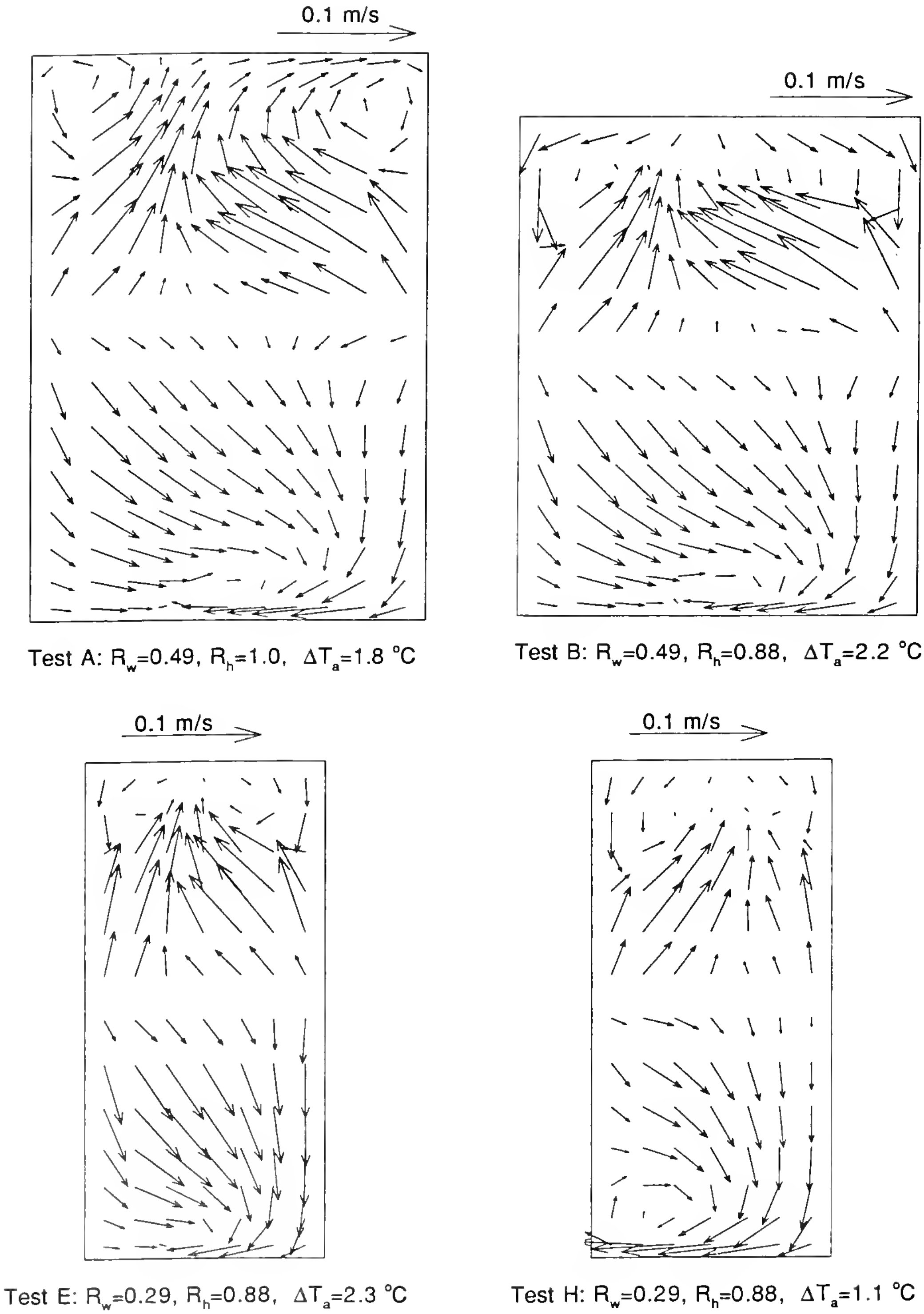


Figure 12. Velocity distribution in aperature plane

cold zones are different in shape. The air flow from the cold zone to the hot zone (**Figures 9** and **10**, Plane $x/H_r = 0.193$) appears to be biased toward the side of the aperture nearest to the irregular extension of the cold zone. The air flow from the hot zone to the cold zone, however, appears to diffuse symmetrically through the aperture (**Figure 9**, Plane $x/H_r = 0.786$, and **Figure 10**, Plane $x/H_r = 0.718$).

Coefficient of Discharge

Using the computed results, the volumetric air flow rate through one-half the aperture (with respect to the neutral plane) was computed by summing the product of the local velocity component normal to the plane of the aperture (Y-direction component) and the corresponding incremental area. Computed volumetric air flow rates, F_c, out of the hot zone (above the neutral plane) and that into the hot zone (below the neutral plane) were identical. The theoretical volumetric flow rate, F_t, was calculated with the relation derived by Brown and Solvason (1962):

$$F_t = W/3\,(g\,\beta\,H^3\,\Delta T)^{0.5} \tag{2}$$

where the symbols are as defined in the nomenclature. The fluid properties were taken at the overall mean air temperature of both zones. Two definitions for the characteristic temperature differential, ΔT, were considered:

- ΔT_m is the difference between air temperatures at the centre (thermocouple tree location, **Figure 1**) of each zone at a level of half the enclosure height, and
- ΔT_v is the difference between average air temperatures of a vertical grid of nodes at the centre of each zone.

The difference between average air temperatures in each zone at a level of half the enclosure height, ΔT_a, was also considered. Computed results using ΔT_a were similar to those using ΔT_m.

The volumetric coefficient of discharge, C_d, was then calculated from the computed volumetric flow rate, F_c, divided by the theoretical one, F_t. The values of C_d were found to be in the range 0.57 to 0.81. Computed C_d values are in good agreement with measured results (Saïd, Barakat, and Whidden 1993), see **Table 4**. Computed C_d values also compare favorably with those reported by Brown and Solvason (1962). They experimentally determined C_d to be in the range 0.6 to 1.0. Their experiments involved a partitioned square enclosure, openings with a maximum size of 0.305 x 0.305 m, and temperature differentials across the opening between 8.3 and 47.2 °C.

Table 4. Coefficient of discharge, computed vs. measured (Saïd, Barakat, and Whidden 1993), R_w=0.29 and 0.49, R_h=0.75—1.0, ΔT_a=1.1—2.5°C

	ΔT_m		ΔT_v	
Test	Computed	Expt.[1]	Computed	Expt.[1]
A	0.81	0.74	0.75	0.75
B	0.68	0.67	0.69	0.73
C	0.57	0.59	0.66	0.66
D	0.67	0.65	0.72	0.70
E	0.63	0.66	0.70	0.74
F	0.60	0.69	0.67	0.75
G	0.64	0.67	0.72	0.63
H	0.65	0.78	0.68	0.72
I	0.60	0.65	0.66	0.64

Using an average C_d value of 0.67 in conjunction with Equation (2) gives the following correlation for computing air flow rates through a doorway-like aperture:

$$F = 0.223\,W\,(g\,\beta\,H^3\,\Delta T)^{0.5} \tag{3}$$

Equation (3) correlates computed (from EXACT3 results) volumetric air flow rates with a goodness of fit $R^2 = 0.85$ for $\Delta T = \Delta T_m$, and $R^2 = 0.95$ for $\Delta T = \Delta T_v$. The results (C_d and Nusselt number) for Test J were not included in the correlation. The aperture size in Test J ($R_w = 0.79$ and $R_h = 0.88$) was such that the two zones were almost like a single zone.

Nusselt Correlation

The natural convective heat flow rate through the aperture was computed from computed air mass flow rate through the aperture and the temperature differential across the aperture. The results are presented in terms of Nusselt number, Nu. In accordance with the conclusion reported by the authors (Saïd, Barakat, and Whidden 1993), the following correlation was considered:

$$Nu = C\,Gr^{0.5}\,Pr \qquad (4)$$

The aperture height, H, was used as the characteristic length in Nu and Gr numbers. Correlation Equation (4) is the theoretical form derived by Brown and Solvason (1962) in which the coefficient $C = C_d/3$. This correlation was based on the inviscid Bernoulli equation.

Similar to the measured results (Saïd, Barakat, and Whidden 1993), the characteristic temperature difference that led to the most accurate Nu correlation ($R^2 = 0.98$) was ΔT_v as compared to $R^2 = 0.87$ when ΔT_m was used. The temperature differential ΔT_m (the difference between air temperatures at the centre of each zone at a level of half the enclosure height) is, however, convenient to measure in practice. Thus, the following is the least squares fit result for the correlation Equation (4) in which ΔT_m was used.

$$Nu_H = 0.215\,Gr_H^{0.5}\,Pr \qquad (5)$$

Figure 13 compares the correlation Equation (5) to that from the experiments (Saïd, Barakat, and Whidden 1993) (C = 0.22) and the lower and upper limits (C = 0.2 and 0.33) by Brown and Solvason (1962). As can be seen, the correlation Equation (5) agrees very well with that derived from the full scale experiments (Saïd, Barakat, and Whidden 1993). The correlation Equation (5) is also in close agreement with the lower limit (C = 0.2) of the correlation by Brown and Solvason(1962).

CONCLUSIONS

- The three-dimensional computation results facilitated better understanding of the air flow pattern and the natural convective flow regime in the two-zone enclosure.
- Computed results for temperature and velocity agree reasonably well with measured data from full scale experiments (Saïd, Barakat, and Whidden 1993) in a realistic building.

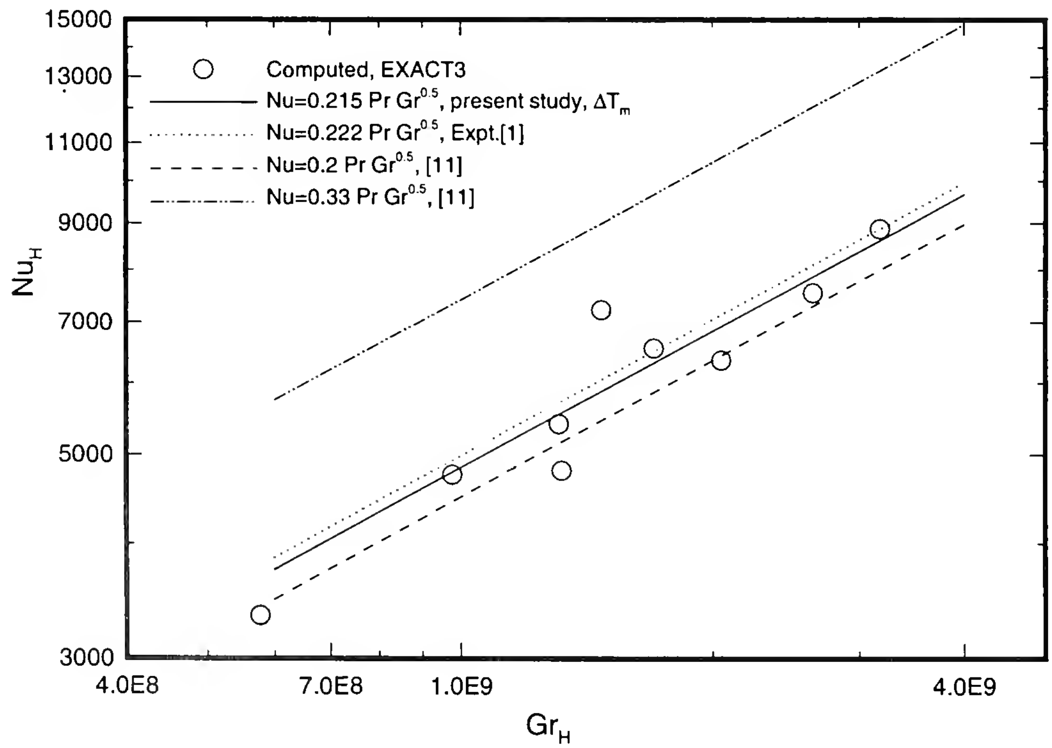


Figure 13. Nusselt number vs. Grashof number

- Coefficients of discharge were found to range between 0.57 and 0.81 for the aperture configurations studied. An average C_d value of 0.67 correlates very well with all computed data. Computed temperature stratification, coefficient of discharge, and Nusselt number agree quite well with those measured.

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Measuring and Analyzing Productivity Using Methods Improvement

Paige L. Watler, Mark S. Malone, and James D. Lutz

ABSTRACT

Productivity and performance of a repetitive construction operation can be determined and improved for an existing operation by using methods improvement techniques. This involves the collection of data using techniques including camcorder, method production delay model, work sampling, five-minute rating, and crew balance. These techniques foster the development of improved methods which may be implemented to enhance productivity, duration, and cost control parameters for the construction operation. The application of methods improvement techniques are presented in this paper using data collected from a concrete placement operation. Values for productivity using these techniques are evaluated, and the performance factor for the operation in terms of actual versus expected productivity is discussed. The methodology for modeling the operation using microCYCLONE is introduced to substantiate the potential for enhanced performance from the implementation of improved methods. Also, the benefits of using simulation as part of a methods improvement program are addressed. A case study is provided.

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INTRODUCTION

Methods improvement techniques provide the means by which the productivity and performance of a repetitive construction operation can be determined and by which improved methods can be implemented in the existing operation. This involves the collection of data using techniques including camcorder, method production delay model, work sampling, five-minute rating, and crew balance. With these techniques, the development of improved methods may be implemented to enhance productivity, duration, and cost control parameters for the construction operation.

A methods improvement study was performed on the concrete column placement activity associated with the construction of the $4 million Auburn University Residence Halls (1992) project constructed by Parker Building Company of Auburn, Alabama. Data collection was performed in the Summer of 1993, and the placement method observed consisted of the crane and bucket operation for pouring concrete columns. A camcorder was used to permanently record repetitive cycles, and manual data collection techniques (e.g., work sampling, five-minute rating, and the statistical delay approach commonly referred to as method production delay model) were then used. Values for productivity determined using the multiple techniques are provided and compared. The performance factor for the operation in terms of actual versus expected productivity is discussed. The use of microCYCLONE is introduced to substantiate the potential for enhanced performance from the implementation of improved methods. The benefits of using simulation as part of a methods improvement program are addressed. This paper reports the findings from this methods improvement study. The purpose of this research was to demonstrate how method improvement techniques can be used to measure and analyze productivity for a construction operation.

THE PROJECT

The construction project studied was the $4 million Auburn University Residence Halls (1992) project constructed by Parker Building Company of Auburn, Alabama. The repetitive construction operation studied was the placement of fresh portland cement concrete (PCC) in the column forms. Placement of concrete in columns was chosen as the operation to study because the columns were critical structural members. Also, the placement of concrete in the column forms was a process which was repeated frequently. Therefore if any productivity improvement could be identified and implemented, the savings would be accrued with every column that was built. On Thursday, July 22, 1993, the first 20 columns supporting the fourth floor (i.e., rising from the third floor slab) of the new dormitory were formed in the morning and filled with concrete in the afternoon. Concrete placement began around 2:15 p.m. with the ambient air temperature around 100 degrees and humidity in excess of 80 percent.

The production cycle was defined as the placement of one complete column of concrete. This was measured from the start of the concrete pour for one column until the start of the pour for the next column. The columns being filled measured 12″ x 12″ x 8′10″, or 0.33 cubic yards each. The production unit was chosen as one cubic yard of placed concrete. The lead resource was a crane and a 3/4 cubic yard concrete bucket.

The production cycle was a six-step process. It involved dispensing concrete from the bucket into the column forms, vibrating the concrete from the bottom of the column to the top, lowering the bucket to the ground behind the concrete truck, loading the bucket with enough concrete for one column, lifting the bucket, and positioning it at the top of the next column form. See the process chart in **Figure 1** for a summary of the cycle. At the beginning of each group of 10 columns (one truckload), the slump of the mix was tested.

The crew consisted of seven workers. Their positions, locations, and duties included:

- **Crane Operator** - (in crane on the ground) lowered, lifted, positioned, and held concrete bucket in place;

	Distance
Fill the column with concrete	
Vibrate the column	
Lower the bucket to the concrete truck	50 ft.
Load the bucket with concrete	
Lift the bucket to the next column	50 ft.
Position the bucket and align the chute with the column	

Note: Because no inherent delays were found in this process, no revised process chart is necessary.

Figure 1. Process chart

- **Bucket Opener** - (at top of column form) released fresh concrete from bucket into column form;
- **Vibrator** - (at top of column form) vibrated concrete as he pulled the vibrator hose out of the column of concrete;
- **Assistant Vibrator** - (on the floor slab) held the vibrator motor, turned the vibrator on/off, carried vibrator between columns;
- **Concrete Truck Driver** - (on the ground) dispensed PCC from the concrete truck to the bucket;
- **Bucket Loader** - (on the ground) told the truck driver when to stop the flow of concrete into the bucket; also performed slump test; and
- **Superintendent** - (on the floor slab and top of form) directed crane operator in lifting bucket into position, gave directions to other crews, and sometimes served as bucket opener.

DATA COLLECTION AND ANALYSIS

A camcorder was used to permanently record repetitive cycles, and manual data collection techniques (e.g., work sampling, five-minute rating, and the statistical delay approach commonly referred to as method production delay model) were then used. Use of these techniques is discussed next.

Videotape Recording

Modern methods of construction data collection include the use of videotape cameras, otherwise known as camcorders. Videotaping a construction operation provides an absolutely complete and permanent record of the events and allows the analyst to review the operation at another time away from the hectic construction site. The process can be viewed repeatedly, with new insights possible on each viewing. In addition, videotape can capture the sounds as well as the sights of a construction project, perhaps assisting in the analysis (Oglesby, Parker and Howell 1989).

This study utilized the modern technique of videotaping to record 13 cycles of concrete placement at the new dormitory. Access to the sixth floor of an adjacent existing dormitory (Sasnett Hall) was obtained and footage was shot from the window of one of the dorm rooms. In addition to providing an excellent overall view of the construction site, this observation point allowed the researchers to zoom in on the repetitive process being studied. The sounds of the concrete truck, the crane, the vibrator, and the shouts of the crew members were also captured on the tape. The audio aspect helped in three ways: (1) the time the vibrator was in use could be calculated, (2) the shouts of the crew members showed if any confusion arose, and (3) a distinction could be made between the crane's idle time and when it was being used. Another advantage of the videotape was that the operation could be played in fast motion. This allowed the analysts to see the whole cycle quickly and gain a general sense of who was doing productive work and who was not. Also, the use of videotaping was not disruptive to the work force.

The use of the camcorder was very beneficial; it provided a permanent audio and video recording which could be reviewed repeatedly. For example, it was determined through viewing the video tape that the concrete truck driver was perfectly capable of loading the bucket without the assistance of the bucket loader. It was also determined that the crane operator had an easier time of positioning the bucket at the top of the column if he could see where he was aiming rather than being directed by a third party.

In addition, the long delay during the 10th cycle was found to be intentional after repeated viewing of the video. In that cycle, the next concrete truck arrived to provide PCC for the second group of 10 columns. While the first truck departed and the second truck took its place, the superintendent had the crane operator reposition the crane, and ordered a rest and water break for the crew. Thus, he took advantage of a natural break in the operation to perform two other important functions. Although this made the delay a little longer, it prevented the need for a second delay a short time later. The videotaping of this construction operation provided a valuable analysis tool.

Table 1. Work sampling

Trial No.	Working	Not working	Total # workers	% Working	% Not working
1	261	133	394	66.24	33.76
2	221	183	404	54.70	45.30
TOTAL	482	316	798	60.40	39.60

Total Effectiveness = 60.40 %

Work Sampling

Work sampling is one productivity measurement approach which is fairly simple to accomplish, is statistically reliable, does not interrupt the workers, and allows the monitoring of trends (Russell and Chang 1987). Work sampling involves walking through a construction site, observing workers, making instantaneous decisions as to whether the worker(s) are working or not working, and recording these observations. To ensure the data collected are statistically valid, with 5 percent limit of error, 50 percent category proportion, and 95 percent confidence level, each trial must include at least 384 observations. This is because as the number of observations increases, the accuracy of the prediction improves (Oglesby, Parker and Howell 1989). In order to achieve at least 384 observations, multiple passes are usually required for each trial.

Two work sampling trials were taken - one on the morning of July 22 during the erection of the forms and one that same afternoon during the placement of the concrete. For the morning trial, the researchers walked through the site many times, making multiple data collection passes until 400 observations had been made.

The work sampling data collected are presented in **Table 1**. As shown, the percent working was 66.2 percent for Trial 1 and 54.7 percent for Trial 2, for an average of 60.4 percent working. This value indicates that the workers were busy.

The fact that the workers observed in Trial 1 were the busier of the two trials can be attributed to two factors. First of all, the workers were scrambling to erect 20 column forms before the concrete arrived at 2:00 p.m. Secondly, it was early morning and the heat of the day had not begun to take its toll.

During Trial 2 the workers were not as busy (54.7 percent) as during Trial 1 (66.2 percent). This was probably because seven of the crew members were involved in the concrete pour, and as one can see from the Existing Crew Balance chart, **Figure 2**, there was some idle time inherent in the concrete placement operation. Finally, the oppressive heat and humidity in the afternoon probably slowed the overall pace on the construction site.

Five Minute Rating

The five minute rating is another simple productivity measurement technique which provided a relatively quick way to make a general work evaluation. It can be accomplished by several classes of personnel, and can identify inefficient work layout, inefficient material management, or crew size problems (Oglesby, Parker and Howell 1989). It involves observing a repetitive construction process for five minutes or one production cycle, whichever is longer. At regular intervals (usually every minute) recordings are made of which crew members are working and which are not working. The results are tablarized and an overall effectiveness for one cycle can be computed.

In an attempt to avoid analyzing a single, perhaps non-representative cycle, the five minute rating was performed over two cycles (even though one cycle lasted eight minutes and would have been acceptable). And to give all the crew members a chance to be seen actually working, readings were taken every 30 seconds instead of every minute. The results of the five

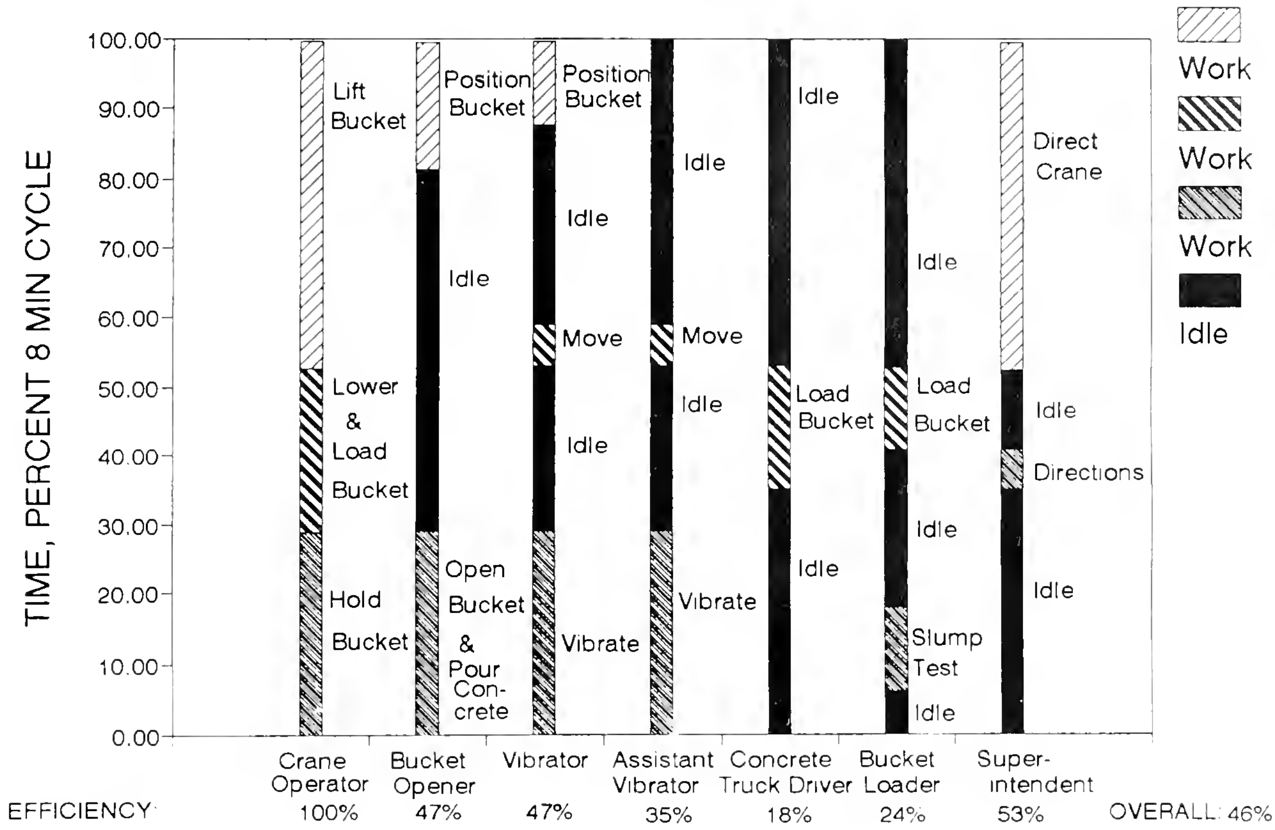

Figure 2. Existing crew balance chart

minute rating yielded an effectiveness rating of 45.6 percent as displayed in **Table 2**.

At first the researchers were surprised at this result, given the work sampling result of 60.4 percent busy, and the fact the crane operator was working 100 percent of each cycle. But a close examination of the data presented in **Table 2** shows the concrete truck driver and the bucket loader were idle for most of the cycle. The table also reveals that for 5 to 6 minutes of the 8 minute cycle, 3 or more crew members were idle. This would help explain the percent effectiveness of less than 50 percent.

Also, the five-minute rating effectiveness (45.6 percent) should really only be compared to work sampling Trial 2 (54.7 percent) because only Trial 2 sampled the same type activity as the five minute rating. But the main reason for the discrepancy is the fact that, according to Thomas (1991), work sampling only shows how "busy" the crafts are and the results cannot be used to predict labor productivity. On this construction site, the workers appeared to be more productive than they actually were.

Crew Balance

Crew balance is a graphical productivity measurement tool used to improve repetitive operations, so benefits accrue with each cycle. It depicts the interrelationships of individual crew members and their equipment. With a crew balance chart, there is no limit to the information that can be shown, and it is easy to see where resources are being wasted (Oglesby, Parker and Howell 1989).

Using the data collected in the five minute rating described above, the crew balance chart was developed as presented in **Figure 2**. The time as a percent of the 8 minute cycle for the various actions of each crew member was plotted. At the bottom of each crew member's column, the percent of time that crew member was actually working is provided. The percent effectiveness ranged from a high of 100 percent for the crane operator, who was always involved with lifting, lowering, positioning, or holding the bucket, to a low of 18 percent for the truck driver, who only got involved with each cycle for the short time it took to load the

Table 2. Five minute crew rating

TIME:	Crane Operator	Bucket Opener	Vibrator	Vibrator Assistant	Concrete Driver	Bucket Loader	Super.	NOTES
START								
16:02:52	X	X	X	X				Start pouring column
	X	X	X	X		X		
16:03:52	X	X	X	X		X		
	X	X	X	X				
16:04:52	X	X	X	X				
	X							
16:05:52	X				X		X	Load bucket
	X				X	X		
16:06:52	X				X	X		
	X		X	X			X	Wait on concrete
16:07:52	X						X	
	X						X	
16:08:52	X		X				X	
	X						X	
16:09:52	X	X					X	
	X	X	X				X	
16:10:52	X	X	X				X	
	X	X	X	X				Start pouring column
16:11:52	X	X	X	X			X	
	X	X	X	X				
16:12:52	X	X	X	X				
	X	X	X	X				
16:13:52	X	X						
	X		X	X			X	
16:14:52	X			X				Lowering bucket
	X			X	X			Load bucket
16:15:52	X				X			
	X				X			
16:16:52	X				X			
	X							Moving bucket
16:17:52	X	X	X					
	X	X	X					
16:18:52	X	X	X	X				
Effective Total Units	33	17	18	15	7	4	11	

NOTES: Observed by Mark Malone and Paige Watler
Data taken 7/22/93
Total Man Units = 231
Effective Man Units = 105
Effectiveness = 105/231 * 100 = 45.64%

bucket. The overall average for the entire 7-person crew was 46 percent.

Inspection of **Figure 2** graphically reveals the large amount of idle time for the truck driver and the bucket loader. It also indicates one part of the cycle (at 30-35 percent) where 6 of the 7 crew members are idle. During at least 20 percent of the cycle, 5 of the 7 workers are idle. It is these type of discoveries that make the crew balance chart so valuable. Based on the crew balance chart, a recommendation was made that the bucket loader position be eliminated.

Process Chart

The process chart in **Figure 1** shows a rather simple 6-step process. This is also a graphical productivity measurement tool; it uses symbolic terminology to represent the processes involved in the construction operation. It is particularly useful for situations where materials are processed in succeeding steps, and identifies excessive or duplicated transportation of materials. It can also point out inefficient work station locations (Oglesby, Parker and Howell 1989). The process chart is a listing of the steps in the operation, with each step accompanied by a symbol and perhaps a transportation distance. The different symbols indicate whether each step is an operation, an inspection, a transportation, a storage, or a delay.

The transportation cycle began with the concrete being dispensed into a bucket and then lifted vertically by the crane and swung through an arc to the top of the column form to be filled. It was estimated the average travel distance for the fresh concrete to be about 50 feet. Of course, the actual travel distance for each cycle depended on which column was being filled. Some of the columns were reached by swinging the bucket in a short clockwise arc; others were attained through a longer counterclockwise arc. The concrete trucks only moved once during the data collection, and that really was not an integral part of the measured cycle.

No delays were found to be inherent in this operation, and storage of materials was not part of the cycle. So for this operation, the process chart did not reveal any problem areas as did some of the other techniques.

DELAY ASSESSMENT

The Method Production Delay Model (MPDM) is a statistical technique which can be used to identify the major delay types in an operation (e.g., environmental, management, labor, equipment, material, etc.) and to assess the impact of delays by delay type. The costs of performing the MPDM are minimal; the model requires only simple mathematics with little skill required to implement it (Adrian and Boyer 1976).

The MPDM involves monitoring multiple production cycles and noting which cycles include delays. These delays are categorized as either environmental, equipment, labor, material, or management delays. Other, specialized, delay categories can be used, too. After several cycles have been recorded, mean cycle times are computed for the overall number of cycles as well as for the cycles which were not delayed. The probability of delays, broken out by category, as well as the relative severity of the delays are computed, as is the expected percentage of delay time per production cycle. Finally, ideal productivity and overall productivity are calculated.

MPDM Results

The results of the MPDM analysis are presented in **Tables 3, 4,** and **5**. In **Table 3** one can see that the delay data were recorded on 13 complete cycles of concrete placement. This took a total of 1 hour and 34 minutes (**Table 4**). The types of delays which were recorded included environmental, equipment, labor, and material. No management delays were witnessed. The environmental delay was a longer-than-expected break due to the 100 degree weather. Most of the equipment related delays involved not being able to quickly position the concrete bucket at the top of the column form. The crew seemed to have trouble getting the bucket to come to rest where they wanted it. The superintendent later indicated that this was due to the long extension of the crane boom and the fact that sometimes the crane operator was working in the blind. The labor delays tended to be situations where the bucket opener was not in position when the bucket of concrete arrived at the top of the column form. The material delays involved lack of concrete when needed—once when the bucket did not

Table 3. Production cycle delay sampling

Production Cycle	Production Cycle Time (secs)	Environmental Delay	Equipment Delay	Labor Delay	Material Delay	Notes	Minus Mean Non-Delay Time
1	487		X			Concrete truck #1	221
2	382		20%	80%			116
3	308		X				42
4	370		X				104
5	385		80%	20%			119
6	296					*	30
7	317		X				51
8	460		10%		90%	Not enough concrete in bucket	194
9	236					*	30
10	1233	20%		10%	70%	Crane reposition-Conc. truck #2	967
11	345			X			79
12	371		X				105
13	436			X			170
	5626						2228

Ideal Productivity = 60 min/hr * 60 sec/min / 266 sec/unit
Ideal Productivity = 13.53 units/hour

Overall Productivity = 60 min/hr * 60 sec/min / 432.8 sec/unit
Overall Productivity = 8.32 units/hour

Mean Non-Delay Cycle = 532 seconds

Table 4. MPDM processing

Units	Production total time (seconds)	Number of Cycles	Mean cycle time (seconds)	Sum[(Cycle time)-(non-delay cycle time)]/n
Nondelayed production cycles	532	2	266.0	30.0
Overall production cycles	5626	13	432.8	171.4

Table 5. Delay information

Time Variance	Environ-ment	Equip-ment	Labor	Material
Occurrences	1	8	5	2
Total added time	193.4	660.8	292.3	851.5
Probability of occurrences	0.077	0.615	0.385	0.154
Relative severity	0.45	0.19	0.14	0.98
Expected percentage of delay time per production cycle	3.4	11.7	5.2	15.1

contain enough to completely fill a column and once when the concrete trucks were being changed. Even though there seemed to be many delays, the only significant one was the changing of the concrete trucks. This is shown in **Table 5** by the fact that the relative severity of the material delay was very high at 0.98.

As shown at the bottom of **Table 3**, the ideal productivity turned out to be 13.5 columns (units) per hour. The overall productivity of the operation as observed was 8.3 columns per hour. However, based upon his experience and the job characteristics, the superintendent had thought that the crew could produce 10 columns per hour. His statement was based on the use of a 50 minute work hour and his estimate that the concrete placement crew could complete one column every 5 minutes. In fact, since the concrete in the truck would begin to harden one hour after leaving the batch plant, each truck held only enough concrete to fill 10 columns (i.e., anticipated 1 hour of work). Since the crew only achieved 8.3 columns per hour, perhaps the extreme weather conditions were taking their toll on the production of the crew.

PRODUCTIVITY EVALUATION

Performance of the concrete placement operation was evaluated by comparing the actual productivity with the estimated (i.e. predicted, expected, forecasted, etc.) productivity. The actual productivity was determined by considering input and output of the operation. This is discussed in the following sections.

Output

The physical measurement approach was selected for use over alternate approaches (e.g., estimated percent complete or earned value) to represent output in the productivity calculation. Output was defined as the number of cubic yards of concrete in one column. This turned out to be 0.33 cubic yards per column.

$$Output = Linear\ feet \times Width\ /\ 27\ ft^3/cy$$

$$= 8.833\ ft \times 1 ft \times 1 ft\ /\ 27\ ft^3\ /\ cy$$

$$= 0.33\ cy$$

Input

Input was defined as man-hours per column in lieu of other definitions (e.g., dollar cost per column). The data from the five minute rating were used to compute the number of man-hours per column. This calculated out to 0.93 man-hours per column.

$$Input = Man\text{–}hours\ for\ pouring\ one\ column$$

$$= 0.93\ man\text{–}hours$$

$$Productivity = Input/Output$$

$$= 0.93\ /\ 0.33$$

$$= 2.83\ man\text{–}hours$$

Based upon the Means Building Construction Cost Data 1992 (1991), the estimated productivity rate for the placement of one 12″ concrete column, using a crane and bucket, is 1.6 man-hours/cy.

Performance

The performance factor was calculated using the estimated and actual productivity. In evaluating a process, theoretically the performance factor should be 1.0. A performance factor larger than 1.0 indicates that crews are more productive than expected, whereas a performance factor smaller than 1.0 indicates that crews are less productive than expected.

$$PF = Estimated\ Productivity\ /\ Actual\ Productivity$$

$$= 1.6\ /\ 2.83$$

$$= 0.57$$

It was determined that there are two possible reasons that the performance factor is less than 1.0 for the given process. First, the crew size for the estimated productivity in the Means Data was for eight crew members. This process only had seven crew members. Secondly, the Means Data had two vibrators for the pour, whereas this process only used one vibrator. Also, this process was a small pour compared to the projects estimated in Means (1991). Therefore, the actual performance factor is probably higher than the 0.57 calculated above.

SIMULATION MODELING

MicroCYCLONE, a discrete event process interaction simulation program, was used to model and simulate the operation (Halpin 1990). A network diagram was prepared using the "circle and square" modeling notation provided by the microCYCLONE environment to graphically depict the active and passive steps of workers and equipment in the operation. Network input statements were developed to describe the sequential logic of work tasks. This is followed by a description of the duration input and the resource input. A listing of the network, resource, and duration input statements developed is provided in **Figure 3**. The input statements are then compiled and a simulation is performed producing tabular reports which contain productivity information about the system as a whole and statistics (e.g., percent busy, percent idle, number of work entities processed or in queue, etc.).

The microCYCLONE model developed for the concrete placement operation is presented in **Figure 4**. As modeled, the main repetitive process begins with filling the bucket with concrete, followed by lifting the bucket, pouring the column, vibrating the column, and lowering the bucket. This repetitive process model starts at a different point in the cycle than the field observations. This is due to the fact that it was easier to model the process by starting at this point. After ten columns have been poured, the next cycle will begin by changing concrete trucks and performing the slump test on the concrete. Then, the next ten cycles will occur. From **Table 6** and **7**, the final cumulative productivity by cycles was determined to be 8.37 (0.1395 units per min.) columns per hour. This result closely matches the overall productivity from the MPDM analysis of 8.32 columns per hour. A productivity plot generated from this data is presented in **Figure 5**. As shown, the cumulative productivity initially passes through a transient or warm-up phase before beginning to level off as the crews approach the "natural rhythm" associated with the process.

CONCLUSIONS

For the construction operation analyzed, it was determined that the concrete placement crew studied was well trained and experienced. There were no major inefficiencies observed. Based on the results of this study, it is recommended that the bucket loader position be eliminated. It was determined that this worker was effective only 24 percent of the time and that his job could actually be handled by the concrete truck driver. Allowing the truck driver to fill the bucket would make the operation about 7 percent more effective and improve the efficiency to 53 percent. This proposed change in tasking should not adversely affect the safety of the concrete placement operation.

The proposed new crew balance is shown in **Figure 6**. Notice it shows the slump test being accomplished by the superintendent. It was determined that he could come down off the structure once per truckload of concrete to do this task without too much disruption or danger of the operation falling apart. Because this is a minor change which only involves the reassignment of one worker from one task to some other task on site, the superintendent could probably have handled this without a major implementation plan or motivational speech.

From this study of the repetitive process of filling column forms with concrete using a crane and bucket, the following conclusions are drawn: (1) the experienced Parker Building Company crew headed by superintendent Ed Strickland were performing an operation they had done many times before and were efficient at placing the concrete; (2) the elimination of one crew member and reassignment of his duties could improve the efficiency of the crew and would put them above 50 percent efficiency; (3) placing concrete by bucket and crane inherently involves unavoidable idle times for several crew members during the back and forth transportation of the concrete bucket; (4) the extreme heat and humidity had a somewhat debilitating effect on this crew; and (5) videotaping is an excellent method of collecting data, providing a permanent record of the operation, and reviewing a process for analysis.

Method improvement techniques can be easily used by contractors to improve the productivity of a repetitive construction process.

```
PROCESS: dorm
---------------------------------------------------------------------------
                              *** NETWORK FILE ***
---------------------------------------------------------------------------
LINE  1 :  NAME RESIDENCE HALLS CONCRETE PLACEMENT LENGTH 10000 CYCLES 13
LINE  2 :  NETWORK INPUT
LINE  3 :  1 QUE 'TRUCK AVAILABLE'
LINE  4 :  2 COM SET 2 'POUR CYCLINDERS' FOL 3 4 PRE 1 3
LINE  5 :  3 QUE 'LOADER CREW AVAILABLE'
LINE  6 :  4 QUE 'READY TO FILL BUCKET' GEN 10
LINE  7 :  5 QUE 'CRANE & BUCKET IDLE'
LINE  8 :  6 COM SET 6 'FILL BUCKET' FOL 3 7 PRE 3 4 5
LINE  9 :  7 NOR SET 7 'LIFT BUCKET' FOL 8
LINE 10 :  8 QUE 'READY TO POSITION'
LINE 11 :  9 QUE 'SUPT. READY'
LINE 12 :  10 QUE 'BUCKET OPENER READY'
LINE 13 :  11 COM SET 11 'POSITION BUCKET' FOL 9 12 PRE 8 9 10
LINE 14 :  12 QUE 'READY TO POUR'
LINE 15 :  13 QUE 'VIBRATOR CREW AND EQUIP. READY'
LINE 16 :  14 COM SET 14 'POUR CONCRETE & VIBRATE' FOL 10 13 15 16 17 PRE 12 13
LINE 17 :  15 NOR SET 15 'LOWER BUCKET' FOL 5
LINE 18 :  16 FUN CON 10 FOL 1
LINE 19 :  17 FUN COU QUA 1 FOL 18
LINE 20 :  18 SINK 'COLUMNS COMPLETE'
LINE 21 :  RESOURCE INPUT
LINE 22 :  1 'TRUCK' AT 1
LINE 23 :  1 'LOADER CREW' AT 3
LINE 24 :  1 'CRANE AND BUCKET' AT 5
LINE 25 :  1 'SUPERINTENDENT' AT 9
LINE 26 :  1 'BUCKET OPENER' AT 10
LINE 27 :  1 'VIBRATOR AND CREW' AT 13
LINE 28 :  DURATION INPUT
LINE 29 :  SET 2 DET 30
LINE 30 :  SET 6 BETA 20 92 0.71 1.69
LINE 31 :  SET 7 BETA 58 112 2.13 1.62
LINE 32 :  SET 11 BETA 21 138 0.53 0.88
LINE 33 :  SET 14 BETA 25 307 0.84 1.91
LINE 34 :  SET 15 BETA 36 179 0.76 1.69
LINE 35 :  ENDDATA
LINE 36 :  ENDDATA
LINE 37 :  ENDDATA
LINE 38 :  ENDDATA
LINE 39 :  ENDDATA
```

Figure 3. MicroCYCLONE Input File

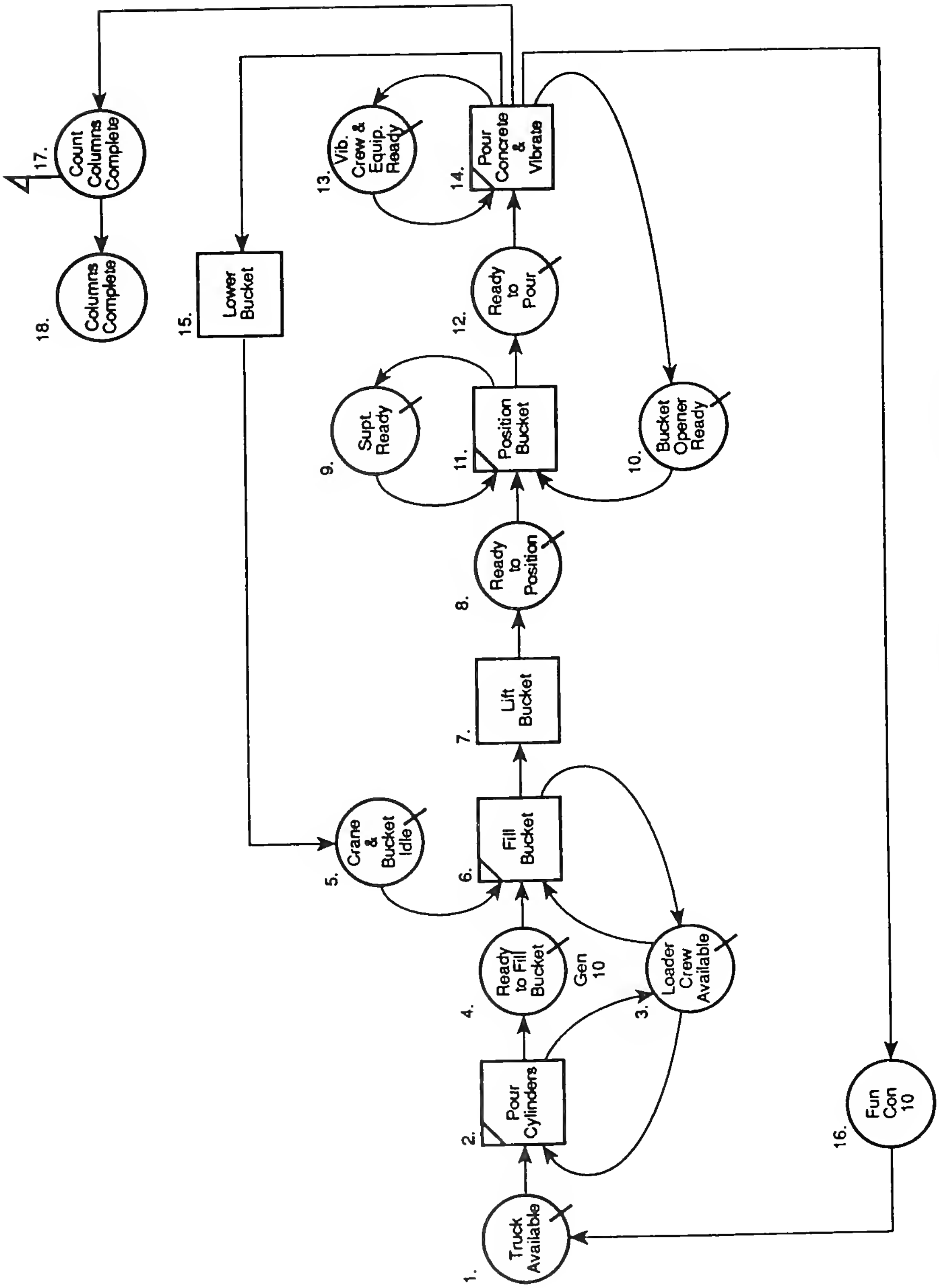

Figure 4. MicroCYCLONE Simulation Model (Concrete Column Model)

Table 6. MicroCYCLONE Report #1 (Report by element)

TYPE	LABEL	DESCRIPTION	STATISTICS				
			COUNT	MEAN DUR.	AR.TIME	AVE.NUM	% BUSY
COMBI	2	POUR CYLINDERS	2	30.00	2212.62	0.01	1.1
COMBI	6	FILL BUCKET	13	44.56	400.25	0.10	10.4
NORMAL	7	LIFT BUCKET	13	90.08	406 05	0.21	20.9
COMBI	11	POSITION BUCKET	13	72.64	408.24	0.17	16.9
COMBI	14	POUR CONC. & VIB.	13	138.99	430.19	0.32	32.3
NORMAL	15	LOWER BUCKET	12	88.40	431.47	0.19	19.0

TYPE	LABEL	DESCRIPTION	STATISTICS			
			AVG.WAIT	AVG.UNIT	UNITS END	% OCCUPIED
QUE	1	TRUCK AVAILABLE	0.00	0.0	0	0.0
QUE	3	LOADER CREW AVAIL.	309.57	0.9	1	88.6
QUE-GEN	4	READY TO FILL BUCKET	1551.77	5.5	7	92.8
QUE	5	CRANE & BUCKET IDLE	2.31	0.0	0	0.5
QUE	8	READY TO POSITION	0.00	0.0	0	0.0
QUE	9	SUPT. READY	332.01	0.8	1	83.1
QUE	10	BUCKET OPENER READY	202.94	0.5	1	50.8
QUE	12	READY TO POUR	0.00	0.0	0	0.0
QUE	13	VIB. CREW & EQUIP. READY	270.40	0.7	1	67.7
SINK		COUNT = 13				

TYPE	LABEL	DESCRIPTION	STATISTICS		
			COUNT	BETWEEN	FIRST
FUN-CON	16		13	430.19	511.41
FUN	17		13	430.19	511.41

Table 7. MicroCYCLONE Report #3 (Production by cycle)

SIMULA. TIME	CYMKUMB.	PRODUCTIVITY (UNITS/MINUTES)
511.4	1	0.1173
995.5	2	0.1205
1490.8	3	0.1207
2097.0	4	0.1145
2447.7	5	0.1226
2739.2	6	0.1314
3173.7	7	0.1323
3614.4	8	0.1328
3927.4	9	0.1375
4395.2	10	0.1365
4821.4	11	0.1369
5136.0	12	0.1402
5592.5	13	0.1395

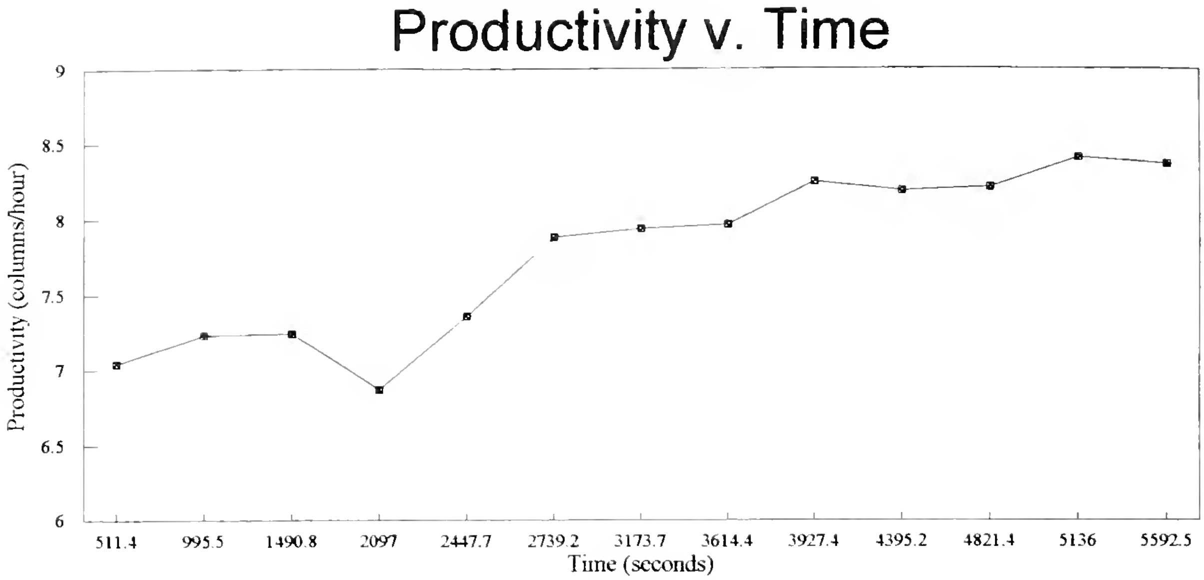

Figure 5. Productivity plot

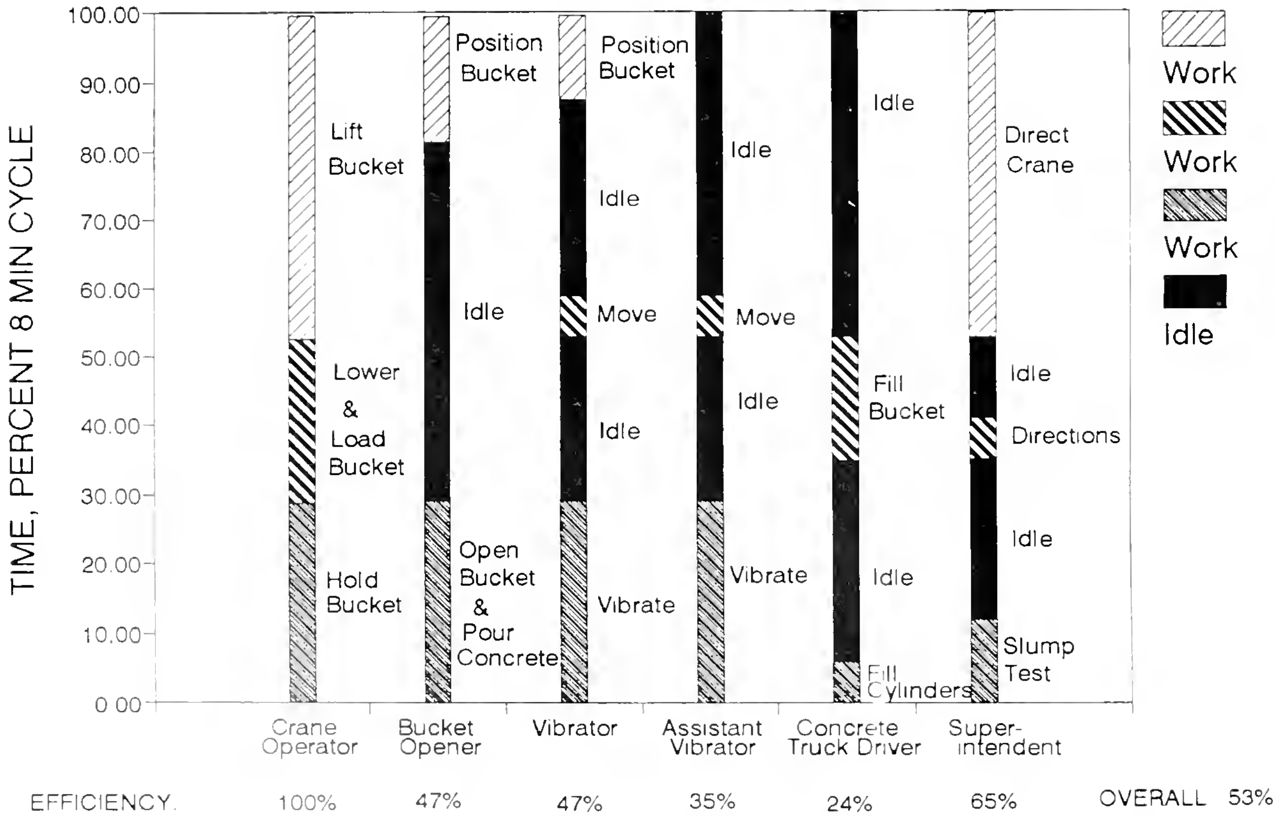

Figure 6. Revised crew balance chart

These techniques include videotape recording, work sampling, five minute rating, crew balance chart, process chart, method production delay model, and performance factor. In addition, computer simulation can be a useful tool in modeling a repetitive concrete placement operation. These approaches can help identify delays and other inefficiencies and can foster appropriate changes to the operation. In practice, it may be beneficial to field test proposed changes and solicit suggestions from the construction crafts as part of a methods improvement program.

ACKNOWLEDGEMENTS

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An Automated System for House Inspection

A. Sawhney, T. J. Toth, and S. M. AbouRizk

ABSTRACT

This paper describes the design and development of an automated system for purchase-related inspection of a single family house. The objectives were to provide a tool that can speed up and enhance the work of a professional inspector and to contribute to the standardization of the inspection process in Canada. The system was developed for the Microsoft Windows environment using Visual Basic programming software. It benefits the inspection process by providing improved accuracy and productivity compared to the manual methods and electronic storage of past inspections. The system was evaluated and validated through actual inspections performed on two houses in Edmonton, Alberta. The authors believe that ongoing use of the system will result in overall improvement to the inspection process and will improve consumer confidence in the pre-purchase inspection of houses.

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INTRODUCTION

It is generally recommended that potential buyers obtain documentation detailing the exact physical condition of a house before finalizing an offer to purchase. Because most consumers lack the technical expertise necessary to do the work involved, the services of professional inspectors are usually retained. During the course of this research, it was found that there is no specific standard governing the inspection process; inspection methodologies used by various inspectors range from assessing the condition of the building based on building code requirements to assessing workmanship. Further, it was observed that the inspection process is highly subjective and relies wholly on the experience and knowledge of the inspector. The authors envisioned that automation of the inspection process could improve present methods and produces more consistent results. This was the source of motivation behind the work.

The objective of this project was to develop an automated system that guides its users through house inspection process and produces a detailed and accurate report of the physical condition of the property. The work resulted in a system, called the Automated House Inspection Advisor which is currently being tested in Alberta.

The program is driven by a knowledge-based expert system. Knowledge-based expert systems are computer programs that incorporate expert human knowledge for a particular problem domain; they can be developed to provide access to stored knowledge by different means including "if...then..." rules and context sensitive help functions. In this research an expert system that models human performance at the user input stage in addition to providing expert knowledge at the output stage was developed. Hence the term "automated system" is used in this paper to refer to this enhanced form of expert system.

INFORMATION SOURCES

Because there is no set standard governing the inspection process in Canada, available information from several sources was examined and utilized as appropriate to ensure that inputs to the system constituted a best-fit representation of generic field work. These sources included industry associations, government agencies and practitioners.

The American Society of Home Inspectors (ASHI) has led the way in developing a structured and systematic way of inspecting houses. ASHI has also developed some preliminary computer programs and training manuals (ASHI, 1991) aimed at assisting inspectors in the reporting procedure. Alberta Consumer and Corporate Affairs publishes a buyer-oriented "tipsheet" (Alberta Consumer and Corporate Affairs, 1992) that shows consumers how to conduct a thorough but non-technical inspection using a detailed checklist. The Canada Mortgage and Housing Corporation distributes checklists and reports (CMHC, 1990) that discuss most inspection issues from the perspective of compliance with the National Building Code of Canada.

An executive official and practicing member of the Canadian Association of Home Inspectors - Prairie Section was chosen as the primary source of practitioner expertise. Inspection checklists from several companies with differing experience in house inspection and inspection procedures were also obtained. The final design of the system was greatly influenced by the study of these inspection checklists.

Detailed information for the development of textual and graphic help was obtained from Smith and Honkala (1990) and Hool et al. (1991). The National Building Code of Canada was used to obtain information pertaining to the identified house components for inclusion in the help libraries.

DESIGN OF THE AUTOMATED SYSTEM

The design of the automated system was driven by two important factors. First, it was clear that efficient design required accurate modeling of the manual inspection process. Second, the complexity of the resulting system was to be minimized. Detailed system design was preceded by three tasks - determination of the inspection process, identification of the components of the house to be inspected and representation of the components to be inspected.

Determination of the Process

In order to provide an efficient automated system it was essential to model the manual process. For this purpose, three different professional inspectors in Edmonton were consulted (all three inspectors have an Bachelor of Science degree in engineering and over ten years of practical experience). Information was obtained through personal interviews and from copies of their inspection checklists. Examination of the checklists showed quite clearly that different inspectors follow different techniques for inspection. One common feature highlighted by this study was, regardless of technique, the inspections followed a logical path, proceeding from the exterior to the interior. System design was, therefore, based on the same premise. Conceptually, the defined work flow process can be represented as follows:

- Exterior - site;
- Exterior - structure from ground level inspection;
- Exterior - structure from roof level inspection;
- Interior - basement;
- Interior - main and upper floors; and
- Interior - attic.

Identification of Components to be Inspected

To best serve industry requirements, a decision to follow the inspection process definition of the American Society of Home Inspectors was made. This definition breaks the process down into eight categories: structural, envelope, roofing, plumbing, heating/ventilation/air conditioning, electrical, interior, and insulation. A ninth category - siteworks - was added. Where necessary the categories were split or subdivided to suit the work flow process as outlined in the previous section. For example, the structural category includes the foundation and floor joists; however, since they will be inspected at different intervals (the foundation from the exterior and the floor joists from the basement), they will not appear together in the system.

Identification of the individual components to be inspected was accomplished through review of the various sample check lists. The resultant list was a combination of items common to all sample lists and items appearing on some sample lists but not on others, all arranged to suit the identified work flow process.

Representation of Components to be Inspected

To be of most benefit to its user, an automated system must do as much of the work as possible. For this system, the aim was to provide all feasible input possibilities so that the user will only need to select, from the options offered, those that best describe the actual component under scrutiny. The following parameters were selected for this characterization of components:

- Usual descriptive name;
- A listing of typical materials that make up the component;
- An indication of the present condition of the component; and
- An indication of whether the component is in need of repair.

To supplement this characterization, descriptions of the functions of each component, to be synthesized into a "help" function within the automated system, were prepared. **Figure 1** shows the typical structuring of parameters of a house component.

DRIVEWAY	
Material	Concrete, Gravel, Asphalt
Condition	Major cracking, Minor cracking, --
Functional	Yes, No
Comments	Driveway in very poor condition

Figure 1. Typical structuring of the parameters of a house component

Conceptual Design of the Automated System

The nature of the house inspection process requires that the system be developed in a hybrid environment, which includes a knowledge-based structure with graphics and text browsing capability. Conceptually the environment contains three distinct parts as shown in **Figure 2**. The user interface had to be designed to guide the user through the inspection process without confusion. Consequently it must contain all necessary subject-related input information together with mechanisms to assist the user in extracting the appropriate knowledge relevant to the inspection being carried out. Output consists primarily of completed inspection reports.

The conceptual model shown in **Figure 2** depicts various features of the user interface, shows the flow of data in the system, and indicates output forms. The user interface is centered around input forms which facilitate the entry of observations during an inspection. The input forms are, in turn, supported by navigation features, help functions and graphics. With the navigation feature, the user can select and move from one input form to another both in the forward and backward direction. The help and graphics features provide context-sensitive help to the user. Using these features, the users can instantaneously get textual and graphic help on a particular component of the house. Once the user (with the aid of the user interface) provides the required information, the automated system internally groups the information into general, textual and factual information. The client and property information entered by the user is the general information which is passed to a subroutine called "text handler" and stored as an array. For each component of the house the user provides information on various characteristics. This is termed as the factual information. Similarly, for each component of the house the user can provide brief comments, called the textual information. Both the textual and factual information are used in various subroutines to provide output reports. At the completion of an inspection session the user can save the information into a text file which can later be retrieved for editing and printing. Additionally, the user can directly print reports on the current inspection session. The automated system provides two types of reports which include a special report

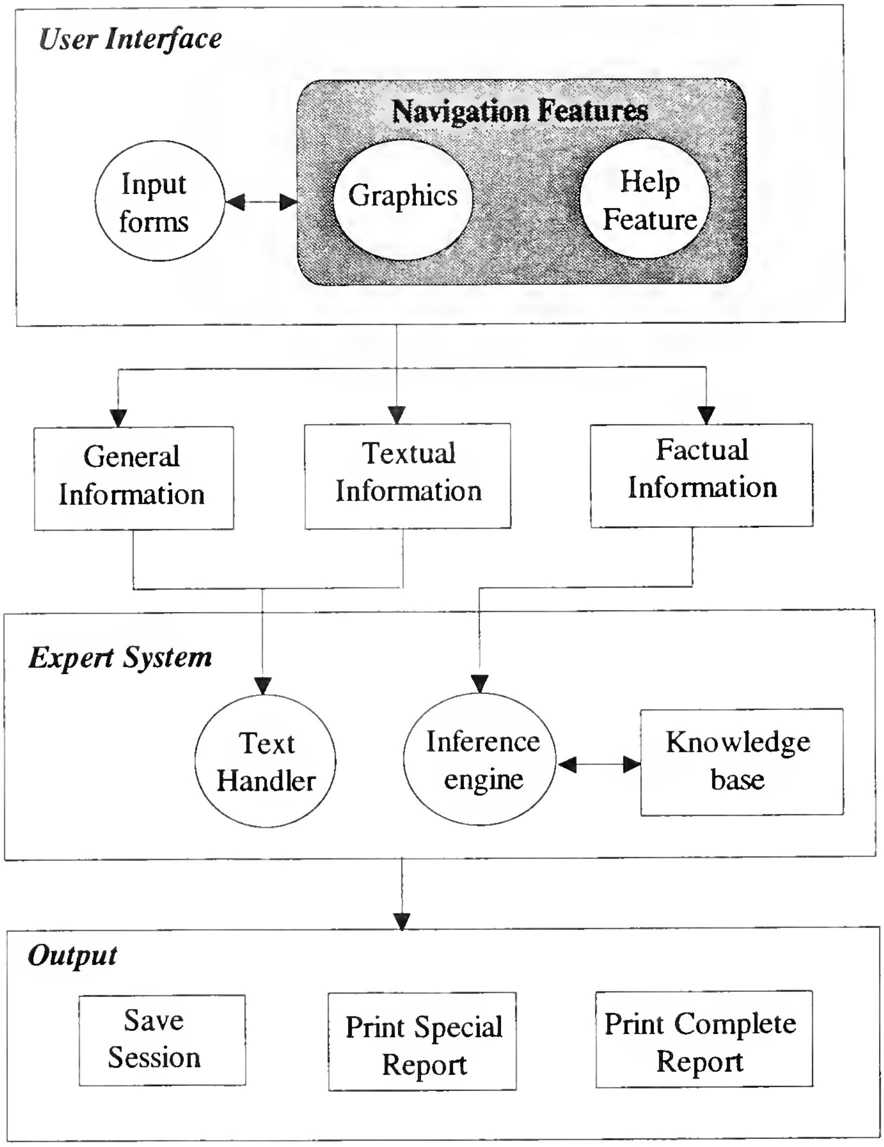

Figure 2. Conceptual Design of the automated system

highlighting the problem areas and a complete report.

IMPLEMENTATION OF THE AUTOMATED SYSTEM

The automated system was developed using Visual Basic programming language for the Microsoft Windows™ environment. The main reason behind the selection of this development environment was the ease with which a graphical user interface could be developed. Additionally, the Visual Basic/Windows combination provides the hybrid environment required by the automated system. This environment allows for the utilization of various tools and techniques including knowledge-based expert systems, hypertext, object-oriented paradigm, event driven programming, dynamic data exchange (DDE), and dynamic link libraries (DLL).

System Development Using Visual Basic

Visual Basic is a development system for Microsoft Windows and OS/2 Presentation Manager specifically attuned to graphics applications (Microsoft, 1993). Visual Basic enables the developer to take full advantage of the supporting features of the graphical environments and operating systems. It supports advanced features like dynamic data exchange (DDE) and dynamic link library (DLL) which allow interaction with other Windows and OS/2 applications. Visual Basic uses the simplified syntax of BASIC and GW-BASIC, and supports nearly all of their capabilities.

Programming in Visual Basic is centered around objects called VB Objects which include:

- Forms; and
- Control objects.

Forms. These are windows that act as templates for the entire program and for other VB objects. Forms have a set of pre-defined properties, events and methods. A program developer can use these to customize the graphical user interface.

Control Objects. These are the graphical objects which can be drawn on a form object to produce the graphical user interface. In the development of the automated system, the following control objects were used:

- Text Box control object: a simple object that can be used to accept textual input from the user.
- ComboBox control object: a drop-down option box in which the user is allowed to select one of the given choices. When the user clicks on the control object a drop down list is displayed and the user can select the appropriate variable using the up and down arrow keys or mouse.
- Command button control object: a graphical object that is displayed to the user for the execution of commands.
- Menu bar control object: a graphical feature which can be used by the programmer to develop drop-down menus for the program.
- Check box control object: an object that allows the user to select an option by clicking on the check box. This allows the user to select one or more of the displayed options.

The automated system implemented in the Visual Basic environment appears to the user in the familiar "Windows" setting. Fully implemented features include:

- Graphic and textual help using Window's help compiler;
- Printing feature;
- Save session feature; and
- Navigation from one screen to any other in either the forward or backward direction.

The program has four major types of screens which include:

- Welcome screen,
- Client information screen,
- Actual inspection screens, and
- Final screen.

Welcome Screen. This initial screen displays copyright information and enables the user to specify the type of session to be run. The options offered include starting a new inspection, accessing an existing inspection file, and printing a blank checklist which can be used for manual inspection when required or desired. The user can also exit the program if desired. (The 'abandon' or exit feature is available on all ensuing screens.)

Client Information Screen. This screen was designed to record information about the client for whom the inspection is being done.

Inspection Screens. The inspection process follows a logical sequence from the exterior to the interior of the house, and the presentation of inspection screens reflects that sequence. **Figure 3** shows a typical inspection screen. On this screen, four different components of the property are displayed by individual panes. The panes can be completed in any order, and information entry within the panes can also be completed in any order. Input information is entered by accessing drop-down menus (clicking on the arrow buttons) and selecting the appropriate descriptor from the options presented. For the "Functional" slot, the inspec-

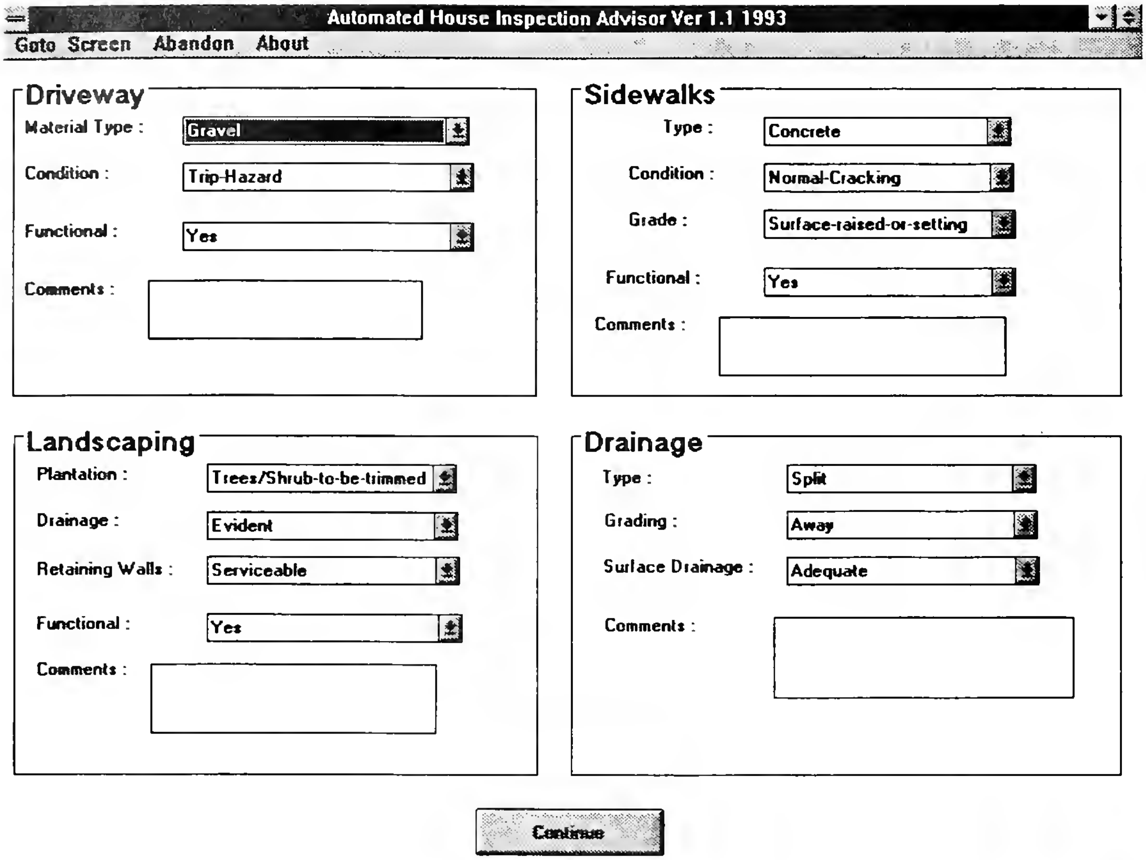

Figure 3. Typical inspection screen.

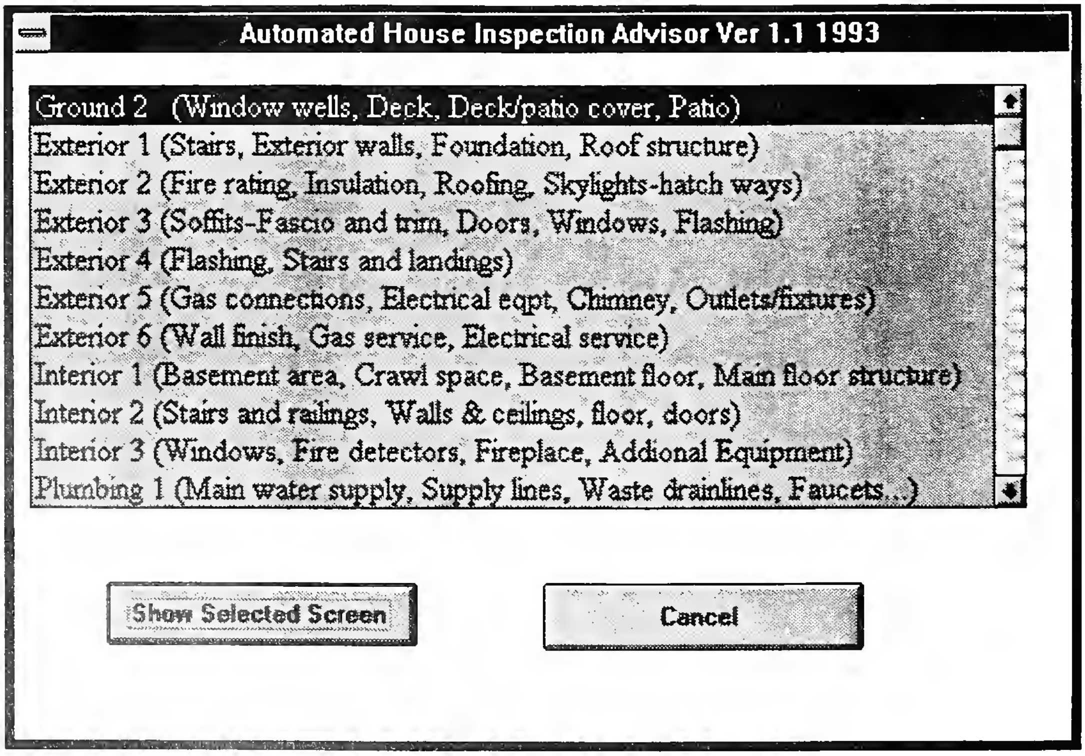

Figure 4. Goto Screen

tor forms an opinion on whether the component being inspected is acceptable, and selects "Yes" or "No" accordingly. In the text box adjacent to "Comments" the inspector can key in any specific observations he has about the particular component. These text entries are limited to 256 characters.

The "Goto Screen" command on the menu bar is an important feature of each inspection screen. Clicking on this command produces the menu screen illustrated by **Figure 4**. The inspector can jump to any other screen by highlighting it and clicking on the "Show Selected Screen" command button. This gives the inspector complete freedom to determine the order of the inspection, or to edit previous screens.

At any time the inspector can call up Help screens by pressing the "F1" key. There is a Help screen for each pane of each inspection screen. The Help screen for the Driveway and Sidewalk panes is illustrated by **Figure 5**.

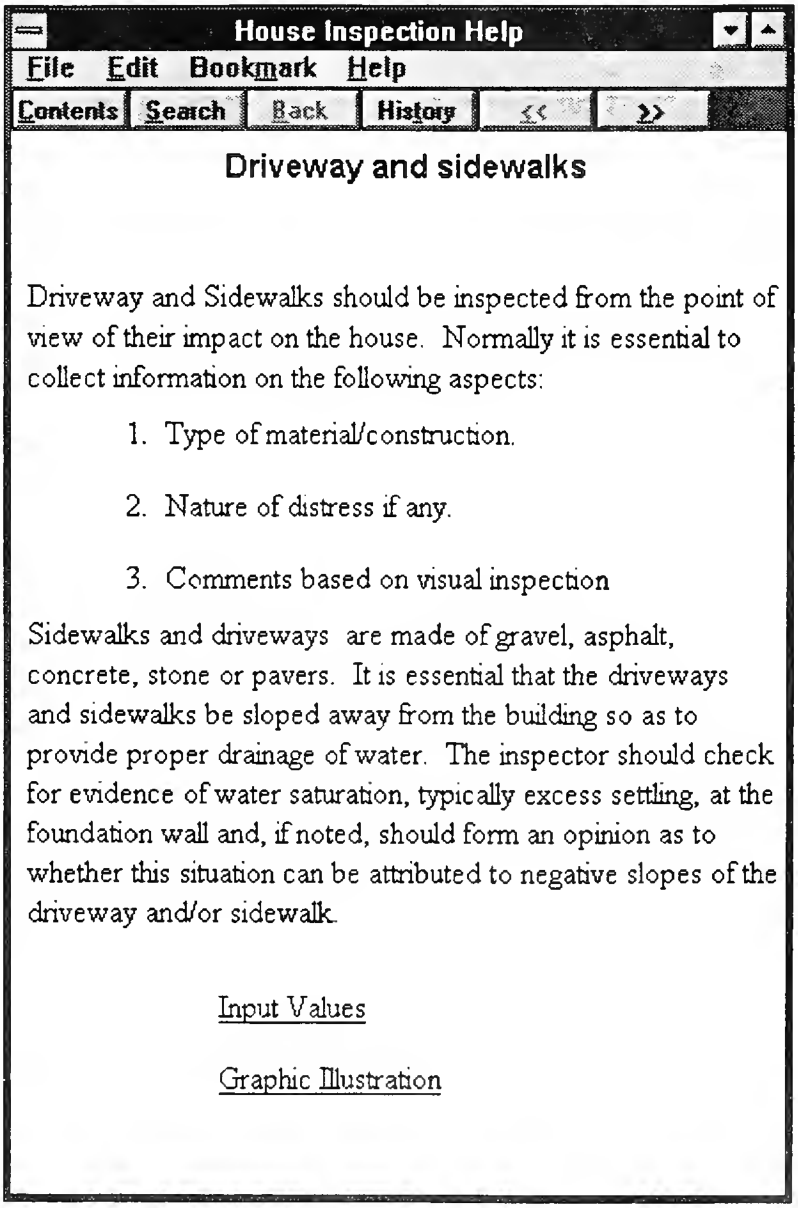

Figure 5. Help screen for the Driveway and Sidewalk panes

The Help feature was developed using the Microsoft Windows Help compiler. Therefore, the Help feature has all the functions that are supported in Windows Help. The following options are available the user:

- print the current topic;
- jump to the contents of the help buttons provided on the screen. For example, on the sample screen of **Figure 5** the user can access the "Input Values" screen and "Graphic Illustration" screen;
- search for help on other topics;
- navigate forward or backward; and
- create bookmark references.

The inspector can also call up graphic illustrations while progressing through the inspection screens. Graphic illustration screens are accessed through the relevant Help screens. Graphics were not included in the scope of this project, but a limited number of graphic illustrations have been included to demonstrate the system's capabilities. Extensive graphic illustrations will be a feature of future versions of the Automated House Inspection Advisor. **Figure 6** shows a typical graphics screen.

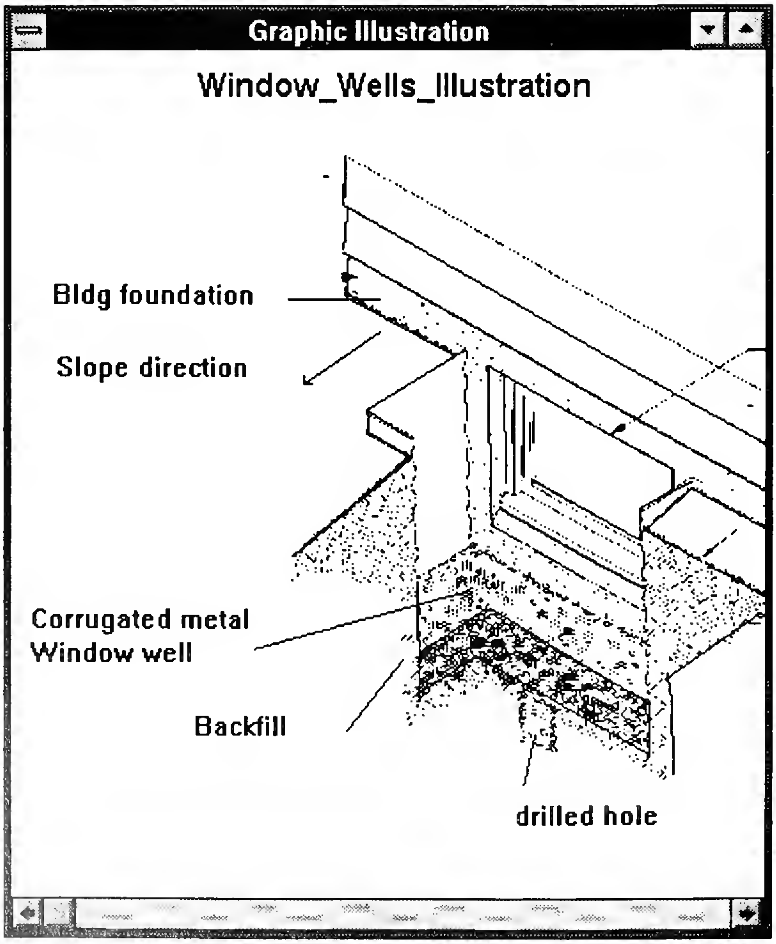

Figure 6. Typical graphics screen

Final Screen. The final screen provides output options which include Save Session, Print Report and Print Special Report. Using the "save-session" option the user can save the session information in a random access file. This feature allows the user to electronically store information on past inspections and retrieve it for editing and printing at a future date. The "print report" option allows the user to produce a complete report of the session using a printer configured for the Windows operating system. The "print special report" option allows the user to produce an executive summary of the components of the house that are not functional. This report uses simple rules to search through the factual information provided by the user and creates a snap-shot of the components that are not functional.

SYSTEM EVALUATION

In order to evaluate the developed system the research team undertook two actual house inspections. The inspections were performed in conjunction with manual inspections performed by the practitioner retained for this project. The first test site was a 12-year old single family dwelling in Sherwood Park, Alberta. It was a 3-bedroom, 1400 square foot, 2-story house with 2 bathrooms and a full basement. The inspection was carried out by a member of the development team, using a laptop computer, in the presence of the professional inspector. The inspection took approximately 5 hours to complete. The manual inspection took about 4 hours.

The second test house was a 10-year old single family dwelling in Beaumont, Alberta. It was a 3-bedroom, 1100 square foot, 2-story house with 3 bathrooms and a full finished basement. Again the inspection was performed by a member of the development team, and was done in conjunction with a manual inspection by the research team's advising inspector. Inspection using the automated system took approximately 3-1/2 hours. This was comparable to 3 hours of manual inspection time. The time difference between the two methods was a function of disparities in practical experiences between the team member and practitioner, not a shortcoming of the automated system. The manual inspection required an additional 1/2 hour for compilation of notes in a form suitable for presentation to the customer. This time was not required for the automated system.

The design team noticed that at numerous occasions the practitioner had to guide the team member performing the inspection on the automated system. This was especially noticed for the "condition" and "functional" slots of various components. The automated system had all the possible choices available, but no mechanism was available to prompt the user to look for particular features of various components. Apart from this, the reports produced by the automated system were similar in content but better in quality than the manual reports. The system's range of input descriptors was judged adequate. Overall, the system produced satisfactory results. The design team noted that a user must have at least a basic understanding of construction methods and materials to benefit from the automated system and produce meaningful results with it.

FUTURE PLANS

Major enhancements, such as tailoring the Help feature to the novice, and tailoring the Help feature to the professional, will be part of an ongoing developmental process. Presently, the Help feature is a "middle-of-the-road" tool. It explains building components in simple terms for the benefit of users with no expertise. For experienced inspectors, it provides a "memory-jog" for ranges of materials used, and it is a valuable aide when answering questions raised by the homeowner during an inspection. Tailoring to the novice will include incorporation of further basic information, while tailoring to the professional will include incorporation of more in-depth technical information, such as detailed building code requirements and applications, and municipal bylaw requirements.

The system as is significantly reduces the chance that various components of the structure will be inadvertently omitted. Future releases will further enhance this quality through the incorporation of "integrity checks" that will list any components that were not inspected during a particular session, for review/verification by the inspector and for the information of the client. This level of recall is difficult to achieve through the manual process because it is subject to the imperfections of human memory.

General enhancements of the knowledge-base and continued graphics development will also be features of future versions.

CONCLUSIONS

This project demonstrated that a variety of computing techniques can be effectively combined in the development of an automated system for house inspections. The Automated House Inspection Advisor proved to be an effective tool that can significantly improve the productivity of the individual inspector while offering major improvement to current practice for the inspection industry in general. Testing of the system revealed that it is best used by someone familiar with the inspection process and with construction methods. A potential buyer of a house with limited knowledge will benefit from the comprehensive automated "check-list" that covers most house components, but would probably not be able to attain reliable results by conducting the inspection independently.

Automation of the inspection process enables an inspector to greatly reduce the time required to produce final high quality reports. Without further effort (aside from a single key stroke), summary reports of problem areas can be generated. This would be of particular interest to prospective buyers. The professional inspector that tested the program confirmed this conclusion.

Producing high quality reports with graphics and text customized to the specific house being inspected may take a considerable amount of time when done manually. The system's ability to generate such reports at the end of an inspection reduces the cost of inspection in addition to improving productivity. In combination, these benefits are likely to attract widespread use of the system by industry practitioners.

ACKNOWLEDGMENTS

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Benchmarking Construction Costs for Innovative Home Building Technologies

Michael A. Mullens, Robert L. Armacost, and William W. Swart

ABSTRACT

Construction cost is an important performance metric for a home building technology. It plays a vital role in determining price, profitability and eventual acceptance of the technology. This paper presents a framework for benchmarking construction costs for innovative home building technologies. The proposed methodology has three components: a set of guidelines for applying the methodology, a construction cost model, and a cost estimating procedure. The methodology is demonstrated by comparing several innovative home building technologies used for the construction of exterior structural walls. The technologies include conventional stick built construction, panelized wood frame (open panel) construction and stress skin insulated core (SSIC) panelized construction. Results are presented for a small sample of manufacturers.

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INTRODUCTION

The National Association of Homebuilders Research Center maintains an innovation database containing approximately nine hundred innovative home building technologies (Goldberg 1991). Most of these technologies promise improved performance over their conventional competitors on a variety of metrics such as lower construction cost, reduced construction cycle time, enhanced quality and improved energy efficiency. While many of these claims may be valid, few have been objectively substantiated. The purpose of this paper is to present a framework for benchmarking a key metric for innovative home building technologies, construction cost. *Benchmarking* refers to the direct comparison of a product's performance against that of established competitors with regard to certain metrics of interest. This form of product benchmarking is widely used in new product development (Hauser and Clausing 1988). *Cost* has been defined as "the summation of all resources required to produce the product" (Stewart 1991). *Construction cost* is similarly defined as the summation of all resources required to construct the house or its primary components.

Construction cost is a critical metric for most stakeholders in the home building process. For builders, construction cost drives pricing and profit, impacting market share and total profitability. Because construction cost drives pricing, it impacts the size and quality of the home which the home buyer can afford. Given these dynamics, both home buyers and builders are generally very sensitive to construction costs (Toole and Tonyan 1992). For manufacturers of innovative home building components, construction cost drives market acceptance and long term technology viability. From a societal perspective, construction cost provides a common denominator for initial resource consumption (materials, labor, capital, etc.). When coupled with other life cycle costs (e.g., energy, maintenance) and compared to competing technologies, construction cost can be used to help establish the relative efficiency or value of an innovative home building technology. Construction costs are also valuable at the elemental level. Detailed construction costs can serve as process benchmarking metrics, used by the component manufacturer and the home builders to identify and evaluate potential product and process improvement opportunities.

Published construction cost estimating tables are widely available for most conventional home building technologies. McDonald (1992) provides an extensive list of these references. In contrast, few comparable quantitative costs have been reported for innovative home building technologies. Friedman (1992) compared the "cost" (actually price), production time and quality of homes built using conventional (stick built) and prefabricated (modular, panelized and pre-cut) construction. His methodology utilized price quotes from builders/manufacturers for comparable architectural house designs. He concluded that conventional construction is less expensive than prefabricated construction, but it takes longer to build. Laquatra et al. (1993) compared panel manufacturing costs for an innovative Optimum Value Engineered long-wall panel against a more typical short wood frame panel. The costing methodology used was not described in the paper.

Several studies have addressed the cost of the innovative stress skin insulated core (SSIC) construction technology (Andrews 1992). Toole and Tonyan (1992) asserted that for most home designs, SSIC costs appear to average 10 percent to 20 percent higher than for conventional stick built construction, primarily due to higher material costs. They provided no substantiating data. Fischer (Nisson 1993), reporting recent side-by-side demonstration results, reported that the actual cost of constructing an SSIC home was lower than the cost of an architecturally similar stick built home with the same thermal specifications. No substantiating data was provided. Brown (1993) suggested that when SSIC panels are used for floor, wall *and* roof framing, cycle time reduction can be significant and can reduce time related costs such as financing and insurance. Brown concluded that when combined with an innovative house design tailored to SSIC panels, initial costs might be comparable or even lower than a conventional, stick-built benchmark. These results are indicative of the varied and conflicting perceptions regarding SSIC construction costs, many of which are legitimately rooted in real world pricing experiences.

In a more focused study, Smith, Grobler and Miller (1993) compared framing labor productivity between traditional (stick built) and systems (modular) home construction. The authors used a more detailed engineering methodology, utilizing video-taped field study results which were analyzed to estimate elemental production process times. Their findings suggested that, ideally, systems framing labor should be significantly less than that for traditional framing methods; however, in practice, the savings were not significant. Another important finding of their study was the difficulty in assuring comparable results. They concluded that the time required to collect and analyze results has been the major impediment to solid, quantitative cost reporting.

The process of estimating costs (cost engineering) has been extensively addressed in the literature for both manufacturing and construction environments (Dagostino 1993; McDonald 1992; Stewart 1991). However, the process of benchmarking construction costs for innovative home building technologies offers several unique challenges. First, conventional cost estimating approaches involve estimating costs for a specific design, as opposed to a technology capable of producing many designs. Second, the house is a very large scale product. Smith, Grobler and Miller's (1993) conclusion, that the time required to collect and analyze results has been the major impediment to solid, quantitative cost reporting, is valid. Third, Stewart (1991) has observed that operating data obtained from field studies are not of uniformly high quality. This is particularly true of innovative technologies in the early stages of commercialization which are likely to be poorly-defined and highly variable. Associated problems which were observed repeatedly in the field include: quality problems from the factory, ill-defined and poorly engineered assembly methods, and poorly trained and unmotivated crews. More mature innovative technologies may be better defined, but may still be particularly susceptible to market fluctuations and resulting plant inefficiencies (e.g., low utilization and high inventories). These factors can make comparisons difficult, particularly when compared to more stable conventional technologies. The methodology developed in this paper extends accepted cost estimating approaches to address the unique challenges associated with benchmarking innovative home building technologies.

The paper is presented in four sections. The study first develops the construction cost benchmarking methodology. Use of the methodology is then demonstrated by comparing several innovative home building technologies used for the construction of exterior structural walls. The technologies include conventional stick built construction, panelized wood frame (open panel) construction and stress skin insulated core (SSIC) panelized construction. Next, results from a small sample of manufacturers are presented and discussed. Finally, the paper is summarized and conclusions are noted.

CONSTRUCTION COST BENCHMARKING METHODOLOGY

There are two general approaches for estimating costs (Stewart 1991): 1) the top-down or parametric approach and 2) the bottom-up or industrial engineering approach. The latter approach, also called definitive estimating (McDonald 1992) and detailed estimating (Dagostino 1993), provides the most credible, supportable, usable and accurate estimate when a detailed definition of work is available (Stewart 1991). The approach involves estimating labor-hours and materials for each element of work and pricing and accumulating all costs into a total cost estimate. This approach is used as the basis of the construction cost estimating methodology described in this section. The methodology has three components: a set of guidelines for applying the methodology, a construction cost model, and a cost estimating procedure.

Guidelines

As stated in the Introduction, the process of benchmarking construction costs for innovative home building technologies offers unique challenges to the cost estimator. This section develops guidelines for applying the methodology which address these challenges. The first set of guidelines deals with cost estimation for a technology capable of producing multiple designs. A common housing element should be defined to serve as the basis for costing each technology. The element should be typical of new housing and, if less than a complete house, should be of sufficient size/scope to assess whole-house technology performance. At the same time size/scope should be limited to reduce unnecessary cost estimation efforts. The element should be interchangeable between technologies and have no significant residual impact on other housing systems.

The second set of guidelines addresses Smith, Grobler and Miller's (1993) conclusion that the time required to collect and analyze results has been the major impediment to solid, quantitative cost reporting. These guidelines seek to improve efficiency in data collection and analysis. Thuesen and Fabrycky (1993) have observed that in evaluating economic alternatives, only the *differences* between alternatives are relevant. Therefore, estimating effort should be focused on those elements which are likely to differ between alternative technologies. Finally, Pareto analyses can serve to focus efforts on the most significant cost items. These guidelines are useful both in defining the size/scope of the common housing element to be costed as well as in selecting the cost components to be considered. They can be of particular importance when addressing the many components of overhead cost.

The third set of guidelines deals with Stewart's (1991) observation that operating data obtained from field studies are not of uniformly high quality. Due to the lack of solid, quantitative data for many innovative technologies, resource requirements needed for costing should be independently developed from on-site field studies. To minimize bias and improve comparability, the estimator should be diligent in identifying and adjusting for non-standard operations, poor business practices, etc. which are not inherent to the technology. A key element of this adjustment process is to assume standard resource utilization rates for common resources (when low utilization is not inherent to the technology). For example, factory labor utilization, site labor utilization and capital facility/equipment utilization should be assumed comparable across technologies.

Finally, rates for materials, wages, and overhead items (production space, equipment, etc.) differ by location and may differ between builders/manufacturers in the same location depending on volume, negotiating expertise, etc. To minimize bias and enhance comparability, standard resource costing rates should be used for common resources (when a rate differential is not inherent to the technology).

Construction Cost Model

The cost model is used to identify elemental cost components and to establish their relationships in defining construction cost. The cost model (Equation 1) consists of two primary components, factory cost and site cost. Innovative home building technologies often utilize innovative factory manufactured components. The first term in the model reflects the sum of the resources required to produce these components. Home building also requires various construction site activities. The resources required to complete these activities are included in the second term.

$$CC = FC + SC \qquad (1)$$

where

CC = construction cost

FC = factory cost

SC = site cost

Factory cost (Equation 2) is the sum of direct material, direct labor and factory overhead (McDonald 1992) and is comparable to the factory cost developed in the Cost of Goods Sold financial statement. Factory cost does not include several non-production cost components which contribute to total cost, including administrative expense (executive salaries; office space; office supplies; office equipment; legal, auditing and other services, etc.) and selling expense (sales/marketing salaries, commissions, office space, travel, entertainment, etc.). The rationale for excluding these costs is that they are far removed from production and less likely to be a function of the home building technologies being considered. Profit is also excluded from factory cost.

Direct material cost is the purchase price of all materials which are directly used in manufacturing the component and become part of the component. This includes the waste and scrap generated by normal processing. Typical material categories include raw materials, purchase parts and sub-assemblies. Direct labor cost reflects all labor performed on the component to convert it to its final shape, including fabrication and assembly. Labor cost consists of wages and fringe benefits, including paid holidays/vacations, sick leave, health insurance, social security, etc. Manufacturing overhead includes all other expenses incurred in production which are not charged to the product as direct material or labor. A partial list includes the amortization of capital expenditures (e.g., facilities, equipment, inventories, software), indirect labor (e.g., manufacturing supervision, janitorial, maintenance, material handling, material procurement, inspection/test, engineering), and other indirect operating expenditures (e.g., facility/equipment rental, utilities, indirect materials, insurance, property taxes).

$$FC = DM_F + DL_F + OH_F \qquad (2)$$

where

DM_F = direct material cost in manufactured components

DL_F = direct labor cost in manufactured components

OH_F = manufacturing overhead in manufactured components

Site cost (Equation 3) is analogous to factory cost where the construction site is the "factory" (Dagostino 1993). Like factory cost, site cost excludes non-production costs associated with general (off-site) office activities. Dagostino (1993) refers to these costs as general overhead. Profit is also excluded from site cost.

Direct material and labor cost components of site cost are analogous to those of factory cost. Note that the home building components manufactured in the factory cost analysis are also direct materials for the construction site; however, they are not double-counted. Also note that their cost estimates do not include separate administrative expenses, selling expenses and profit for the manufacturer. This is consistent with the scenario of a large, vertically integrated home builder seeking an optimal production strategy. Job site overhead (Dagostino, 1993) includes all other expenses incurred on the construction site or as a result of the job which are not charged to the product as direct material or labor. The following is a partial list of job site overhead items which may be applicable to home building: salaries (construction supervision), temporary office (rent, setup and removal, utilities, office equipment, office supplies), bonds (performance), insurance (fire, theft, property damage, liability), temporary utilities (including sanitary), and other miscellanea (temporary buildings/enclosures, barricades, engineering services, clean-up, repair of street and pavement, damage to adjoining structures/property, permits/licenses, tools/equipment, signs, dust/erosion control, fuels).

$$SC = DM_S + DL_S + OH_S \qquad (3)$$

where

DM_S = direct material cost for materials added on site

DL_S = direct labor cost for site operations

OH_S = job overhead

Cost Estimating Procedure

The final component of the construction cost benchmarking methodology is a structured procedure for estimating the construction costs required by the cost model. The bottom-up cost estimating procedure described by Stewart (1991) consists of the following steps:

- 1. Collect and review all relevant drawings, documents, and other specifications to develop an understanding of the scope of work and deliverables required.
- 2. Based on the specifications, develop a detailed process plan describing the manufacturing, construction and support activities which must be performed and their precedence relationships.
- 3.Perform a material take-off, identifying the types and quantities of material required for each activity.
- 4. Perform a labor take-off. Breakdown each activity into estimatable units by discipline. Use industrial engineering standards, judgement of skilled personnel and other accepted estimating methods to estimate labor requirements (manhours) for each activity unit. Identify and apply applicable allowances to account for expected performance against these estimates.
- 5. Cost material and labor using standard unit prices and current wage and fringe rates.
- 6. Identify and develop best estimates for overhead expenses.

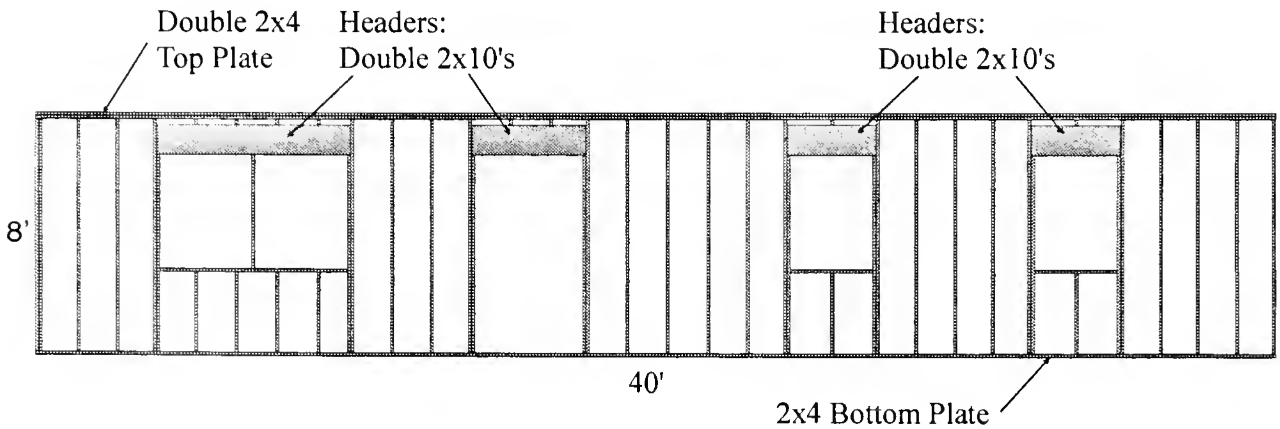
DEMONSTRATION OF CONSTRUCTION COST BENCHMARKING METHODOLOGY

In this section the proposed construction cost benchmarking methodology is demonstrated using a field study comparing several innovative home building technologies used for constructing exterior, structural walls. Exterior, structural walls represent a legitimate domain for cost analysis. They are a primary component of most houses and contribute significantly to total construction cost and thermal efficiency. Several recent studies have addressed cost-related issues in this domain (Friedman 1992; Laquatra et al. 1993; Smith, Grobler and Miller 1993). Study methodologies and results were discussed previously.

The specific technologies considered in this analysis include site-built wood frame construction, wood frame panelized construction, and SSIC panelized construction. *Site-built wood frame construction* is, by far, the most common home building technology used in the U.S. It is used as a benchmark against which the more innovative technologies can be gauged. Dimensional lumber, sheathing and other building materials are delivered directly to the construction site. Walls are framed on site, then plumbed, wired, insulated, and finished. *Wood frame panelized construction* has become the home building technology of choice for a number of large production builders. "Open" (framed and sheathed) panels are manufactured in a factory and shipped to the construction site. They arrive at the site as preconstructed wall, floor, and ceiling assemblies that workers erect and join. Once erected, the walls are virtually indistinguishable from conventional site-built construction. All electrical, plumbing and code inspections are completed on-site, as is most finishing. An *SSIC panel* is a prefabricated panel consisting of an insulative foam core sandwiched between two structural faces (Andrews 1992). SSIC panels are used to build exterior structural walls, roofs and floors in light commercial and home construction applications. Although widely available commercially for over 10 years, SSIC panels have made only marginal market penetrations and, in many ways, resemble an emerging technology. Current research interest is motivated by the SSIC panel's significant thermal benefits over conventional wood frame construction of comparable depth.

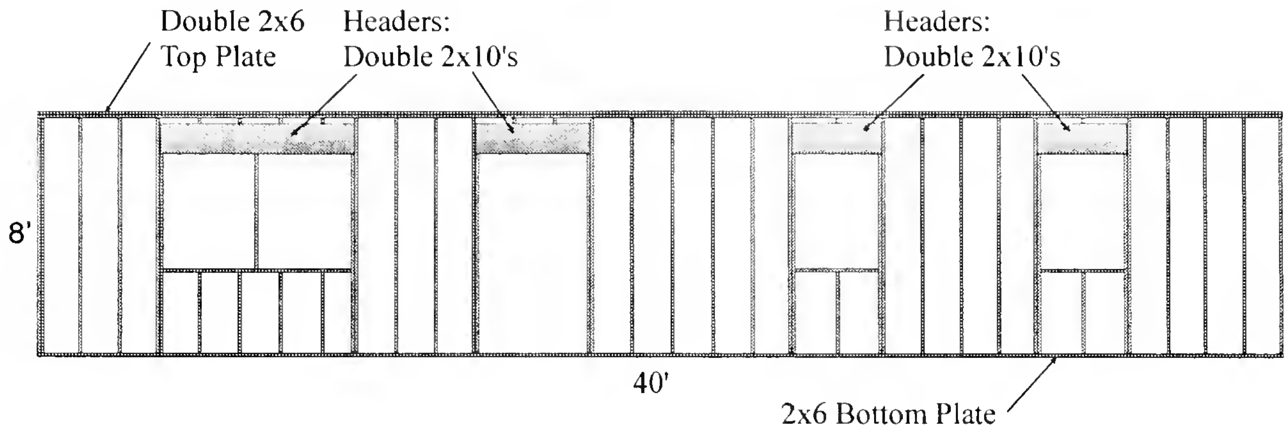
The first task is identification and documentation of the common housing element to be analyzed. The common element selected (termed the standard wall) was a single exterior structural wall, 40 ft long by 8 ft high, containing 3 windows and 1 door, and standing on-site, fully assembled and finished. The interior is specified as 1/2 in. sheetrock, finished and painted. Vinyl siding is specified for the exterior surface. It is assumed that the walls are constructed on a completed floor surface (either slab-on-grade or raised deck). It is also assumed that the wall will eventually be joined to a roof system (conventional truss or SSIC panel) and to other walls, both exterior end walls and interior walls. Configurations of the standard wall are shown in **Figures 1** through **6** for the following technologies: 2 × 4 stick built, 2 × 6 stick built, 2 × 4 factory frame #1, 2 × 4 factory frame #2, 2 × 6 factory frame, 4 in. SSIC #1, and 4 in. SSIC #2.

The standard wall satisfies the intent of the guidelines regarding selection of a common housing element. The wall construction technologies under consideration are largely interchangeable and have little residual cost impact on the rest of the house. Therefore, the impact of wall construction technology on whole-house cost can be assessed by focusing on the walls. The standard wall was defined to be of sufficient size and scope to represent all exterior structural walls in a new house and to be typical for new housing in general. Also note that the theoretical thermal performance of the standard wall differs between technologies. Duplicate studs in the panelized wall increase the level of thermal conduction slightly over that of a stick-built wall. The SSIC panelized wall has significant thermal advantages over the competing wood frame wall technologies, including



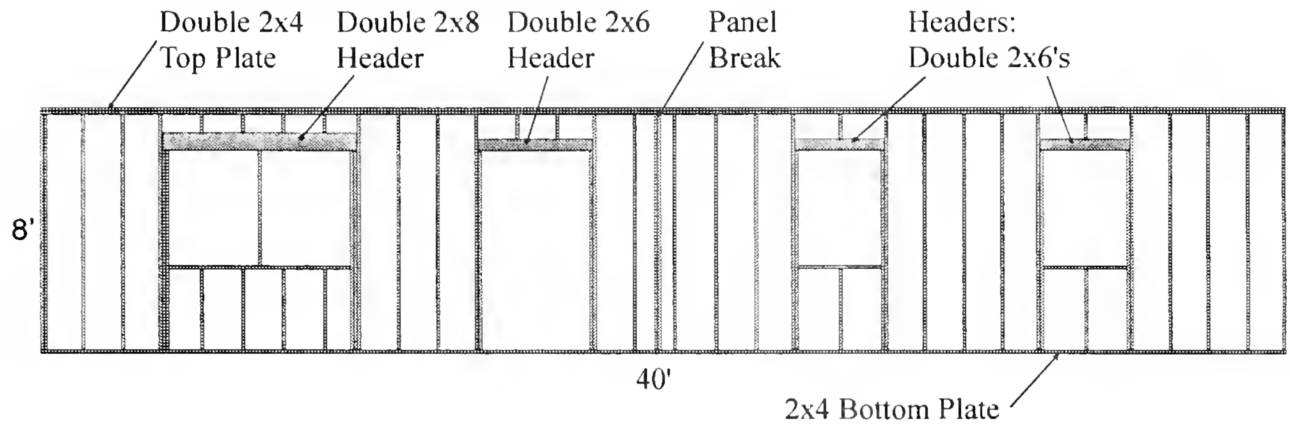
Wood Frame Construction Specifications:
Studs at 16" O.C., 7/16" OSB skins, 1/2" sheetrock interior sheathing, wiring and rough electric completed, windows and door installed, taping and spackling completed, interior painting completed, and vinyl siding installed.

Figure 1. 4" Stick built.



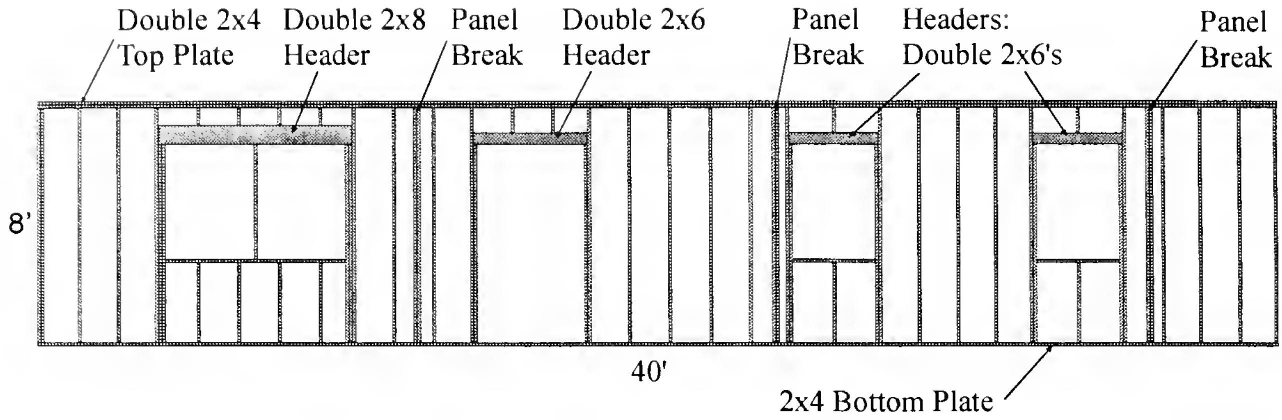
Wood Frame Construction Specifications:
Studs at 16" O.C., 7/16" OSB skins, 1/2" sheetrock interior sheathing, wiring and rough electric completed, windows and door installed, taping and spackling completed, interior painting completed, and vinyl siding installed.

Figure 2. 6" Stick built.



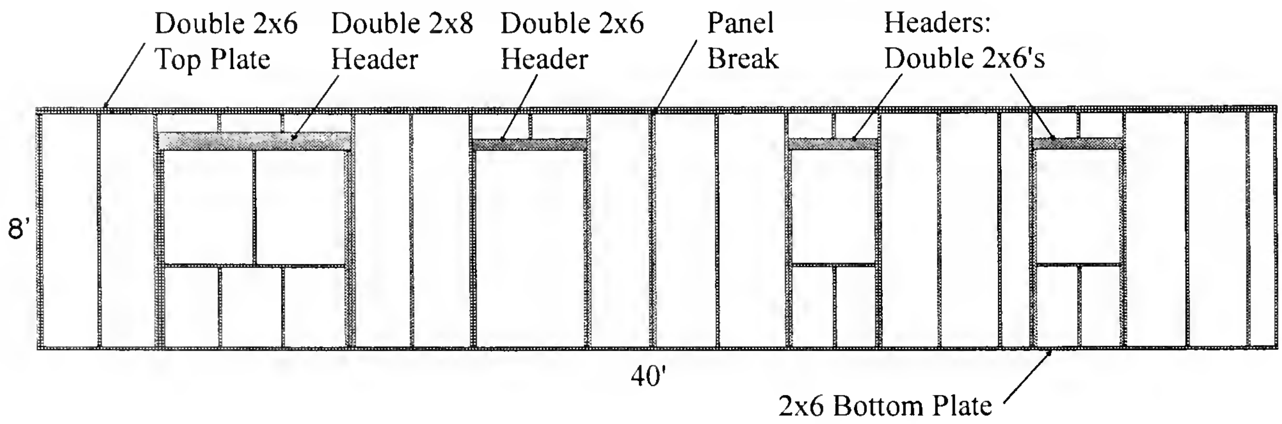
Wood Frame Construction Specifications:
Studs at 16" O.C., 7/16" OSB skins, 1/2" sheetrock interior sheathing, wiring and rough electric completed, windows and door installed, taping and spackling completed, interior painting completed, and vinyl siding installed.

Figure 3. 4" Factory frame #1.



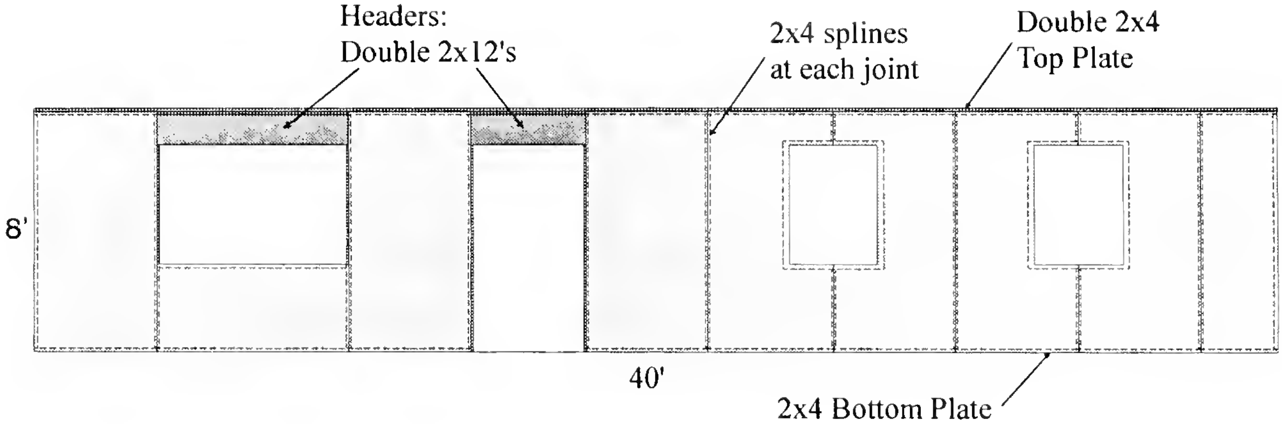
Wood Frame Construction Specifications:
Studs at 16" O.C., 1/8" Thermo-Ply skins, 1/2" sheetrock interior sheathing, wiring and rough electric completed, windows and door installed, taping and spackling completed, interior painting completed, and vinyl siding installed.

Figure 4. 4" Factory frame #2.



Wood Frame Construction Specifications:
Studs at 24" O.C., 7/16" OSB skins, 1/2" sheetrock interior sheathing, wiring and rough electric completed, windows and door installed, taping and spackling completed, interior painting completed, and vinyl siding installed.

Figure 5. 6" Factory frame.



Stress Skin Construction Specifications:
3 5/8" thick EPS insulation, 7/16" OSB skins, 1/2" sheetrock interior sheathing, wiring and rough electric completed, windows and door installed, taping and spackling completed, interior painting completed, and vinyl siding installed.

Figure 6. 4" SSIC #1 and #2.

reduced conduction and lowered air infiltration (Rudd and Chandra 1993).

The second step of the procedure involves development of detailed process plans describing the manufacturing, construction and support activities required for production of the standard wall. Data for the process plans were obtained during detailed field studies at four panel factories and six construction sites. Methods of data collection included: personal observation, conversations with laborers and supervision, video taping and work sampling. Observers also maintained written documentation of deviations from standard practice and their cause (weather, defects from factory, assembly difficulties, problems with interfacing systems, crew training, material shortages, delivery delays, inspection delays, supervision problems, etc.). Process activities were identified during subsequent analysis of field study results. All non-standard activities were identified and eliminated, as suggested by guidelines regarding the quality of field data. Activities were documented using Boothroyd-Dewhurst's Design for Assembly (DFA) software (Boothroyd and Dewhurst 1992). Activities were added to the DFA User Operations Library, which serves as a database for all home building activities. The activities were then used to construct the appropriate DFA Structure Charts and DFA Worksheets for each technology. A sample DFA Structure Chart and detailed DFA Worksheet for the SSIC configuration of the standard wall are shown in **Figures 7** and **8** respectively. Note that the model is a hierarchical representation of the product, with parts, sub-assemblies and activities defined at each level.

In the third step of the procedure a material takeoff was performed, identifying the types and quantities of materials required for each activity. Data was generated from the drawings shown in **Figures 1** through **6** and information gathered during the field studies. Materials were added to the DFA User Items Library (the materials database) and then added to the DFA Structure Charts and DFA Worksheets.

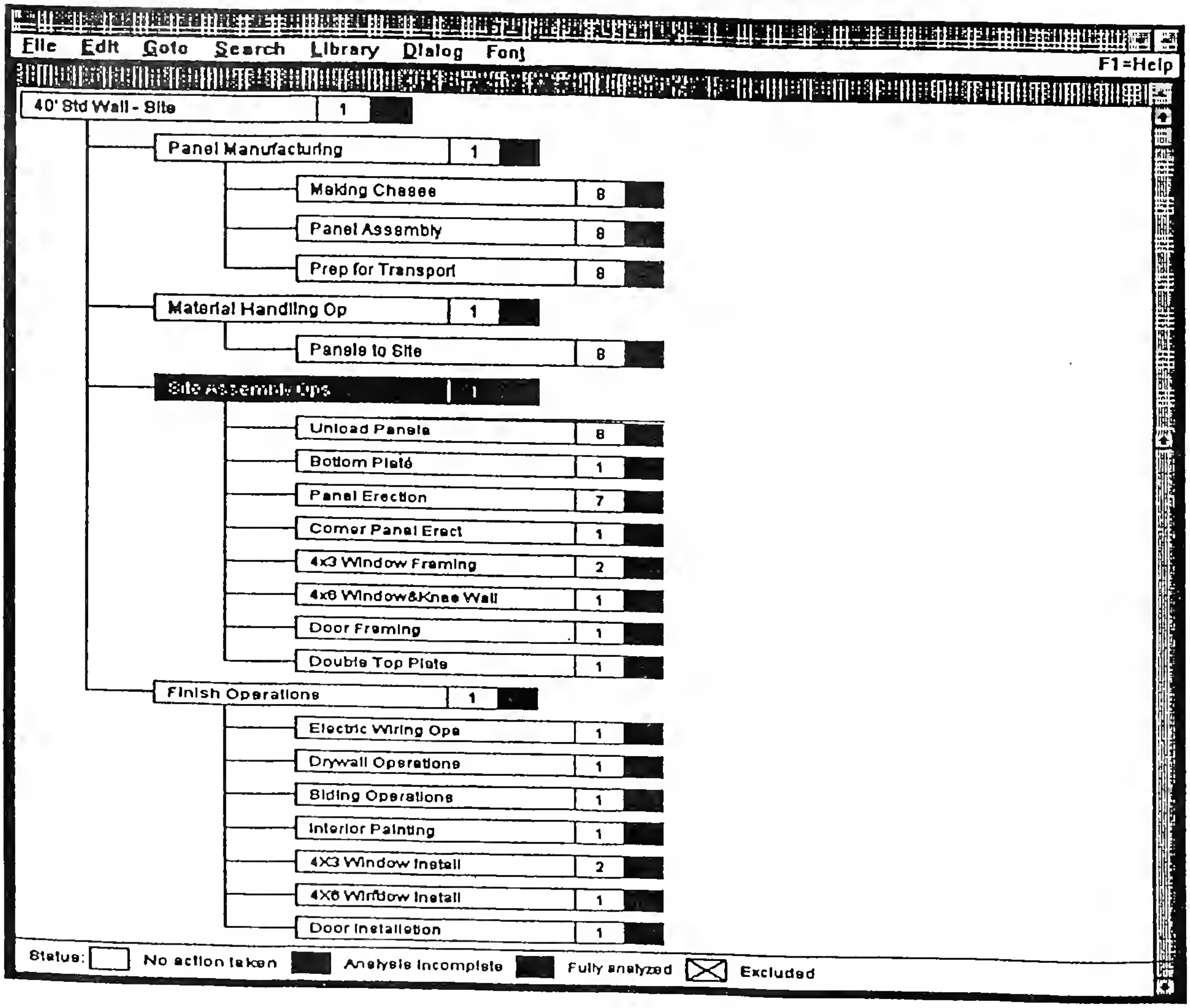


Figure 7. DFA structure chart for SSIC standard wall.

In the fourth step of the procedure, the labor take-off was completed. To quantify the labor requirements for each activity, methods and time studies were performed on the video taped field operations. To calculate the standard time for an operation, multiple replications were located on the tape, timed and averaged. Observed work pace was assumed to be 100 percent of a reasonable, sustainable daily rate. Observations influenced by obvious anomalies or off-standard conditions were eliminated, as suggested by guidelines regarding the quality of field data. A limited number of elemental times for activities thought to be relatively consistent for all home building technologies (for example, drywall hanging) were developed using published cost estimating tables (Walker 1992). Standard times were added to the corresponding activities in the DFA User Operations Library and then to the DFA Structure Charts and DFA Worksheets. A final task in the fourth step involved identifying and applying applicable allowances to account for expected performance against the time estimates. Factors to account for personal, fatigue and delay (PF&D) were estimated to be 25 percent and 40 percent for factory labor and site labor respectively. The former is reflective of several proprietary studies performed in the industrialized housing industry. The latter is based on the general perception that construction site labor is more susceptible to lost time due to climactic conditions, working conditions, etc. (Dagostino 1993). The same factors were applied to all technologies as

Design For Assembly

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DFA Structure Chart - 40' Std Wall - Site

DFA Worksheet - Panel Erection

Subassembly: Panel Erection Labor rate: 12.50/hr DFA Index: 0.0

No.	Item Type	Name	Repeat Count	Min. Parts	Tool Acquis'n Time	Item Handling Time	Item Insertion Time	Total Oper Time	Total Oper Cost	Item Cost	Tool Cost	Item Weig
1	Oper	Picking Up Glue Gun	1	-	-	-	-	5.0	0.02	0.00	0	0.0
2	Oper	Applying Glue to B P	1	-	-	-	-	12.0	0.04	0.00	0	0.0
3	Part	Constn Glue/Bottom	1	0	0.0	0.0	0.0	0.0	0.00	0.56	0	0.0
4	Oper	Carrying the Panel	1	-	-	-	-	33.0	0.11	0.00	0	0.0
5	Oper	Placing the Panel	1	-	-	-	-	32.0	0.11	0.00	0	0.0
6	Oper	Picking Up StapleGun	1	-	-	-	-	30.0	0.10	0.00	0	0.0
7	Oper	Stapling Panel	2	-	-	-	-	16.0	0.06	0.00	0	0.0
8	Part	Staples/Bottom Plate	1	0	0.0	0.0	0.0	0.0	0.00	0.12	0	0.0
9	Oper	Stapling the Spline	2	-	-	-	-	53.2	0.18	0.00	0	0.0
10	Part	4x8' Wall Panel	1	0	0.0	0.0	0.0	0.0	0.00	0.00	0	0.0
11	Part	Staples/Spline	1	0	0.0	0.0	0.0	0.0	0.00	0.24	0	0.0
12	Oper	Applying Glue	1	-	-	-	-	19.0	0.07	0.00	0	0.0
13	Part	Constn Glue/Spline	1	0	0.0	0.0	0.0	0.0	0.00	0.56	0	0.0
14	Oper	Picking Up Spline	1	-	-	-	-	21.0	0.07	0.00	0	0.0
15	Oper	Placing 2x4 Spline	1	-	-	-	-	12.5	0.04	0.00	0	0.0
16	Part	2X4X8' Stud	1	0	0.0	0.0	0.0	0.0	0.00	1.93	0	0.0
17	Oper	Stapling the Spline	2	-	-	-	-	53.2	0.18	0.00	0	0.0
18	Part	Staples/Spline	1	0	0.0	0.0	0.0	0.0	0.00	0.24	0	0.0
19	Oper	Apply Glue to Spline	1	-	-	-	-	19.0	0.07	0.00	0	0.0
20	Part	Const Glue/Spline	1	0	0.0	0.0	0.0	0.0	0.00	1.12	0	0.0
21	Oper	Pick Squaring Jig	1	-	-	-	-	21.0	0.07	0.00	0	0.0
Totals:			24	0				326.9	1.14	4.77	0	0.0

Figure 8. Typical DFA worksheet for SSIC standard wall element.

suggested by the guideline regarding the use of standard resource utilization rates.

The fifth step in the procedure was to cost the material and labor requirements identified in the take-offs. The guideline regarding the use of standard resource costing rates was utilized to minimize bias and enhance comparability. Unit material costs were estimated using a local modular manufacturer's computerized purchasing data base, effective March 1989. The prices were thought to be generally representative of current prices except for wood products which had recently risen approximately 90 percent. These prices were adjusted accordingly. A 5 percent premium was added to the cost of materials used on the construction site to reflect additional handling. Unit material costs were added to the DFA User Items Library and then to the DFA Structure Charts and DFA Worksheets. Wage rates for all technologies were estimated to be $10 per hour in the factory and $15 per hour on site, including fringes. These rates were estimated by an experienced industrialized home builder on the project team and were judged to be reflective of local wage rates. Wage rates were added to the DFA Structure Charts and DFA worksheets. The DFA software automatically calculates direct material and labor costs. The labor costs were then adjusted using the appropriate PF&D factors.

The sixth and final step of the procedure was the identification and estimation of overhead costs. These costs were the most difficult to assess as evidenced by the number of simplifying assumptions and liberal use of guidelines to reduce the data collection and analysis effort. In summary, we sought to include only those costs which were significant in magnitude and which were likely to differ between technologies. Several other guidelines were widely used in estimating overhead costs. These included: 1) standard resource costing rates for resources common to multiple technologies (e.g., floor space), 2) standard resource utilization rates for resources common to multiple technologies (e.g., facility/equipment utilization) and 3) adjustments to compensate for poor business practices.

A partial list of manufacturing overhead items includes the amortization of capital expenditures (e.g., facilities, equipment, inventories, software), indirect labor (e.g., manufacturing supervision, janitorial, maintenance, material handling, material procurement, inspection/test, engineering), and other indirect operating expenditures (e.g., facility/equipment rental, utilities, indirect materials, insurance, property taxes). The following capital items were included in the analysis: facility floor space, equipment and inventory. Floor space was measured during the field study and was valued at standard rates based on type of facility: \$10 per ft^2 for roof only, \$20 per ft^2 for a pre-engineered "Butler" type facility, and \$40 per ft^2 for a high value, high bay, industrial facility. Manufacturing process equipment was inventoried during the field study and costed at its suggested retail price. Inventory estimates for raw materials, work-in-process (WIP) and finished goods were taken from computerized inventory reports where available and on observation elsewhere. Obvious anomalies were noted for several capital items. For example, one SSIC panel manufacturer was observed to have considerably more floor space and finished goods inventory than was appropriate. A discussion with factory management indicated that the situation was atypical and was being remedied. The data was adjusted to reflect more normal conditions. Capital costs were annualized using discounted annual worth (Thuesen and Fabrycky 1993), assuming a ten year study period and a 20 percent minimum attractive rate of return (MARR). This measure includes recovery of capital over the study period with compounded interest accruing at the MARR. The study period and MARR were estimated by the home builder serving on the project team and were judged to be reflective of current financial expectations in the industry. Note that the analysis was done on a "before income tax" basis and, therefore, the impact of accounting depreciation on taxes was not considered.

The only factory indirect labor overhead item considered in the analysis was manufacturing supervision. This was costed at the actual salary (including fringes) since the span of responsibility varied greatly between operations. All material handling, inspection/test and customer delivery functions associated with normal operations were included with the direct labor estimates. All of these functions (except delivery) were performed by production operators. Routine janitorial and maintenance functions were also performed by production operators and are, arguably, included in the 25 percent PF&D factor. Other routine overhead functions such as production scheduling and control were largely handled by the production supervisor in collaboration with sales, engineering and company executives. One important function which was not included in this analysis is engineering. Engineering related overhead includes salaries, office space, office equipment, computer hardware/software and professional services. The implicit assumption was that total engineering costs, factory plus construction site, are comparable for all technologies. In fact, engineering costs appeared to be driven more by the level of value-added design services which the producer (manufacturer/builder) chose to provide than on the technology used. This was driven largely by the market(s) being served, high end custom homes which required considerable design versus lower end standard designs.

Other factory indirect operating expenditures considered in the analysis included delivery truck lease and utilities. Annual delivery truck lease costs were estimated at standard market rate. Utility estimates provided by industry were used when available. Where these estimates were not available, estimates were provided by the home builder serving on the project team, estimated at local rates. No indirect materials, insurance or property taxes were considered in the analysis.

Annual factory overhead costs were then summed and distributed equally over the number of equivalent standard walls produced by the factory annually. It should be noted that several manufacturers were operating well below 100% capacity while others were operating above (including a partial second shift). Reflecting the guideline regarding the use of standard utilization rates, it was assumed that each factory produces panels at a rate equivalent to 100 percent of single shift capacity. Capacity estimates were provided by manufacturers and ranged from .4 to 3.5 million sq. ft. of wall annually, depending on technology and specific manufacturing system configuration. A MICROSOFT EXCEL^{TM} spreadsheet was used to perform all factory overhead analyses. An example for SSIC manufacturing is shown in **Figure 9**.

Job site overhead items include: salaries (construction supervision), temporary office (rent, setup and removal, utilities, office equipment, office supplies), bonds (performance), insurance (fire, theft, property damage, liability), temporary utilities (including sanitary), and other miscellanea (temporary buildings/enclosures, barricades, engineering services, cleanup, repair of street and pavement, damage to adjoining structures/property, permits/licenses, tools/equipment, signs, dust/erosion control, fuels). With one exception, all job site overhead items were assumed comparable and largely independent of technology. The only item explicitly considered in the analysis was equipment rental for the construction crane when required. This was costed at the local market rate. Total crane costs for the job (construction of one house) included transport to/from site and the time on site (estimated from field study observations). Costs were allocated to the standard wall based on the fraction of crane time required to construct the wall versus the total time spent at the job-site.

After all cost components (direct labor, direct materials and overhead expenses) were estimated, they were summed to yield total construction cost for each technology.

RESULTS

Summary cost results are presented and discussed in this section. Results are given for a base case as well as for several alternative scenarios. Note that the costs presented may differ significantly from those experienced by the manufacturers/builders observed during field studies. This results from the use of guidelines including: 1) the use of standardized resource cost and utilization rates and the exclusion of atypical cost elements (to promote comparability) and 2) the exclusion of cost elements judged to be insignificant or likely to be similar for the technologies considered (to simplify data collection and analysis). The *differences* in the costs reported, however, are thought to be indicative of actual cost differences between technologies.

Before examining the results, it is useful to summarize each alternative. A more detailed description is provided in Armacost, Mullens and Swart (1994). The specific alternatives examined are characterized by the technology used, the wall panel design and the manufacturing/construction operations observed in the field study.

- *2x4 Stick Built*: The standard wall built using 2x4 conventional stick built construction is shown in **Figure 1**. No significant problems were observed on the construction site.

- *2x6 Stick Built:* The configuration of the standard wall is shown in **Figure 2**. Note that studs were located on 16 in. centers (versus more typical 24 in. on center for 2x6 construction). Although plywood sheathing was used in the field, OSB was assumed for comparability. No significant problems were observed on the construction site.

- *2x4 Factory Frame #1:* The factory, a low cost open air facility built on a concrete slab, was operating near capacity. It utilized used framing equipment including a roller deck framing table, an overhead shock cord-suspended router and a bridge-mounted sheathing stitcher. Windows were factory installed. The factory manufactured large (20 ft) panels. The panel layout for the standard wall, consisting of two large panels, is shown in **Figure 3**. Panels were installed on-site using a large rental crane, which was also used to set roof trusses. No significant problems were observed in either factory manufacturing or site construction operations.

- *2x4 Factory Frame #2*: The factory, a modern, high quality industrial facility, was operating near capacity. Raw materials were delivered to the line via overhead bridge crane. Panel manufacturing lines utilized

			EEIH PROJECT		
		PANEL COST ANALYSIS: FIXED COSTS			
PANEL MANUFACTURER:			Current and Normalized Business Practice		
4" SSIC #2 & 6" SSIC					
STUDY PARAMETERS					
Max. Capital Recovery Period (yr.)		10			
Minimum Attractive Rate of Return		20%			
CAPITAL COSTS					
FACILITIES					
Mfg. Space (sq.ft.)		6,000			
Capital Cost per sq.ft.		$20			
Sub-Total			$120,000		
EQUIPMENT					
Roll Coater			$28,000		
Large Vacuum Press			$8,000		
Small Vacuum Press			$3,000		
Hot wiring table with jigs			$1,000		
Small forklift			$15,000		
Sub-Total			$55,000		
WORKING CAPITAL - INVENTORY					
Raw Materials			$43,379		
Work in Process			$0		
Finish Goods			$2,920		
Sub-Total			$46,299		
TOTAL CAPITAL COSTS			$221,299		
TOTAL ANNUAL EQUIV. CAPITAL			$52,784.85		
ANNUAL OPERATING EXPENSES					
Production Supervision			$40,000		
FACILITY LEASE					
Mfg. Space (sq ft.)		6,000			
Annual lease cost per sq.ft.		$0.00			
Sub-Total			$0		
EQUIPMENT LEASE					
Delivery Trucks			$12,500		
Sub-Total			$12,500		
UTILITIES					
Utilities			$600		
Forklift			$1,200		
Vacuum Presses			$240		
Roll coater			$1,200		
Sub-Total			$3,240		
TOTAL ANNUAL OPERATING COSTS			$55,740		
TOTAL FIXED COST ANALYSIS					
TOTAL ANNUAL EQUIV. COSTS			$108,524.85		
PARAMETERS					
Plant Capacity (lineal ft. of wall)		52,000			
Length of Standard Wall (lineal ft.)		31			
COST/40 ft wall @ 33% CAPACITY			$196		
COST/40 ft wall @ 66% CAPACITY			$97		
COST/40 ft wall@ 100% CAPACITY			$65		

Figure 9. Sample overhead cost calculation spreadsheet.

framing equipment including a roller deck framing table, an overhead shock cord-suspended router and a bridge-mounted sheathing stitcher. The panel layout for the standard wall, consisting of three 12 ft panels and one 4 ft panel, is shown in **Figure 4**. Light-weight insulative sheathing was used instead of OSB, also eliminating the need for felt. No construction crane was used on the construction site. All panels (and trusses) were man-handled. No significant problems were observed in either factory manufacturing or site construction operations.

- *2x6 Factory Frame:* The panel layout for the standard wall is shown in **Figure 5**. This option was not observed. Instead, cost results were extrapolated from those of the 2x4 Factory Frame #1 option, using appropriate material and labor cost increases associated with handling larger components. It was assumed that studs are located on 24 in. centers.

- *4 in. SSIC #1:* The factory, a modern, high quality industrial facility, was operating at roughly one-third of its estimated capacity. Factory floor space greatly exceeded that required for production. SSIC panel manufacturing equipment included powered hand tools for hot wire and cut-to-size work centers, a roll-coater for construction adhesive application, and two conveyorized laminating layup stations feeding two hydraulic platen presses. Material handling within the facility was by lift truck, hand cart and conveyor. Inventory levels for raw materials and finished goods were very high. Inventories were stored inside the facility and occupied a considerable amount of floor space. The factory produced a range of panel sizes, from small (4x8 ft) to large (8x24 ft) panels. The standard wall (**Figure 6**) was constructed using 7.7 4x8 ft panels. Note that SSIC construction costs are very sensitive to scrap levels. A construction decision resulting in a square foot of SSIC panel scrap is much more costly than a similar decision impacting OSB or a cheaper grade of sheathing. This analysis assumed that the only SSIC panel scrap was that portion of the small window cutouts which were not used in the large window knee-wall. Panels were cut on site, not pre-cut in the factory. A standard 2x4 spline was used to join panels. Operating difficulties were observed both in the factory and on the construction site. After reviewing conditions with factory management and the builder, the following assumptions were made: factory floor space and inventories were reduced by 50% and the excess labor associated with off-standard conditions observed were not included in the study.

- *4 in. SSIC # 2*: The factory, a low cost pre-engineered industrial building, was operating far below capacity. Factory floor space was well-used, if not tight. SSIC panel manufacturing equipment included a custom-built EPS foam cutting table with stationary hot wire, a roll-coater for construction adhesive application, two custom-built pneumatic vacuum presses and a cut-to-size work center which utilized powered hand tools. Material handling within the facility was by lift truck. Inventory levels for raw materials and finished goods were appropriate. Finished panels were wrapped in plastic and stored in the yard. The factory produced a range of panel sizes, from small (4x8 ft) to larger panels. The panel layout for the standard wall was the same as that used for the 4 in. SSIC #1 option described above. No difficulties were observed in factory manufacturing operations, however, several problems at the construction site slowed panel erection. The problems were assumed to be atypical and the excess labor was not included in the study.

- *6 in. SSIC*: This option was not observed. Instead, cost results were extrapolated from those of the 4 in. SSIC #2 option, using appropriate material cost increases.

Note that not all factors were standardized. For example, sheathing materials and panel sizes were allowed to vary for the wood frame technologies. The rationale for allowing this variation was to assess the impact of some common design variations within the technologies considered.

A summary of cost results for the base case are shown in **Table 1(a)**. Key findings include:

- 1. Conventional wood framed construction costs were similar for both stick-built and factory panelized construction. Although capital costs were higher for factory panelized operations, this was partially recovered by labor savings. The lowest cost option, 4 in. Factory Frame #2, gains its cost advantage by the use of a light-weight insulative sheathing instead of the more expensive OSB. The 6 in. frame wall construction technologies were about 7 percent more costly than comparable 4 in. construction, largely the result of higher dimensional lumber cost.
- 2. The costs for the two 4 in. SSIC alternatives were similar, with the primary difference being greater capital facility costs for the 4 in. SSIC #1 option. The 6 in. SSIC costs were 6 percent higher than comparable 4 in. costs, the result of higher materials costs.
- 3. The 4 in. SSIC construction costs were 18 percent higher than 4 in. frame construction and 10 percent higher than 6 in. frame construction. For the 4 in. frame comparison, this is driven by cost differences in materials and labor.

Several sensitivity analyses provide additional insight from the cost results. First, consider the impact of market demand on cost. These results are shown in **Figure 10**. An important financial advantage of stick built construction is the flexibility of operating without significant fixed costs such as plant and equipment costs. This contrasts with the two factory technologies shown which experience significant per unit cost increases as demand falls, capacity utilization drops and fewer units of production are forced to absorb the same level

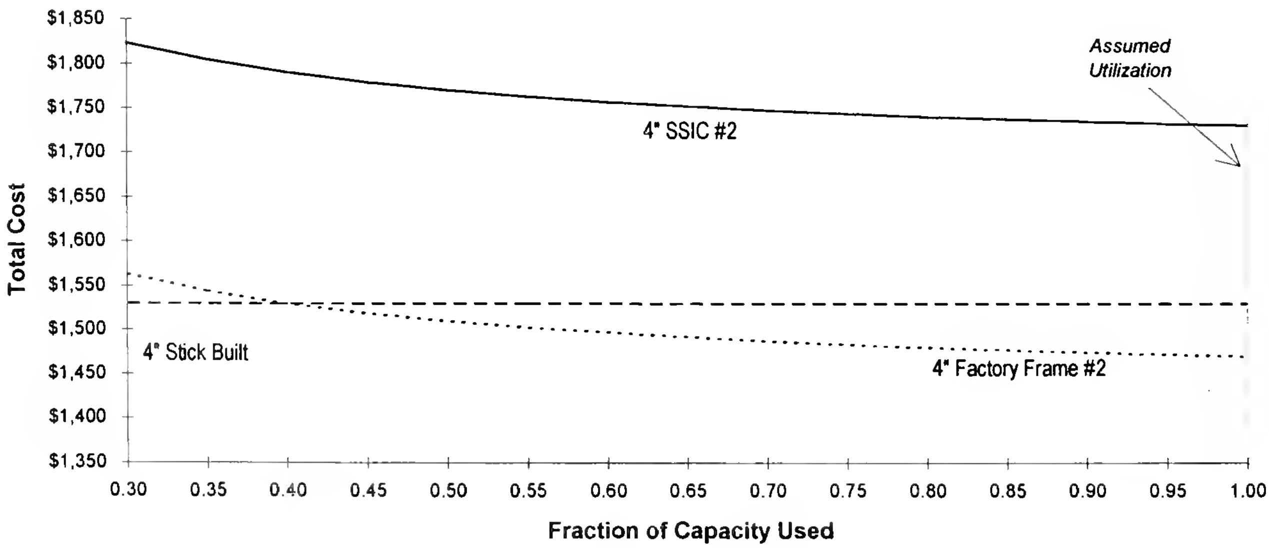

Figure 10. Impact of demand on total cost.

Table 1. Cost per standard wall.

(a) Base Case

	4" Stick Built	6" Stick Built (16" OC)	4" Factory Frame #1	4" Factory Frame #2	6" Factory Frame (24" OC)	4" SSIC #1	4" SSIC #2	6" SSIC
Material	1140	1,230	1140	1060	1,200	1,260	1,240	1,350
Labor	390	390	340	370	340	440	450	450
Overhead	0	0	60	40	60	80	70	70
Total	1,530	1,620	1,540	1,470	1,600	1,780	1,760	1,870

(b) SSIC Cost Reduction Scenario

	4" Stick Built	6" Stick Built (16" OC)	4" Factory Frame #1	4" Factory Frame #2	6" Factory Frame (24" OC)	4" SSIC #1	4" SSIC #2	6" SSIC
Material	1140	1,230	1140	1060	1,200	1,260	1,240	1,350
Labor	390	390	340	370	340	350	360	360
Overhead	0	0	60	40	60	40	40	40
Total	1,530	1,620	1,540	1,470	1,600	1,650	1,640	1,750

NOTE: ALL COSTS ROUNDED TO NEAREST $10

of fixed costs. This becomes critical as utilization falls below 50 percent and costs rise at a greatly increasing rate. It should be noted that while the frame panel factories were observed to be operating at capacity (and even some overtime), the SSIC factories were observed to be operating at less than 50 percent of their available capacity. Finally, note that factory production of frame panels became more efficient than stick building when production exceeds 57 percent of plant capacity.

A second sensitivity analysis explored the impact of potential forest product price increases. The results are shown in **Figure 11**. Note that the SSIC technology did not become more competitive as the cost of forest products rose. In fact, the SSIC technology actually became less competitive with 4 in. Factory Frame #2. The reason for these results was that the SSIC technology has roughly the equivalent forest product cost of 4 in. Factory Frame #1 (which uses OSB as sheathing), and has greater cost than 4 in. Factory Frame #2 (which uses light-weight insulative sheathing).

A third sensitivity analysis addressed the longer term potential of SSIC technology as the industry matures into a major player in the home building industry. It is possible that SSIC costs can decrease significantly as a result of productivity improvements in the factory and on the construction site. Factory improvements might be based on flexible manufacturing concepts, allowing the manufacturer to produce an increasing variety of "custom" shapes at high volumes. The introduction of automation will allow greatly increased capacity with minimal increase in personnel and floor space, significantly lowering per unit factory production costs. Construction site improvements might be driven by better product designs, allowing more efficient erection and window installation. This scenario assumes that it will be possible to cut all SSIC factory labor and capital costs by 50 percent and all construction site labor costs by the same amount. Results shown in **Table 1(b)** indicate that 4 in. SSIC construction costs may be no more than 9 percent higher than 4 in. frame construction and roughly equivalent to 6 in. frame construction.

To assist in identifying long term cost improvement opportunities, key elemental cost differences were identified. The lowest cost SSIC alternative (4 in. SSIC #2) was benchmarked against the lowest cost frame alternative (4 in. Factory Frame #2). Base case scenario results are shown in **Table 2**. First, note that the six items shown described $223 of the $280 total cost differential. Second, note that the SSIC options did result in cost savings for certain items including dimensional lumber and site installation labor for insulation. However, these cost savings were more than offset by cost increases for materials (sheathing, adhesive, and insulation) and panel erection labor. This resulted in a net cost increase of $223

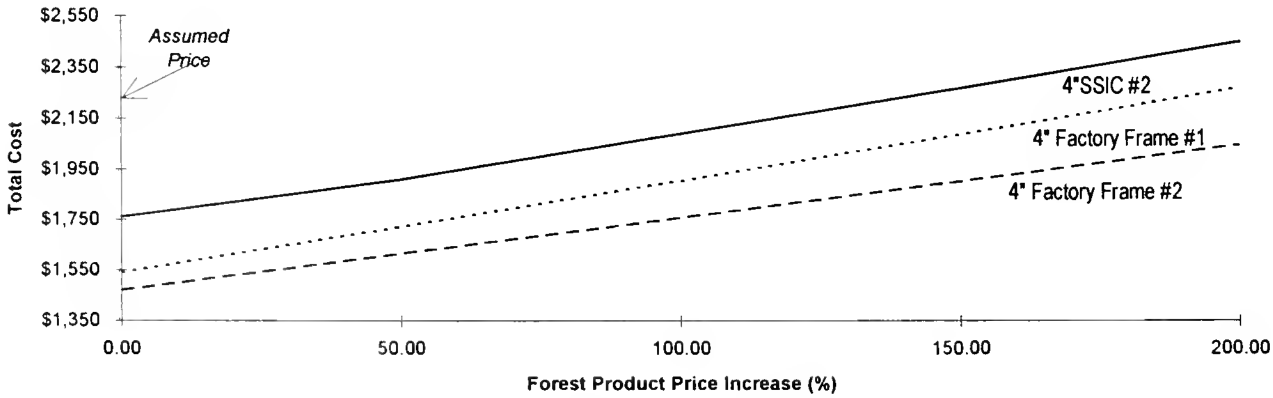

Figure 11. Impact of forest product price on total cost.

Table 2. Key cost differentials for "Base case scenario"

Line Item	4" Factory Frame # 2	4" SSIC # 2	Differential
Sheathing (incl. felt)	$ 38	$196	$158
Dimensional Lumber	$248	$161	[$ 87]
Insulation	$ 28	$ 86	$ 58
Adhesive (factory & site)	$ 0	$ 44	$ 44
Panel Erection	$ 16	$ 84	$ 68
Install Insulation (site)	$ 18	$ 0	[$ 18]
Total	**$348**	**$571**	**$223**

for the standard wall. Stated as a rate this differential represented:

- $70 per ft^2 of total wall area
- $88 per ft^2 of wall, excluding openings
- $5.76 per running foot of wall

The top 4 items were construction material related. Sheathing was the largest single item. The SSIC technologies required 15.4 sheets of OSB to cover both the interior and exterior surface of the wall panels. In comparison, the Factory Frame #2 option used a less expensive light-weight insulative sheathing on the exterior surface of the panel only. Other framing technologies used OSB on the exterior only. Dimensional lumber was required by both technologies for top plates, bottom plates and window and door framing. While the SSIC technologies had an advantage since they required no studs, they did require 2x4 splines on 4 ft centers. This advantage would be even greater if larger SSIC panels were used, thus requiring fewer splines. The third line item, construction adhesive, was used in the factory to manufacture SSIC panels and on the construction site for panel erection. Note again that the 4 ft SSIC panel required joints (which must be glued) on 4 ft centers. Using a larger SSIC panel would reduce the number of joints and conserve construction adhesive. Finally, the EPS foam cores used in SSIC panel production were significantly more expensive than the fiberglass batt insulation used in most framing applications. The only other significant line item was panel erection costs. There are several reasons why the SSIC technologies had higher erection costs. First, erection costs for the SSIC technologies included the cost of cutting and framing-out windows and doors, a very labor intensive process. Door and window framing were completed in the factory for the factory framing technologies. Second, the SSIC technologies utilized a small 4 ft x 8 ft panel, while the two factory frame technologies utilized larger panels, 20 ft x 8 ft and 12 ft x 8 ft respectively. This resulted in significantly more panel handling and joining for the SSIC technologies.

SUMMARY AND CONCLUSIONS

Construction cost is an important performance metric for a home building technology. It plays a vital role in determining price, profitability and eventual acceptance of the technology. At an elemental level, it can suggest both product and process improvement opportunities. Benchmarking construction costs for innovative home building technologies offers unique challenges as compared to conventional cost estimating. These challenges have been an impediment to solid, quantitative cost reporting. This paper has described a framework for benchmarking construction costs for innovative home building technologies. The proposed methodology has three components: a set of guidelines for applying the methodology, a construction cost model, and a cost estimating procedure.

From a theoretical standpoint, the benchmarking methodology is sufficiently robust to comprehend all production oriented costs including direct material, direct labor and manufacturing/job overhead. Should the analyst wish to extend the model to include other more general cost elements such as general administrative expense, sales expense, and profit, they may be incorporated. From a practical standpoint, experience gained in using the methodology suggests that it can readily account for direct materials and direct labor. Overhead, however, is much more difficult to assess. There are many categories of overhead expense, both on the construction site and in the factory. Many overhead expenses are not well documented, making data collection difficult. Even when cost data is available, the relationship between overhead cost and technology is not always clear. This can make it difficult to determine how much of the observed overhead to attribute to the technology. An example is engineering costs which appear to be highly market dependent. Future research in this area might address white-collar business processes which support home building, focusing on the differences between conventional and innovative technologies. This research might utilize business process re-engineering techniques using customer value-added as a primary criteria. Finally, findings suggest that there may be a learning curve associated with innovative technologies which extends beyond direct labor to overhead. Future research might address the productivity of overhead expenditures (e.g., floor space, inventories) for innovative home building technologies over time and develop factors where appropriate.

Additional research may improve on the selection of the common housing element used for analysis.

It is likely that relative costs (between technologies) will change as the size, scope and design complexity of the common element changes. Future research might attempt to define these relationships and develop factors where appropriate. Future research might also consider the use of a sample of common housing elements, either selected randomly or purposely selected based on projected demand.

Finally, it is useful to put the wall construction cost results in perspective. Results are based on a small sample of home builders. They do not comprehend a number of factory overhead costs including software, janitorial, maintenance, material procurement, engineering, indirect materials, insurance, and property taxes or job overhead costs including construction supervision, temporary site office, performance bonds, insurance, temporary site utilities, and other miscellanea (temporary buildings/enclosures, barricades, engineering services, clean-up, repair of street and pavement, damage to adjoining structures/property, permits/licenses, tools/equipment, signs, dust/erosion control, fuels). The implicit assumption is that these items are largely independent of technology. While based on limited data, the basic results are consistent with those of Toole and Tonyan (1992) who assert that for most home designs SSIC costs appear to average 10 percent to 20 percent higher than for conventional stick built construction, primarily due to higher material costs.

Future research suggested by the wall construction cost benchmarking results include: 1) development of alternative SSIC panel sheathing materials, 2) construction cost analysis of "long" SSIC panels versus the conventional 4x8 ft panel, 3) development of alternative materials and processes for framing windows and doors in SSIC construction and 4) consideration of potential energy savings (Rudd and Chandra 1993) and other life cycle cost advantages of the SSIC technology against its apparently higher construction cost.

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The Impact of an Energy Education Program

Anne L. Sweaney and Carol B. Meeks

ABSTRACT

Energy counseling programs are expensive to operate: therefore, it is critical that the program have a long term impact for the clientele as well as the sponsoring agency. The purpose of this study was to evaluate the impact of an energy education program. The populations addressed were those at risk for high energy costs and poor quality housing structures, mainly limited income, elderly individuals. Data concerning demographic and housing characteristics as well as energy conservation behaviors were collected for 601 subjects in two time periods. Respondents added insulation to their housing units between time one and time two as well as low cost air infiltration barriers. In order of declining importance these were: weather-stripping, air guards, caulking, and plastic over the windows. The results of this evaluation show a positive long-term effect of energy education on client energy conservation practices and behaviors.

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INTRODUCTION

There is renewed world-wide interest in how people manage their energy resources. The growing population living in poverty is especially vulnerable to changing energy and housing markets. In the United States, a number of energy conservation programs have been sponsored by both the public and private sectors to help people living in less than adequate conditions improve their energy related behaviors (Walsh and Howard 1986). Brown and Rollinson (1985) suggest that lack of information inhibited both elderly and low-income groups from changing their behavior. Thus, it is important to determine whether information (education) will result in changes in conservation behavior.

As future programs are developed it is essential to access the impact of previous education efforts. This research attempts to measure the lasting effects of an Energy Education Program which began five years ago and was sponsored by the Georgia Office of Energy Resources and conducted by the Family and Consumer Science Program Unit at the Georgia Center for Continuing Education (Grogan, Valente and Chapman 1991). To measure what behaviors the clients had exhibited since the initial contacts, face to face interviews were conducted. Rarely are long term evaluations of educational programs made which is why this research is so valuable. Only by determining the long term impacts of programs can educational providers ascertain whether they are focusing their efforts in the right direction and whether their money has been well spent.

The Energy Education Program was developed to provide energy education and counseling to individuals on a one-to-one basis in their homes or in small group settings. Due to their limited economic resources, the clientele were only shown energy conservation techniques that could be done at low cost.

The form of delivery system used, namely the use of home visits, is unique. It helped overcome some of the barriers faced by clientele in coming to a meeting. For example, health and transportation problems prohibited many individuals from leaving their homes. In addition, the home visits allowed the energy counselors to observe the energy practices and conservation techniques being adopted by the clientele. The 27 energy counselors who provided the energy information to the clientele were residents of the community and were representative of the clients' race, age and gender. The fact that the clients were relating to a peer helped to relieve the barriers of fear, mistrust and low educational levels.

The para-professional energy counselors were trained by personnel from the Family and Consumer Science Program Unit of the Georgia Center for Continuing Education. Support for the training was provided by the Georgia Office of Energy Resources.

Not only will the adoption of energy conservation measures improve the economic well-being of the households, they will also contribute to improved health, comfort, and safety. Difficult to measure but beneficial to clients are the sense of control they gain over events in their lives and an improved sense of well-being. In 1988, Laquatra presented a comprehensive review of the literature on housing education and residential energy efficiency. This review serves as a resource for educators, builders, and community leaders who are working on energy related programs.

One-on-one energy counseling programs are expensive to operate; thus, it is critical that the program have a long term impact for the clientele as well as the sponsoring agency. Therefore, this research attempts to measure the changes in energy behavior over time.

METHODOLOGY

Development of Questionnaire

The design for this study was a simple test-treatment-retest quasi-experimental design, to determine if subjects had changed their energy behaviors over the five-year interval between the first and second tests. The questionnaire development, sample and procedures used are described below.

The questionnaires for time one were developed by program specialists in the Energy Education Program Office of the Family and Consumer Sciences Program Unit of the Georgia Center for Continuing Education and the director from the Georgia Office of Energy Resources (Sweaney and Meeks 1993). The original questionnaire was adapted from an instrument used to survey clients participating in "The Energy Event," a project developed by the Oklahoma State University Cooperative Extension Service and the Oklahoma Corporation Commission. Over the course of the work with families in the energy education program, the questionnaire was revised so that three versions of the questionnaire for time one were used. After using the original questionnaire it was found that changes were needed to make the instrument more user friendly.

The questionnaire for time two was based on a composite of the time one questionnaires. The questionnaire was further pretested in December 1992 for ease of use. The final questionnaire was both shortened and the language of some of the questions was revised.

Data Collection

The data for time one were collected from November 1986 until 1990. Interviews were conducted by the energy education counselors for each of the families they visited. After recording the demographic and energy behaviors of the household, the counselor conducted an energy education program. The energy counselors spent 45 minutes to an hour with the clients training them to do the energy upgrades. Many of the households were visited a second time by the energy counselors during which a similar process was followed.

For time two, interviewers were obtained from Community Action and other social service agencies in the local communities. Interviewers were trained in April 1993 by research scientists from the University of Georgia. Data collection began as soon as the first group of interviewers were trained in April. The final surveys were completed in July of 1993. During this time, data were again collected on demographic characteristics, housing characteristics, heating system characteristics, participation in weatherization programs, energy changes since the first visit, factors that influence energy changes, and future plans for energy changes.

A comparison is made between the two samples to determine changes in energy conservation behaviors. Factors that influence these changes are examined. An assessment such as this is critical to determine the overall impact of the program and the factors which have a lasting effect on the energy behaviors of households.

Sample

There were 1301 completed questionnaires from time one. In time two, 858 households were contacted. Of these 601 questionnaires were used in the analysis. Of the remaining 257 contacts, 169 households from the original sample had moved, 42 respondents were deceased, 16 did not answer after at least two attempts, 2 refused, and 28 were miscoded, with the most common problem being missing names or using incorrect code numbers. The reinterview rate of 46 percent is high considering the amount of time which had lapsed between the two interview periods.

RESULTS

Description of Respondents

In this section, the sample is described and the energy conservation behaviors of the participants in time one and time two are presented. Further, planned changes in energy conservation behaviors are described.

More whites than blacks were interviewed in both time one and time two (**Table 1**). In time two, whites accounted for 63 percent of the interviews whereas in time one whites accounted for 59 percent. This may suggest that whites were somewhat more likely to remain in the housing unit over time. Further, the high level of white participation indicates that the population at risk in Southern nonmetropolitan areas is not only black. Interview rates for males and females were consistent over time. Females represented about 80 percent of the sample while males represented about 20 percent. Thus, the major audience for the educational program and follow-up were females. This may be due to the fact that females were more likely to be home and that many of the females were widows living alone.

In time one, 50 percent of the sample were 65 years of age or older. In time two, the 65+ age group had increased to 62 percent. This increase is due in part to the passage of time but also may be related to lack of mobility by elderly households so that they were more likely to be in the same housing unit during time two. The elderly are low participators in conservation programs, but growing in number in the population (Meeks 1990). Thus, the high rate of personal contact which is a characteristic of the Energy Counseling Program is extremely important.

The predominant marital status category of the respondents was widowed. In time two, widowed respondents accounted for 56 percent of those interviewed whereas in time one, 43 percent of the respondents were widowed. This is in part related to the age of the sample and the high rate of female participation. The next category of marital status with the most respondents was married. This declined from 25 percent in time one to 21 percent in time two. Single, never married respondents and divorced or separated respondents accounted for the remainder of the sample. The majority of the sample was composed of people living alone in both time one and time two. Related to the increase in number of widows, the number of people living alone increased from time one to time two. Furthermore, almost 90 percent of the sample were living in households with three or fewer members.

Sixty-two percent of the respondents lived in traditional single family detached homes in time two. Another 14 percent resided in mobile homes in time two. At that time, 16 percent lived in assisted housing; an increase of 5 percent over time one. The remainder (7 percent) lived in apartments or duplexes.

Table 1. Demographic description of the sample.

Variable	Time 1 n	Time 1 %	Time 2 n	Time 2 %
Race				
Black	536	41.4	219	36.8
White	758	58.5	375	63.0
Other	2	0.2	1	.2
Total	1296		595	
Gender				
Male	255	19.7	113	18.8
Female	1039	80.3	488	81.2
Total	1294		601	
Age				
44 years and younger	297	23.4	83	14.2
45-54 years	123	9.7	64	10.9
55-64 years	192	15.2	74	12.7
65 years and older	655	51.7	364	62.2
Total	1267		585	
Marital Status[a]				
Single, never married	40	16.3	51	8.5
Married	61	24.9	125	20.9
Divorced or separated	39	15.9	86	14.4
Widowed	105	42.9	336	56.2
Total	245		598	
Family Size				
1	640	49.3	330	55.7
2 or 3	431	33.2	196	33.2
4 or 5	169	13.0	51	8.6
More than 5	59	4.5	14	2.4
Total	1299		591	
Type of House				
Apartment or duplex	77	5.9	43	7.2
Housing project unit	141	10.8	98	16.3
Mobile home	241	18.5	87	14.5
Single family dwelling	841	64.7	372	62.0
Total	1300		600	
Tenure				
Own the house	806	62.6		
Rent the house	471	36.6	NA	
Live with relatives or friends	10	0.8		

[a]Question included on two of the three questionnaires only

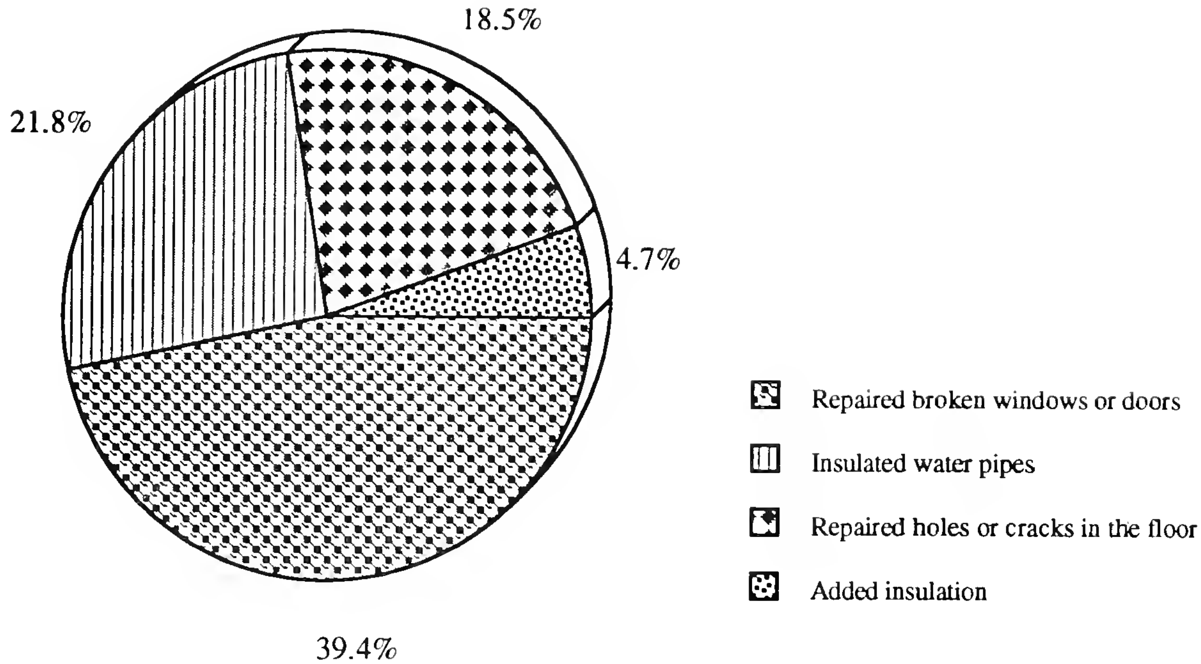

Figure 1. Energy changes made from time one to time two.

Energy Changes

The energy changes made to the dwelling from time one to time two are shown in **Figure 1**. The major changes the households made following the counseling session in time one were repairs to broken windows and doors, followed by insulating hot water pipes, and repairing holes or cracks in the floor. Since 64 percent of the homes were reported as insulated in time one, it is not surprising that adding insulation did not rank higher in the overall changes made to the home.

It is a well known fact that one of the most cost effective energy changes that consumers can make is adding insulation to their dwelling, if it has little or no insulation. Adding insulation to an already insulated home is not as cost effective. The households were asked in time one as well as in time two about the presence of insulation in the home. The respondents insulated their housing units over time **(Figure 2)**. In time two, 72 percent reported that their homes were insulated either partially or fully compared with 64 percent in time one. Although the number of respondents reporting no insulation dropped from 36 percent to 13 percent, the number reporting an increase in insulation was only 9 percent. The difference is that 14 percent of the respondents in time two reported that they didn't know if their housing units were insulated or not. This was not an option on the time one questionnaires.

The impact of the energy education program is clearly seen by the increase in the number of households that added barriers to limit air infiltration **(Figure 3)**. Almost 38 percent of the households added weather-stripping between time one and time two. Close to half of the housing units were weather-stripped by the time of the second interview. Thirty percent or more of the households in time two limited air infiltration by using air guards, by caulking, and by placing plastic over their windows. All of these air infiltration barriers are relatively low-cost and easy for the homeowners to do once they are shown the methods.

As there was no control group as part of the research design of this study, a comparison is made using the Energy Information Administration, Housing Characteristics 1990: Residential Energy Consumption Survey (1992) shown in **Figure 4**. This shows the levels of weather-stripping, caulking and wall insulation of two regions of the South (based on cooling degree days (CDD)) and the change from

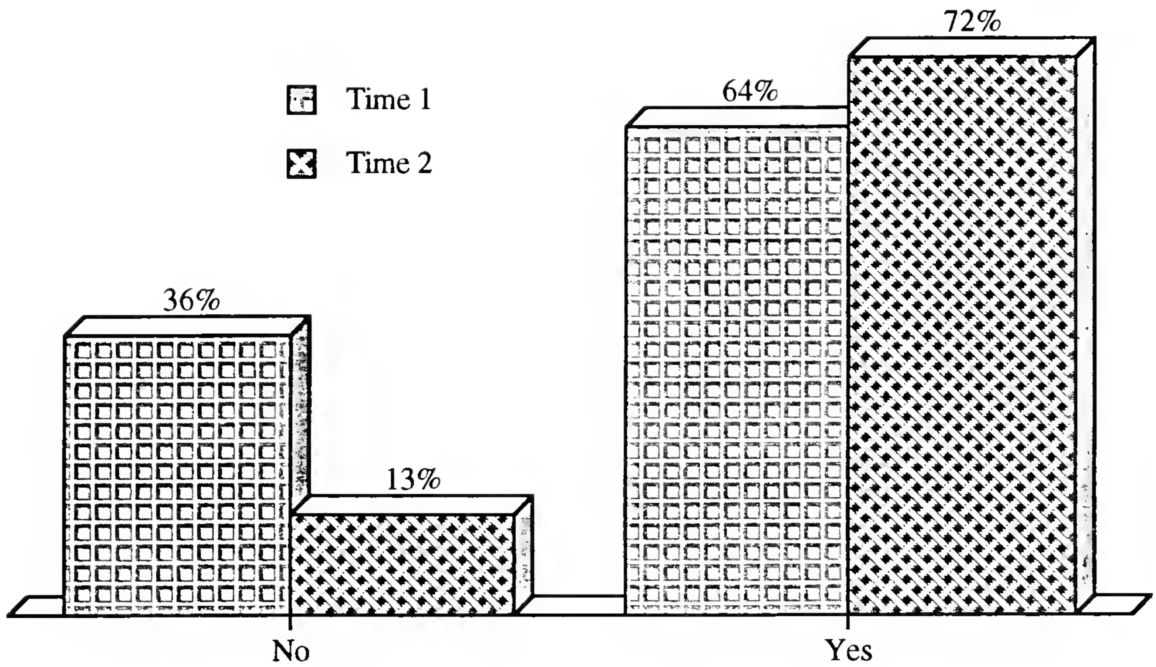

Figure 2. Presence of insulation in the home.

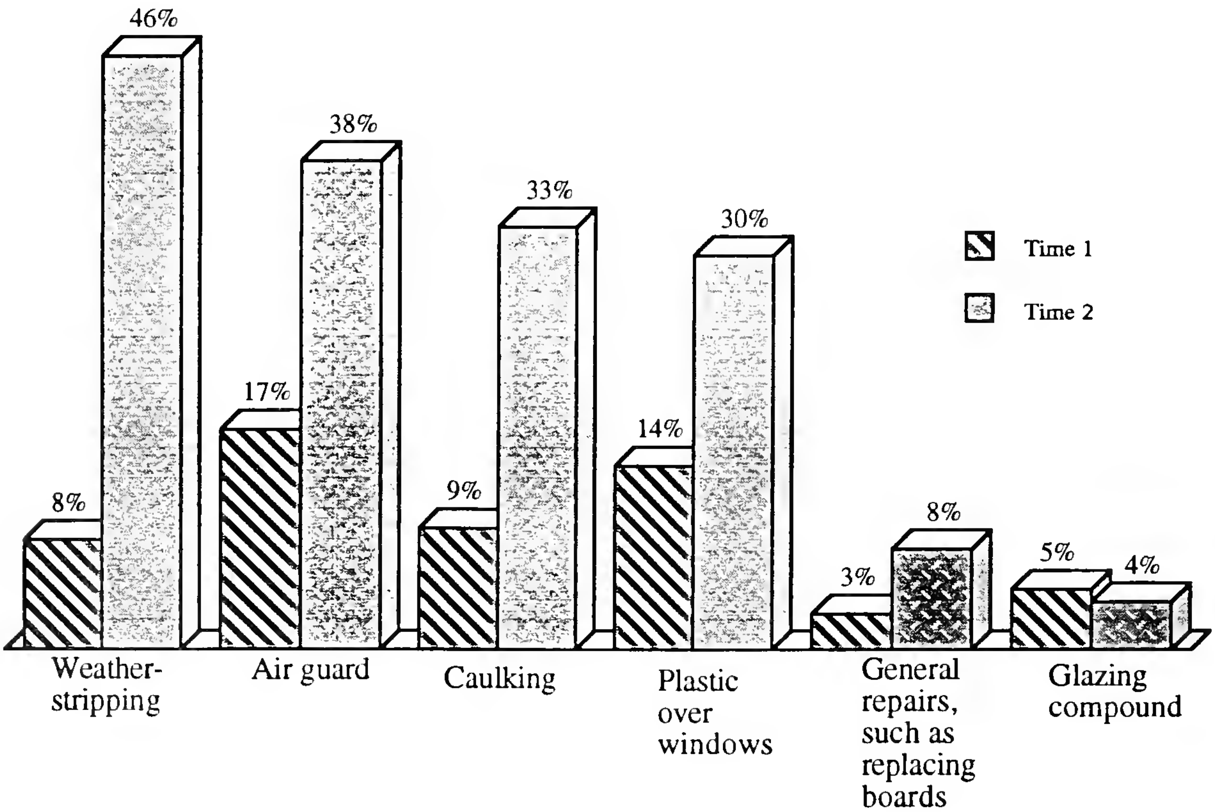

Figure 3. Air infiltration barriers.

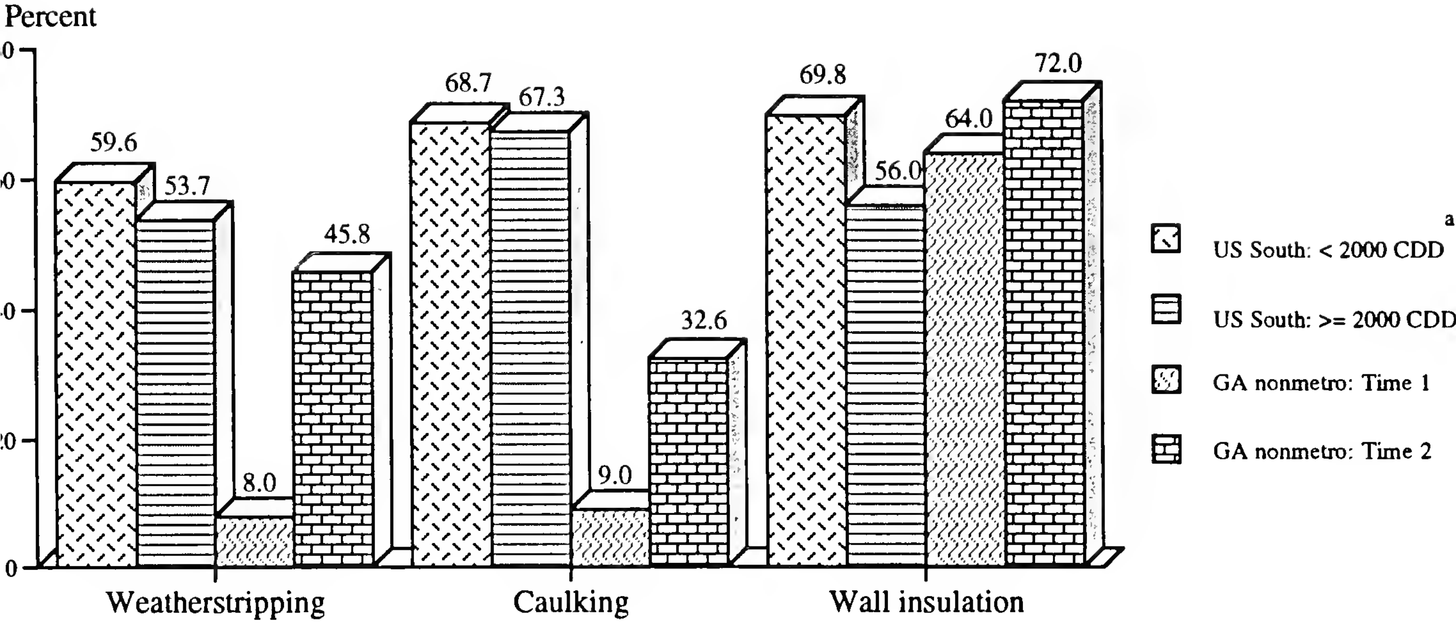

Figure 4. A Comparison of energy conservation in US households vs. nonmetropolitan Georgia households.
a: CDD, Cooling Degree Days, is a measure of how hot a location was over a period of time relative to a base temperature.
Source: Energy Information Administration (1992). *Housing Characteristics*. US Department of Energy, Washington, D.C.

time one to time two of the present study. The greatest changes are with weather-stripping and caulking while the results of time two do not reach the levels found in the Department of Energy Study. The presence of wall insulation in time two was consistent with the findings of the Department of Energy study.

As changes in consumers' energy behaviors are an on-going process, the households were asked about their plans for energy changes in the future. The respondents offered a variety of plans for making energy improvements with no one item dominating the energy agenda **(Table 2)**. Adding insulation and insulating hot water pipes topped the list of these future plans, followed by physical repairs to the structure, caulking, and weather-stripping.

Table 2. Future plans for energy changes.

Variable	n	%
Insulate water pipes	169	28.1
Repair broken windows or doors	100	16.6
Repair holes or cracks in the floor	62	10.3
Add insulation	174	29.0
Caulk	103	17.1
Weatherstrip	94	15.6
Other[a]	21	3.5

[a]Includes: add storm doors or windows or house already well-weatherized.

IMPLICATIONS

This study addressed populations at risk for high energy costs and poor quality housing structures. The sample interviewed in nonmetropolitan areas of Georgia was predominately white. Respondents were most often female which may be related to who is home during the day. However, many of the respondents were elderly, widowed, and living alone. Since these respondents are often low participators in energy conservation programs (Meeks 1990), their inclusion in this program is extremely important.

Respondents lived primarily in traditional single family detached homes, including manufactured housing. Home ownership dominates the housing profile of the sample. Many factors have contributed to the increase in home ownership such as, the post-World War II building boom, low interest rates and tax incentives for home owners. Nationally the number of elderly people who own single family dwellings has increased in the past decade (from 76 percent to 82 percent for those 65-74) (Hitschler 1993).

Even though a number of these people have paid for their homes and do not have the expense of mortgage payments, other expenses of home ownership still need to be met. Housing related expenses that are part of the housing budget, i.e, utilities (30 percent), property taxes (13 percent), and maintenance, repairs and insurance (11 percent) still need to be paid (Hitschler 1993). Using a factor analytic approach with 424 households, Gmelch and Dillman (1988) found that home ownership and single-family residence were related to personal benefits received from energy conservation. They concluded that conservation was a strong motivating factor for all segments of the population.

Between time one and time two, clientele added low cost air infiltration barriers. In order of declining importance these were: weatherstripping, air guards, caulking, and plastic over the windows. No cost energy conservation behaviors that over 60 percent of the respondents in the study adopted after visits by the energy counselors were: closing curtains on sunny summer days, decreasing the hot water temperature, and closing off rooms not being used. Physical repairs to the house, such as repairing windows and doors and repairing cracks in the floor, were made.

Respondents added insulation to their housing units between time one and time two as shown in **Figure 2**. It is of interest to note that the increase in the level of insulation (64-72 percent) surpassed the average level of insulation found by the Department of Energy in the Housing Characteristics Survey in 1990: Residential Energy Consumption Survey (Energy Information Administration 1992) which was 63.8 percent in the South. This illustrates that when people are informed about what to do, such as insulating their home, they take action. Although insulation has an economic cost, the rate of return is substantial. Energy conservation programs need to give attention to the appropriateness of the insulation levels in the housing units. Adding insulation to a home often takes more physical and economic resources than other energy conserving techniques. Given that many of the households represented in this sample consisted of elderly women living alone, one could speculate that adding insulation would not be as easy to accomplish. Programs that provide both labor and financial support could be of great value to these people.

D'Alessandris (1991) noted that it is more economical to install higher levels of insulation during construction than it is to retrofit existing homes. The building community needs to emphasize energy efficient housing while educators need to improve consumer understanding of energy savings from insulation.

Respondents have a variety of plans for making energy improvements with no one item dominating the energy agenda. Adding insulation and insulating hot water pipes topped the list for future plans followed by physical repairs to the structure, caulking, and weatherstripping.

It is critical that at risk populations receive support to improve the energy use of their dwellings. Hitschler (1993) reported that the largest expenditure for Americans in both 1980 and 1990 was for housing. Utilities consume 30 percent of the housing budget (Hitschler 1993). Thus, energy conserving adaptions made to the home and changes in energy conservation behavior are important and can improve the economic well-being of the households.

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