Improving the Energy Efficiency of Office Buildings in Montréal

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ABSTRACT

Improving the Energy Efficiency of Office Buildings in Montréal

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In recent years, a great deal of interest has been directed towards minimizing energy consumption in buildings which account for one-third the total energy consumed in Canada.

A major research effort was undertaken by an investigating team (including the author of this thesis) at the Centre of Building Studies, in collaboration with le Bureau de l'Efficacité Énergétique du Québec and the Montréal Downtown Energy Forum programme to study the pattern of energy use in office buildings in Montréal. The analysis indicated that Montréal office buildings consumed an average 69% more energy than recommended target values for energy efficient buildings. Based on these results, the purpose of this research is to improve the energy efficiency of office buildings in Montréal.

A reference office building is developed in accordance to ASHRAE Standard 90.1-1989. Using existing building energy analysis programs (BLAST, BESA), research is performed to evaluate the effect of different energy conservation measures applied to HVAC systems, and optimize fenestration areas for the reference building based on the annual energy performance.

In addition, a dynamic computer model for predicting the thermal comfort of building occupants is developed to evaluate acceptable temperature drifts as a mode of energy conservation.

This research will also present existing approaches in defining the design weather data for HVAC systems, and discuss some recommendations for improving the design weather data in Montréal based on frequency and duration of temperature occurrences, and the thermal inertia of buildings.

Finally, a database which contains the entire simulations that are performed in this thesis is developed, which can be useful to the engineer at different levels of the design process.

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NOMENCLATURE

A	- surface area
A_D	- surface area of average sized man
A_G	- glazing area
AFR	- supply and exhaust air flow rates
BF	- ballast factor
C_c	- specific heat of core of human body
CLF	- cooling load factor
CLO	- insulation value for clothing
CLTD	- cooling load temperature difference
C_p	- specific heat of air
$C_{p,bl}$	- specific heat of blood
C_{RES}	- sensible heat loss
CS	- convective heat loss from the human body
$CSIG_{CR}$	- cold signal from core
$CSIG_{SK}$	- cold signal from skin
C_{sk}	- specific heat of skin
DISC	- thermal discomfort
dT_{CR}	- change in core temperature
dT_{SK}	- change in skin temperature
$d\theta$	- increment of time
ECON	- energy consumption
ECOS	- energy cost
E_{DIFF}	- rate of heat loss from the diffusion of water vapour through the skin

NOMENCLATURE

e_i	- emissivity factor
E_{MAX}	- maximum evaporative heat loss
E_{RES}	- latent heat loss
E_{RSW}	- rate of heat loss from the evaporation of sweat
$E_{RSW,REQ}$	- rate of regulatory sweating that provides thermal comfort
E_{SK}	- evaporative heat loss from the skin
f	- ventilation factor
F	- monthly infiltration factor
FACL	- the fractional increase in body surface attributed to clothing
$FA_{i,k}$	- radiation view factor
F_E	- equipment usage factor
F_L	- lighting usage factor
F_P	- people usage factor
FP	- fan power
FR	- water flow rate
h_{cvi}	- convective inside surface coefficient
h_c	- convective heat transfer coefficient
h_e	- evaporative heat transfer coefficient
h_r	- linearized heat transfer coefficient
h_v	- latent heat of vaporization
i	- interest rate, duration
IP_i	- solar incident radiation on inside surface

NOMENCLATURE

j	- escalation rate of energy
k	- effective conductance between the core and skin
LF	- heat loss factor
m	- body mass of average sized man
M	- metabolic energy produced within the body
$\dot{m}$	- mass flow rate
$\dot{m}_{infil}$	- air flow rate due to infiltration
$\dot{m}_s$	- supply air flow rate
MSHGF	- maximum solar heat gain factor
n	- amortization period
N	- actual number of operating hours per day
NECON	- normalized energy consumption
NECOS	- normalized energy cost
N_p	- number of people
N_{REF}	- reference number of operating hours
P	- surface area of floor
P_A	- ambient vapour pressure
PP	- chilled water pump power
P_{SK}	- water vapour pressure at the skin
PW	- present worth
PWEF	- present worth escalation factor
Q_c	- rate of respiratory heat loss
Q_{cool}	- cooling plant load

NOMENCLATURE

Q_{CRSK}	- rate of heat transport from core to the skin
q_i	- heat flow
Q_E	- internal heat gain from equipment
Q_{heat}	- heating plant load
Q_l	- latent heat gain per person
Q_L	- internal heat gain from lighting
q_{lat}	- latent infiltration load
q_o	- plant diversified loads during occupied period
Q_O	- internal heat gain from occupants
Q_r	- rate of radiative heat loss
Q_{res}	- rate of respiratory heat loss
Q_s	- sensible heat gain per person
q_{sens}	- sensible infiltration load
q_u	- plant diversified loads during unoccupied period
r_e	- fraction of internal heat gain from equipment
R_i	- common ratio of the conduction transfer function coefficients
r_l	- fraction of internal heat gain from lighting
r_o	- fraction of internal heat gain from occupants
RS	- radiant heat loss from the body
REG_{SW}	- regulatory sweat generated
SC	- shading coefficient
S_{CR}	- rate of heat storage in the core compartment
S_i	- area of surface

NOMENCLATURE

SLT	- sunlit ratio
SKBF	- rate of blood flow
S_{SK}	- rate of heat storage in the skin compartment
T_A	- ambient temperature
T_B	- mean body temperature
$T_{B,C}$	- cold setpoint for evaporative regulation zone
$T_{B,H}$	- hot setpoint for evaporative regulation zone
$T_{B,N}$	- mean body temperature at its neutral value
T_{CL}	- surface temperature of clothed body
T_{CR}	- core temperature
$T_{CR,N}$	- core temperature at its neutral value
T_D	- design outdoor temperature
T_{DD}	- duration design temperature
TDB	- outdoor dry-bulb temperature
T_E	- extreme outdoor temperature
TIS_i	- inside surface temperature
T_O	- outdoor design temperature
TOS_i	- outside surface temperature
T_r	- mean radiant temperature
T_R	- room air temperature
T_S	- space heating setpoint temperature
TSENS	- thermal sensation
T_{SK}	- skin temperature

NOMENCLATURE

$T_{SK,N}$	- skin temperature at its neutral value
U	- overall heat transfer coefficient
V	- velocity of moving air in the space
w	- fraction of skin surface covered by water
W	- external work done by muscles
W_c	- weight of core
W_O	- humidity ratio of outdoor air
W_R	- humidity ratio of return air
W_{RSW}	- portion of a body that must be wetted to evaporate the regulatory sweat
W_S	- humidity ratio of indoor air
$WSIG_B$	- warm signal from the body
$WSIG_{CR}$	- warm signal from the core
$WSIG_{SK}$	- warm signal from the skin
W_{sk}	- weight of skin
X_i, Y_i	- conduction transfer function coefficients
α	- fraction of total body mass attribuited to the skin compartment
Δp	- total pressure losses
ΔT	- temperature rise
ΔT_R	- acceptable change in indoor temperature
ε_{EV}	- evaporative efficiency
η	- efficiency of centrifugal fans
τ_b	- time constant of building

CHAPTER 1

INTRODUCTION

1.1 ENERGY PERFORMANCE OF OFFICE BUILDINGS

The world oil crisis in the 1970's was the beginning of the end of low cost energy. Coinciding with recent critical environmental issues (acid rain, greenhouse effect, etc...) increased public awareness of the environment and consequent programs to achieve energy efficiency has gained prominent importance at all levels of society. Yet, Canada's domestic requirement for energy has increased 27% from 1983 to 1989 (32% increase per capita) [1].

In 1985, the International Energy Agency [2] stated that Canada is one of the most inefficient users of energy among the western industrialized countries. A report released 5 years later in October of 1990 by Southam News [3], indicated that Canadians still lead the western industrialized world in energy consumption per person.

About one third of the total energy consumed in Canada in 1981 was used in buildings for heating, cooling, lighting and ventilation [4]. Furthermore, commercial and public administration buildings required 12% of the total energy used in Canada in 1984 [5].

More than fifty indices are used to describe the thermal performance of buildings. Several prominent indices are:

- annual energy consumption, kWh/m^2 yr

- annual energy cost, $\$/m^2$ yr
- UA value of the building, $W/m^2\,^{o}C$
- Time constant of the building, $^{o}C/hr$
- Peak load, kW
- Comfort Index
- Air changes per hour
- Equipment size, kW
- Surface to volume ratio
- Percent glass
- Solar load ratio
- Lighting load, W/m^2

A survey was conducted by Loftness and Crenshaw [6] in 1985 to determine the preferred indices to measure the thermal performance of buildings in the public and private sector. The majority of the responses favoured that a database on the thermal performance of buildings should focus on standardizing data collection in kWh/m^2 yr and $\$/m^2$ yr.

In the early 1980's, the average energy consumption in large office buildings in Canada was about 457.5 kWh/m^2 yr [7]. A study conducted by the Bureau de l'Efficacité Énergétique du Québec [8] in 1987 for 24 office buildings in Montréal, indicated an average energy consumption of 388 kWh/m^2 yr. For comparison, recommended targets for energy efficient office buildings by the Building Energy Performance Standards (BEPS) are 200 to 270 kWh/m^2yr in northern climates.

In the United States, buildings consumed 36% of the country's energy supply in the late 1980's [9]. Commercial buildings required 40% of the total annual energy bill for buildings. Of the commercial building types, office buildings consumed the most energy in the U.S. [10].

During the 1970's, energy use in buildings in the United States decreased about 30%. However, since the price of oil fell sharply in 1986 to about $12.00 a barrel U.S., energy use in the building sector once again began to rise at a rate of 3.3% per year.

Recently, world events had raised concern over the supply of relatively inexpensive energy to the industrialized countries. The invasion of Kuwait by Iraq in August of 1990 had dramatically increased the price of oil, therefore increasing the interest for energy conservation programs before the price of oil dropped to the original cost after the conflict.

Piette, Wall and Gardiner [11] studied the energy performance of 88 energy-efficient office buildings located in the United States and Canada. The majority of the buildings (over 60%) have energy budgets between 126 to 221 kWh/m^2 yr. The median energy performance for large office buildings was 186 kWh/m^2 yr and 148 kWh/m^2 yr for small offices. Comparatively, energy budgets proposed by ASHRAE Standard are 135 to 180 kWh/m^2 yr for large buildings, and 123 to 160 kWh/m^2 yr for small buildings.

Spielvogel [12] presented the results of several studies performed on office buildings in the United States. The energy budgets in the office buildings ranged from 230 to 3000 kWh/m^2 yr. He suggested buildings with comparatively high annual energy use generally service conditioned computer rooms which normally require 24-hour operation. The analysis of the different building types indicated the following average annual energy consumption:

a) high-rise and federal office buildings: 662 kWh/m^2 yr,

b) general office buildings: 322 kWh/m^2 yr, and

c) owner-occupied office buildings: 622 kWh/m^2 yr.

A leading study was undertaken by Battelle Pacific Northwest Laboratory [13,14], sponsored by the U.S. Department of Energy. The purpose of the study was to develop a database on energy performance for the Building Energy Performance Standards (BEPS), and to evaluate the potential for energy savings of new buildings in the United States. Energy performance data was collected for 22 office buildings designed and built in the mid 1970's and located in 17 cities to examine the range of climatic impacts. Initial findings from the research indicated the average annual energy consumption for small buildings (< 5000 m^2) is 243.5 kWh/m^2 yr, while for large office buildings is 217.6 kWh/m^2 yr.

Brodrick et al. [15] indicated two levels of descriptive information are needed to effectively plan and evaluate research and development of commercial office buildings:

1) general demographic information (location, floor area,

number of stories, etc...), and

2) specific, detailed technical information such as space heating/cooling loads.

They detailed a new approach in categorizing the existing office building sector based on statistical (cluster) techniques, coupled with available databases on office buildings. Cluster analysis is a statistical procedure that identifies groups or clusters of data points having similar attributes. Data points that are close together based on this distance measure are grouped into the same cluster, while distant data points are arranged into separate clusters. Their approach intended to improve the design of building energy studies. Their analysis of the 1979 NBECS study in the United States defined 20 categories (clusters) for the 1,139 buildings. Some of their findings suggest small offices consume about four times as much energy per square foot as large offices, due mostly to higher surface-to-volume ratios and thus relatively higher heat losses through building exterior surfaces.

The two main objectives of the following section are:

a) Present the results of a major research effort evaluating the annual energy performance of office buildings in Montréal in 1988. The study provides a detailed representation for the entire stock of privately owned office buildings in Montréal.

b) Perform a comprehensive analysis of the database obtained from the survey, and identify the principal factors which contribute to the overall annual energy budget of the office buildings.

1.2 SURVEY OF OFFICE BUILDINGS IN MONTRÉAL

This section presents the objectives of the survey and the procedure followed by the investigating team to obtain data for the sample buildings.

1.2.1 Objectives

In 1989, a major research effort was administered between May and October by an investigating team (including the author of this thesis, at the Centre of Building Studies, Concordia University [16], in collaboration with le Bureau de l'Efficacité Énergétique du Québec and the Montréal Downtown Energy Forum programme. The objectives were the following:

- to define the pattern of energy use in office buildings in Montréal in 1988,
- to develop a detailed database, useful at different levels of the decision-making process,
- to make available to the building designers target values of energy use for new or renovated buildings,
- to aid the building owners and managers to compare their buildings to the overall energy performance of office buildings in Montréal, and then to consider possible

means to improve on the energy performance,

- to estimate the energy savings in office buildings for successive years.

1.2.2 Sample Buildings

The initial source of information for selecting sample buildings was the "Montreal Office Space Directory - 1989," [17].

Following a preliminary phone survey, 128 office buildings were targeted to be studied. Subsequently, 77 letters signed jointly by the Centre for Buildings Studies and the Bureau de l'Efficacité Énergétique were mailed (May 15, June 9 & 15, and July 31) to explain the purpose of the survey and ask for consequent participation in the research effort.

The team made phone calls two or three weeks after each mailing to arrange appointments with the people involved in the building management. Approximately 400 phone calls were made during this stage. The number of calls for each building varied between 1 and 12, with an average of 5.2. As a result, a total of 45 people accepted to take part in the survey, which represents a coefficient of acceptance of 58%.

It is interesting to recognize the reasons why 32 people did not participate in the survey:

- no answer to the letter and to the phone calls = 8
- no interest in survey = 7

- no time for interview and/or release of data = 6
- new building or new owner of the building, thus the utility bills for the entire year 1988 were not available = 5
- building was sold = 4
- no approval from lawyer to release the required information = 1
- utility bills were not available to the owner since the tenants were paying directly for heating and electricity = 1

The people accepting to take part in the study were individually interviewed for a duration of 15 to 20 minutes. More than 95% of them provided access to the monthly utility bills, while the remaining 5% supplied only the annual energy cost and/or energy consumption. Eventually, information was obtained for 74 of the 128 buildings, albeit 6 buildings were eliminated due to insufficient data.

The survey is representative of the entire building stock in Montréal since the total floor area of the sample buildings was about 2.5 million m^2, which represents about 40% of the Montréal gross office space area. Additionally, it covers extensively each building parameter such as year of construction (Figure 1.1), building class and type (Figures 1.2 and 1.3), number of floors above grade (Figure 1.4), and fuel type (Figure 1.5).

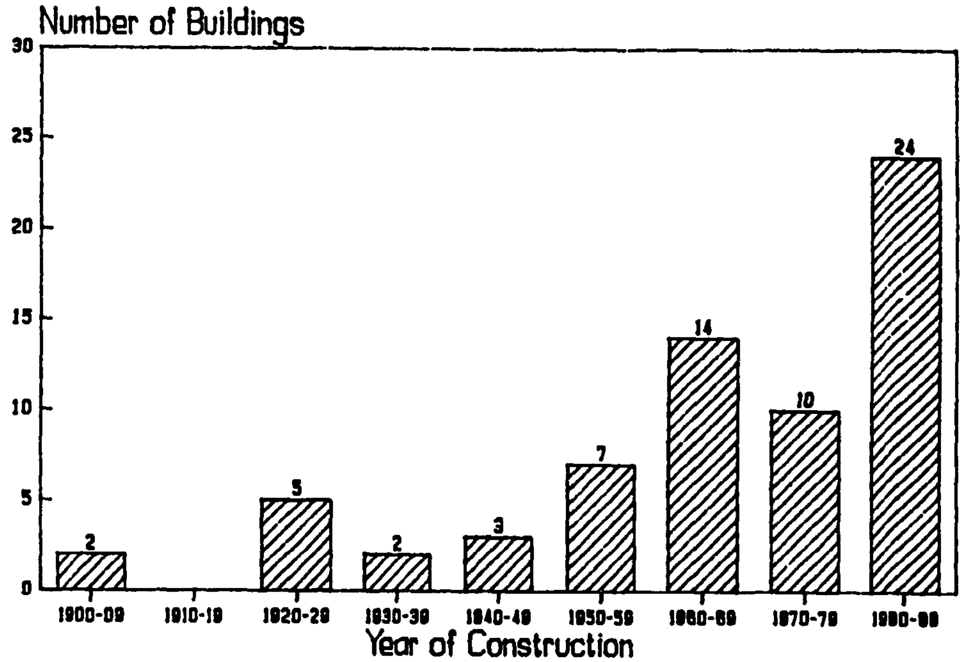

Figure 1.1 Year of construction of buildings in survey

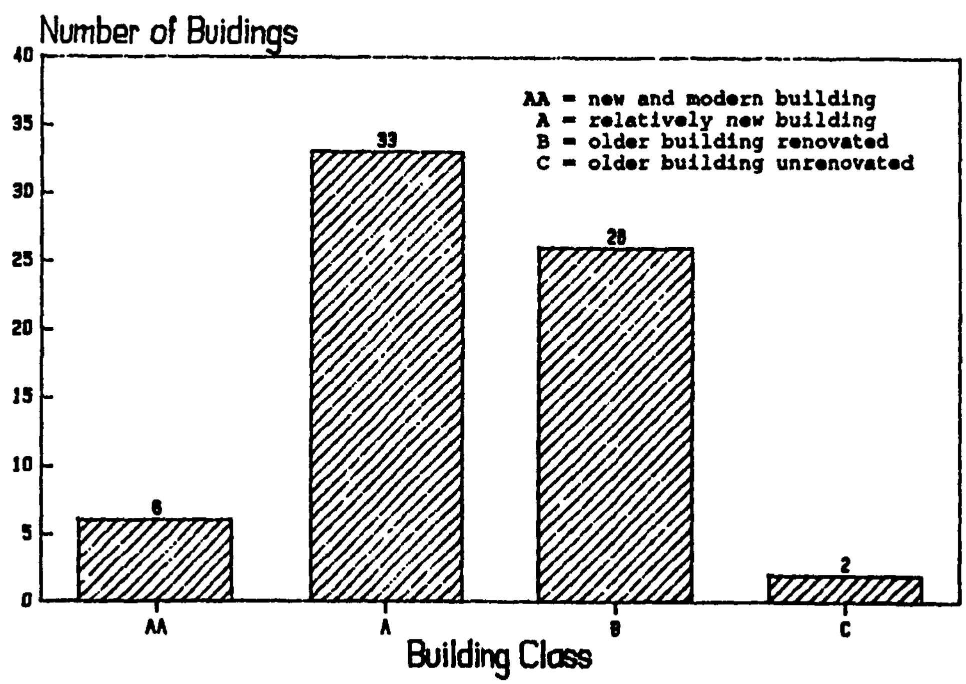

Figure 1.2 Class of buildings in survey

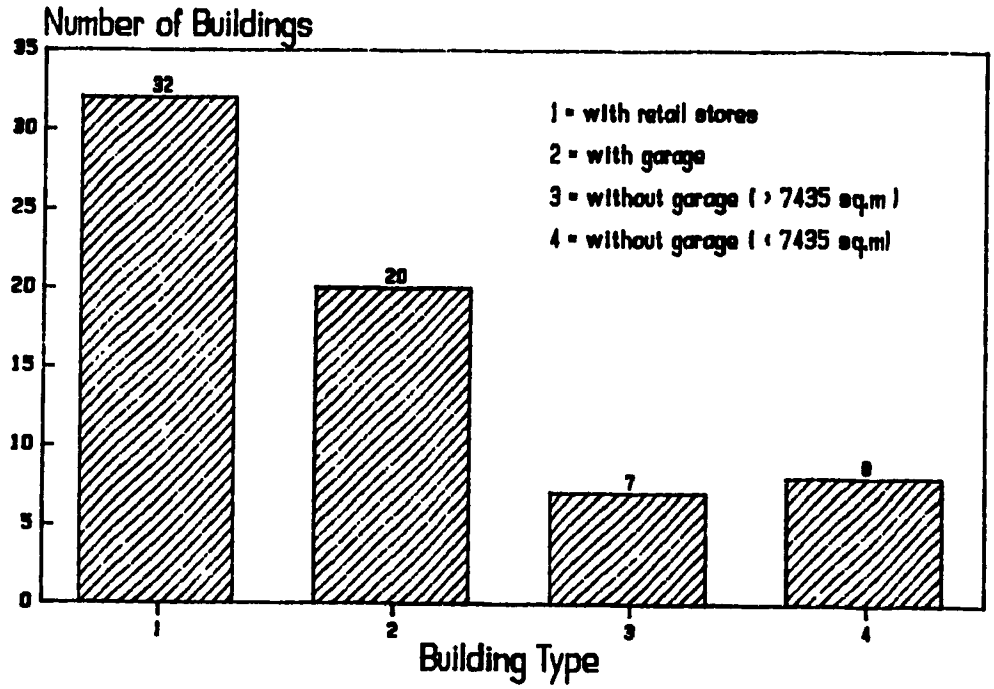

Figure 1.3 Type of buildings in survey

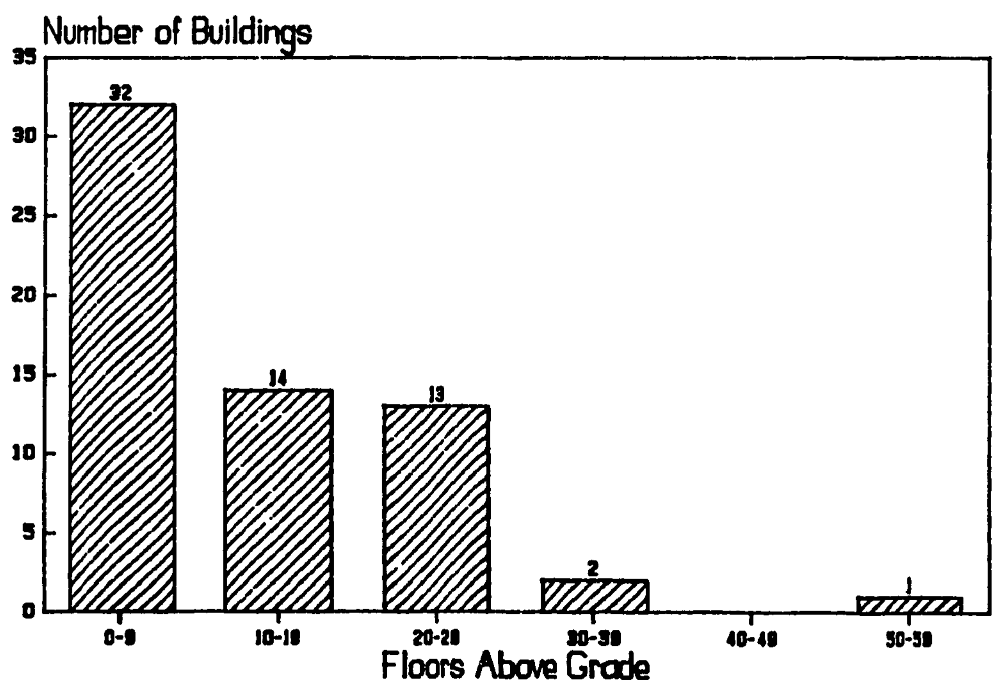

Figure 1.4 Height of buildings in survey

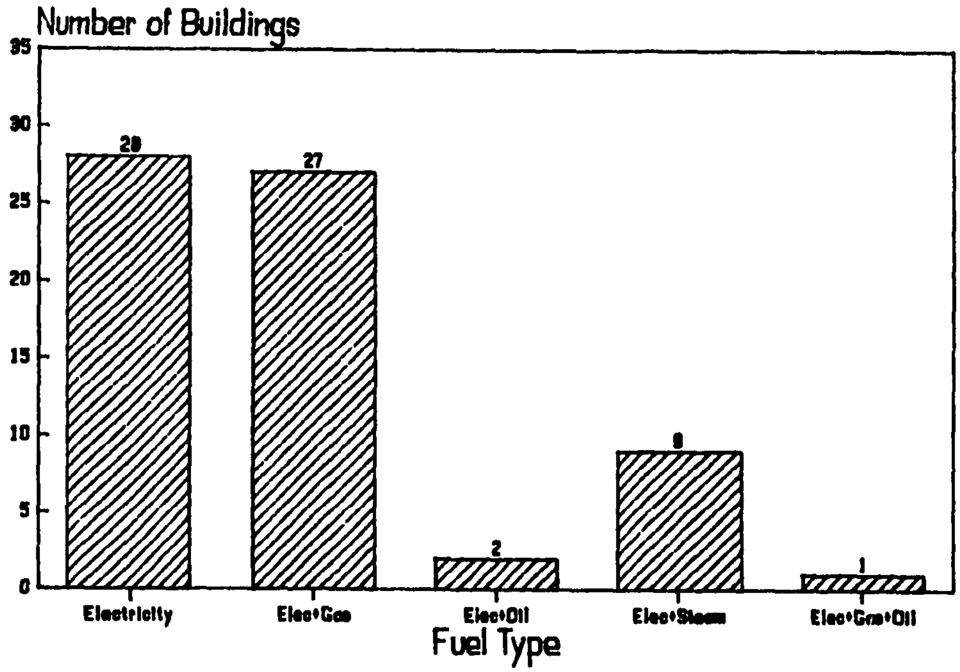

Figure 1.5 Fuel type used in buildings in survey

1.2.3 Methodology

The questionnaires and the utility bills provided the following:

- code number, required to confidentially maintain the names and addresses of the owner and the building,
- year of construction,
- building type (BOMA classification):

  1 = office building with retail stores,
  2 = office building with garage,
  3 = office building without garage, surface area > 7435 m^2,
  4 = office building without garage, surface area < 7435 m^2,

- building class (BOMA classification):

  AA = a very new and modern building incorporating the latest in environmental architecture, situated in a prime location, and having the highest occupancy rates,
  A = a relatively new building in a prime location with high occupancy rates and highly competitive rental rates,
  B = an older building renovated to modern standards in a prime location, and with high occupancy rates; or a new building in a non-prime location,
  C = an older, unrenovated building in fairly good condition; moderate to low rental rates; good occupancy, though possibly slightly lower than city average,

- gross rental area,

- number of floors above grade,

- number of floors under grade,

- floor-to-floor height,

- average percentage of exterior shading, due to other buildings,

- glazing type:

  1 = single glazing,
  2 = double glazing,
  3 = triple glazing,
  4 = single + reflective/absorbent,
  5 = double + reflective/absorbent,

- average percentage of glazing,

- number of operating hours per day for HVAC system and lighting,

- type of HVAC system,

- annual electrical energy consumption, in kWh,

- annual gas energy consumption, in kWh,

- annual oil energy consumption, in kWh,

- annual steam consumption, in kWh,

- annual total energy consumption, in kWh,

- annual electrical energy cost,
- annual gas energy cost,
- annual oil energy cost,
- annual steam cost,
- fuel type:

  1 = all electrical,
  2 = electrical + gas,
  3 = electrical + oil,
  4 = electrical + steam,
  5 = electrical + gas + oil,

- percentage of electrical energy use from total energy use,
- percentage of electrical energy cost from total energy cost,
- average electrical demand, in W/m^2 floor area,
- index of energy consumption (ECON), in kWh/m^2 yr,
- index of energy cost (ECOS), in \$/m^2 yr.

The equivalent energy in kWh for gas (m^3) and oil (litres) consumption were calculated using an average efficiency of 70%, and the following heating values of fuels: 37.89 MJ/(m^3 gas) and 39.0 MJ/(L oil). The latent heat of condensation for steam used in the calculation is 1071.2 Btu/(lb steam).

The indices of the energy consumption (ECON) and the energy cost (ECOS) can be used by the building owners and managers, to compare their building with similar spaces in Montréal. These are the actual energy consumption and cost. Since several factors affect the energy consumption of buildings, the calculations must be performed using common operating conditions. For instance, the number of operating hours in the sample buildings for lighting and HVAC equipment ranged from 8 to 24 hours, with a mean and mode of 16 hours per day. Therefore, the normalized energy performance is calculated as follows:

$$NECON = ECON \times \frac{N_{REF}}{N}$$

$$NECOS = ECOS \times \frac{N_{REF}}{N}$$

where:

NECON = normalized energy consumption, in kWh/m^2yr,

NECOS = normalized energy cost, in $\$/m^2$ yr,

ECON = energy consumption, in kWh/m^2 yr,

ECOS = energy cost, in $\$/m^2$ yr,

N_{REF} = reference number of operating hours, 16 hr/day,

N = actual number of operating hours per day

1.3 PATTERN OF ENERGY USE IN OFFICE BUILDINGS

The following section examines patterns of energy use and the effect of different parameters on the annual energy consumption and cost for office buildings located in Montréal.

1.3.1 Energy Performance of Entire Sample

Figure 1.6 illustrates the average energy consumption based on year of construction for the sample buildings. The annual energy consumption for office buildings built between 1950 and the early 1970's in Montréal rose from 392.8 kWh/m^2 yr to 542.6 kWh/m^2 yr. Since the energy crisis in the early 1970's till the mid 1980's, energy consumption in Montréal office buildings decreased by approximately 38% to 337.8 kWh/m^2 yr. Necessitated by higher energy costs, building designers reduced energy consumption by:

- installing double glazed windows
- improving lighting efficiencies
- installing variable air volume (VAV) systems

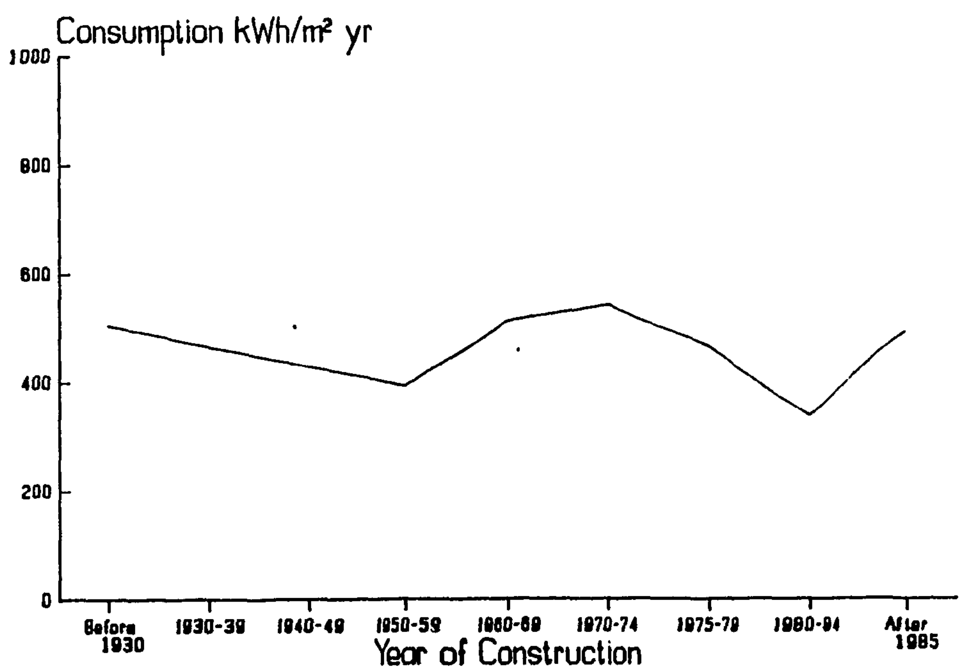

Figure 1.6 Average energy consumption of office buildings

However, with the dramatic fall of oil prices in 1986 to about $15.00 a barrel U.S., the average energy consumption in Montréal office buildings built after 1986 is once again increasing at an annual rate of 15% (491.8 kWh/m^2 yr in 1988).

Table 1.1 summarizes the energy performance of the entire sample of office buildings.

Table 1.1 Statistical measures of the energy performance of office buildings in Montréal in 1988.

	ECON kWh/m^2 yr	NECON kWh/m^2 yr	ECOS $/$m^2$ yr	NECOS $/$m^2$ yr
Average	455.3	502.2	17.9	19.5
Median	406.5	443.8	17.1	17.9
Mode	318.9	363.5	13.6	17.9
Standard Deviation	166.0	212.8	8.4	9.7
Minimum	251.4	185.7	6.6	6.9
Maximum	938.3	1134.9	60.5	60.5

The monthly average energy consumption for the entire sample of all the buildings using electricity as the sole fuel supply is illustrated in Figure 1.7. The non-weather dependent energy consumption for cooling of interior spaces, lighting, office equipment, domestic hot water, fans and pumps averaged 21.4 kWh/m^2. From October to March, the average increase in energy consumption due to heating above the constant monthly consumption was 52% per month (74% in January). During the cooling season from June to August, the average increase in monthly energy use due to cooling also above the constant monthly consumption was 21% (30% in August).

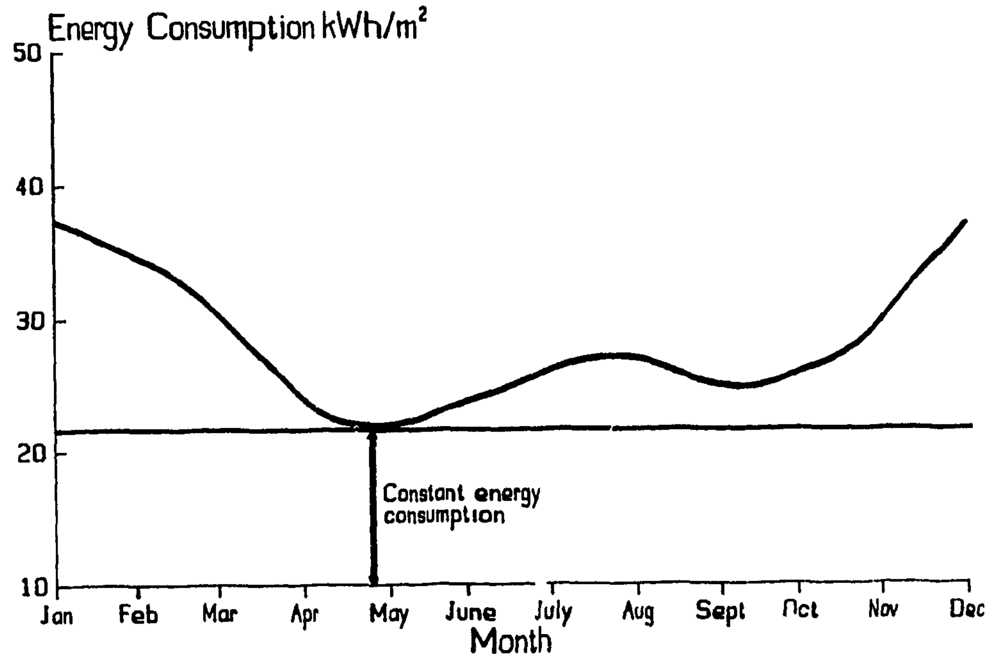

Figure 1.7 **Monthly energy consumption for sample buildings using electricity as the unique source of energy.**

1.3.2 Effect of Fuel Type on Energy Cost

Table 1.2 summarizes the energy performance of buildings in terms of fuel types. As one can observe, buildings which use electrical energy as the sole energy supply compared to any other combined fuel supply attained the highest monetary cost per kWh (0.050 $/kWh). It is interesting to note, the majority of the sample buildings (89%) built after 1985 used only electricity to supply all the energy requirements for the building. A combination of electricity and oil fuel supply produced the lowest costs (0.023 $/kWh).

Table 1.2 Summary of energy performance for several fuel types

Building	Consumption kWh/m^2 yr		Cost \$/m^2 yr		Cost of equiv. kWh
	Actual	Norm.	Actual	Norm.	
Electricity Average	423.5	490.5	21.42	24.29	0.050
Median	351.5	460.7	18.88	21.96	0.054
Std Deviation	189.4	218.0	11.26	11.82	---
Elec + Gas Average	467.3	464.5	15.36	14.91	0.033
Median	451.2	399.9	13.56	13.99	0.030
Std Deviation	127.9	183.3	4.61	5.86	---
Elec + Oil Average	477.0	807.9	10.92	17.91	0.023
Median	477.0	807.9	10.92	17.91	0.023
Std Deviation	227.2	462.5	1.24	0.03	---
Elec + Steam Average	483.8	547.6	16.49	19.21	0.034
Median	445.8	692.7	17.89	17.89	0.040
Std Deviation	180.9	196.8	3.75	7.32	---
Elec+Gas+Oil Average	693.1	693.1	17.89	17.89	0.026
Median	693.1	693.1	17.89	17.89	0.026
Std Deviation	000.0	000.0	00.00	00.00	---

The variation of the energy consumption and cost versus the ratio of total electrical use / total energy use is represented in Figures 1.8 and 1.9. Contrary to the trend in Figure 1.8 where energy consumption decreased as the ratio increased above 60%, Figure 1.9 illustrates the larger the

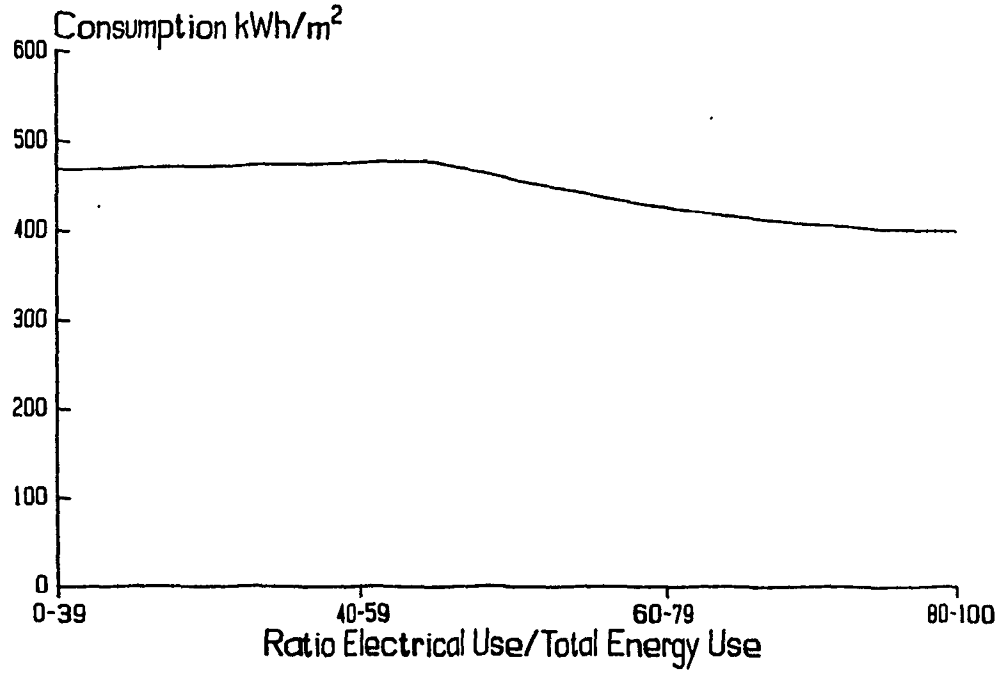

Figure 1.8 Ratio of electrical use versus energy consumption

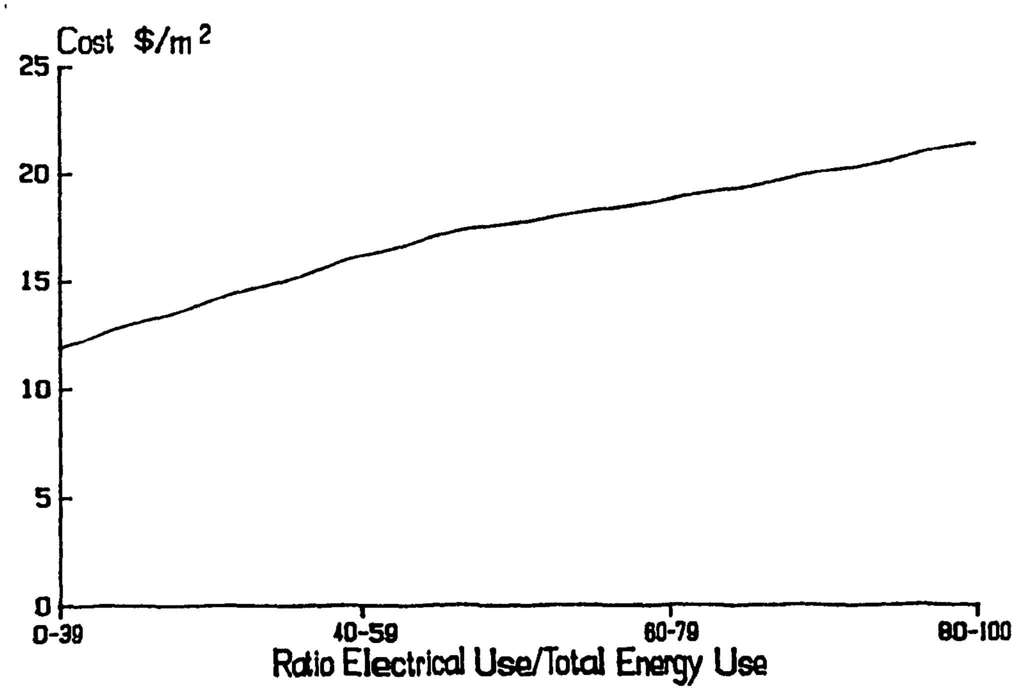

Figure 1.9 Ratio of electrical use versus energy cost

electrical use ratio, the higher the average annual energy cost for the building.

One of the main reasons for the increase in energy costs owing to a larger ratio of electrical energy use was the accompanied increase in electrical demand (Fig. 1.10). The average rate of increase for energy cost was 4.4% per 10 watt rise in electrical demand.

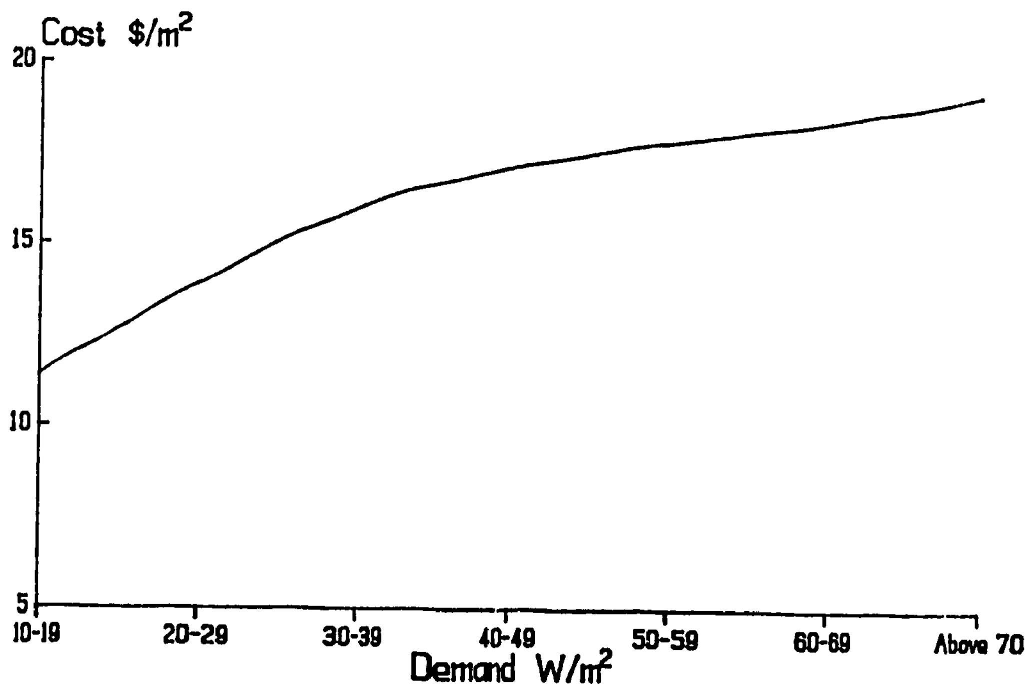

Figure 1.10 Electrical demand versus energy cost

1.3.3 Effect of Building Size on Energy Performance

A summary of the energy performance for large and small office buildings is presented in Table 1.3. Twenty-five percent of the office buildings had a gross floor area less than 7435 m^2, a nominal dividing line between small and large buildings [17].

Table 1.3 indicates the normalized energy consumption for small office buildings (530.0 kWh/m^2) is slightly higher (6.9%) than the large office buildings (493.4 kWh/m^2). Cost comparison between small and large office buildings reveal that small buildings have a normalized annual operating cost 17.0% greater than large buildings, which may be due in part to a larger demand per unit area. A simple observation of Table 1.3 shows the demand for small buildings is 60.00 W/m^2, which is 16.1% higher than the demand found in large buildings (50.33 W/m^2).

Table 1.3 Summary of energy performance for small and large buildings in Montréal in 1988

Building	Consumption kWh/m^2 yr		Cost $\$/m^2$ yr		Demand W/m^2
	Actual	Norm.	Actual	Norm.	
Small Average	441.6	530.0	20.05	22.35	60.00
Median	445.8	471.1	20.40	22.81	55.90
Std Deviation	142.8	278.0	4.94	8.63	11.45
Large Average	459.7	493.4	17.21	18.55	50.33
Median	404.2	418.0	15.81	16.94	38.10
Std Deviation	173.9	190.3	9.17	9.96	28.36

1.3.4 Effect of Building Type on Energy Performance

Table 1.4 demonstrates small buildings less than 7435 m^2 without a garage (Type 4) had the largest energy budget (502.7 kWh/m^2 yr) of the four building types. These results are consistent with the analysis presented in Section 1.3.3 which indicates small office buildings consume more annual energy per unit area than larger buildings. Office buildings with retail stores (Type 1) expend the second largest energy, due to the following reasons:

- increased thermal loads owing to the larger frequency of people entering and leaving the building,
- increased lighting and HVAC system operation hours (16 hrs/day), more than any other building type.

Buildings with a garage (Type 2) consume more energy than large buildings without a garage (Type 3). This effect is primarily due to larger heating loads required to maintain set temperatures for the indoor parking.

Alluding to the annual energy cost of the building types, Table 1.4 indicates that electrical demand procures a greater influence on the total annual cost rather than the total energy consumption. For instance, small buildings without a garage (Type 4) comprise the second largest cost budget (18.98 $\$/m^2$ yr), albeit the largest energy consumption; whereas buildings with a garage (Type 2) have the largest annual energy cost (21.75 $\$/m^2$ yr) despite having the third largest energy use. This consequence is best attributed to the required demand of the building. Building Type 2 maintained the largest electrical demand (63.21 w/m^2), while building Type 4 required a lower demand (58.60 w/m^2). Further, Type 2 buildings had the largest electrical use/total energy use ratio (79%) and electrical cost/total energy cost ratio (91%).

Table 1.4 Summary of energy performance for various building types in Montréal in 1988

Building	Consumption kWh/m^2 yr		Cost $\$/m^2$ yr		Demand W/m^2
	Actual	Norm.	Actual	Norm.	
Type 1 Average	461.2	510.3	15.63	17.20	40.39
Median	456.7	463.7	15.81	15.91	32.60
Std Deviation	142.8	213.0	5.00	7.72	17.06
Type 2 Average	453.6	492.0	21.75	23.28	63.21
Median	348.8	390.6	18.23	19.61	55.90
Std Deviation	210.3	228.5	12.66	12.71	31.57
Type 3 Average	376.3	471.7	16.59	20.42	50.62
Median	357.7	476.0	18.88	18.88	46.65
Std Deviation	64.9	132.6	4.50	7.40	24.42
Type 4 Average	502.7	521.5	18.98	18.68	58.60
Median	490.0	507.6	17.96	15.44	58.60
Std Deviation	190.3	260.6	6.96	9.40	12.44

Note: Type 1= office building with retail stores
Type 2= office building with garage
Type 3= office building without garage (≥ 7435 m^2)
Type 4= office building without garage (< 7435 m^2)

1.3.5 Effect of Glazing Areas on Energy Performance

Figure 1.11 shows the relationship between normalized energy consumption and glazing area for the buildings surveyed. Energy consumption increased 95% when the glazing area increased from 20% to 70% of the exterior wall area.

However, the minimum normalized energy costs occurred for glazing areas between 35 and 40% for the sample buildings (Fig. 1.12). One possible explanation for this outcome may in part be due to increased solar heat gains in winter, which in turn may have reduced heating loads and/or electrical demand as indicated in Figure 1.13, or by coincidence of other factors.

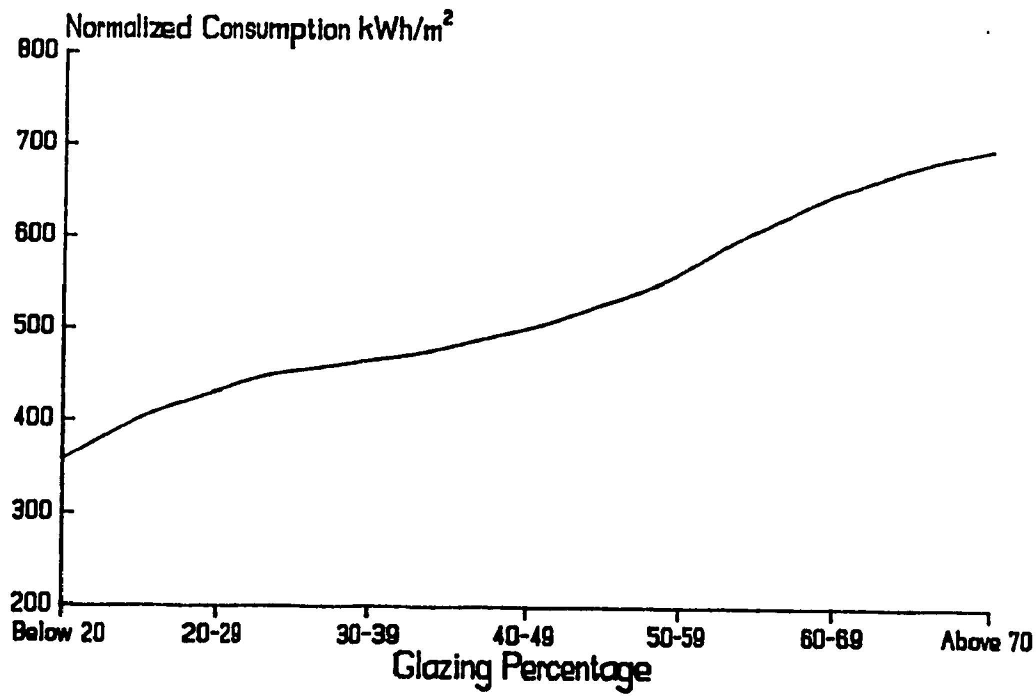

Figure 1.11 Normalized energy consumption versus glazing area

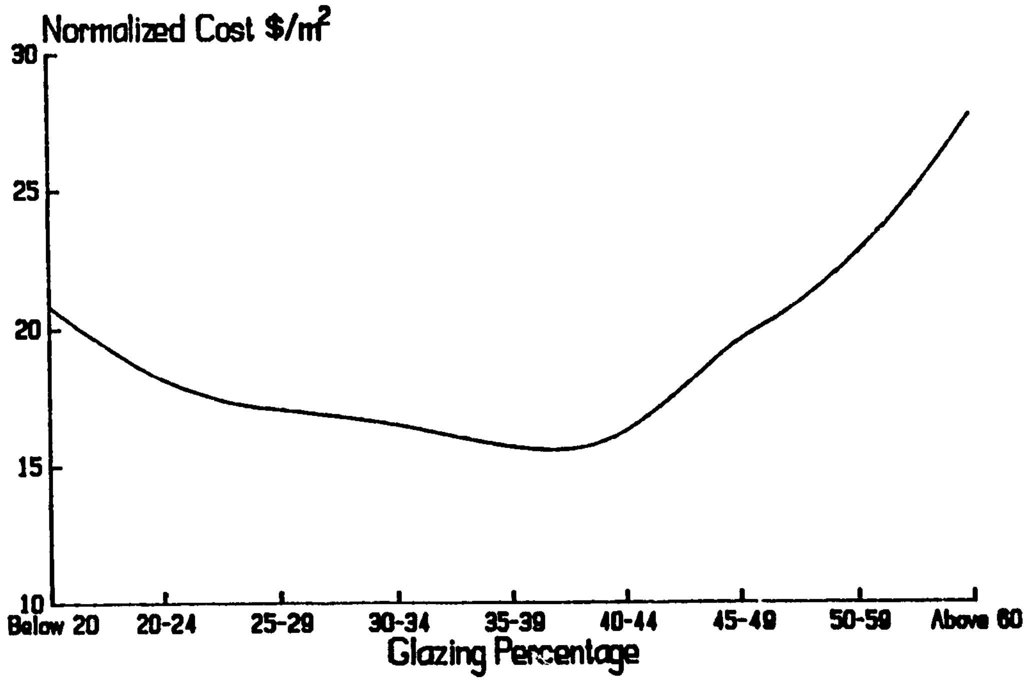

Figure 1.12 Normalized energy cost versus glazing area

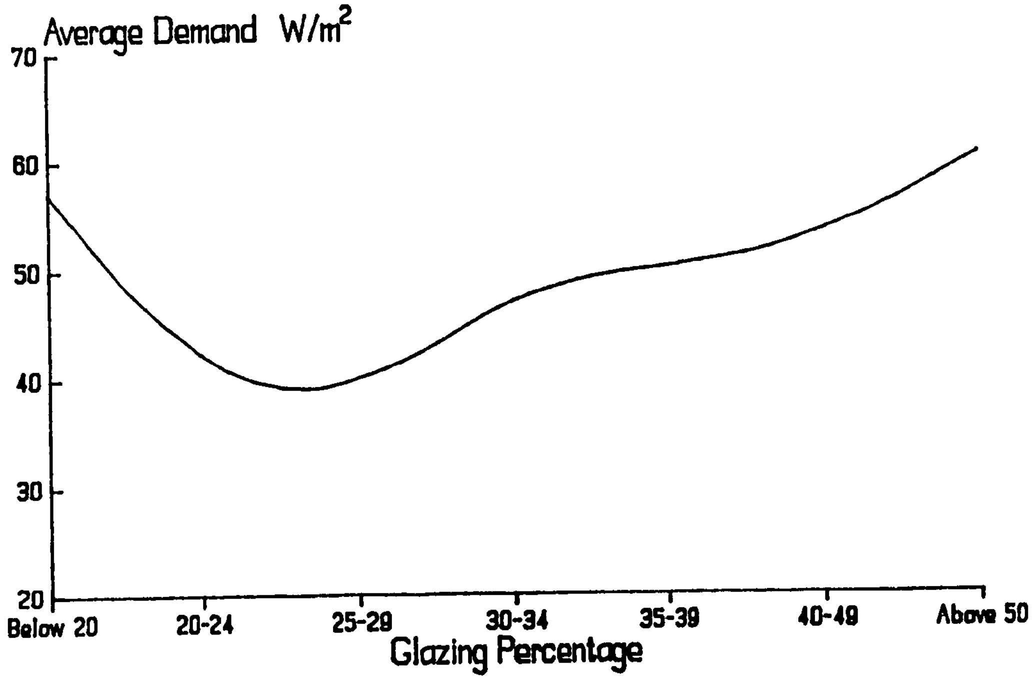

Figure 1.13 Electrical demand versus glazing area

Table 1.5 indicates the percentage of buildings using various glazing types. The majority of new office buildings constructed after the energy crisis in the 1970's employed double reflective/absorbent windows, which conserve energy by reducing thermal losses in winter, and solar heat gains in summer. However, there are still 20% of office buildings using single glazing.

Table 1.5 Glazing type of sample buildings

Glazing Type	Percentage of Buildings
Single	20.0%
Double	17.0%
Triple	0.0%
Single Reflective/Absorbent	2.0%
Double Reflective/Absorbent	61.0%

1.4 CONCLUSIONS

The results presented in this chapter were compiled from a comprehensive analysis of a database, obtained from a six month survey analyzing the energy performance of office buildings in Montréal in 1988. Most of the office buildings surveyed (88%) were operating at energy intensities higher than recommended BEPS target levels of 200 to 270 kWh/m^2 yr. The average energy performance of office buildings in Montréal in 1988 was 455.3 kWh/m^2 yr and 17.9 $\$/m^2$ yr.

Analysis of the age of the building stock in the survey indicated energy consumption in newer office buildings has increased at an average annual rate of 12% since 1986, following a 51% decrease in energy consumption for office buildings built between the energy crisis in the early 1970's to the fall of oil prices in 1986.

Several key factors were identified which effected the overall energy performance of the buildings.

The average energy cost for buildings using only an electrical fuel supply in 1988 was higher than any other combined fuel supply employing electricity with steam, gas and/or oil. The majority of the buildings (89%) built after 1985 using electricity as the main source of energy had an average energy cost of 0.050 \$/kWh. Buildings with a high ratio of electrical-to-total energy use were observed to have higher electrical demands. Results from numerous office building utility bills reveal a 4.4% average rate of increase in energy costs per an additional 10 watt rise in annual electrical demand.

Large office buildings which represent 75% of the buildings surveyed consumed an average 6.9% less energy than small office buildings. Additional examination of building types revealed small office buildings without a garage had the largest annual energy consumption (502.7 kWh/m^2 yr), followed by buildings with retail stores (461.2 kWh/m^2 yr), buildings with indoor parking (453.6 kWh/m^2 yr) and large office buildings without a garage (376.3 kWh/m^2 yr).

Glazing areas significantly affected the annual energy performance of the office buildings. A 95% increase in normalized energy consumption was observed when glazing area percentages in respective buildings increased from under 20% to above 70%. However, optimum normalized energy costs resulted for glazing areas between 35% and 40%.

The survey presented in this chapter as well as the information from other reports indicate there is a large potential for energy savings in office buildings in Montréal. Hence, in the following chapters several possible means for improving the energy performance of office buildings will be developed.

In Chapter 2, optimization of glazing areas for office buildings in Montréal is presented.

In Chapter 3, application of acceptable temperature drifts as a mode of energy conservation in office buildings is evaluated.

In Chapter 4, the energy performance of office buildings in Montréal following ASHRAE Standard 90.1-1989 is presented. Then, different energy conservation measures are analyzed for this building in order to improve the design.

In Chapter 5, a new approach that defines design weather data is presented which combines the duration of outdoor temperatures and the time constant of a building.

In Chapter 6, a database which contains the computer simulations performed in this research is developed.

In Chapter 7, conclusions and recommendations for further research are presented.

CHAPTER 2

OPTIMIZATION OF GLAZING AREAS IN OFFICE BUILDINGS

2.1 INTRODUCTION

In commercial buildings, space conditioning (heating and cooling) requires one of the largest proportions of the total energy consumption. Consequently, some building designers appropriately reduce the fenestration area to lower energy use for space heating and cooling. Frequently this approach is not justified since it neglects to consider the effect of daylighting, and the occupant visual response to this measure. Elder and Tibbott [18] surveyed the occupant response to an energy-saving office building. Overwhelmingly, the majority of respondents in the survey were most dissatisfied with the smaller window areas. Sixty-four percent of the occupants were either 'somewhat dissatisfied' or 'very dissatisfied' with the size of the window. Eighty-seven percent thought the windows were too small, seventy-eight percent felt they were too narrow, and eighty-two percent thought they provided an insufficient view of the outside world. Almost all of the occupants described their response to the lack of window area as 'limited' and 'confined'.

Nevertheless, there are buildings in Montréal with large window areas that do not respect the requirements of the law on energy conservation in buildings in Québec [19], which indicates the maximum amount of glazing for buildings. The Quebec Law stipulates that the total area of glazing that separates heated space from outside or unheated space shall not be higher than 15% of the floor area or 40% of the total area of the walls separating heated space from outside.

Recently, the new ASHRAE Standard 90.1-1989 provides the Alternate Components Package (ACP) tables [20], which indicate the maximum percentage of fenestration area for buildings in the United States in terms of the following design parameters:

- Internal Load Density, in W/m^2 floor area
- Projection Factor, defined as percentage of shading created by exterior elements (i.e. overhangs)
- Shading Coefficient
- Thermal Transmittance, in W/m^2 ^oC

Despite their validity for cities located in the United States, these tables cannot be directly applied to Canadian cities.

Previous studies have discussed the effect of building envelope parameters on annual heating and cooling loads. Rudoy and Duran [21] indicated the type of installed glass (i.e SC value) can reduce the cooling load in an office building by approximately 15 to 30% below that for clear glass. Granit and Möller [22] noted that the geometric form and the amount of glazing area per floor has a significant influence on both energy requirements and qualities of working environment in the case of office buildings. Brotherton et al. [23], and Turiel et al. [24] performed parametric analyses of several design variables including roof and wall insulation, building aspect ratio and glazing wall area ratio on the annual energy performance of office buildings. Their results showed a direct increase in the annual energy consumption when the glazing area is increased.

Johnson et al. [25] have investigated the optimum window size and orientation for large non-daylit office buildings in:

- Fort Worth, Texas
- Saskatoon, Saskatchewan
- Denver, Colorado
- Boston, Masachussetts

Their study concluded a windowless building was the optimum design regardless of the climatic conditions. Increased window area caused the capital costs of the building envelope and HVAC equipment to increase, and the annual cost of electrical and natural gas energy to rise.

Crawley [26] analyzed several glazing alternatives for an office building in Cleveland, Ohio, on the basis of annual energy cost savings and construction costs. He determined that Solex & Heat Mirror double pane glazing produces an optimum savings of 4.5% as compared to the base case design with clear double pane.

Johnson et al. [27] performed several life cycle cost sensitivity studies in which the building design and operating parameters were varied, they found that fenestration area caused the single largest variation in the building life cycle cost.

This chapter presents the determination of the optimum glass wall area ratio based on the annual energy consumption and the life cycle cost for a reference building in Montréal. Reference tables similar to ASHRAE's Alternate Components Package (ACP) Tables are developed. In addition this research will enhance the existing knowledge base of building envelope studies by optimizing fenestration design based on economic and energy consumption profiles for non-daylit office buildings located in cold northern climates.

To achieve the objectives of this research and to study the effect of glass wall area ratios on the energy performance of an office building, the following procedure will be executed:

i) Design of a reference office building in accordance with the design requirements outlined by ASHRAE Standard 90.1-1989.

ii) Selection of a building energy analysis computer program to evaluate the prescribed building's energy performance.

iii) Evaluation of various glazing design alternatives using a selected building energy analysis program.

iv) Analysis of the results and development of an ACP table for Montréal.

2.2 ASHRAE STANDARD 90.1-1989

ASHRAE/IES Standard 90.1-1989 "Energy-Efficient Design of New Buildings Except Low-Rise Residential Buildings" [20] was developed as a guideline for energy efficient design of new buildings. Standard 90.1 differs considerably from the old Standard 90-1980 [28], since it recognizes that the component approach used in Standard 90-1980 towards the building envelope neglects to consider important interactions between internal loads and various features of the building envelope (i.e. glazing, orientation, shading and building mass). Thus, one of the key advances of the new standard is its flexibility in design. Crawley and Briggs [29] quantified the average percentage of energy savings obtained by using the Standard 90.1-1989 instead of Standard 90-1980 for medium sized office buildings to be approximately 16%.

The purposes of Standard 90.1-1989 are as follows [20]:

- Set minimum requirements for the energy efficient design of new buildings so that they may be constructed, operated, and maintained in a manner that minimizes the use of energy without constraining the building function nor the comfort or productivity of the occupants.
- Provide criteria for energy efficient design and methods for determining compliance with these criteria.
- Provide sound guidance for energy efficient design.

The requirements of Standard 90.1 cover all the design aspects of new buildings for energy efficient use, including:

- lighting
- exterior envelope
- HVAC systems and equipment
- service water heating
- energy management, which monitors the energy use and distribution within the building.

To comply with Standard 90.1, the designer must satisfy the general requirements outlined by the standard and also follow either the system component or building energy cost budget method.

1) System Component Method: this may be used when the minimum amount of effort to determine compliance is desired. The designer must check for compliance with either the Prescriptive criteria (which provides precalculated prescriptive requirements for lighting, HVAC systems and equipment as well as selected exterior envelope configurations prescribed in the ACP tables), or the Performance criteria (which includes two microcomputer programs to determine compliance with lighting systems requirements and external envelope requirements). If the design fails to meet the prescribed criteria, it is altered and the process is repeated.

2) Building Energy Cost Budget Method: this provides greater flexibility for the design of energy efficient buildings, and can be used when the design parameters fail to meet the design criteria set forth by the Prescriptive or Systems Performance. Compliance under this method is achieved when the estimate of annual energy cost for the design does not exceed the energy cost budget. Estimates are determined by calculating the energy consumption and energy cost of either a Prototype building (which assigns fixed design parameters as per orientation, form, occupancy etc...), or Reference building (which permits additional flexibility in design).

In this chapter, reference tables for selecting the optimum glazing area for office buildings in Montréal similar to the Alternate Components Package (ACP) tables are developed.

2.3 BUILDING MODEL

A model of a 10-story reference office building was developed to determine optimum fenestration areas, and was designed with strict accordance to ASHRAE Standard 90.1-1989, Building Energy Cost Budget Method. The building geometry, orientation, roof and wall thermal transmittance values, scheduling and internal loads (lighting, occupancy and equipment) remained constant throughout the simulations so as to examine the effects of different glazing parameters and areas on the annual energy cost and consumption of the reference building.

A general description of the reference building called building "A" is outlined below:

1. Architecture:
   10 stories,
   9000 m^2 total floor area,
   900 m^2 per floor (30m x 30m)

2. Orientation:
   4 facades directly facing individual polar axis

3. Wall construction:
   U-value=0.313 W/m^2 ^oC
   Spandrel Glass Wall,

4. Roof Construction:
   Flat masonry roof with built-up roofing,
   U-value=0.204 W/m^2 ^oC

5. Windows:
   On North, South, East, and West facing walls

6. Internal Loads:
   - Lights - 18 W/m^2,
     operating hours; 7:00 to 23:00 hrs, weekdays
   - Equipment - 6 W/m^2,
     operating hours; 7:00 to 23:00 hrs, weekdays
   - Occupancy - 7 people/100 m^2,
     8:00 to 23:00 hrs, weekdays

7. Infiltration Rates:
   0.02 m^3/s (0.40 cfm/m^2 ext. surface area) infiltration shall only occur for perimeter zones while the HVAC system is off.

8. Ventilation Rate:
   10.0 L/s/person

9. Temperature Controls:
   - Heating = 21.1 ^oC
   - Cooling = 24.0 ^oC
   - Setback = 13.0 ^oC

10. HVAC System:
    Variable Air Volume with Terminal Reheat serving all zones,
    - operating hours; 7:00 to 23:00 hrs, weekdays
    - setback; 23:00 to 07:00 hrs, weekdays
      00:00 to 24:00 hrs, weekends
    - minimum circulation rate of 4.5 air changes per hour

11. Central Plant
    - centrifugal chiller with 1000 kW capacity
    - hot water boiler with 1000 kW capacity

While varying the glazing wall area ratios from 20 to 70% by increments of 10%, the energy consumption of the reference building was determined for several shading coefficients (1.0, 0.6, 0.38, 0.25) and glazing U-values (3.86, 2.61, 2.22, 1.10 $W/m^2\ ^oC$).

Further simulations were performed for other building designs, which have the following individual design characteristics (Fig. 2.1):

"B"→ floor area 30 x 30 m, with fenestration only on the North and South facades;

"C"→ floor area 30 x 30 m, with fenestration only on the East and West facades;

"D"→ floor area 40 x 22.5 m, with fenestration on all four facades;

"E"→ floor area 40 x 22.5 m, with fenestration only on the North and South facades.

2.4 BUILDING ENERGY SIMULATION PROGRAM

The Building Load Analysis and System Thermodynamics (BLAST) program developed by the U.S. Army Construction Engineering Research Laboratory is a powerful program that

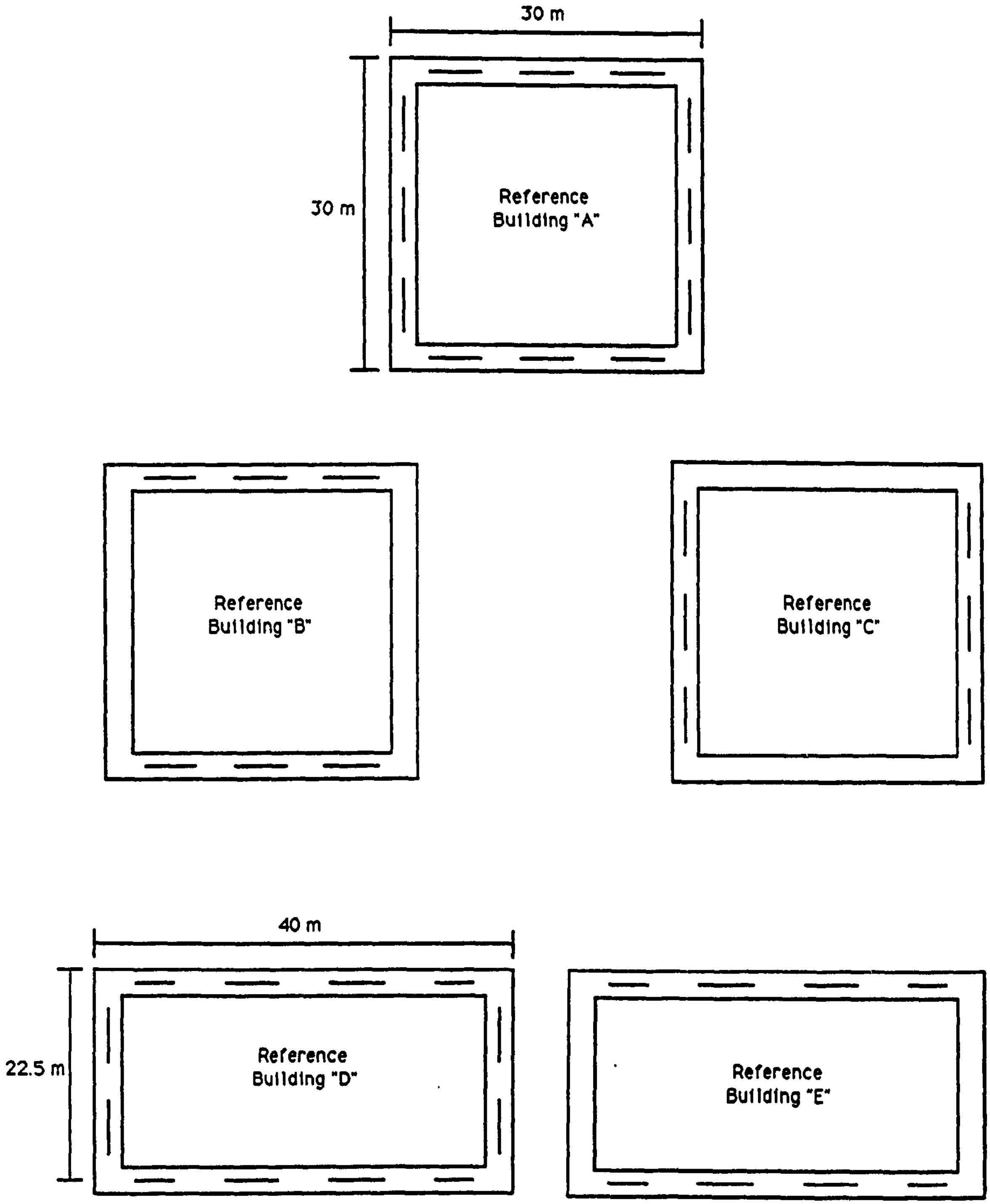

Figure 2.1 Reference buildings "A" through "E"

uses hourly computations to predict energy consumption and systems performance in buildings [30]. Apart from the program developers' verification, certain subsections of the program have been experimentally verified by independent investigators. A report by Yuill, G.K. [31] stated "... the Blast predictions of energy consumption and temperature and the measured data are close enough when compared on an hourly, daily, monthly and annual basis to indicate that the program is functioning correctly in all the areas utilized, ... and that the algorithms model correctly the major energy flows".

Yuill and Phillips [32] compared the energy consumption of two office buildings to the energy consumption predictions of the BLAST program. Their study concluded the total energy consumption predicted of the first building was 90% of the actual monitored energy consumption. The prediction of electrical and winter gas consumption of the second building was within 1%.

Subsequent reasoning for the selection of BLAST to simulate the energy performance of the reference building in this study above other similar programs are defined as follows;

a) The BLAST program uses detailed algorithms to compute loads and simulate mechanical systems.
b) Accessibility of the BLAST program at the Centre of Building Studies, where the research was performed.

To predict the thermal loads in the conditioned space, BLAST performs a detailed heat balance. A solution of a system of simultaneous linear equations for each hour simulated which includes transmission loads, solar and internal heat gains, infiltration loads and indoor control temperature profiles is required to determine the heat balance for all surfaces in the space and the room air. The transient heat transfer through walls is calculated by the conduction transfer function [33]:

$$q_{i,t}=\sum_{j=0}^{N_i} X_{i,j}\,TIS_{i,t-j}-\sum_{j=0}^{N_i} Y_{i,j}\,TOS_{i,t-j}+R_j\,q_{i,t-j}$$
$$=h_{c,v}(T_{R,t}-TIS_{i,t})+\sum_{k=1}^{N_s} G_{i,k}(TIS_{k,t}-TIS_{i,t})+R_{i,t} \qquad (2.1)$$

where:

q_i	= heat flow, in W/m^2
X_i, Y_i	= Conduction Transfer Function coefficients, in $W/m^{2o}C$
R_i	= common ratio of the Conduction Transfer Function coefficients
TIS_i	= inside surface temperature, in ^oC
TOS_i	= outside surface temperature, in ^oC
T_R	= room air temperature, in ^oC
h_{cvi}	= convective inside surface coefficient, in $W/m^{2o}C$
$G_{i,k}$	= $4\ e_i\ FA_{i,k}\ (T_{Rt}+460)^3 0.1714*10_{-8}$
e_i	= emissivity factor
$FA_{i,k}$	= radiation view factor between the surface i and k
$R_{i,t}$	= $IP_{i,t} + [(i-r_e)Q_E+(1-r_o)R_O+(1-r_l)R_L] / \sum S_i$
IP_i	= solar incident radiation on inside surface i, in W/m^2
r_e, r_o, r_i	= fraction of internal heat gain from equipment, occupants and lighting that are assumed to be convective
S_i	= area of surface i, in m^2
Q_E, Q_O, Q_L	= internal heat gains generated by equipment, occupants and lighting, in W

To connect all the convective heat flows which occur within the space, the BLAST program evaluates the following heat balance for the room air [33]:

$$\sum_{i=1}^{N_s} S_i (TIS_{i,t} - T_{R,t})\, h_{cv_i} + \dot{m}_{infil} C (TDB_t - T_{R,t}) + \dot{m}_{s,t} C (T_{S,t} - T_{R,t}) + Q_E r_e + Q_O r_o + Q_L r_l = 0 \qquad (2.2)$$

where:
$\dot{m}_{infil}$ = air flow rate due to infiltration, in kg/s
c = specific heat of air, in J/kg°C
TDB = outdoor dry-bulb temperature, in °C
$\dot{m}_s$ = supply air flow rate, in kg/s

2.4.1 BLAST User-Input

To facilitate user-input and analysis of existing user-input files, BLAST uses English-like commands to compute all necessary data regarding the building's energy consumption and system performance.

For a complete analysis of a building, 4 major sections must be described in the BLAST input file (Fig. 2.2):

a) Lead Input

b) Building Description

c) Fan System Description

d) Central Plant Description

Lead Input

The purpose of the lead input is:

a) to indicate which simulations are to be performed by BLAST (i.e. zones, systems, central plant),

```
BEGIN INPUT;
     RUN CONTROL:
        ⋮
     DEFINE: LOCATION, CONTROLS, MATERIALS, SCHEDULES;
        ⋮
     WEATHER TAPE;

                         ⇓

  BEGIN BUILDING DESCRIPTION;
       ZONE 1:
         WALLS, PEOPLE, LIGHTS, ELECTRIC EQUIPMENT,
         INFILTRATION, CONTROLS;
       END ZONE;
       ZONE 2:
          ⋮
  END BUILDING DESCRIPTION;

                         ⇓

  BEGIN FAN SYSTEM DESCRIPTION;
       VARIABLE VOLUME SYSTEM 1;
          FOR ZONE 1:
          ⋮
       OTHER SYSTEM PARAMETERS:
          ⋮
       COOLING COIL DESIGN PARAMETERS:
          ⋮
       EQUIPMENT SCHEDULES:
          ⋮
  END FAN SYSTEM DESCRIPTION;

                         ⇓

  BEGIN CENTRAL PLANT DESCRIPTION;
       PLANT 1 "BOILER AND CHILLER";
       EQUIPMENT SELECTION:
          ⋮
       PART LOAD RATIOS;
          ⋮
  END CENTRAL PLANT DESCRIPTION;

END INPUT
```

Figure 2.2 Overview of BLAST user-input

b) to define space temperature controls,

c) to define hourly and daily profiles used to schedule lighting, equipment, occupancy and infiltration,

d) to define materials for walls, roofs, windows, and

e) to indicate the location of the building and the design and/or actual weather data for the simulation period.

Represented below is the information describing the lead input for the reference building as presented in BLAST;

```
BEGIN INPUT;
RUN CONTROL:
   NEW ZONES, NEW SYSTEMS, CENTRAL PLANT,
   REPORTS (ZONE LOADS, COIL LOADS, SYSTEM),
   UNITS(IN=METRIC, OUT=METRIC);
DEFINE LOCATION:
   MONTREAL=(LAT=45,LONG=74,TZ=5);
END;
DEFINE CONTROLS (HEATN):
   PROFILES:
      HEAT=(1.0 AT 13.0, 0.90 AT 20.0, 0.0 AT 21.7, -0.11
            AT 22.0, -0.13 AT 23.0, -0.40 AT 24.0, -1.0 AT
            40.0),
    SETBACK=(1.0 AT 13.1, 0.0 AT 13.0, 0.0 AT 40.0, -1.0
             AT 40.1);
   SCHEDULES:
      MONDAY THRU FRIDAY=(07 TO 23 -HEAT, 23 TO 07 -
                          SETBACK),
      SATURDAY THRU SUNDAY =(00 TO 24 -SETBACK),
      HOLIDAY=SUNDAY;
END CONTROLS;
```

The RUN CONTROL command instructs BLAST which simulations are to be performed. For example, the previous input file tells BLAST to calculate and report loads for the NEW ZONES described in the BUILDING DESCRIPTION section, the NEW SYSTEMS described in the FAN SYSTEM DESCRIPTION and the CENTRAL PLANT described in the CENTRAL PLANT DESCRIPTION.

The CONTROL PROFILES assign the control strategy for heating and cooling to a time of day for each day of the week. The space temperature control profile "HEAT" for the reference building is illustrated in Figure 2.3. When the space temperature is above 24°C, cooling with the VAV dampers fully open is to operate and about 40% of the cooling capacity is used. VAV dampers are closed to their minimum position of 20% at 23°C. Reheat is to operate when the space temperature is equal or smaller than 21.7°C.

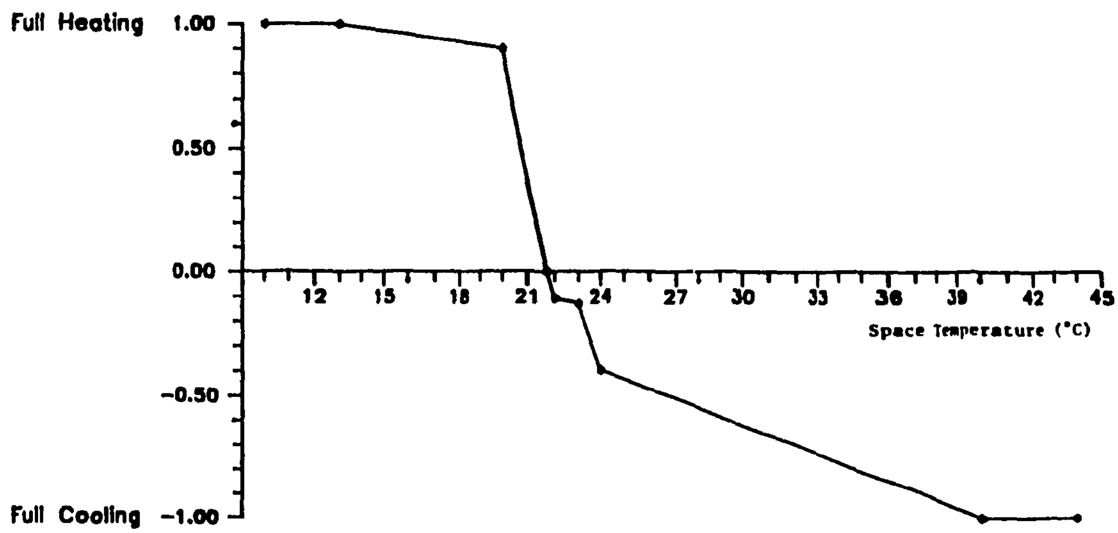

Figure 2.3 Temperature control profile "HEAT" for reference building

The HVAC system will switch to the "SETBACK" profile according to the weekday and weekend schedules defined in the user-input. For instance, the BLAST user-input instructs the SETBACK profile to operate between 23:00 and 07:00 on weekdays, while for the weekend the SETBACK profile operates continuously. The SETBACK control profile allows the space temperature to drop to a minimum 13°C before full heating is turned on.

BLAST user-input for the reference building's envelope is shown below. Materials such as spandrel glass (SPGLS), gypsum (GYP), and glass fibre insulation (R02, R10) are defined in the user-oriented input language since materials with the required properties are not available in the BLAST library. For example, the exterior wall (EXTWALL) is composed of spandrel glass (WGLS), air cavity (ACTY), thermal insulation (R10) and gypsum (GYP):

```
DEFINE MATERIALS:
     WGLS=(R=0.36, SC=0.34, GLASS),
     ACTY=(R=0.166, AIR),
     R10=(L=0.1, K=0.04, D=48, CP=1.2),
     R02=(L=0.02, K=0.04, D=30, CP=1.2),
     GYP=(L=0.01, K=0.43, D=1200, CP=1.08),
     SPGLS=(R=0.109, SC=1.0, GLASS);
END MATERIALS;
DEFINE WALLS:
     EXTWALL=(WGLS,ACTY,R10,GYP),
     PTN=((GYP,R02,GYP);
END WALLS;
DEFINE ROOFS:
     RUFX=(E2-1/2 IN SLAG OR STONE, E3-3/8 IN FELT AND
     MEMBRANE, B6-2 IN DENSE INSULATION, B6-2 IN DENSE
     INSULATION, B6-2 IN DENSE INSULATION, B5-1 IN DENSE
     INSULATION, C13-6 IN HW CONCRETE, E4-CEILING
     AIRSPACE,E5 ACOUSTIC TILE);
END ROOFS;
DEFINE WINDOWS:
     WDW=(SPGLS);
END WINDOWS;
```

Weekday schedule profiles for occupancy, lighting and equipment are illustrated in Figure 2.4 and 2.5.

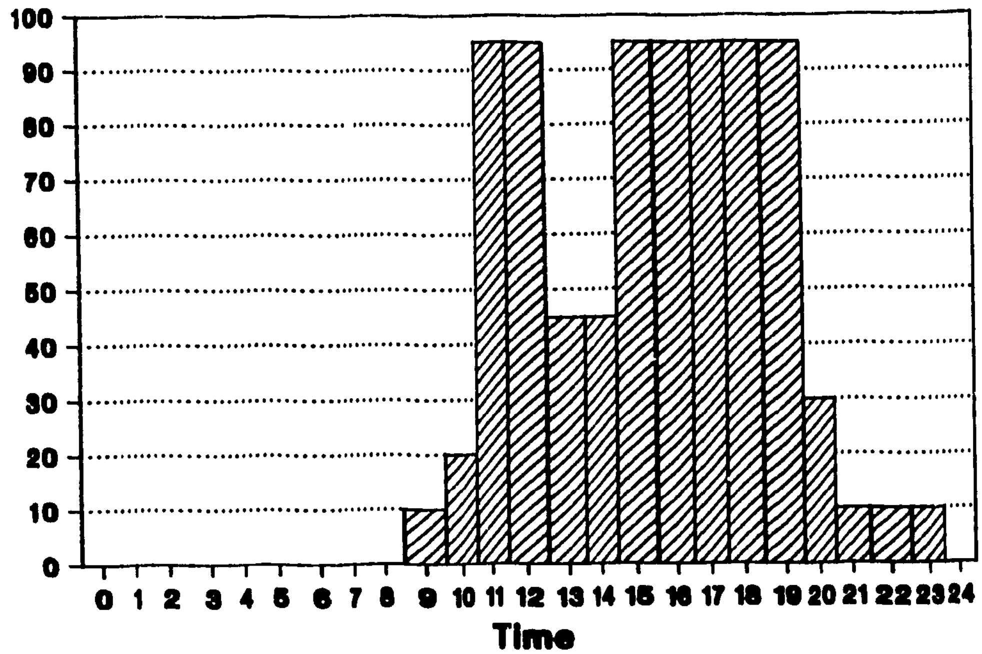

Figure 2.4 Weekday schedule profile for occupancy

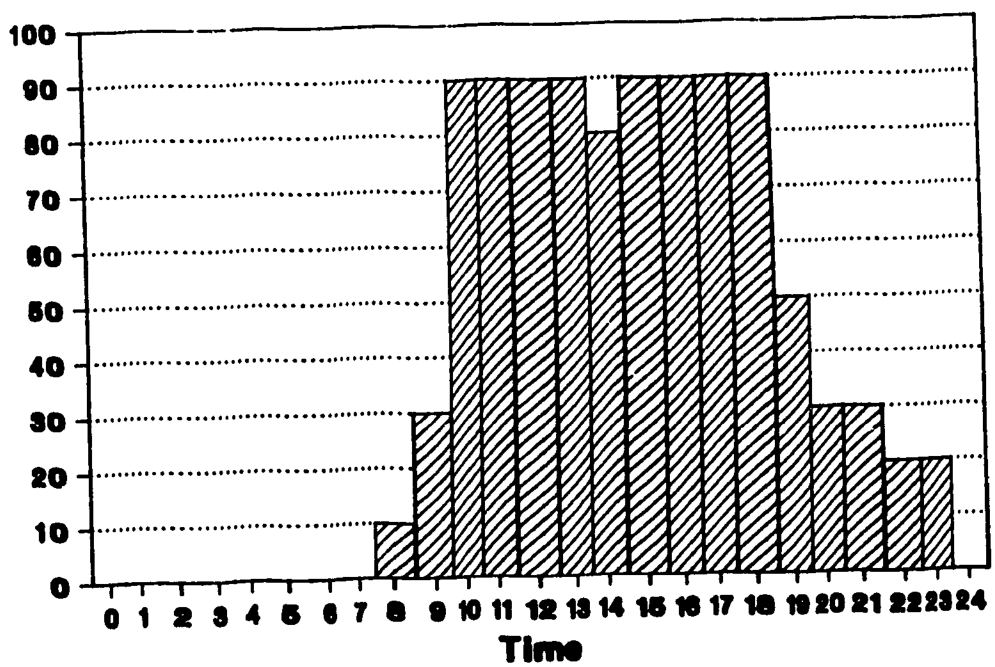

Figure 2.5 Weekday schedule profile for lighting & equipment

These profiles establish the percentage of people that are present, and of the installed power for lighting and equipment that is on every hour. Occupancy and lighting & equipment percentage multipliers for design of the reference building were set to zero during the weekend.

Infiltration within the building perimeter zones is assumed to occur only when the HVAC system is off [20]. Figure 2.6 describes a weekday infiltration rate multiplier for the building. The weekend infiltration rate for the office building is specified at 100%.

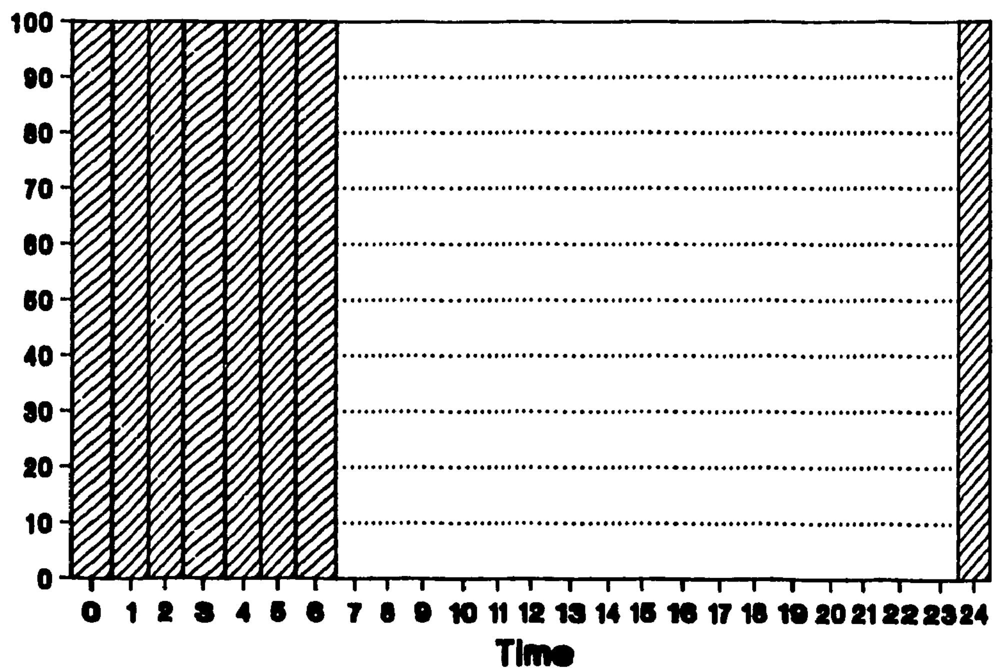

Figure 2.6 Weekday infiltration rate multiplier

The BLAST program uses a 24-hour schedule for each of the factors mentioned previously:

```
DEFINE SCHEDULE (OCCUPANCY):
  MONDAY THRU FRIDAY=(23 TO 08- 0.0, 0.1, 0.2, 0.95,
                      0.95, 0.45, 0.45, 0.95, 0.95, 0.95,
                      0.95, 0.95, 0.3, 0.1, 0.1, 0.1),
  SATURDAY THRU SUNDAY=(00 TO 24-0.0),
  HOLIDAY=SUNDAY;
END;
DEFINE SCHEDULE (LIGHTING):
  MONDAY THRU FRIDAY=(23 TO 07- 0.0, 0.1, 0.3, 0.9, 0.9,
                      0.9, 0.9, 0.8, 0.9, 0.9, 0.9, 0.9,
                      0.5, 0.3, 0.3, 0.2, 0.2),
  SATURDAY THRU SUNDAY=(00 TO 24-0.0),
  HOLIDAY=SUNDAY;
END;
DEFINE SCHEDULE (INFIL1):
  MONDAY THRU FRIDAY=(07 TO 23-0.0, 23 TO 07-1.0),
  SATURDAY THRU SUNDAY=(00 TO 24-1.0),
  HOLIDAY=SUNDAY;
END;
PROJECT="REFERENCE";
LOCATION=MONTREAL;
WEATHER TAPE FROM 01 JAN THRU 31 DEC 80;
```

The weather data for Montréal (Canada) formatted as required by the BLAST program is available at the Centre of Building Studies for ten years (1974-1983). Analyses of the annual energy consumptions for the reference building within the ten-year available weather data revealed an average 3.1% deviation as compared to the 1980 simulation period. Thus, one-year simulations of the energy consumption for the reference building with varying glazing parameters were performed from January 1st through December 31st, 1980.

Building Description

A standard method is to separate the entire floor area to at least five thermal zones, in order to divide the perimeter zones with heating and cooling loads through the building envelope from the internal zones with cooling loads due to internal heat gains. Moreover, each zone can be additionally partitioned into several sub-zones if the thermal control parameters (i.e. room air temperature) or the schedules of operation are different.

Ten thermal zones are defined for the entire reference building. The intermediate level floors 1 to 9, which are identical in terms of both internal and external loads are defined by zone numbers 1, 3, 5, 7, and 9. The top floor (10), which has added thermal loads due to the roof is defined by zone numbers 2, 4, 6, 8, and 10. The zone distribution per floor of the reference building is shown in Figure 2.7 and Table 2.1.

The building orientation and shape for user-input in BLAST must be co: ectly described to accurately determine the effect of solar radiation on the reference building. A cartesian coordinate system is used in BLAST to describe the building and its various zones. The wall azimuth is measured from the North axis, thus for surfaces facing North the wall azimuth is 0°, for East is 90°, for South is 180° and for West is 270°.

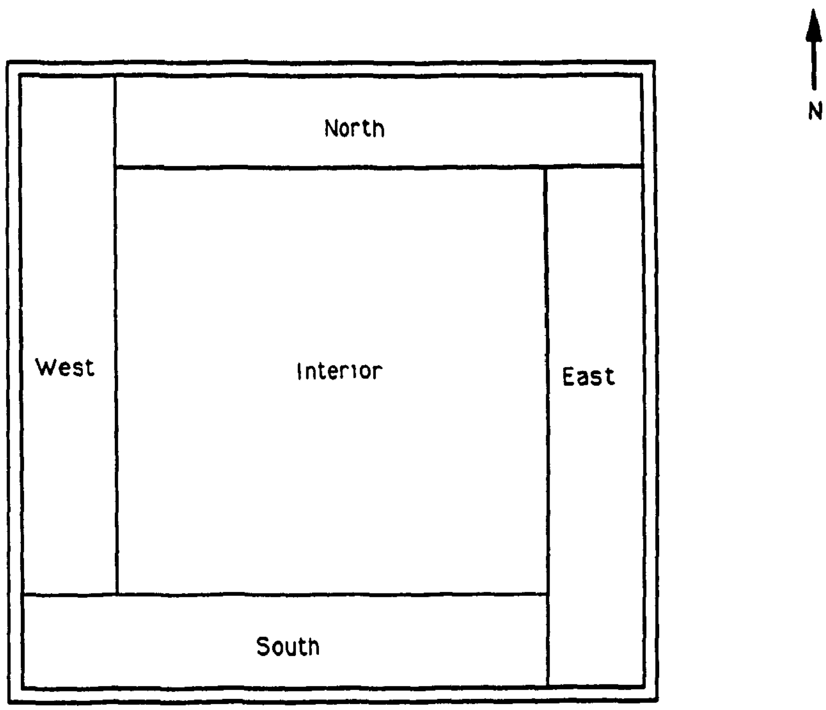

Figure 2.7 Zone distribution per floor of reference building

Table 2.1 Characteristics of thermal zones in building

Zone	Zone Multiplier	Floor Area m^2	External Wall Area m^2	Roof Area m^2
1-South (I)	9	114.75	108.0	---
2-South (T)	1	114.75	108.0	114.75
3-West (I)	9	114.75	108.0	---
4-West (T)	1	114.75	108.0	114.75
5-North (I)	9	114.75	108.0	---
6-North (T)	1	114.75	108.0	114.75
7-East (I)	9	114.75	108.0	---
8-East (T)	1	114.75	108.0	114.75
9-Interior (I)	9	441.00	---	---
10-Interior (T)	1	441.00	---	441.00

I = intermediate floor
T = top floor

Normally the southwest corner of the building is selected as the building origin (Fig. 2.8a). The location of the zone origin is relative to the building origin and is usually described at the lower left-hand corner of the surface (Fig. 2.8b). Once the zone origin has been defined, the rest of the surfaces bounding the zone can be described relative to the zone origin.

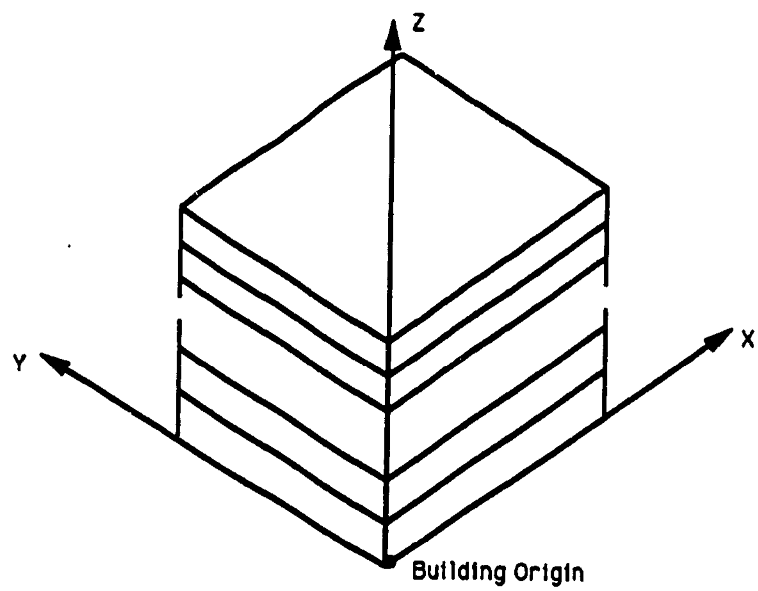

Figure 2.8a Elevation

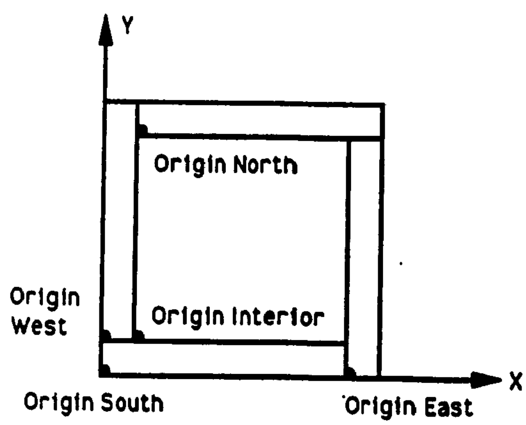

Figure 2.8b Plan

Figure 2.8 Zone description for user-input in BLAST

Description of the roof/ceiling, floor and window surfaces are as follows;

Roof/Ceiling → The lower left corner of the surface facing south is located as the starting point relative to the zone origin. The surface is projected upward so as to face the South and then treated as an X,Y plane with its starting point (0,0) (Fig. 2.9a).

Floor → The upper left corner of the surface is defined as the starting point relative to the zone origin. The surface is projected downward facing South and then treated as an X,Y plane with its starting point (0,0) (Fig. 2.9b).

Window → The lower left-hand corner of the window in relation to the assigned wall direction, and relative to the wall lower left corner is designated as the starting point (Fig. 2.9c).

The subprogram in BLAST that predicts the space load requires geometric and descriptive information about the building envelope. A typical example of BLAST user input for space load calculations for the reference building is represented below:

```
ZONE 5 "NORTH":
  ORIGIN: (4.5,25.5,0);
  NORTH AXIS=0;
  EXTERIOR WALLS:
     STARTING AT (25.5,4.5,0) FACING (0)
     EXTWALL (25.5 BY 3.6)
       WITH WINDOWS OF TYPE
       WDW (6.0 BY 3.6)
       AT (0,0),
     STARTING AT (25.5,0,0) FACING (90)
     EXTWALL (4.5 BY 3.6);
```

```
PARTITIONS:
   STARTING AT (0,0,0) FACING (180)
   PTN (25.5 BY 3.6)
   STARTING AT (0,4.5,0) FACING (270)
   PTN (4.5 BY 3.6);
FLOOR:
   STARTING AT (0,4.5,0) FACING (180)
   FLOOR39 (25.5 BY 4.5);
CEILING:
   STARTING AT (0,0,3.6) FACING (180)
   CEILING39 (25.5 BY 4.5);
```

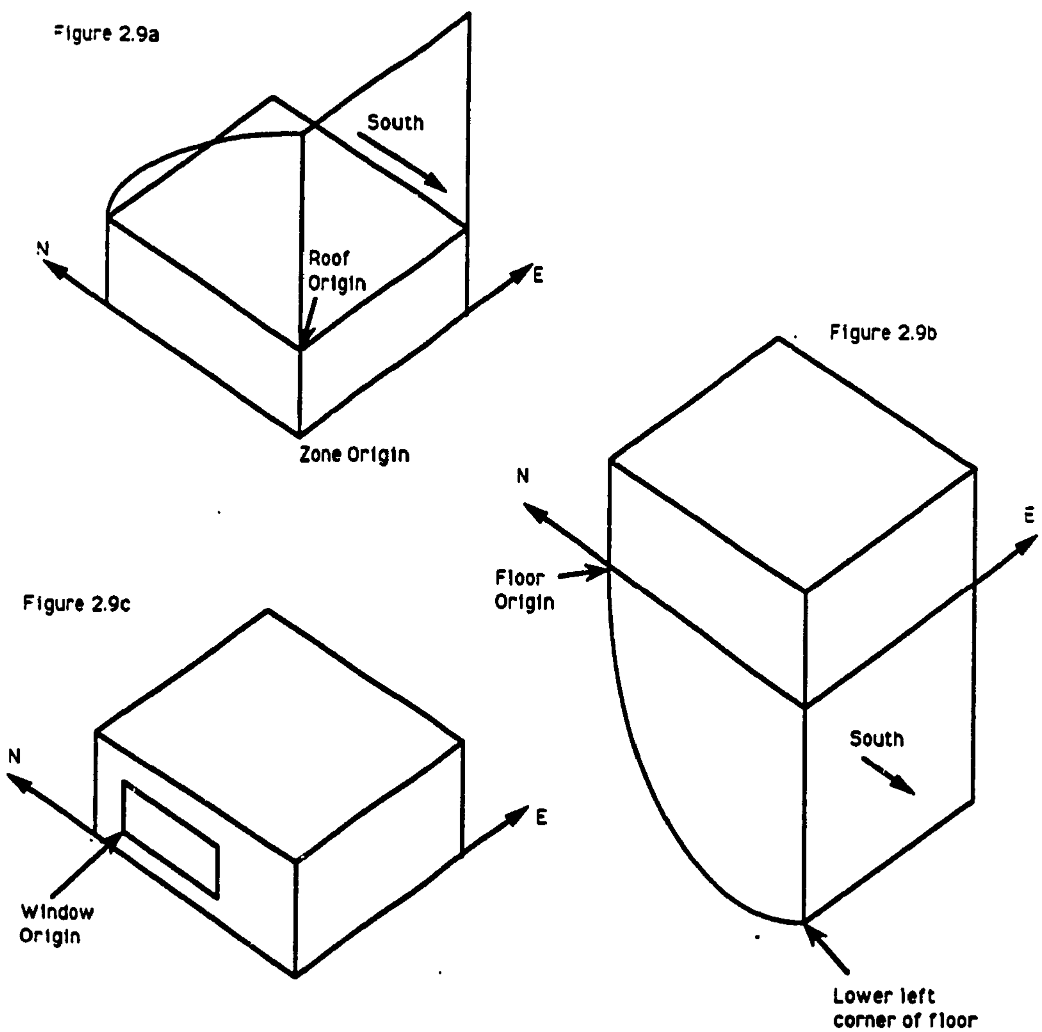

Figure 2.9 Description of surfaces circumscribing the zone

Fan System Description

The following input data in BLAST describes the type of air distribution system for the reference building (i.e. VARIABLE VOLUME SYSTEM), and specifies the air distribution system variables (OTHER SYSTEM PARAMETERS, COOLING COIL DESIGN PARAMETERS, EQUIPMENT SCHEDULES).

For example:

- the maximum air flow rate under peak conditions (SUPPLY AIR VOLUME) for zone 1 is 0.50 m^3/s,
- the minimum amount of supply air to be delivered to zone 1 during occupied hours (MINIMUM AIR FRACTION) is 45% of the maximum rate,
- the amount of air to be exhausted from zone 1 during occupied hours (EXHAUST AIR VOLUME) is 0.1 m^3/s,
- the reheat capacity for zone 1 (REHEAT CAPACITY) is 20kW.
- the supply and return fan pressures for the variable air volume system serving the entire building are 1000 and 250 Pa respectively,
- the minimum amount of fresh air to be introduced into the building during occupied hours (OUTSIDE AIR VOLUME) is 40.8 m^3/s.

```
BEGIN FAN SYSTEM DESCRIPTION;
VARIABLE VOLUME SYSTEM 1 "MAIN" SERVING ZONES 1 THRU 10;
     FOR ZONE 1:
        SUPPLY AIR VOLUME=0.52;
        MINIMUM AIR FRACTION=0.45;
        EXHAUST AIR VOLUME=0.1;
        REHEAT CAPACITY=20;
        REHEAT ENERGY SUPPLY=HOT WATER;
     END ZONE;
```

```
OTHER SYSTEM PARAMETER:
     SUPPLY FAN PRESSURE=1000;
     RETURN FAN PRESSURE=250;
     :
     MIXED AIR CONTROL=RETURN AIR ECONOMY CYCLE;
     :
     OUTSIDE AIR VOLUME=40.8;
     :
END OTHER SYSTEM PARAMETERS
COOLING COIL DESIGN PARAMETERS:
     COIL TYPE=CHILLED WATER;
     ENTERING WATER TEMPERATURE=6.7;
     :
     LEAVING WATER TEMPERATURE=12.2;
     :
END COOLING COIL DESIGN PARAMETER:
EQUIPMENT SCHEDULES:
     SYSTEM OPERATION=INTERMITTENT;
     :
END EQUIPMENT SCHEDULES;
END SYSTEM;
END FAN SYSTEM DESCRIPTION;
```

Central Plant Description

The central energy plant description simply requires selection of the equipment and size specifications of the plant. Design and equipment performance parameters are assigned default values by the program.

For example:

- a BOILER OF SIZE 1000 kW is selected to serve system 1 (VARIABLE AIR VOLUME SYSTEM),
- similarly, a CHILLER OF SIZE 1000 kW is selected to serve the same system.

```
BEGIN CENTRAL PLANT DESCRIPTION;
PLANT 1 "BOILER AND CHILLER" SERVING SYSTEM 1;
     EQUIPMENT SELECTION:
       1 BOILER OF SIZE 1000;
       1 CHILLER OF SIZE 1000;
     END EQUIPMENT SELECTION;
     :
```

END CENTRAL PLANT DESCRIPTION;
END INPUT;

2.5 ECONOMIC ANALYSIS

The economic analysis is performed by using the life cycle cost (LCC) method, which uses the sum of all expenditures associated with the building during its entire useful life. For the purpose of the economic analyses of the reference building, life cycle costs will consist of the initial cost and operating cost.

The initial cost of the reference building will consider the exterior wall and glazing. The cost of structural elements is not included since it is assumed to be constant regardless of the glazing area. Operating costs are annual costs that are necessary to operate and maintain the intended function of the building (i.e. HVAC systems, lighting and equipment). The costs related to maintenance, administration, taxes and loans are not included, since they are also unaffected by the glazing area.

The present worth of the building is the initial investment plus monies necessary for all future operating costs to be spent over a selected amortization period (the time over which annual operating costs of the building are made).

The present worth (PW) is obtained [34]:

$$PW = Initial\ Cost + Operating\ Cost \times PWEF \qquad (2.3)$$

The present worth escalation factor (PWEF) [34], is determined by using an interest rate for money (i), cost escalation rate for energy (j), and an amortization period (n, in years):

$$PWEF=\frac{[(1+j)/(1+i)]^n}{1-(1+i)/(1+j)} \tag{2.4}$$

2.6 RESULTS AND DISCUSSION

Optimization of the energy performance for the reference building was first defined in terms of the annual energy consumption, and second in terms of the life cycle cost of the building.

2.6.1 Energy Consumption

The variation of the energy consumption for reference building "A" versus the glazing wall area percentage is illustrated in Figure 2.10. The annual energy consumption increased by 9% when the glazing area with a thermal transmittance value of 1.10 W/m^2 °C was raised from 20 to 70% (Fig. 2.10a). Similarly, for a thermal transmittance value of 2.22 W/m^2 °C the increase was 25% (Fig. 2.10b), for a thermal transmittance value of 2.61 W/m^2 °C the increase was 28% (Fig. 2.10c), and finally for a glazing thermal transmittance value of 3.86 W/m^2 °C the energy consumption increased by 35% (Fig. 2.10d).

Figure 2.10 also indicates the annual energy consumption

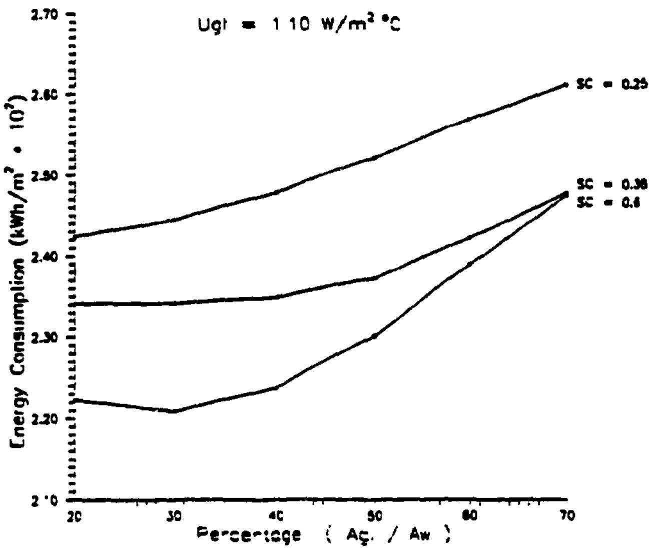

Figure 2.10a

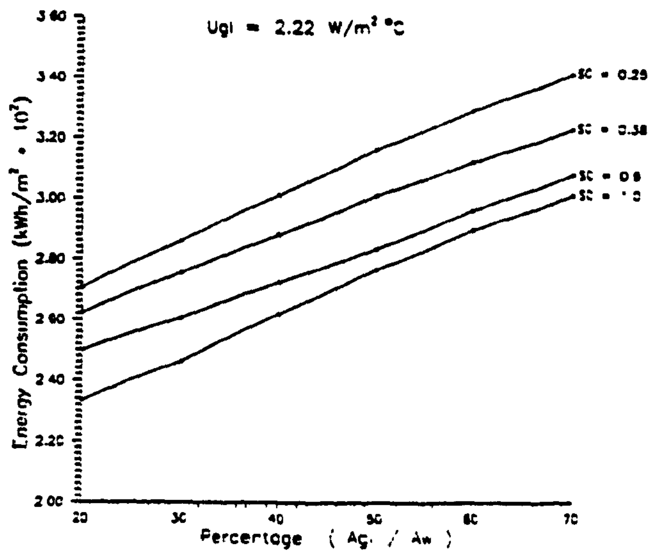

Figure 2.10b

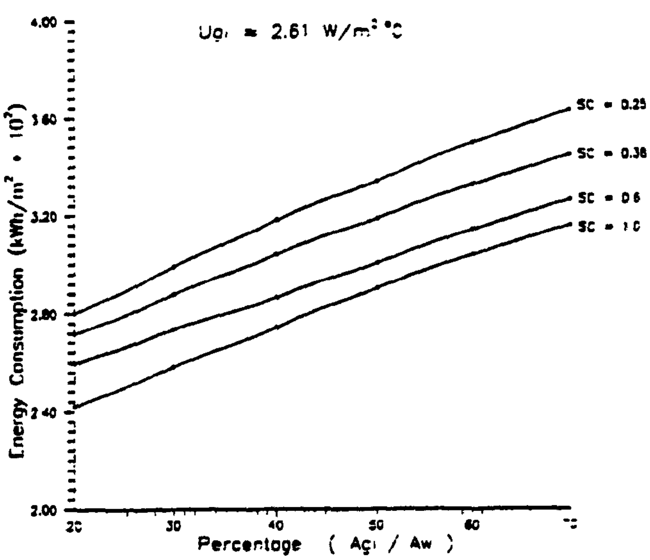

Figure 2.10c

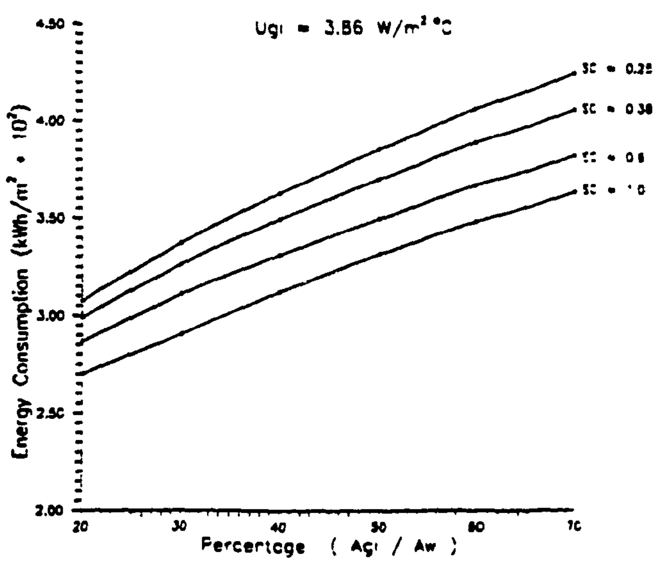

Figure 2.10d

Figure 2.10 **Annual energy consumption for reference building "A"**

of the reference building for several shading coefficient values. Clear glass with a shading coefficient (SC) value of 1.0 required less annual energy as compared to slightly reflective glass with an SC value of 0.60, followed by reflective glass (SC=0.38) and highly reflective glass (SC=0.25) for a common percentage of glazing area and glazing thermal transmittance. Since higher shading coefficient values permit more solar radiation to enter the conditioned space, the winter heating load will consequently be less as illustrated in Figure 2.11. For instance, in Figure 2.11(b) with a glazing thermal transmittance value of 2.22 W/m^2 ^oC, the heating load for a shading coefficient value of 1.0 at 30% glazing area is 80.9 kWh/m^2, whereas the heating load for a 0.38 SC-value at the corresponding glazing area is 102.0 kWh/m^2, a savings of 21.1 kWh/m^2. However, higher SC-values will also increase the cooling loads for the reference building in summer due to the added solar gains (Fig. 2.12). For example, in Figure 2.12(b) with a glazing thermal transmittance value of 2.22 W/m^2 ^oC, the cooling load for a shading coefficient value of 1.0 at 30% glazing area is 63.2 kWh/m^2, while the cooling load for an SC value of 0.38 at the same glazing area is 49.8 kWh/m^2 (increase of 13.4 kWh/m^2). Nevertheless, the increase in summer cooling loads accompanied by higher SC values is modest when compared to the heating load savings in winter; thus the use of higher SC values leads to lower annual energy use as compared to low SC values.

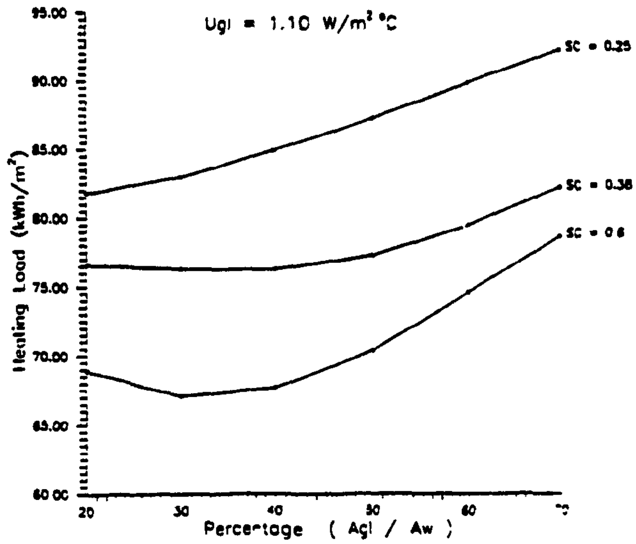

Figure 2.11a

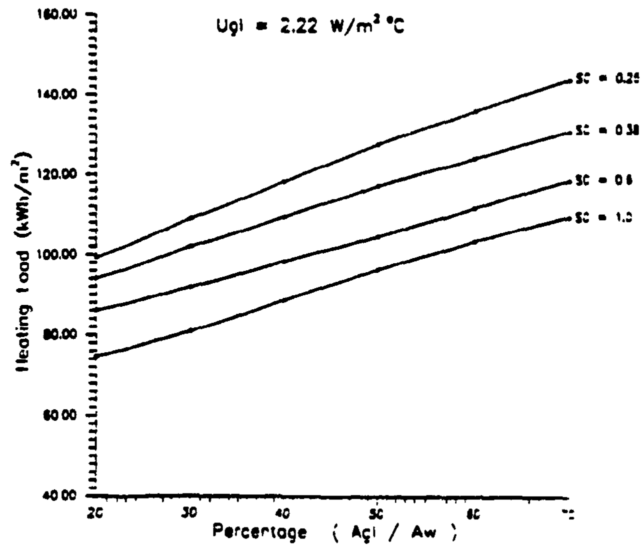

Figure 2.11b

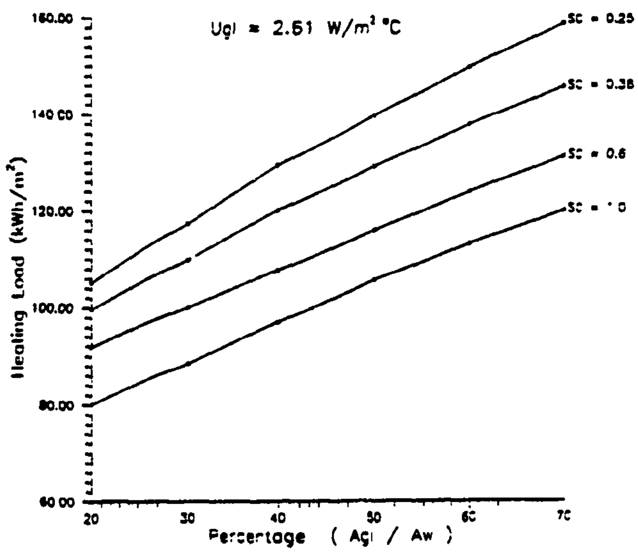

Figure 2.11c

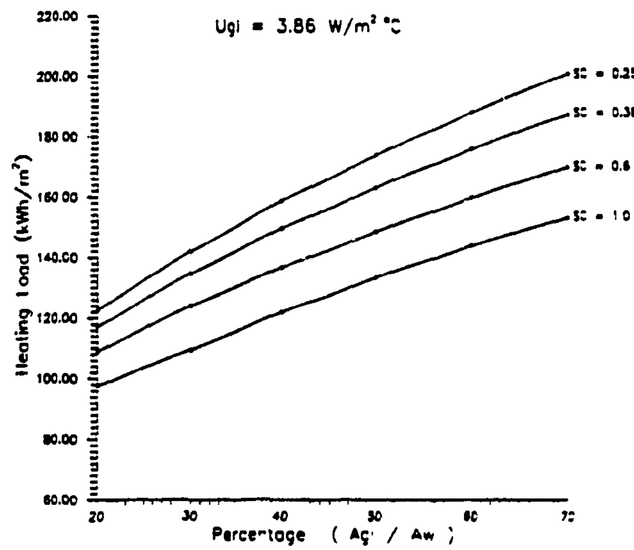

Figure 2.11d

Figure 2.11 **Variation of the annual heating load for reference building "A"**

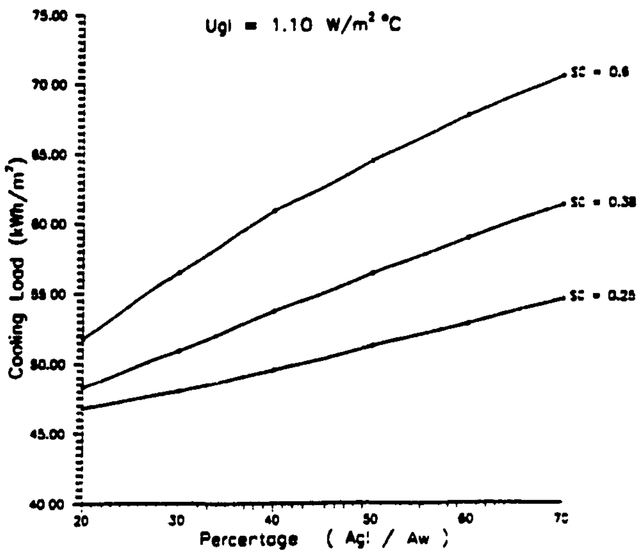

Figure 2.12a

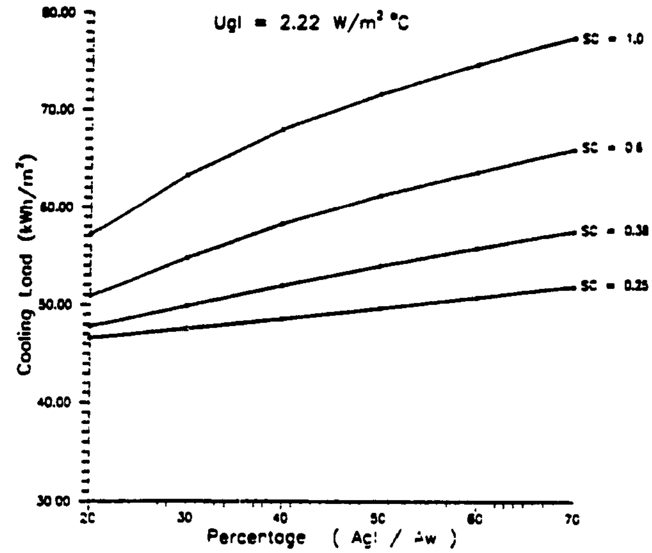

Figure 2.12b

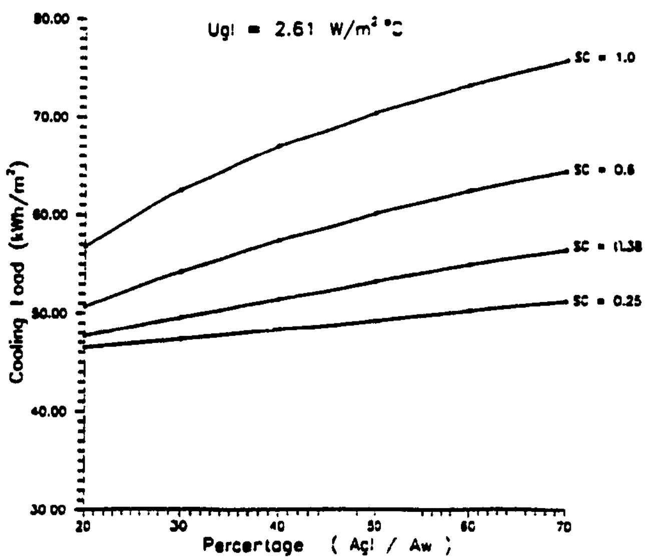

Figure 2.12c

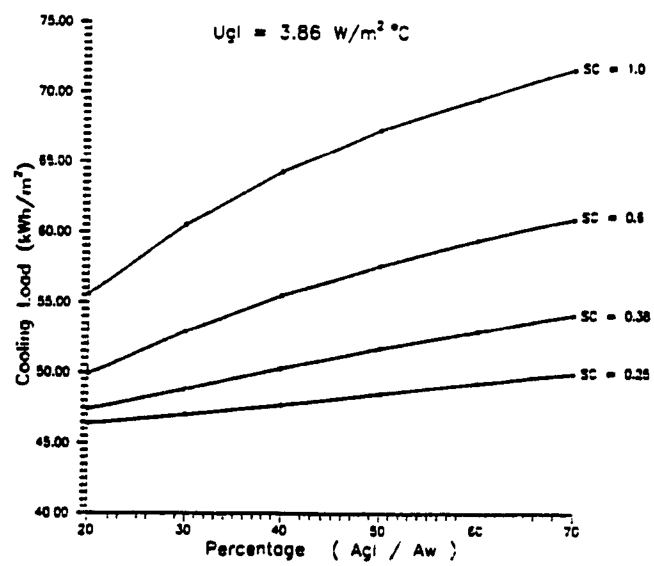

Figure 2.12d

Figure 2.12 **Variation of the annual cooling load for reference building "A"**

Figures 2.13 and 2.14 show the annual energy performance for reference building "B" with glazing on the North and South exposures, and reference building "C" with glazing on the East and West exposures. The curves observed in these figures are quite similar to the curves represented in Figure 2.10. One can notice a definite increase in the annual energy consumption of the reference building when the glazing area is increased from 20% to 70%.

Comparison between Figures 2.13 and 2.14 show little variances in the annual energy consumption for both reference buildings "B" and "C". Generally, building "C" required slightly less annual energy use than building "B". For example, reference building "C" with 40% glazing and a SC and U-value of 0.6 and 2.61 W/m^2 ^oC respectively (Fig. 2.14c), has an annual energy consumption of 276.2 kWh/m^2, while the energy consumption for building "B" with similar parameters (Fig. 2.13c) is 282.8 kWh/m^2 (2.4% difference).

Further comparison amongst all three buildings indicate reference building "A" with glazing on all four exposures as having the largest annual energy consumption. For instance, the energy consumption for building "A" is 300.7 kWh/m^2 ^oC when the glazing area is 50% and the SC and U-values are 0.6 and 2.61 W/m^2 ^oC, compared to an annual energy consumption of 293.5 and 286.5 kWh/m^2 for buildings "B" and "C" respectively. Since reference building "A" has a larger total glazing area in comparison to buildings "B" and "C", additional energy use

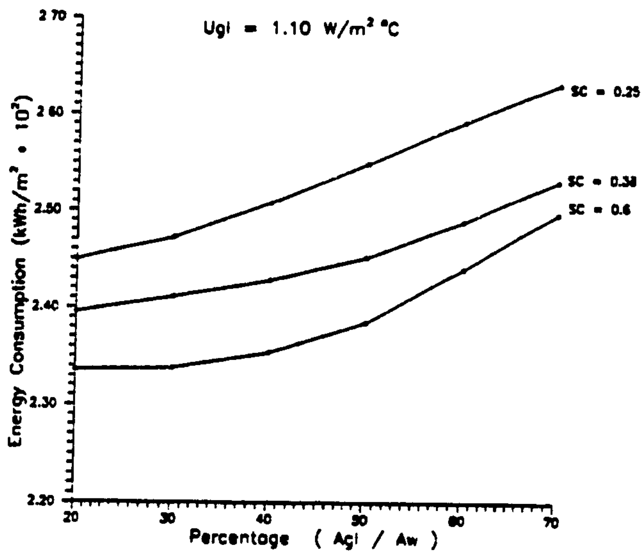

Figure 2.13a

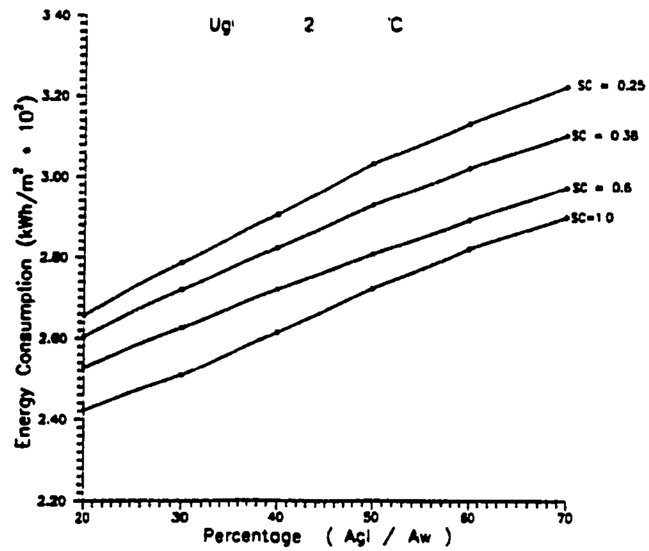

Figure 2.13b

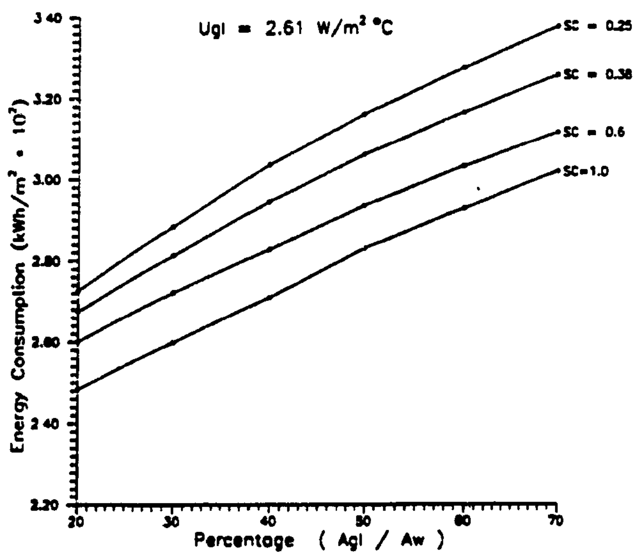

Figure 2.13c

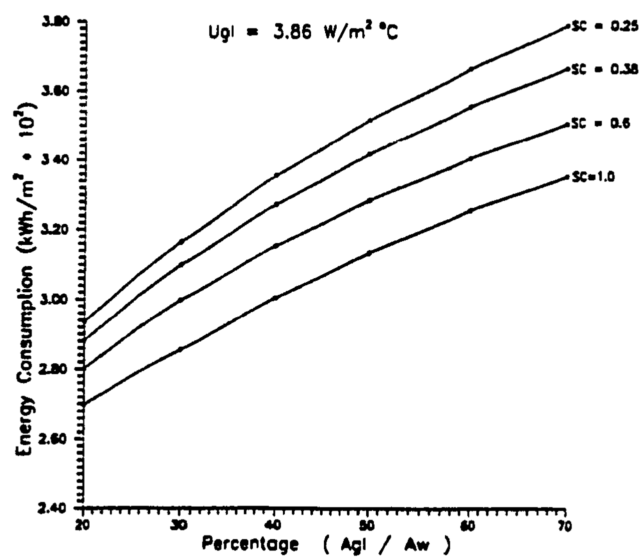

Figure 2.13d

Figure 2.13 Annual energy consumption for reference building "B"

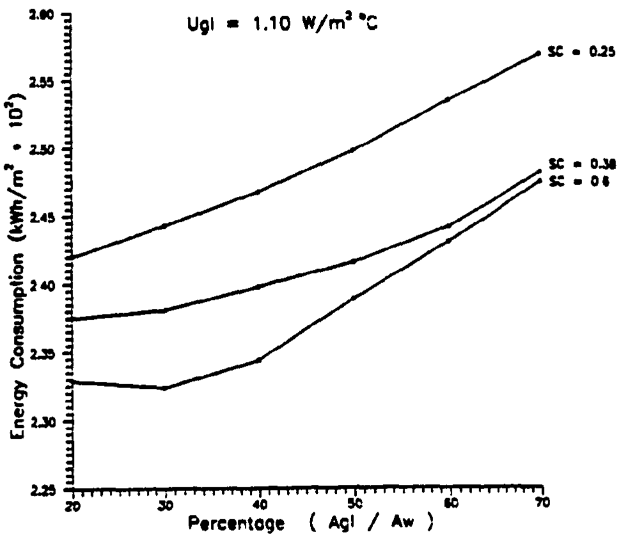

Figure 2.14a

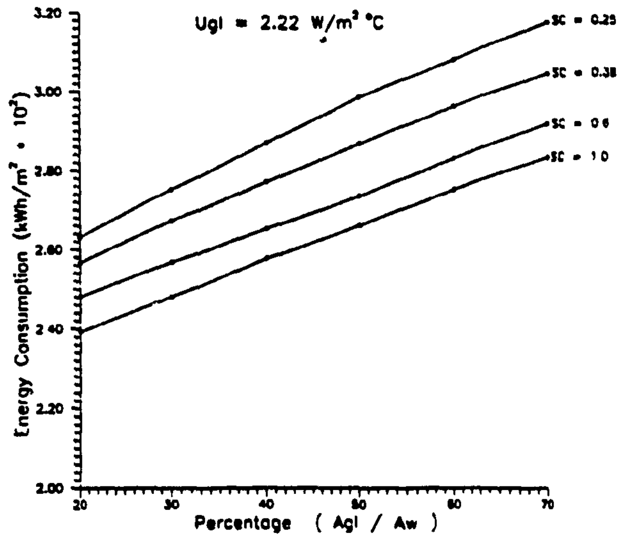

Figure 2.14b

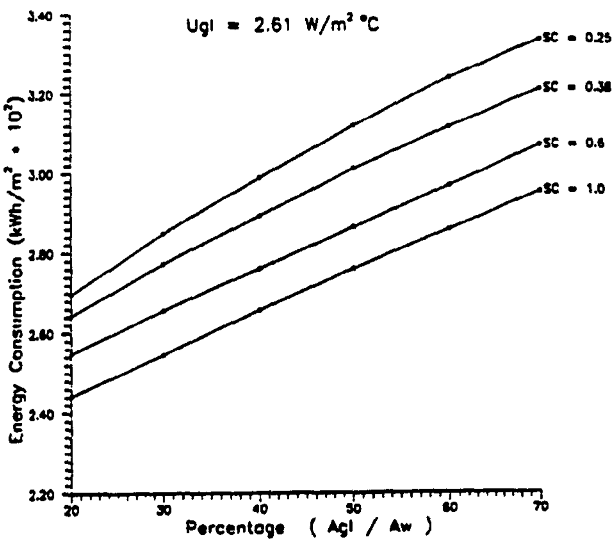

Figure 2.14c

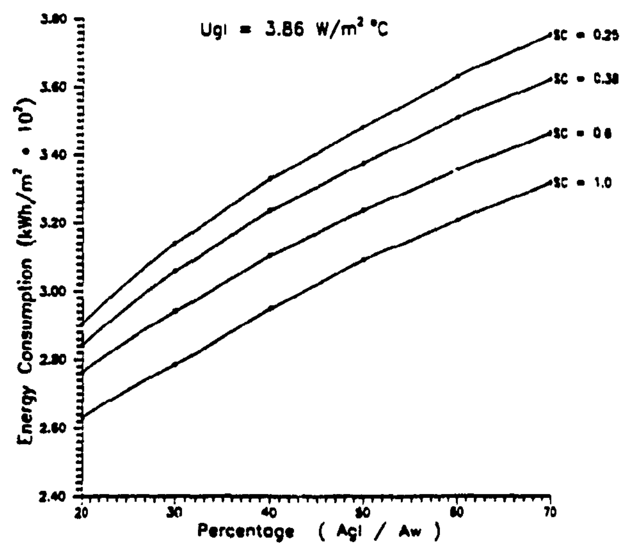

Figure 2.14d

Figure 2.14 Annual energy consumption for Reference Building "C"

is required with larger glazing areas as previously indicated in Figures 2.10 through 2.14.

Several exceptions to this trend were observed for windows with low thermal transmittance values (≤2.22 W/m^2 °C), high shading coefficient (SC=1.0) and glazing wall area ratios (GWAR) less than 40%. For instance, the annual energy consumption for reference building "A" with glazing area 30%, SC and U-values equal to 1.0 and 2.22 W/m^2 °C is 246.3 kWh/m^2, whereas the corresponding annual energy consumptions for reference buildings "B" and "C" are 250.8 and 257.6 kWh/m^2 respectively. Since the total glazing area at 30% GWAR for reference building "A" with glazing on all 4 facades is larger than buildings "B" and "C" with glazing on only 2 facades, more solar radiation is allowed to enter the space while the low thermal transmittance value of the glazing minimizes thermal losses to the outdoor environment, thus prompting reference building "A" to have a better annual energy performance. However, glazing wall area ratios above 40% permit too much solar radiation to enter the space thus causing the cooling load for the building to increase sharply, therefore reference buildings "B" and "C" with less total glazing area than building "A" will be more energy efficient.

Figures 2.15 and 2.16 show the annual energy performance for reference buildings "D" and "E" versus percentage of glazing for similar shading coefficient and glazing thermal transmittance values as in the previous figures for buildings

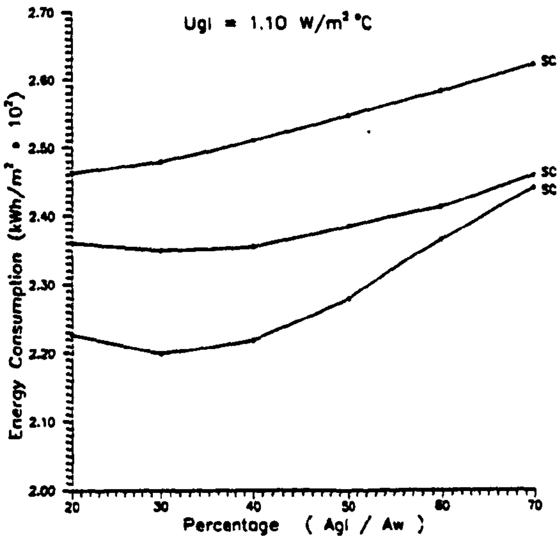

Figure 2.15a

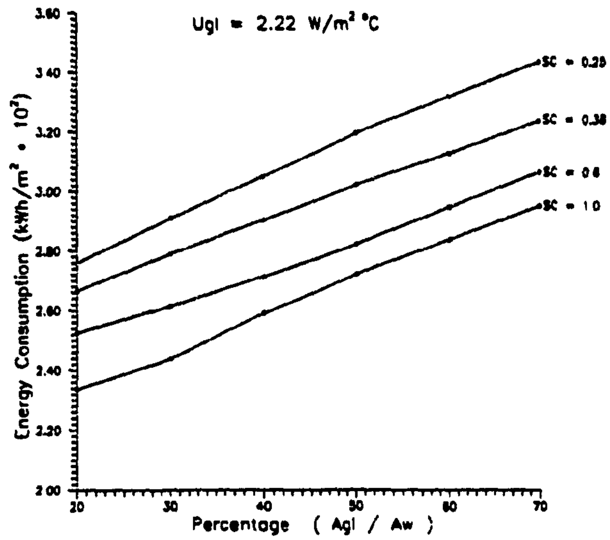

Figure 2.15b

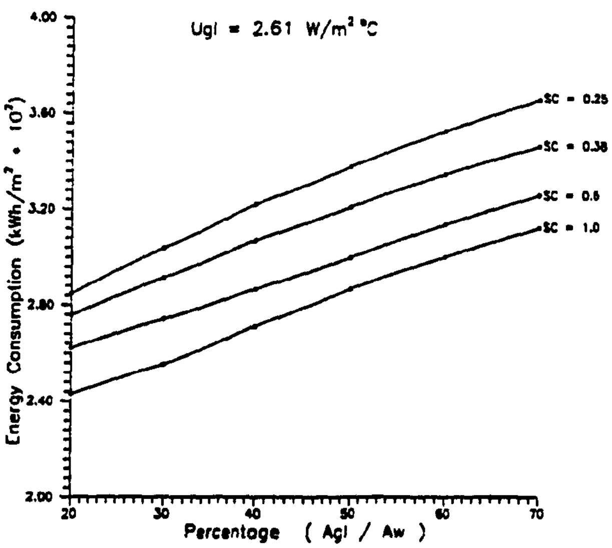

Figure 2.15c

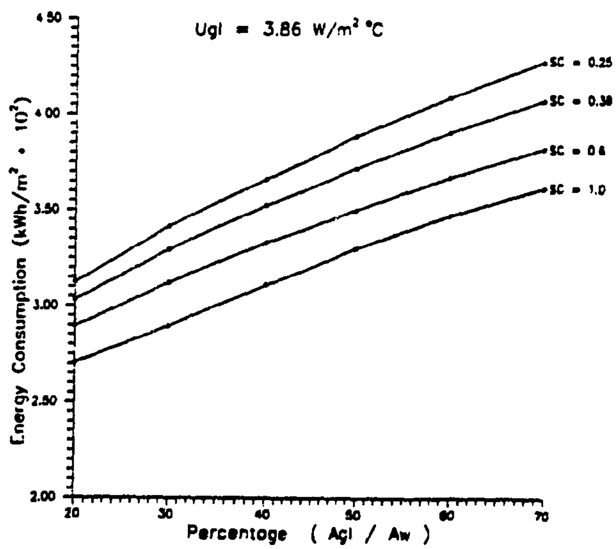

Figure 2.15d

Figure 2.15 Annual energy consumption for reference building "D"

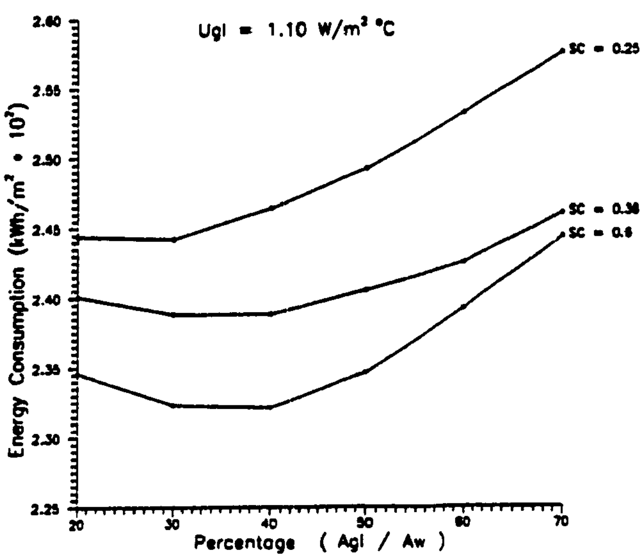

Figure 2.16a

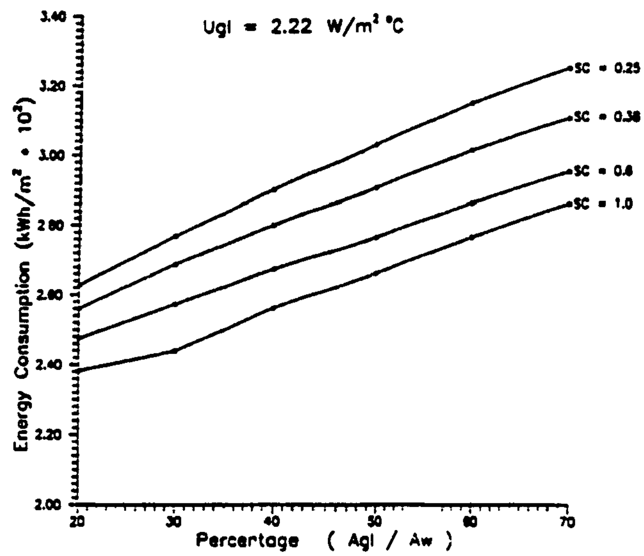

Figure 2.16b

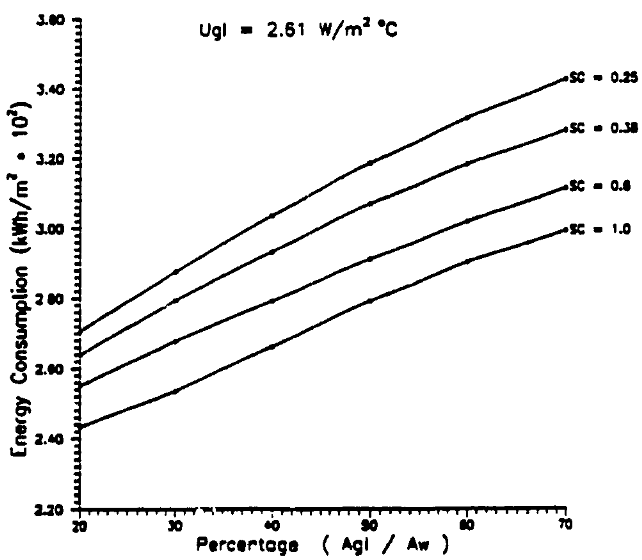

Figure 2.16c

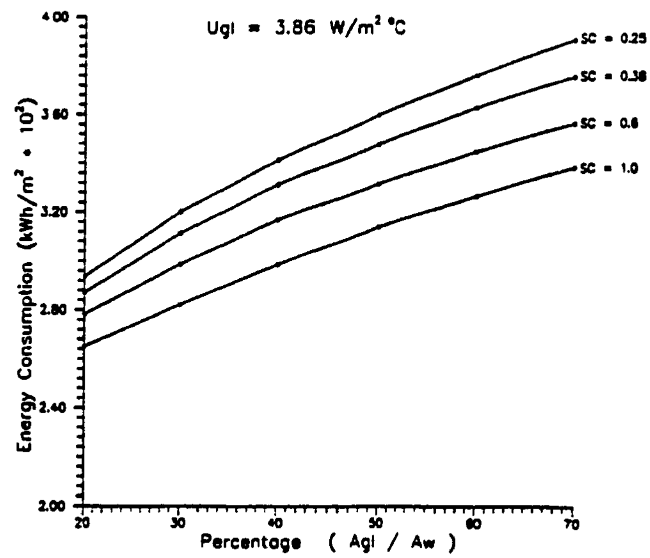

Figure 2.16d

Figure 2.16 Annual energy consumption for reference building "E"

"A", "B" and "C".

Generally, the annual energy consumption for reference buildings "D" and "E" with building dimensions 40 x 22.5m increased as the percentage of glazing area increased for the two buildings, although Figures 2.15a and 2.16a showed a slightly different trend. In these figures the corresponding glazing area based on the minimum annual energy consumption is between 20 and 40% for SC values 0.38 and 0.6. Since the glazing thermal transmittance value is low (1.10 W/m^2 °C) which reduces thermal losses through the building envelope, the percentage of glazing area is allowed to increase permitting more solar radiation to enter the space thus reducing the annual heating load.

The annual energy consumption for reference building "D" in Figure 2.15 is larger than the annual energy consumption for building "E" in Figure 2.16 for low SC values and high U-values. Since thermal losses along the East and West exposures due to the glazing area are eliminated for building "E", the annual energy consumption for this building is therefore expected to be less than building "D" with glazing on all four exposures. However, for relatively clear glass (SC>0.6) and low U-values (≤2.22 W/m^2 °C), the annual energy consumption in building "D" is less than building "E" since the added glazing area in reference building "D" permits more solar radiation to enter the space consequently reducing winter heating loads.

From the graphical results presented in Figures 2.10 through 2.16, the optimum glazing areas for office buildings in Montréal can be determined. For instance, the curve which represents the annual energy consumption for reference building "A" versus the percentage of glazing at a SC and U-value of 0.6 and 2.22 W/m^2 °C is represented in Figure 2.17. In this figure, the minimum annual energy consumption (250.0 kWh/m^2) occurs at 20% GWAR. If a five percent allowance is permitted due to error, then the annual energy consumption is 262.5 kWh/m^2 and the optimum glazing area for the reference building 32%.

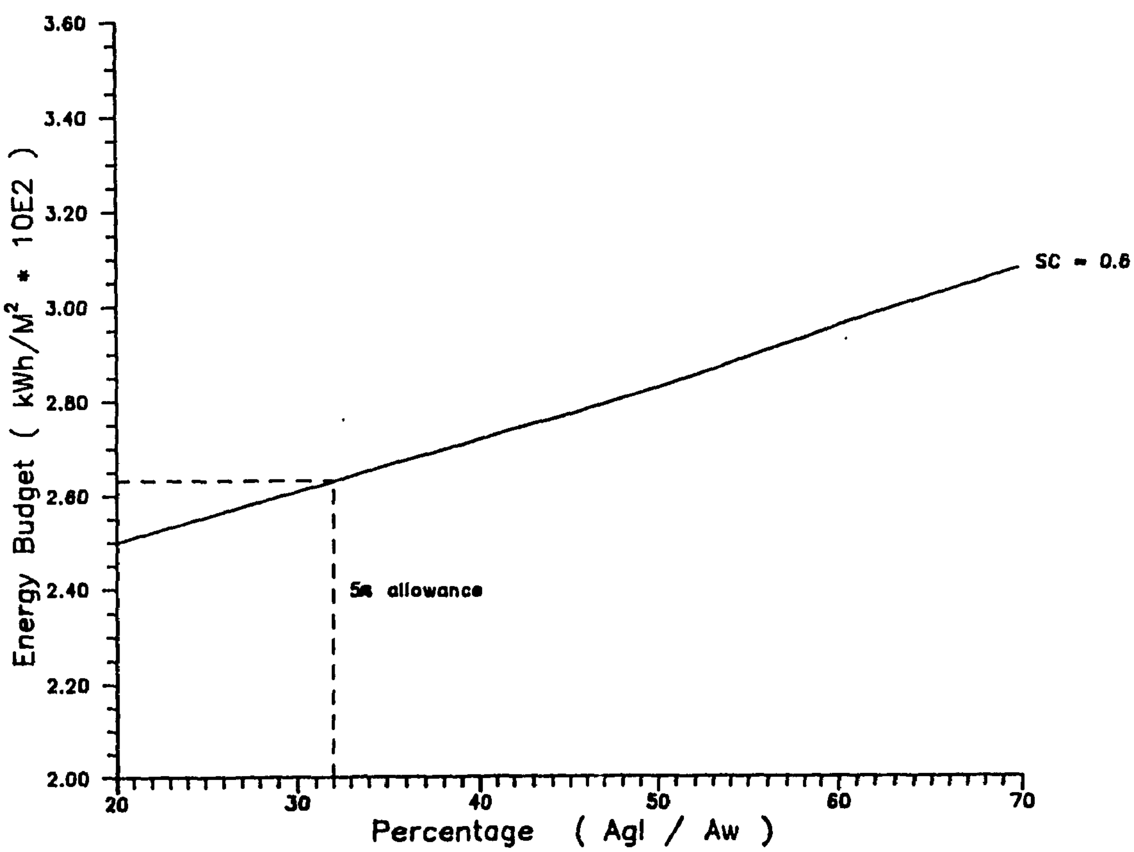

Figure 2.17 Optimum glazing areas based on a 5% technical allowance

Table 2.2 displays the optimum glazing areas for office buildings in Montréal similar to Alternate Components Package (ACP) tables in ASHRAE 90.1-1989. One can notice small differences between the results for the 5 buildings. Hence, an average optimum glazing is defined.

Table 2.2 Optimum percent glazing for office buildings in Montréal

U-value W/m^2 °C	SC	Reference Building					
		"A"	"B"	"C"	"D"	"E"	Average
1.10	0.60	52	62	62	53	69	60
	0.38	66	66	70	70	70	68
	0.25	55	55	61	60	67	60
2.22	1.00	29	33	33	31	35	32
	0.60	32	33	34	34	32	33
	0.38	30	32	32	30	30	31
	0.25	29	30	31	30	30	30
2.61	1.00	27	30	32	30	32	30
	0.60	29	30	32	30	30	30
	0.38	28	30	30	29	29	29
	0.25	27	29	29	28	28	28
3.86	1.00	27	29	29	27	28	28
	0.60	26	27	28	26	27	27
	0.38	25	27	27	26	26	26
	0.25	25	26	26	28	26	26

Building "A" = 30 x 30m, glazing on all four facades,
Building "B" = 30 x 30m, glazing on North & South
Building "C" = 30 x 30m, glazing on East & West,
Building "D" = 40 x 22.5m, glazing on all four facades,
Building "E" = 40 x 22.5m, glazing on North & South

2.6.2 Life Cycle Cost

Optimization of glazing areas for office buildings in Montréal based on life cycle costs are presented in this section.

The initial material and labour costs for the construction of the reference building envelope are obtained from Hanscomb [35] and are listed in Tables 2.3a and 2.3b.

Table 2.3a Initial cost of exterior walls

Section	Unit Price $\$/m^2$
a) Painting (standard): walls - 2 coats, rolled	5.35
b) Gypsum Plaster: 2 coats on gypsum lath	21.25
c) Gypsum Wallboard: Standard sheets, 1200mm wide 12mm thick; (supply) (installation)	4.49 5.80
d) Membrane Waterproofing: Flexible Membrane 3mm, polyethylene base sheet	18.50
e) Building Insulation: Glass fibre, 2 x 51mm	30.70
f) Framing System for Glazing: 1200mm modules, Tinted anodized finish	270.00
g) Tinted Glass: Two panes of 6mm	173.00
Sub-Total	529.09

Table 2.3b Initial cost of glazing

U-value ($W/m^{2}{}^{o}C$)	Shading Coefficient	Unit Price $\$/m^2$
1.10	Clear Glass: (SC=1.0)	518.00
	Tinted Glass: (SC=0.6 & 0.38)	526.00
	Reflective Glass: (SC=0.25)	810.00
2.22 & 2.61	Clear Glass: (SC=1.0)	435.00
	Tinted Glass: (SC=0.6 & 0.38)	443.00
	Reflective Glass: (SC=0.25)	728.00
3.86	Clear Glass: (SC=1.0)	298.00
	Tinted Glass: (SC=0.6 & 0.38)	309.00
	Reflective Glass: (SC=0.25)	590.00
Framing System with Glazing: 1200mm modules, Tinted anodized finish		270.00

The life cycle costs are evaluated for a 5 and 25 year amortization period using equation 2.3. These amortization periods were selected for two extreme scenarios:

- a 5 year amortization period would be selected if the building owner decided to sell the building relatively soon after completion,
- a 25 year amortization period would be selected if the building will remain the property of the owner.

The same procedure was followed as in the previous section by permitting a 5% technical allowance to determine the optimum glazing areas for office buildings in Montréal, based this time on life cycle cost of the building instead of the annual energy consumption.

Tables 2.4 and 2.5 indicate the optimum glazing areas for reference building "A" with amortization periods of 5 and 25 years respectively. Generally, the optimum glazing areas for reference building "A" based on the building's life cycle cost are larger than optimum glazing areas based on the annual energy consumption. For instance, the optimum glazing area can reach 70% for a 5 year amortization period at interest i=10% and energy escalation rate j=5% (Table 2.4), when the reference building "A" has SC=0.6 and U-value of 2.61 $W/m^2\ ^oC$; similarly the optimum glazing area for a 25 year amortization period is 58% (Table 2.5). On the other hand, the optimum glazing area based on energy consumption for the same reference building and glazing parameters is only 29% (Table 2.2). The life cycle cost for a 25 year amortization period is largely dependant on the operating costs rather than the initial costs, hence the annual energy consumption which is affected by the percentage of glazing is lower as compared to the 5 year period.

Tables 2.6 through 2.13 show the optimum glazing areas based on 5 and 25 year life cycle costs for reference buildings "B", "C", "D" and "E". Optimum glazing areas and trends illustrated in these tables are similar to those obtained for the reference building "A".

An average optimum glazing area from the 5 reference buildings based on life cycle cost are defined in Table 2.14 (n=5 years) and Table 2.15 (n=25 years).

Table 2.4 Optimum percentage glazing area for reference building "A" in Montréal, based on the life cycle cost method.
(Amortization period = 5 years)

U_{gl}\SC	1.0				0.6				0.38				0.25			
1.10					N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
					10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-32	20-30	20-32
					12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-32	20-32	20-32
					15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-32	20-32	20-32
					Energy Cons. 20-52				Energy Cons. 20-66				Energy Cons. 20-55			
2.22	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
	10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-33	20-33	20-33
	12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-35	20-33	20-33
	15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-33	20-33	20-33
	Energy Cons. 20-29				Energy Cons. 20-32				Energy Cons. 20-30				Energy Cons. 20-29			
2.61	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
	10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-32	20-32	20-32
	12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-32	20-32	20-32
	15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-33	20-32	20-32
	Energy Cons. 20-27				Energy Cons. 20-29				Energy Cons. 20-28				Energy Cons. 20-27			
3.86	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
	10%	55-70	53-70	51-70	10%	53-70	51-70	49-70	10%	52-70	50-70	47-70	10%	20-40	20-38	20-37
	12.5%	56-70	54-70	53-70	12.5%	54-70	52-70	50-70	12.5%	53-70	51-70	49-70	12.5%	20-40	20-39	20-38
	15%	56-70	55-70	53-70	15%	55-70	53-70	51-70	15%	54-70	52-70	50-70	15%	20-41	20-40	20-38
	Energy Cons. 20-27				Energy Cons. 20-26				Energy Cons. 20-25				Energy Cons. 20-25			

Table 2.5 Optimum percentage glazing area for reference building "A" in Montréal, based on the life cycle cost method. (Amortization Period = 25 years)

U_{gl}\SC	1.0				0.6				0.38				0.25			
1.10					N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
					10%	20-70	20-70	20-66	10%	20-70	20-70	20-70	10%	20-33	20-35	20-37
					12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-33	20-34	20-36
					15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-33	20-34	20-35
					Energy Cons. 20-52				Energy Cons. 20-66				Energy Cons. 20-55			
2.22	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
	10%	20-70	20-57	20-40	10%	20-70	20-70	20-49	10%	20-70	20-67	20-44	10%	20-32	20-31	20-30
	12.5%	20-70	20-70	20-46	12.5%	20-70	20-70	20-57	12.5%	20-70	20-70	20-51	12.5%	20-32	20-32	20-31
	15%	20-70	20-70	20-56	15%	20-70	20-70	20-69	15%	20-70	20-70	20-66	15%	20-32	20-32	20-31
	Energy Cons. 20-29				Energy Cons. 20-32				Energy Cons. 20-30				Energy Cons. 20-29			
2.61	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
	10%	20-70	20-50	20-37	10%	20-70	20-58	20-42	10%	20-70	20-51	20-38	10%	20-31	20-30	20-29
	12.5%	20-70	20-68	20-42	12.5%	20-70	20-70	20-48	12.5%	20-70	20-66	20-43	12.5%	20-31	20-31	20-30
	15%	20-70	20-70	20-50	15%	20-70	20-70	20-57	15%	20-70	20-70	20-50	15%	20-32	20-31	20-30
	Energy Cons. 20-27				Energy Cons. 20-29				Energy Cons. 20-28				Energy Cons. 20-27			
3.86	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
	10%	20-70	20-70	20-39	10%	20-70	20-70	20-37	10%	20-70	20-62	20-34	10%	20-33	20-30	20-28
	12.5%	35-70	20-70	20-50	12.5%	26-70	20-70	20-47	12.5%	20-70	20-70	20-40	12.5%	20-34	20-31	20-29
	15%	45-70	20-70	20-70	15%	40-70	20-70	20-70	15%	34-70	20-70	20-57	15%	20-35	20-32	20-30
	Energy Cons. 20-27				Energy Cons. 20-26				Energy Cons. 20-25				Energy Cons. 20-25			

**Table 2.6 Optimum percentage glazing area for reference building "B" in Montréal, based on the life cycle cost method.
(Amortization period = 5 years)**

U_{gl}\SC	1.0				0.6				0.38				0.25			
1.10					N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
					10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-41	20-42	20-42
					12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-41	20-42	20-42
					15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-41	20-41	20-42
					Energy Cons. 20-62				Energy Cons. 20-66				Energy Cons. 20-55			
2.22	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
	10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-42	20-42	20-40
	12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-42	20-42	20-41
	15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-42	20-42	20-42
	Energy Cons. 20-33				Energy Cons. 20-33				Energy Cons. 20-32				Energy Cons. 20-30			
2.81	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
	10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-40	20-40	20-40
	12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-41	20-40	20-40
	15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-41	20-40	20-40
	Energy Cons. 20-30				Energy Cons. 20-30				Energy Cons. 20-30				Energy Cons. 20-29			
3.86	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
	10%	26-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-50	20-48	20-46
	12.5%	29-70	21-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-52	20-50	20-47
	15%	31-70	25-70	20-70	15%	25-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-53	20-50	20-48
	Energy Cons. 20-29				Energy Cons. 20-27				Energy Cons. 20-27				Energy Cons. 20-26			

Table 2.7 Optimum percentage glazing area for reference building "B" in Montréal, based on the life cycle cost method.
(Amortization period = 25 years)

U_{gl}\SC	1.0				0.6				0.38				0.25			
1.10					N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
					10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-43	20-45	20-47
					12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-43	20-44	20-46
					15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-42	20-43	20-45
					Energy Cons. 20-62				Energy Cons. 20-66				Energy Cons. 20-55			
2.22	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
	10%	20-70	20-65	20-47	10%	20-70	20-70	20-50	10%	20-70	20-61	20-45	10%	20-39	20-37	20-35
	12.5%	20-70	20-70	20-36	12.5%	20-70	20-70	20-58	12.5%	20-70	20-70	20-51	12.5%	20-40	20-36	20-36
	15%	20-70	20-70	20-64	15%	20-70	20-70	20-69	15%	20-70	20-70	20-60	15%	20-40	20-39	20-37
	Energy Cons. 20-33				Energy Cons. 20-33				Energy Cons. 20-32				Energy Cons. 20-30			
2.61	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
	10%	20-70	20-57	20-43	10%	20-70	20-58	20-44	10%	20-70	20-51	20-40	10%	20-36	20-34	20-32
	12.5%	20-70	20-70	20-48	12.5%	20-70	20-70	20-50	12.5%	20-70	20-61	20-44	12.5%	20-37	20-36	20-34
	15%	20-70	20-70	20-56	15%	20-70	20-70	20-57	15%	20-70	20-70	20-50	15%	20-38	20-36	20-34
	Energy Cons. 20-30				Energy Cons. 20-30				Energy Cons. 20-30				Energy Cons. 20-29			
3.86	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
	10%	20-70	20-70	20-42	10%	20-70	20-60	20-38	10%	20-70	20-50	20-35	10%	20-38	20-34	20-30
	12.5%	20-70	20-70	20-51	12.5%	20-70	20-70	20-44	12.5%	20-70	20-70	20-40	12.5%	20-40	20-35	20-33
	15%	20-70	20-70	20-70	15%	20-70	20-70	20-58	15%	20-70	20-70	20-49	15%	20-42	20-37	20-33
	Energy Cons. 20-29				Energy Cons. 20-27				Energy Cons. 20-27				Energy Cons. 20-26			

Table 2.8 Optimum percentage glazing area for reference building "C" in Montréal, based on the life cycle cost method. (Amortization period = 5 years)

U_{gl}\SC	1.0				0.6				0.38				0.25			
1.10					N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
					10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-42	20-42	20-42
					12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-41	20-43	20-42
					15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-41	20-42	20-42
					Energy Cons. 20-62				Energy Cons. 20-70				Energy Cons. 20-61			
2.22	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
	10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-42	20-42	20-41
	12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-43	20-42	20-42
	15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-43	20-42	20-42
	Energy Cons. 20-33				Energy Cons. 20-34				Energy Cons. 20-32				Energy Cons. 20-31			
2.61	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
	10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-40	20-40	20-40
	12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-41	20-40	20-40
	15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-41	20-41	20-40
	Energy Cons. 20-32				Energy Cons. 20-32				Energy Cons. 20-30				Energy Cons. 20-29			
3.86	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
	10%	24-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-51	20-48	20-46
	12.5%	27-70	20-70	20-70	12.5%	21-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-52	20-50	20-47
	15%	29-70	23-70	20-70	15%	25-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-53	20-51	20-42
	Energy Cons. 20-29				Energy Cons. 20-28				Energy Cons. 20-27				Energy Cons. 20-26			

Table 2.9 Optimum percentage glazing area for reference building "C" in Montréal, based on the life cycle cost method.
(Amortization Period = 25 years)

U_g\SC	1.0				0.6				0.38				0.25			
1.10					N\i	0%	5%	10%	N\i	0%	5%	10%	N\i	0%	5%	10%
					10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-44	20-46	20-48
					12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-43	20-45	20-47
					15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-43	20-44	20-46
					Energy Cons. 20-62				Energy Cons. 20-70				Energy Cons. 20-61			
2.22	N\i	0%	5%	10%	N\i	0%	5%	10%	N\i	0%	5%	10%	N\i	0%	5%	10%
	10%	20-70	20-70	20-51	10%	20-70	20-70	20-53	10%	20-70	20-64	20-46	10%	20-39	20-37	20-35
	12.5%	20-70	20-70	20-59	12.5%	20-70	20-70	20-60	12.5%	20-70	20-70	20-54	12.5%	20-40	20-38	20-36
	15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-70	20-70	20-63	15%	20-40	20-38	20-37
	Energy Cons. 20-33				Energy Cons. 20-34				Energy Cons. 20-32				Energy Cons. 20-31			
2.61	N\i	0%	5%	10%	N\i	0%	5%	10%	N\i	0%	5%	10%	N\i	0%	5%	10%
	10%	20-70	20-61	20-45	10%	20-70	20-60	20-45	10%	20-70	20-53	20-42	10%	20-37	20-35	20-33
	12.5%	20-70	20-70	20-51	12.5%	20-70	20-70	20-51	12.5%	20-70	20-64	20-46	12.5%	20-38	20-35	20-34
	15%	20-70	20-70	20-60	15%	20-70	20-70	20-59	15%	20-70	20-70	20-53	15%	20-39	20-37	20-35
	Energy Cons. 20-32				Energy Cons. 20-32				Energy Cons. 20-30				Energy Cons. 20-29			
3.86	N\i	0%	5%	10%	N\i	0%	5%	10%	N\i	0%	5%	10%	N\i	0%	5%	10%
	10%	20-70	20-70	20-40	10%	20-70	20-63	20-39	10%	20-70	20-50	20-35	10%	20-37	20-33	20-30
	12.5%	20-70	20-70	20-47	12.5%	20-70	20-70	20-46	12.5%	20-70	20-70	20-40	12.5%	20-40	20-33	20-32
	15%	20-70	20-70	20-67	15%	20-70	20-70	20-60	15%	20-70	20-70	20-49	15%	20-42	20-37	20-33
	Energy Cons. 20-29				Energy Cons. 20-28				Energy Cons. 20-27				Energy Cons. 20-26			

Table 2.10 **Optimum percentage glazing area for reference building "D" in Montréal, based on the life cycle cost method. (Amortization period = 5 years)**

U_{gl}\SC	1.0				0.6				0.38				0.25			
1.10					N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
					10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-32	20-32	20-32
					12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-32	20-32	20-32
					15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-32	20-32	20-32
					Energy Cons. 20-53				Energy Cons. 20-70				Energy Cons. 20-60			
2.22	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
	10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-33	20-33	20-33
	12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-33	20-33	20-33
	15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-33	20-33	20-33
	Energy Cons. 20-31				Energy Cons. 20-34				Energy Cons. 20-30				Energy Cons. 20-30			
2.61	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
	10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-33	20-32	20-32
	12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-33	20-32	20-32
	15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-33	20-33	20-32
	Energy Cons. 20-30				Energy Cons. 20-30				Energy Cons. 20-29				Energy Cons. 20-28			
3.86	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
	10%	55-70	54-70	52-70	10%	54-70	52-70	50-70	10%	53-70	50-70	48-70	10%	20-40	20-40	20-38
	12.5%	56-70	55-70	53-70	12.5%	54-70	53-70	50-70	12.5%	49-70	53-70	50-70	12.5%	20-41	20-40	20-38
	15%	56-70	55-70	54-70	15%	55-70	54-70	52-70	15%	54-70	53-70	51-70	15%	20-42	20-40	20-39
	Energy Cons. 20-27				Energy Cons. 20-26				Energy Cons. 20-26				Energy Cons. 20-28			

Table 2.11 **Optimum percentage glazing area for reference building "D" in Montréal, based on the life cycle cost method. (Amortization period = 25 years)**

U_{gl}\SC	1.0				0.6				0.38				0.25			
1.10					N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
					10%	20-70	20-70	20-67	10%	20-70	20-70	20-70	10%	20-33	20-35	20-38
					12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-33	20-34	20-36
					15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-33	20-34	20-35
					Energy Cons. 20-53				Energy Cons. 20-70				Energy Cons. 20-60			
2.22	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
	10%	20-70	20-70	20-44	10%	20-70	20-70	20-54	10%	20-70	20-70	20-48	10%	20-32	20-32	20-31
	12.5%	20-70	20-70	20-52	12.5%	20-70	20-70	20-64	12.5%	20-70	20-70	20-59	12.5%	20-32	20-32	20-31
	15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-33	20-32	20-30
	Energy Cons. 20-31				Energy Cons. 20-34				Energy Cons. 20-30				Energy Cons. 20-30			
2.61	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
	10%	20-70	20-57	20-42	10%	20-70	20-66	20-46	10%	20-70	20-56	20-40	10%	20-31	20-30	20-30
	12.5%	20-70	20-70	20-47	12.5%	20-70	20-70	20-53	12.5%	20-70	20-70	20-46	12.5%	20-31	20-31	20-30
	15%	20-70	20-70	20-57	15%	20-70	20-70	20-64	15%	20-70	20-70	20-55	15%	20-32	20-31	20-30
	Energy Cons. 20-30				Energy Cons. 20-30				Energy Cons. 20-29				Energy Cons. 20-28			
3.86	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
	10%	20-70	20-70	20-42	10%	20-70	20-70	20-39	10%	20-70	20-70	20-34	10%	20-33	20-30	20-28
	12.5%	39-70	20-70	20-58	12.5%	33-70	20-70	20-54	12.5%	20-70	20-70	20-43	12.5%	20-34	20-32	20-29
	15%	46-70	20-70	20-70	15%	43-70	20-70	20-70	15%	39-70	20-70	20-70	15%	20-36	20-33	20-30
	Energy Cons. 20-27				Energy Cons. 20-26				Energy Cons. 20-26				Energy Cons. 20-28			

Table 2.12 **Optimum percentage glazing area for reference building "E" in Montréal, based on the life cycle cost method. (Amortization period = 5 years)**

U_{gl}\SC	1.0				0.6				0.38				0.25			
1.10					N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
					10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-38	20-38	20-39
					12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-38	20-38	20-38
					15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-38	20-38	20-38
					Energy Cons. 20-69				Energy Cons. 20-70				Energy Cons. 20-67			
2.22	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
	10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-38	20-38	20-38
	12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-38	20-38	20-37
	15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-39	20-38	20-37
	Energy Cons. 20-35				Energy Cons. 20-32				Energy Cons. 20-30				Energy Cons. 20-30			
2.61	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
	10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-37	20-37	20-36
	12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-37	20-37	20-37
	15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-38	20-37	20-37
	Energy Cons. 20-32				Energy Cons. 20-30				Energy Cons. 20-29				Energy Cons. 20-28			
3.86	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
	10%	42-70	38-70	32-70	10%	39-70	33-60	23-70	10%	35-70	28-70	20-70	10%	20-46	20-44	20-42
	12.5%	43-70	40-70	35-70	12.5%	40-70	36-70	30-70	12.5%	38-70	32-70	20-70	12.5%	20-47	20-45	20-43
	15%	44-70	42-70	38-70	15%	42-70	38-70	33-70	15%	40-70	35-70	26-70	15%	20-48	20-46	20-34
	Energy Cons. 20-28				Energy Cons. 20-27				Energy Cons. 20-26				Energy Cons. 20-26			

Table 2.13 Optimum percentage glazing area for reference building "E" in Montréal, based on the life cycle cost method. (Amortization period = 25 years)

U_{gl}\SC	1.0				0.6				0.38				0.25			
1.10					Ni	0%	5%	10%	Ni	0%	5%	10%	Ni	0%	5%	10%
					10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-40	20-43	20-47
					12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-40	20-42	20-45
					15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-40	20-41	20-43
					Energy Cons. 20-69				Energy Cons. 20-70				Energy Cons. 20-67			
2.22	Ni	0%	5%	10%	Ni	0%	5%	10%	Ni	0%	5%	10%	Ni	0%	5%	10%
	10%	20-70	20-70	20-52	10%	20-70	20-70	20-50	10%	20-70	20-62	20-45	10%	20-36	20-34	20-33
	12.5%	20-70	20-70	20-60	12.5%	20-70	20-70	20-59	12.5%	20-70	20-70	20-51	12.5%	20-36	20-35	20-33
	15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-70	20-70	20-60	15%	20-37	20-36	20-34
	Energy Cons. 20-35				Energy Cons. 20-32				Energy Cons. 20-30				Energy Cons. 20-30			
2.61	Ni	0%	5%	10%	Ni	0%	5%	10%	Ni	0%	5%	10%	Ni	0%	5%	10%
	10%	20-70	20-60	20-44	10%	20-70	20-59	20-44	10%	20-70	20-50	20-39	10%	20-34	20-33	20-31
	12.5%	20-70	20-70	20-50	12.5%	20-70	20-70	20-50	12.5%	20-70	20-62	20-43	12.5%	20-35	20-36	20-32
	15%	20-70	20-70	20-60	15%	20-70	20-70	20-59	15%	20-70	20-70	20-49	15%	20-36	20-34	20-33
	Energy Cons. 20-32				Energy Cons. 20-30				Energy Cons. 20-29				Energy Cons. 20-28			
3.86	Ni	0%	5%	10%	Ni	0%	5%	10%	Ni	0%	5%	10%	Ni	0%	5%	10%
	10%	20-70	20-70	20-42	10%	20-70	20-60	20-37	10%	20-70	20-51	20-34	10%	20-35	20-32	20-29
	12.5%	20-70	20-70	20-53	12.5%	20-70	20-70	20-45	12.5%	20-70	20-70	20-39	12.5%	20-37	20-33	20-30
	15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-70	20-70	20-50	15%	20-39	20-33	20-32
	Energy Cons. 20-28				Energy Cons. 20-27				Energy Cons. 20-26				Energy Cons. 20-26			

Table 2.14 Optimum percentage glazing area, for the average of five reference buildings in Montréal, based on the life cycle cost method. (Amortization period = 5 years)

U_{gl}\SC	1.0				0.6				0.38				0.25			
1.10					N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
					10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-37	20-37	20-37
					12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-37	20-37	20-37
					15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-37	20-37	20-37
					Energy Cons. 20-60				Energy Cons. 20-68				Energy Cons. 20-61			
2.22	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
	10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-38	20-38	20-37
	12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-38	20-38	20-37
	15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-38	20-38	20-37
	Energy Cons. 20-32				Energy Cons. 20-33				Energy Cons. 20-32				Energy Cons. 20-30			
2.61	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
	10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-70	20-70	20-70	10%	20-36	20-36	20-36
	12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-37	20-36	20-36
	15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-37	20-37	20-36
	Energy Cons. 20-30				Energy Cons. 20-30				Energy Cons. 20-29				Energy Cons. 20-28			
3.86	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%	N	0%	5%	10%
	10%	40-70	37-70	35-70	10%	37-70	35-70	32-70	10%	36-70	34-70	31-70	10%	20-45	20-44	20-42
	12.5%	42-70	38-70	36-70	12.5%	38-70	36-70	34-70	12.5%	36-70	35-70	32-70	12.5%	20-46	20-45	20-43
	15%	43-70	40-70	37-70	15%	40-70	37-70	35-70	15%	38-70	36-70	33-70	15%	20-48	20-45	20-40
	Energy Cons. 20-28				Energy Cons. 20-27				Energy Cons. 20-26				Energy Cons. 20-26			

Table 2.15 Optimum percentage glazing area, for the average of five reference buildings in Montréal, based on the life cycle cost method. (Amortization period = 25 years)

U_{gl}\SC	1.0				0.6				0.38				0.25			
1.10					Nj	0%	5%	10%	Nj	0%	5%	10%	Nj	0%	5%	10%
					10%	20-70	20-70	20-69	10%	20-70	20-70	20-70	10%	20-39	20-41	20-43
					12.5%	20-70	20-70	20-70	12.5%	20-70	20-70	20-70	12.5%	20-38	20-40	20-42
					15%	20-70	20-70	20-70	15%	20-70	20-70	20-70	15%	20-38	20-39	20-41
					Energy Cons. 20-60				Energy Cons. 20-68				Energy Cons. 20-60			
2.22	Nj	0%	5%	10%	Nj	0%	5%	10%	Nj	0%	5%	10%	Nj	0%	5%	10%
	10%	20-70	20-66	20-47	10%	20-70	20-70	20-51	10%	20-70	20-65	20-46	10%	20-36	20-34	20-33
	12.5%	20-70	20-70	20-51	12.5%	20-70	20-70	20-60	12.5%	20-70	20-70	20-53	12.5%	20-36	20-35	20-33
	15%	20-70	20-70	20-66	15%	20-70	20-70	20-70	15%	20-70	20-70	20-64	15%	20-36	20-35	20-34
	Energy Cons. 20-32				Energy Cons. 20-33				Energy Cons. 20-31				Energy Cons. 20-30			
2.61	Nj	0%	5%	10%	Nj	0%	5%	10%	Nj	0%	5%	10%	Nj	0%	5%	10%
	10%	20-70	20-57	20-42	10%	20-70	20-60	20-44	10%	20-70	20-52	20-40	10%	20-34	20-32	20-31
	12.5%	20-70	20-70	20-48	12.5%	20-70	20-70	20-50	12.5%	20-70	20-65	20-44	12.5%	20-34	20-34	20-32
	15%	20-70	20-70	20-57	15%	20-70	20-70	20-59	15%	20-70	20-70	20-51	15%	20-35	20-34	20-32
	Energy Cons. 20-30				Energy Cons. 20-30				Energy Cons. 20-29				Energy Cons. 20-28			
3.86	Nj	0%	5%	10%	Nj	0%	5%	10%	Nj	0%	5%	10%	Nj	0%	5%	10%
	10%	20-70	20-70	20-41	10%	20-70	20-65	20-38	10%	20-70	20-57	20-34	10%	20-35	20-32	20-29
	12.5%	27-70	20-70	20-52	12.5%	24-70	20-70	20-47	12.5%	20-70	20-70	20-40	12.5%	20-37	20-33	20-31
	15%	30-70	20-70	20-69	15%	29-70	20-70	20-66	15%	27-70	20-70	20-55	15%	20-39	20-34	20-32
	Energy Cons. 20-28				Energy Cons. 20-27				Energy Cons. 20-26				Energy Cons. 20-26			

2.7 SUMMARY

The percentage glazing based on the minimization of the energy consumption is usually greater than the values introduced by the ASHRAE addendum (Table 2.16). One can notice the increase in the average percent glazing for the reference buildings as compared to the addendum. The variation in the percentage areas defined by ASHRAE and the results obtained from this study can be attributed to several reasons:

- Alternate component package tables provided by ASHRAE are only applicable to cities located in the United States,
- A detailed description of the reference building used to perform the simulations is not provided by ASHRAE. However, it is supposed that the ASHRAE recommendations for developing a reference building were used to develop the ACP tables.

If however, the designer prefers to select the optimum percentage of glazing area for the reference buildings based on the life cycle cost, then the designer can increase the glazing area of the building without the burden of any additional costs to the owner over the selected amortization period. For example, Table 2.16 indicates the average percent glazing for the reference buildings with amortization periods of 5 and 25 years (i=10%, j=5%) are generally larger than values indicated by the energy consumption.

It is interesting to note that the optimum percent glazing for SC=0.25 based on energy consumption is almost equal to that given by the life cycle cost.

Table 2.16 Comparison between the results from this research and the recommendations from ASHRAE Standard 90.1-1989

Ugl $W/m^{2o}C$	SC	Energy Cons.	LCC		ASHRAE		Québec Law[3]
			n=5	n=25	90.1[1]	addendum[2]	
1.10	0.60	60	70	70	32	25	40
	0.38	68	70	70	42	35	
	0.25	60	37	41	50	43	
2.22	1.00	32	70	66	23	20	
	0.60	33	70	70	27	24	
	0.38	31	70	65	31	32	
	0.25	30	38	34	34	38	
2.61	1.00	30	70	57	18	19	
	0.60	30	70	60	20	22	
	0.38	29	70	52	22	28	
	0.25	28	36	32	23	32	
3.86	1.00	28	70	70	18	19	
	0.60	27	70	65	20	22	
	0.38	26	70	57	22	28	
	0.25	26	44	32	23	32	

[1]ASHRAE Standard 90.1A-1989, Alternate Components Package, Table 8A-33 (for cities such as Burlington, Vt. and Binghamton, NY, which are comparable to Montréal in terms of heating and cooling degree-days).

[2]ASHRAE Standard 90.1a-1989, Addendum, December 1990.

[3]Québec Law 1984, % glazing = min {40% glazing area or 15% of floor area}.

Building simulations were not performed for a thermal transmittance value of 1.10 W/m^2 °C and shading coefficient value of 1.0. The shading coefficient value is defined as the ratio of the solar heat gain through a glazing system under a specific set of conditions to the solar gain through a single light of double-strength sheet glass under the same conditions. Since triple glazing is required to obtain a U-value of 1.10 W/m^2 °C, a corresponding SC value of 1.0 would not be justified because more light is reflected in triple glazed rather than double glazed windows.

2.8 CONCLUSIONS

The research developed in this chapter intended to propose optimization of glazing areas for office buildings in Montréal, Québec, similar to the Alternate Components Package (ACP) tables presented in ASHRAE Standard 90.1-1989 for cities located in the United States. The results have indicated that the optimum glazing areas based on the annual energy consumption for office buildings in Montréal are slightly higher than glazing areas defined by ASHRAE in cities such as Burlington, Vt. and Binghamton, NY., which are comparable to Montréal in terms of heating and cooling degree-days.

Optimization of glazing areas based on the life cycle cost method illustrated the percentage of glazing areas for the reference buildings as being significantly higher in comparison to proposed limits defined by the annual energy consumption.

CHAPTER 3

EFFECT OF AIR TEMPERATURE DRIFTS IN OFFICE BUILDINGS ON THERMAL COMFORT AND ENERGY USE

3.1 INTRODUCTION

The primary objective of heating, ventilating and air conditioning systems is to provide thermal comfort for the occupants. However, due to the shortage and escalating cost of energy, it is not always feasible to provide optimal thermal comfort. Of the principal elements which govern human comfort, that is air movement, humidity and air temperature, the latter can significantly moderate energy use. This chapter deals with the effect of controlling the room air temperature on thermal comfort of occupants and energy efficiency in buildings.

In 1987, Hayter [36] stated there are numerous opportunities for reducing energy consumption in buildings based on human responses to the thermal environment. He mentioned the heating and cooling equipment are typically oversized to ensure occupant satisfaction under any conditions. McNall et al. [37] noted that very significant energy savings in both heating and cooling were possible by using control strategies which allow ambient temperatures to drift upon the perimeters of thermal comfort zone, a process that does not require energy use. A study conducted by Fleming [38] concluded the comfort conditions which provide the greatest energy savings (up to 10%) in office buildings are those which touch upon perimeters of the comfort zone. ASHRAE Standard 90-1975 [39], as well as later revisions, encouraged engineers to design HVAC systems that would operate at minimum energy levels within the comfort envelope rather than at a single design point.

ASHRAE Standard 55-1981 [40] specifies the combination of factors such as air temperature, mean radiant temperature, humidity and air movement which are necessary for thermal comfort. Figure 3.1 outlines acceptable ranges of operative temperature and humidity for persons clothed in typical summer and winter clothing. Operative temperature is defined as the numerical average, weighted by respective heat transfer coefficients of the air and mean radiant temperatures.

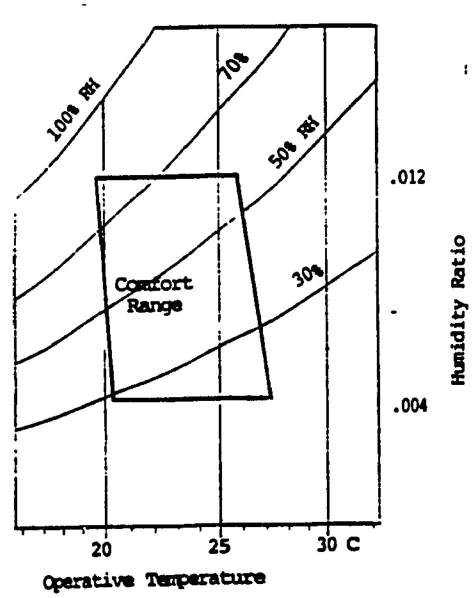

Figure 3.1 **Acceptable range of operative temperature specified by ASHRAE Standard 55-1981 [40]**

ASHRAE Standard 55-1981 further allows the operative temperature to temporarily deviate beyond the limits of the comfort envelope. A section on temperature drifts or ramps in ASHRAE 55-1981 states that [40]:

> *"Slow rates of operative temperature change (approximately 0.6 °C/hr) during the occupied period are acceptable provided the temperature during a drift or ramp does not extend beyond the comfort zone by more than 0.6 °C and for longer than one hour".*

In recent years, environmental control systems have been developed to provide more accurate thermal control. Proposed strategies to conserve energy in buildings suggest:

a) lowering thermostat settings in winter and raising them in summer, and

b) the elimination of environmental control in halls, entryways and storerooms.

Nelson et al. [41] suggested that maintaining an office 1°C cooler in winter would represent a 5% savings in annual heating costs.

However, implementation of these strategies may have adverse effects on the thermal comfort of occupants in the actual environment [42]. Berglund [43] remarked one way to assess the thermal comfort of occupants in buildings is to compare the measured or predicted thermal parameters of the space with ASHRAE Standard 55-1981 which defines acceptable thermal environmental conditions for human occupancy.

Schiller and Arens [44] and Schiller et al. [45] conducted a study on environmental conditions and occupant comfort in ten San Francisco Bay area office buildings to assess the thermal comfort in office buildings, and also to compare actual occupant responses of thermal conditions to ASHRAE Standard 55-81. About 78.2% of measured parameters in winter and 52.8% in summer fell within the respective winter and summer comfort zones defined by ASHRAE Standard 55-1981. The occupant response to thermal comfort for both heating and cooling seasons were uniform with 80 to 85% acceptability, but dropping to 59% at the upper boundary of the summer comfort zone. The results presented by Schiller and Arens suggested:

a) neutral temperature (defined as the temperature at which the greatest percentage of people are experiencing neutral thermal sensation) was 22.0°C in winter and 22.6°C in summer,
b) workers preferred conditions slightly cooler (0.3 - 0.6°C) in winter and summer than those established by the ASHRAE Standard 55-1981.

Griffiths and McIntyre [46] evaluated the human responses to a steady temperature change of 0, 0.5, 1.0 and 1.5 °C/hr for six hour periods. They recommended a maximum rate of temperature change of 0.75°C/hr with a maximum deviation of 2.25°C from the mean comfort temperature (23°C). However, a report released later by McIntyre and Griffiths [47], indicated there is no appreciable difference in terms of thermal comfort between an indoor environment with a constant temperature and one with a temperature change of 0.5, 1.0 and 1.5 °C/hr, provided that the maximum deviations from neutral temperatures are respected.

Berglund and Gonzalez [48] performed a study with 12 college age subjects to develop energy conservation strategies. These would allow the temperature of living space to drift with outside conditions and internal loads due to intermittent or reduced capacity of temperature control equipment, providing the rate and duration of the temperature drift is acceptable to the occupants. The study consisted of testing subjects dressed in three different levels of clothing (0.5, 0.7 and 0.9 CLO), each of whom experienced seven rates of temperature change (0, ±0.5, ±1.0 and ±1.5°C/hr). Their findings indicated that at faster rates of temperature change (i.e. 1.0 and 1.5 °C/hr), the permissible deviation from neutral temperature was larger than the acceptable comfort limits at a 0.5 °C/hr rate of temperature change. In another experiment, Berglund and Gonzalez [49] reported that a temperature ramped steadily from an initial 25°C at ±0.6 °C/hr for eight hours was thermally acceptable between 23 and 27°C to more than 80% of the subjects wearing typical summer clothing.

Berglund [50] indicated that a 2.5°C temperature deviation from the optimum where acceptability is about 95%, will lead to a decrease in acceptance to about 80%.

Consequently, Berglund mentioned the optimum temperature for office spaces is mainly a function of the occupant's clothing, which is influenced by or chosen for the season and outside conditions.

Rohles et al. [51] studied the response of sedentary humans to cool, comfortable and warm thermal environments during summer and winter months. They concluded that thermal sensation response to temperatures that are higher than comfortable are affected more by the season and the location, rather than temperatures that are comfortable or cooler than comfortable. Subsequently, the way an individual responds to his thermal environment at any given time depends upon the length of time he has been exposed to that environment and the temperature he experienced just prior to exposure to that environment, which implies thermal comfort models should consider the transient rather than steady-state conditions.

In 1990, Hensen [52] described thermal conditions in a building are seldom steady-state due to the thermal interaction between the building structure, climate, occupancy and HVAC system. He also indicated for situations with a larger variation of room air temperature, the Fanger model which is based on steady-state and neutral conditions does not seem to be appropriate for use.

Therefore, the objectives of this chapter are the following:

a) Develop a transient comfort computer model by adapting the available published mathematical models.

b) Evaluate acceptable temperature drifts, as a mode of energy conservation in office buildings in Montréal, and the corresponding energy savings.

3.2 THERMAL COMFORT

Thermal comfort is defined when a person can maintain skin and core temperatures within narrow limits while requiring a minimum of physiological effort [43]. Computer simulation techniques using mathematical modelling of human comfort have become valuable instruments for the design of buildings and HVAC systems. These models can be helpful in assessing the consequences on occupant acceptability of energy conservation schemes that affect the thermal environment of a space [53].

The reaction of a person to the thermal environment is proportional to the rate of heat generation and loss. These in turn are a function of the following six parameters;

- air velocity,
- mean radiant temperature,
- air temperature,
- humidity,
- metabolic rate, and
- insulation of clothing.

Stimulation to the thermal environment is related to physiological factors such as skin temperature, core temperature, sweat rate, skin wettedness and thermal conductance between the core and the skin.

3.3 TWO-NODE MODEL

A. P. Gagges's experimental research [53] demonstrated skin temperature is a good indicator of both thermal sensation and comfort in cold environments. However, at conditions where sweating occurs, the skin temperature changes are small and in this region, skin wettedness (fraction of skin surface covered by water) is a better indicator of discomfort. To simulate skin temperature and skin wettedness in any environment, a two-node model was developed for a standard man qualified for low and medium activity levels (typical office work).

The two-node model regards man as two concentric thermal compartments representing the skin and core of the body (Fig. 3.2). The skin compartment assumes the epidermis and dermis. The temperature within a compartment is said to be uniform so that only temperature gradients are between the compartments. All the metabolic heat generation is assumed to develop within the core department of the two-node model.

Berglund [43,54] tested the Fanger comfort model and a transient two-node physiological model against experimental data for low exercise stress. Berglund's results indicated both models are good predictors near neutral, but the transient two-node model is more accurate as conditions

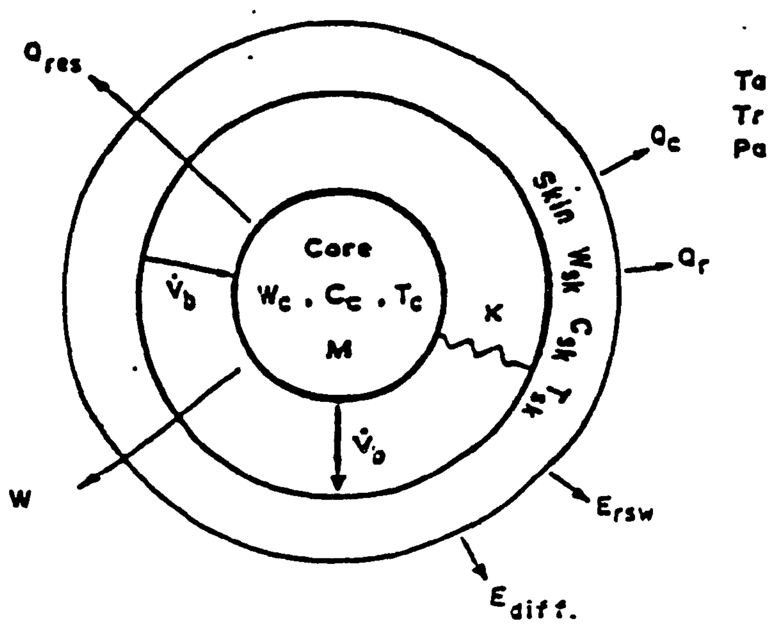

Figure 3.2 Two-node model for man [53]

where:

T_a = ambient air temperature
T_r = mean radiant temperature
P_a = ambient vapour pressure
Q_{res} = rate of respiratory heat loss
Q_c = rate of convective heat loss
Q_r = rate of radiative heat loss
E_{rsw} = rate of heat loss from the evaporation of sweat
E_{diff} = rate of heat loss from the diffusion of water vapour through the skin
W = rate of which energy is leaving the body due to performance of work
W_{sk} = weight of skin
C_{sk} = specific heat of skin
T_{sk} = skin temperature
K = thermal conductance between core and skin
V_b = blood flow rate
W_c = weight of core
C_c = specific heat of core
T_c = core temperature
M = metabolic energy produced within the body

deviate from neutral. The two-node model which predicts thermal sensation and discomfort is dynamic and can respond to changes in the environment, whereas the Fanger model which determines mean thermal sensation (PMV) and predicted percent dissatisfied (PPD) is valid for steady-state conditions.

Doherty and Arens [55] compared their transient two-node model predictions with observed values from a database containing physiological responses underlying thermal comfort for humans over a wide range of environmental conditions. Their analysis clearly indicated that the two-node model is accurate for simulations of sedentary humans.

3.4 METHODOLOGY

A transient energy balance introduced in ASHRAE Fundamentals [56] states that the rate of heat storage is equal to the net rate of heat gain minus the heat loss:

$$S_{CR} = M - W - (C_{RES} - E_{RES}) - Q_{CRSK}$$
$$S_{SK} = Q_{CRSK} - (CS + RS + E_{SK})$$

where:

- S_{CR} = rate of heat storage in the core compartment, W/m^2
- S_{SK} = rate of heat storage in the skin compartment, W/m^2
- C_{RES} = sensible heat loss
- E_{RES} = latent heat loss
- RS = radiant heat loss from the body
- CS = convective heat loss from the body
- Q_{CRSK} = rate of heat transport from core to skin
- E_{SK} = evaporative heat loss from the skin

The rate of change of temperature in each compartment can be expressed in terms of the rate of heat storage and the thermal capacity of the body:

$$\frac{dT_{CR}}{d\theta} = \frac{S_{CR} \cdot A_D}{(1-\alpha) \cdot m \cdot C_{p,bl}}$$

$$\frac{dT_{SK}}{d\theta} = \frac{S_{SK} \cdot A_D}{\alpha \cdot m \cdot C_{p,bl}}$$

where:

dT_{CR} = change in core temperature, °C/hr
dT_{SK} = change in skin temperature, °C/hr
m = body mass of average sized man, 70 kg
A_D = surface area of average sized man, 1.8 m^2
$d\theta$ = skin and core temperatures are updated every minute.
$C_{p,bl}$ = specific heat of blood, 4.187 kJ/kg°C

Thermoregulatory control processes (rate of blood flow, sweating and shivering) are governed by temperature signals from the skin and core. Five signals control these processes: warm signal from the core ($WSIG_{CR}$), cold signal from the core ($CSIG_{CR}$), warm signal from the skin ($WSIG_{SK}$), cold signal from the skin ($CSIG_{SK}$), and the warm signal from the body ($WSIG_B$):

$$WSIG_{CR} = \begin{cases} 0 & T_{CR} \le T_{CR,N} \\ T_{CR} - T_{CR,N} & T_{CR} > T_{CR,N} \end{cases}$$

$$CSIG_{CR} = \begin{cases} T_{CR,N} - T_{CR} & T_{CR} < T_{CR,N} \\ 0 & T_{CR} \ge T_{CR,N} \end{cases}$$

$$WSIG_{SK} = \begin{cases} 0 & T_{SK} \le T_{SK,N} \\ T_{SK} - T_{SK,N} & T_{SK} > T_{SK,N} \end{cases}$$

$$CSIG_{SK} = \begin{cases} T_{SK,N} - T_{SK} & T_{SK} < T_{SK,N} \\ 0 & T_{SK} \ge T_{SK,N} \end{cases}$$

$$WSIG_B = 0 \qquad T_B \le T_{B,N}$$
$$T_B - T_{B,N} \qquad T_B > T_{B,N}$$

The average core and skin temperatures are at their neutral values:

$$T_{CR,N} = 36.8\ ^{o}C$$
$$T_{SK,N} = 33.7\ ^{o}C$$
$$T_{B,N} = 36.49\ ^{o}C$$

The mean body temperature can be determined by the weighted average of the skin and core temperatures:

$$T_B = \alpha T_{SK} + (1-\alpha)\, T_{SK} \qquad {}^{o}C$$

where alpha (α) is described by Doherty and Arens [55] as the fraction of total body mass attributed to the skin compartment:

$$\alpha = 0.0417737 + \frac{0.74518328}{SKBF + 0.585417}$$

and the rate of blood flow (SKBF, L/hr m^2) depends on the skin and core temperature deviations from their respective setpoints:

$$SKBF = \frac{6.3 + 200\, WSIG_{CR}}{1 + 0.5\, CSIG_{SK}}$$

Heat transfer coefficients are necessary to solve the equations describing heat transfer from the body [55].

$$hr = 4(0.72)\sigma\varepsilon\left(\left(T_{CL}+T_R\right)/2 + 273.15\right)^3$$

where:
σ = Stefan Boltzmann constant
ε = skin emissivity

However, the linearized heat transfer coefficient (h_r) for typical indoor temperatures is nearly constant [56]:

$$h_r = 4.7 \qquad W/(m^2\ {}^{o}C)$$

Heat transfer by convection (h_c) is usually caused by air movement within the space [56]:

$$h_c = 8.6 \cdot V^{0.53} \qquad W/(m^2\ {}^{o}C)$$

where:
V = velocity of moving air in the space, (assumed to be 0.1 m/s)

The evaporation heat transfer coefficient (h_e) can be related to the convective heat transfer coefficient through the modified Lewis number [55]:

$$h_e = \frac{2.2 \cdot h_c}{1+0.92\ K\ CLO \cdot h_c} \qquad W/(m^2\ {}^{o}C)$$

where:
CLO = insulation value for clothing
K = unit conversion factor, 0.155 m^2 °C/(CLO W)

Respiratory heat losses are estimated by the following equations [55]:

$$C_{RES} = 0.0014 \cdot M \cdot (34 - T_A)$$

$$E_{RES} = 0.0023 \cdot M \cdot (44 - P_A)$$

where:
T_A = ambient temperature, °C
P_A = ambient vapour pressure, Torr [54]

$$P_A = \exp(18.6686 - 4030.183/(T_{DP} + 235))$$

T_{DP} = dew point temperature, °C

Radiant heat loss from the body (RS) is defined in terms of the difference between the clothed body surface temperature (T_{CL}) and the mean radiant temperature (T_R) [55]:

$$RS = h_r \cdot Facl \cdot (T_{CL} - T_R) \qquad W/m^2$$

Convective heat loss (CS) from the body varies linearly with the temperature difference between the ambient environment and the clothed body [55]:

$$CS = h_c \cdot Facl \cdot (T_{CL} - T_A) \qquad W/m^2$$

where:

Facl = the fractional increase in body surface attributed to clothing, (Facl = 1 + 0.2 CLO)

Rate of heat transport from the core to the skin (Q_{CRSK}) can be written as [56]:

$$Q_{CRSK} = (k + C_{p,bl} \cdot SKBF) \times (T_{CR} - T_{SK}) \qquad W/m^2$$

where:

k = effective conductance between the core and skin, 5.28 $W/m^2\,^{o}C$

The clothed body surface tempe..ature (T_{CL}) can be evaluated as [55]:

$$T_{CL} = \frac{\dfrac{T_{SK}}{0.155\,CLO} + Facl \cdot (h_c \cdot T_A + h_r \cdot T_R)}{\dfrac{1}{0.155\,CLO} + Facl \cdot (h_c + h_r)} \qquad ^{o}C$$

Evaporative heat loss from the skin (E_{SK}) depends on the difference between the water vapour pressure (P_{SK}) at the skin and in the ambient environment (P_A) [55]:

$$E_{SK} = w\, h_e\, (P_{SK} - P_A) \qquad W/m^2$$

The maximum evaporative heat loss (E_{MAX}) occurs when the skin surface is completely wetted (w=1.0) [55]:

$$E_{MAX} = h_e\, (P_{SK} - P_A) \qquad W/m^2$$

Regulatory sweating evaporative heat loss (E_{RSW}) is directly proportional to the regulatory sweat generated (REG_{SW}) [55]:

$$E_{RSW} = 0.68 \cdot REG_{SW} \qquad W/m^2$$

where:

$$REG_{SW} = 170 \cdot WSIG_B \cdot e^{\frac{WSIG_{SK}}{10.7}}$$

The fraction of skin surface (w) covered by water is [55]:

$$w = \frac{E_{RSW}}{E_{MAX}}$$

The diffusion evaporation heat loss (E_{DIFF}) is then given as [55]:

$$E_{DIFF} = (1 - w_{RSW}) \cdot 0.06 E_{MAX} \qquad W/m^2$$

After calculating values of t_{SK}, t_{CR}, and t_B, the two-node model uses empirical expressions to predict thermal sensation and thermal discomfort. These indices are based on 11-point numerical scales, where positive values represent the warm side of neutral sensation or comfort, and negative values represent the cool side.

TSENS = +5 intolerably hot
+4 very hot
+3 hot
+2 warm
+1 slightly warm
0 neutral
-1 slightly cool
-2 cool
-3 cold
-4 very cold
-5 intolerably cold

Thermal Sensation (TSENS) is defined in terms of deviations of mean body temperature [56]:

$$TSENS = \begin{cases} 0.4685\,(T_B - T_{B,C}) & T_B < T_{B,C} \\ 4.7\,\varepsilon_{EV}(T_B - T_{B,C}) / (T_{B,H} - T_{B,C}) & T_{B,C} \le T_B \le T_{B,H} \\ 4.7\,\varepsilon_{EV} + 0.4685\,(T_B - T_{B,H}) & T_{B,H} < T_B \end{cases}$$

where:
T_B = mean body temperature
$T_{B,C}$ = cold setpoint for evaporative regulation zone
$T_{B,H}$ = hot setpoint for evaporative regulation zone
ε_{EV} = evaporative efficiency (0.85)

Cold and hot setpoints for the evaporative regulation zone are dependant on the net rate of heat production and are determined as follows [56]:

$$T_{B,C} = (0.194/58.15)\,(M-W) + 36.301$$
$$T_{B,H} = (0.347/58.15)\,(M-W) + 36.669$$

where:

M = metabolic energy (seated = 58.15 W/m^2)

W = external work done by muscles (assumed = 0 W/m^2)

Thermal discomfort (DISC) is equal to TSENS when T_B is below its cold setpoint $T_{B,C}$, and is related to skin wettedness when body temperature is regulated by sweating [56]:

$$DISC = \begin{cases} 0.4685\,(T_B - T_{B,C}) & T_B < T_{B,C} \\ 4.7\,(E_{RSW} - E_{RSW,REQ}) \\ \quad /\,(E_{MAX} - E_{RSW,REQ} - E_{DIFF}) & T_{B,C} \le T_B \end{cases}$$

where:

$E_{RSW,REQ}$ = rate of regulatory sweating that provides thermal comfort, W/m^2 $(0.42(M - W - 58.15))$

This index uses the following scale:

DISC = ± 5 Intolerable
± 4 Limited tolerance
± 3 Very uncomfortable
± 2 Uncomfortable and unpleasant
± 1 Slightly uncomfortable but acceptable
0 Comfortable

Hence, using the above mathematical models from published literature, a micro-computer program was developed called the Transient Comfort Model, which will henceforth be referred to as the TCM program. Figure 3.3 details the calculation path through the process core where thermal sensation and discomfort are determined by the TCM program.

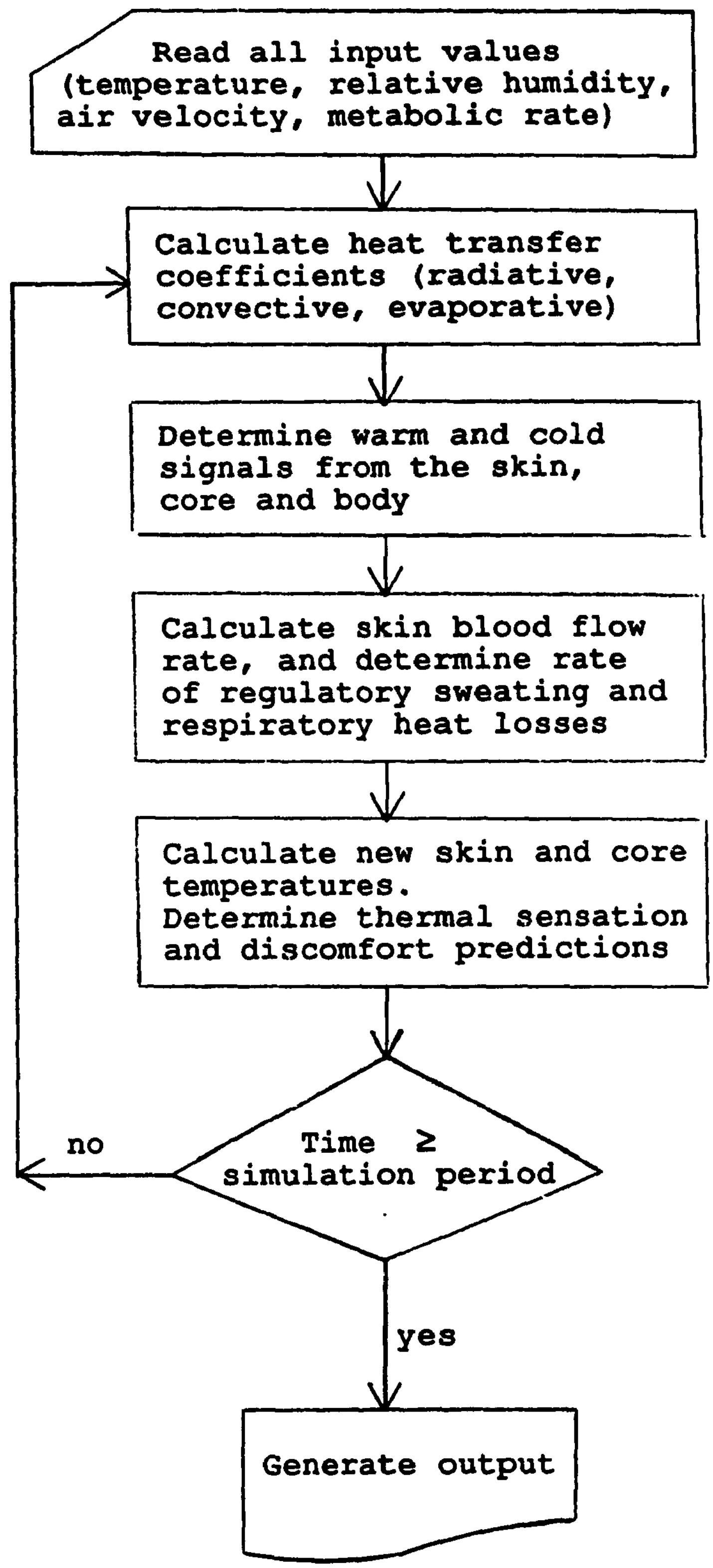

Figure 3.3 Flowchart of TCM program

The program first asks the user the initial conditions of the environment, and second the rate of temperature change:

DURATION OF EXPOSURE ?	7	(hr)
AMBIENT TEMPERATURE ?	25.0	(^{o}C)
CLOTHING INSULATION VALUE ?	0.9	(CLO)
HOUR OF TEMPERATURE CHANGE ?	2	(hr)
RATE OF TEMPERATURE CHANGE ?	+1.0	(^{o}C/hr)

In this program, developed mainly for office buildings, some default values are used (M=1.0, W=0, and V=0.1m/s).

If the user does not wish to have any temperature changes throughout the analysis (i.e. steady-state conditions), then the HOUR OF TEMPERATURE CHANGE value must be greater than the DURATION OF EXPOSURE value.

The TCM program lists the corresponding output values for the length of exposure (TIME), ambient temperature (TA), core temperature (TCR), skin temperature (TSK), thermal sensation prediction (TSENS) and discomfort prediction (DISC).

TIME	TA	TCR	TSK	TSENS	TDISC
0.00	25.00	36.83	34.13	0.40	0.24
0.50	25.00	36.84	34.38	0.89	0.60
1.00	25.00	36.84	34.41	0.94	0.63
1.50	25.00	36.84	34.41	0.94	0.63
2.00	25.00	36.84	34.41	0.94	0.63
2.50	25.50	36.84	34.46	1.01	0.69
3.00	26.00	36.85	34.53	1.12	0.77
3.50	26.50	36.85	34.61	1.22	0.84
4.00	27.00	36.85	34.68	1.32	0.92
4.50	27.50	36.86	34.75	1.42	1.01
5.00	28.00	36.86	34.82	1.52	1.09
5.50	28.50	36.86	34.89	1.61	1.17
6.00	29.00	36.87	34.96	1.71	1.26
6.50	29.50	36.87	35.03	1.81	1.35
7.00	30.00	36.88	35.10	1.90	1.44

3.5 VALIDATION OF THE TCM COMPUTER PROGRAM

ASHRAE Standard 55-1981 "Thermal Environment Conditions for Human Occupancy" [40] specifies conditions in which 80% or more of the occupants will find the environment thermally acceptable (Table 3.1).

Table 3.1 Thermal acceptability limits in ASHRAE 55-1981 [40]

Season	CLO	Neutral Temperature	Temperature Limits for 80% acceptability
Winter	0.9	21.7 °C	20.0 - 23.6 °C
Summer	0.5	24.4 °C	22.8 - 26.1 °C

Table 3.1 defines thermal acceptability for sedentary or slightly active persons (≤1.2 met) at 50% relative humidity with air movement in the occupied zone less than 0.15 m/s.

Comparison between the results of the TCM program developed in this research and the ASHRAE 55-1981 for the case of neutral temperatures are similar. The TCM program predicted neutral temperatures in winter and summer to be 20.9 and 23.4 °C respectively (3.1 and 4.1% less than applicable ASHRAE values). However, the 80% thermal acceptability limits predicted by the TCM program surpassed the limits defined by ASHRAE (Fig. 3.4 and 3.5). For instance, the lower and upper acceptable space temperatures in winter specified by ASHRAE are 20.0 and 23.6°C, whereas the TCM program predicted the same limits to be approximately 17 and 25.5°C for a constant temperature. Further, as the rate of temperature change

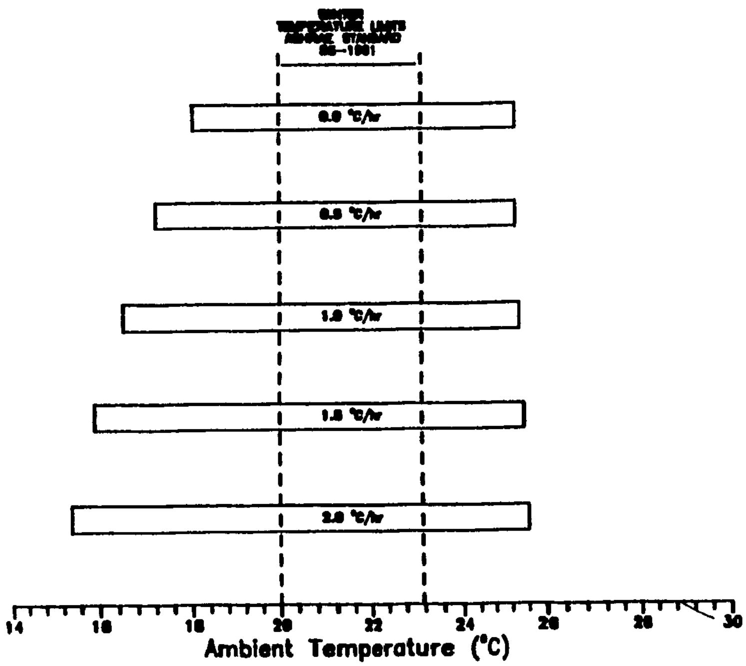

Figure 3.4 Compa-.-ison of 80% thermal acceptability limits in winter (CLO=0.9) for the TCM program and ASHRAE Standard 55-1981 [40].

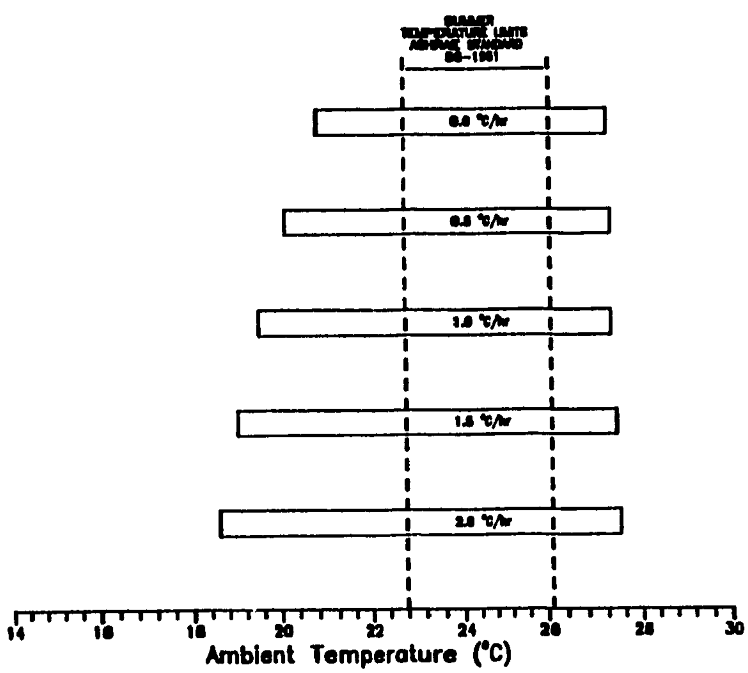

Figure 3.5 Comparison of 80% thermal acceptability limits in summer (CLO=0.5) for the TCM program and ASHRAE Standard 55-1981 [40].

increased, the acceptable lower limits for space temperature in winter are lower. For example, at a 1.5 and 2.0°C/hr change, the acceptable lower limits are 16 and 15.4°C.

The predicted thermal sensation and discomfort levels given by the TCM program were compared with the results carried out by Berglund and Gonzalez [49] on 12 college age students (Fig. 3.6–3.11). The students remained in a test chamber at 25°C for a half hour, after which the temperature was ramped to gage the students thermal sensation, discomfort and thermal acceptability responses.

Figure 3.6 shows the TCM program predicted the thermal sensation of people with warm clothing ensembles (0.9 CLO) to be uncomfortable after the third hour of a +0.5 °C/hr ramp. Thermal discomfort was experienced for the actual test subjects with warm clothing ensembles also after the third hour.

The results of the 1.0 and 1.5 °C/hr up ramps (Fig. 3.7, 3.8) indicate that predicted and actual thermal sensation and discomfort limits for the subjects were generally reached from 2 to 3 hours after exposure.

The responses of the down ramps (Figures 3.9, 3.10 and 3.11) illustrate as expected the warmer clothed subjects (i.e 0.9 vs 0.5 CLO) in the actual experiment and the simulated model were more comfortable under these conditions. Although the trends for the experimental and predicted data are similar, the TCM program generally overestimates the thermal

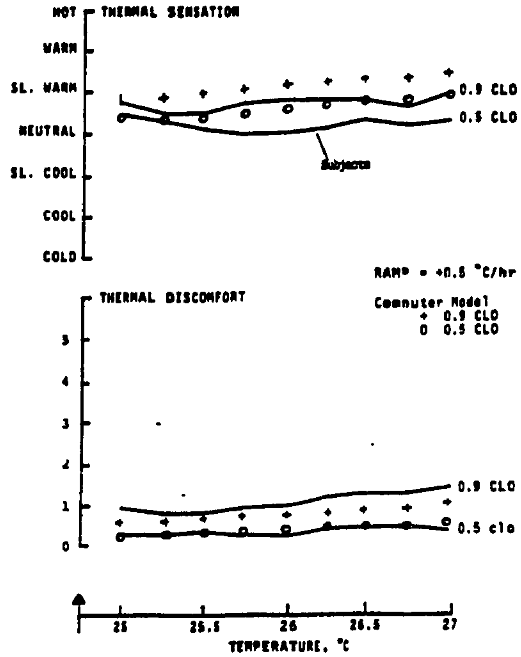

Figure 3.6 Mean response levels for 12 subjects vs predicted values for 0.5 °C/hr

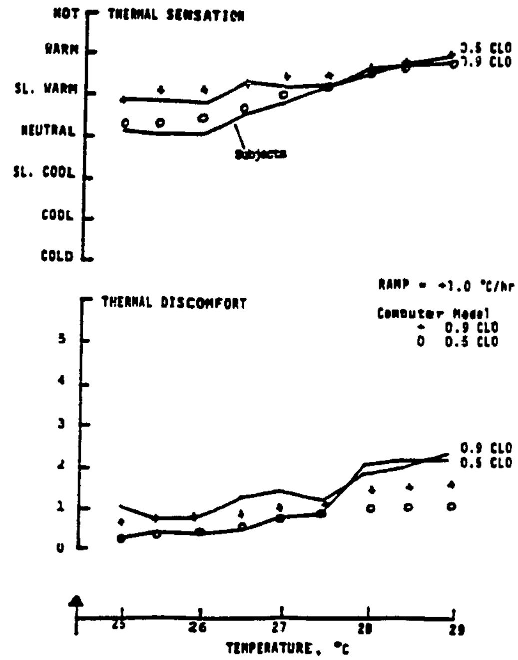

Figure 3.7 Mean response levels for 12 subjects vs predicted values for 1.0 °C/hr

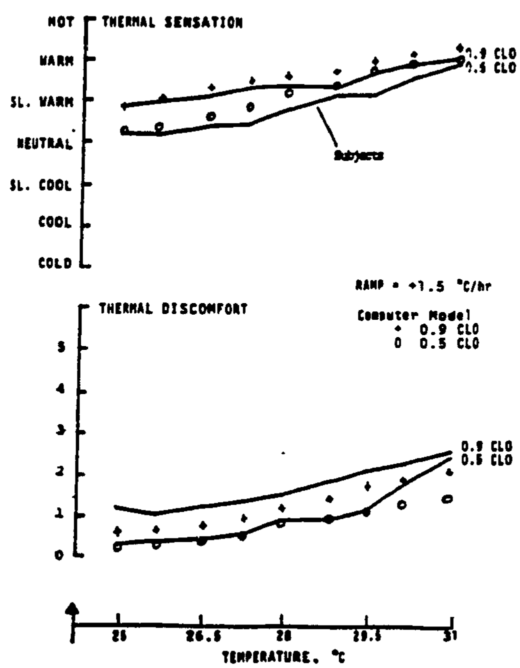

Figure 3.8 Mean response levels for 12 subjects vs predicted values for 1.5 °C/hr

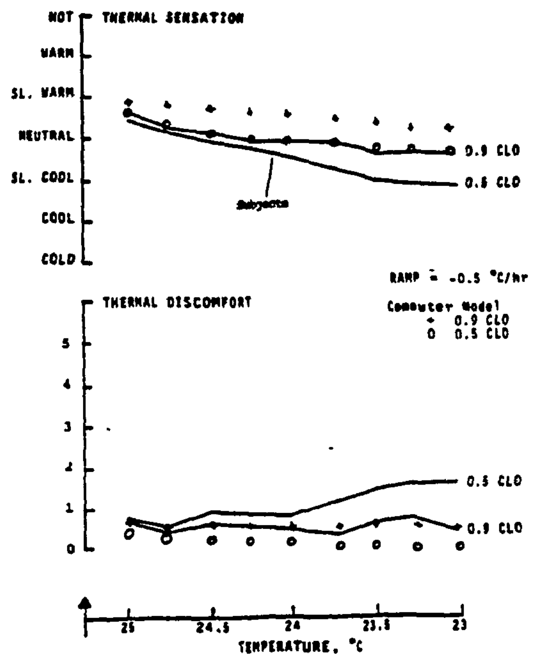

Figure 3.9 **Mean response levels for 12 subjects vs predicted values for -0.5 °C/hr**

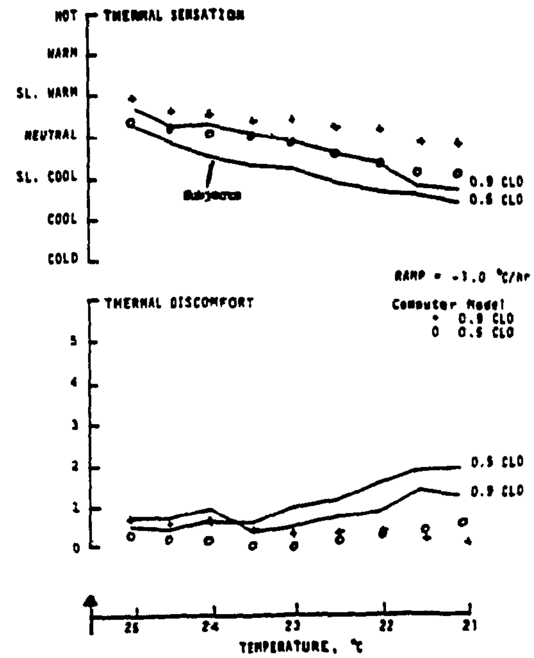

Figure 3.10 **Mean response levels for 12 subjects vs predicted values for -1.0 °C/hr**

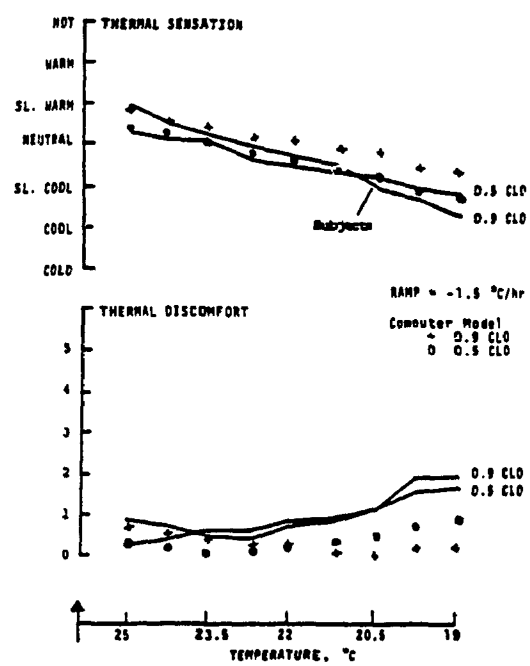

Figure 3.11 **Mean response levels for 12 subjects vs predicted values for -1.5 °C/hr**

sensation and underestimates discomfort in the warm region.

Berglund and Gonzalez [48] also developed a multiple linear equation from their experimental data which relates the mean thermal sensation to the clothing insulation value and temperature:

$$TSENS = 0.305\, T_A + 0.996\, CLO - 8.08$$

Illustration of the difference between the regression analysis and the TCM program predictions for summer and winter clothing ensembles is presented below in Figure 3.12.

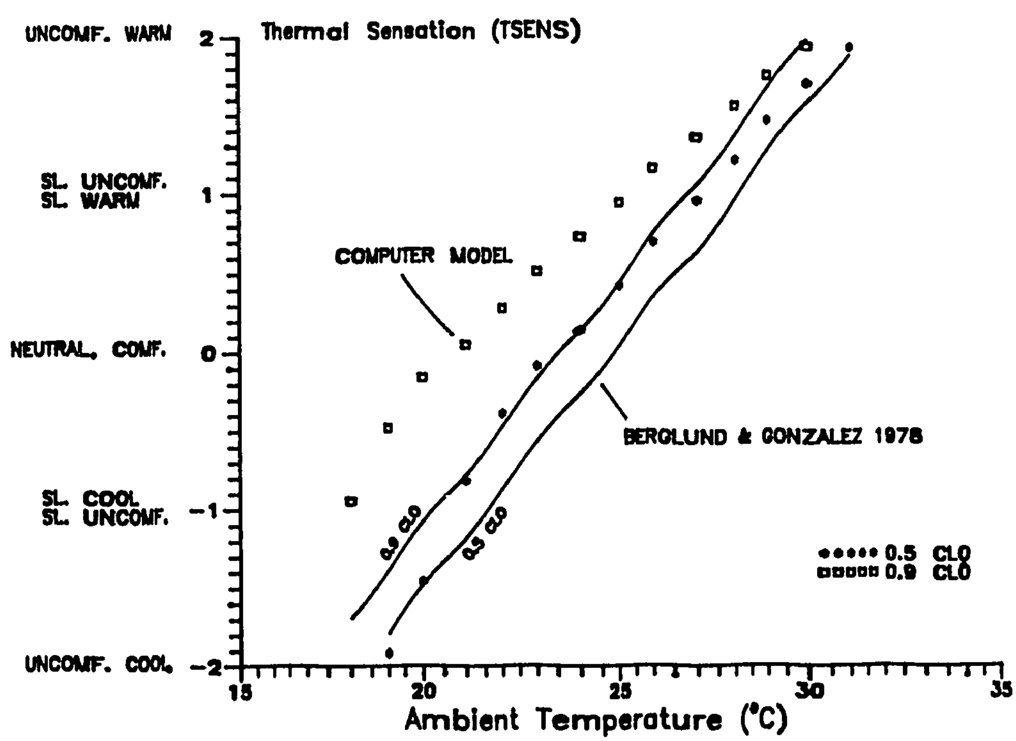

Figure 3.12 **Regression equation developed by Berglund and Gonzalez [48] versus the TCM program estimates.**

Rohles et al. [57] compiled the thermal sensation responses of 1600 subjects exposed for 3 hours to various air temperatures and humidity levels. The subjects were clothed in a standard uniform consisting of a long sleeved shirt and trousers (0.6 CLO). For air temperatures between 20 and 32 °C at 50% relative humidity, Rohles et al. determined that the mean thermal sensation of the subjects could be estimated from the following regression equation:

$$TSENS = 0.325\,T_A - 8.444$$

Using the regression equation, slightly warm and slightly cool thermal sensations occurred at 29.0 and 22.9 °C respectively. For a similar environment, the TCM program estimates slightly warm and slightly cool sensations at 26.8 and 19.6 °C (Fig. 3.13).

Warm discomfort (DISC) is linearly proportional to skin wettedness or the fraction of the body surface wet with perspiration. Gagge et al. [58] define thermal discomfort as the relative thermoregulatory strain necessary to restore a state of comfort and thermal equilibrium by sweating (threshold wettedness). Values of thermal discomfort presented by Gagge et al. from computer simulations are compared to thermal discomfort levels predicted by the TCM program (Fig. 3.14) for a similar environment (met=1.25, CLO=0.57, RH=50% and V=0.2 m/s). Thermal discomfort estimates from both models show very little difference in comfort limits

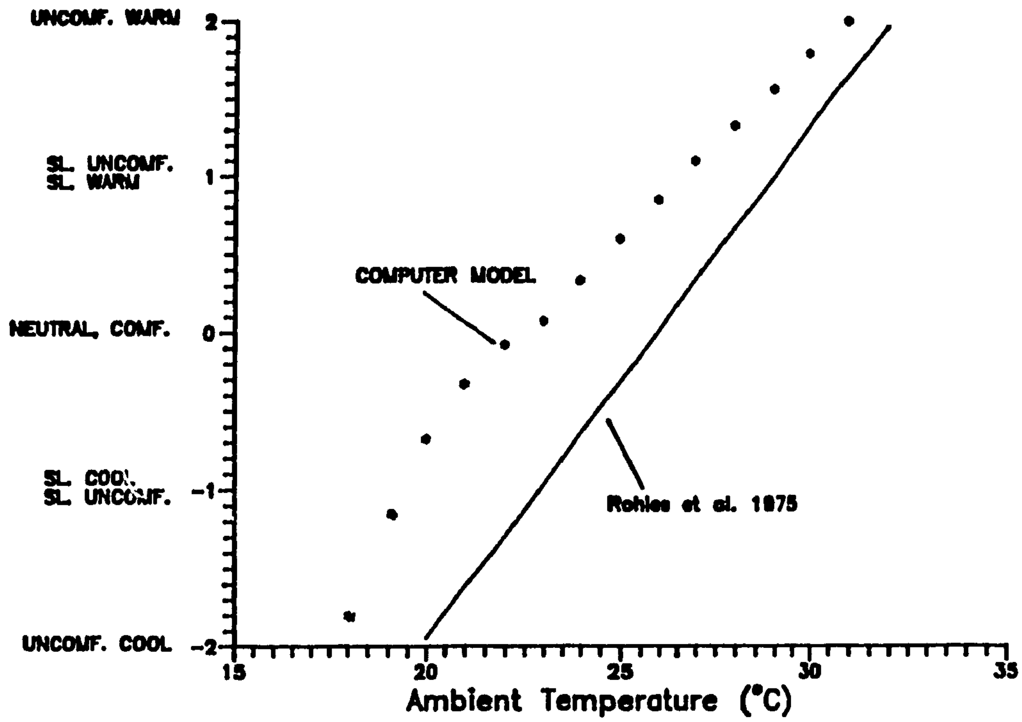

Figure 3.13 **Thermal sensation comparisons: TCM program versus Rohles et al. [57].**

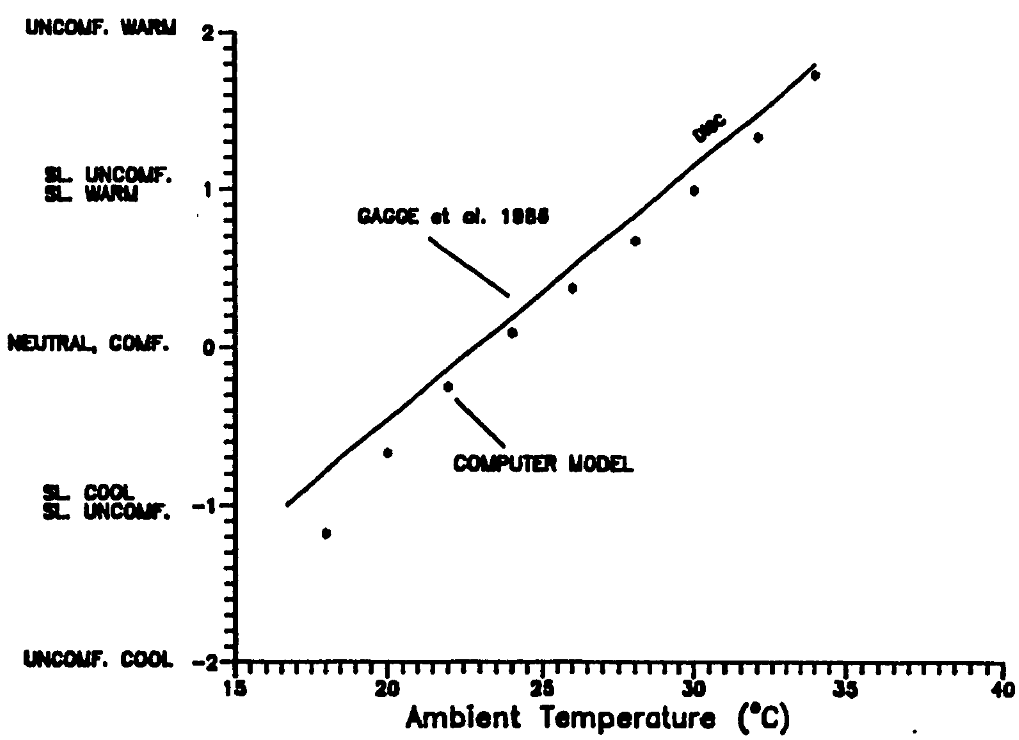

Figure 3.14 **Thermal discomfort comparisons: TCM program versus Gagge et al. [58].**

as indicated in Table 3.2.

Table 3.2 Thermal discomfort estimates: TCM program versus Gagge et al. [58].

Thermal Discomfort	Gagge et al.	TCM Program	Percent Difference
Sl. Warm	29.3	30.3	2.4
Neutral	22.7	23.3	1.3
Sl. Cool	17.0	18.5	8.8

Berglund [43] predicted the thermal sensation and thermal discomfort levels for non-steady environments and those beyond optimum comfort through the use of a transient two-node physiological model. Comparison of Berglund's model and the TCM program developed in this research is illustrated in Figure 3.15. The thermal sensation and discomfort curves predicted by both models under identical environments (M=1.0, CLO=0.6, RH=50% and V=0.1 m/s) are very similar, with only the TCM program estimates displaced slightly to the cool region (Table 3.3).

Table 3.3 Thermal sensation and discomfort estimates: TCM program versus Berglund [43]

Thermal Discomfort	Berglund	TCM Program	Percent Difference
Sl. Warm	28.7 (30.7)*	26.7 (29.0)*	7.0 (5.5)*
Neutral	24.5	23.0	6.1
Sl. Cool	20.5	19.4	5.4

* bracketed terms represent discomfort estimates

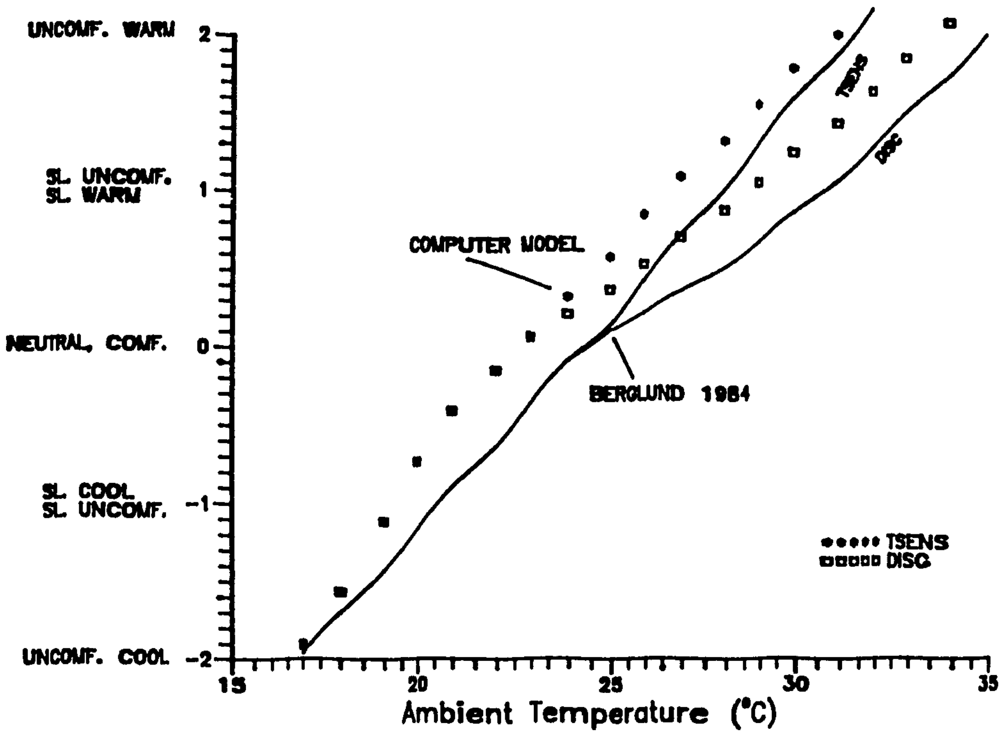

Figure 3.15 **Thermal sensation and discomfort comparisons: TCM program versus Berglund [43].**

Thus, from the previous analysis, one can conclude the TCM program provides good estimates of the thermal sensation and discomfort of occupants under steady-state and transient conditions.

3.6 APPLICATION OF TEMPERATURE DRIFTS AS A MODE OF ENERGY CONSERVATION

Simulation of indoor space temperature drifts are performed using the BLAST building energy simulation program presented in Chapter 2 in order to determine the potential for energy conservation in office buildings in Montréal for the summer cooling season (June to September).

Initially, the thermal environment of the reference building (T_A=24.5°C, RH=50% and air velocity ≤ 0.15m/s), designed in accordance to ASHRAE 55-1981 [43] is simulated using the BLAST program. The ambient temperature is then allowed to drift after a specified period of time to reduce the energy consumption of the reference building. Results of hourly, daily and monthly energy use are presented in the following discussion for the base case and proposed thermal environments. Then, the previously presented TCM program is used to evaluate the thermal comfort of the occupants.

3.6.1 Design Day Analysis

3.6.1.a Daily Profiles

A hot summer day in 1980 in Montréal with a high average daily temperature (high=27.4 °C, low=20.8 °C) was selected since it would presumably produce the largest cooling load.

The hourly space temperatures in the interior zone of the reference building are illustrated in Figure 3.16. The two curves represent: a) summer space temperatures for the base case, and b) the proposed temperature profile.

The interior zone temperature for the base case is kept at an acceptable limit according to ASHRAE 55-1981 from 07:00 to 23:00 hours. During the highest occupancy period (09:00 - 18:00 hrs), the space temperature is relatively constant at 24.6°C for the base case. The space temperature for the proposed design is approximately 25.2°C from 09:00 to 15:00. However, after 15:00 hours the space temperature is allowed to

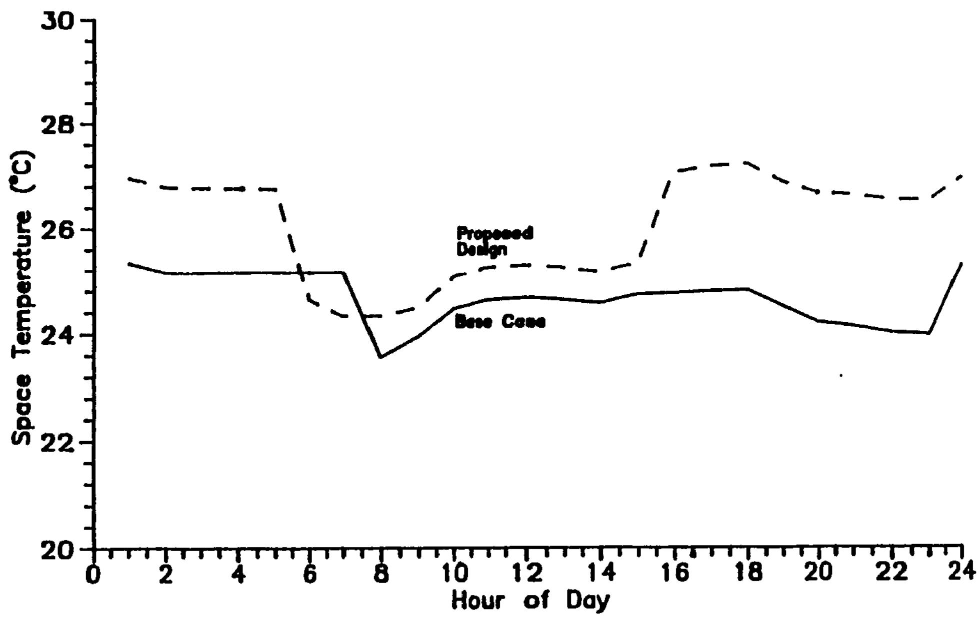

Figure 3.16 Ambient temperature in the interior zone for a hot summer day

drift to about 27°C for the rest of the occupied period.

Since the overnight temperature for the proposed design is about 2°C higher than the base case, the HVAC system for the proposed design is turned on two hours earlier (5:00 am) to reduce the early peak demand.

The space cooling load for the simulated period is shown in Figure 3.17. The peak space cooling load for the base case is 9.1 kW, and it occurs at 17:00 hours. For the proposed design, the peak space cooling load occurs 3 hours earlier. The magnitude of the peak cooling load for the proposed design is 9.3 kW, which is 3.2% larger than the base case.

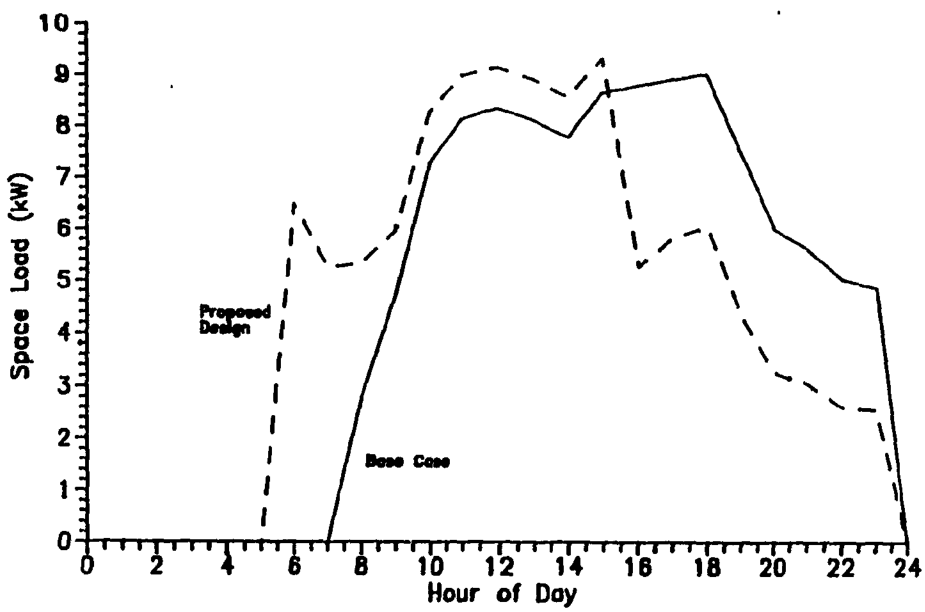

Figure 3.17 Interior zone space cooling load for a hot summer day.
Base Case: Peak=9.1kW, Total=111.8kWh
Proposed Design: Peak=9.3kW, Total=109.3kWh

The proposed design cooling load after 15:00 hours is less than the base case since the space temperature for the proposed design is allowed to drift to 27°C following this period. The space cooling load for both designs decreases dramatically after 18:00 hours since the internal loads are significantly reduced, thus realizing a slight drop in space temperature for the same period of time in Figure 3.16.

The total cooling load of the base case design for the simulated period is 111.8 kWh. Similarly, the daily cooling load for the proposed design is 109.3 kWh, which is 2.2% less.

In order to evaluate the energy and cost savings of the proposed design, the designer/engineer must observe the load on the cooling coil of the HVAC system rather than the space cooling load. (Fig. 3.18).

The two curves represented in Figure 3.18 are almost identical until 15:00 hours. The peak loads for both designs occur at 11:00 hours. The proposed design peak load (260.8 kW) is 5.5% less than the base case peak load (276.0 kW).

This may be attributed to the following reasons:

1) The early start-up of the HVAC system for the proposed design will reduce the demand on the system throughout the early occupied hours of the day.

2) The cooling throttling range for the proposed design is slightly larger than the base case for the same period of time (i.e. start-up to 15:00 hrs). This will permit the space temperature to deviate from the set point temperature during high periods of demand, thus reducing the peak load demand.

Nevertheless, the actual energy savings occur after 15:00 hours when the space temperature for the proposed design is allowed to drift. The chilled water load for the proposed design is much less than for the base case. Results obtained from BLAST indicate the chilled water consumption of the proposed design is 1866 kWh, or 35% less than for the base case (2869 kWh).

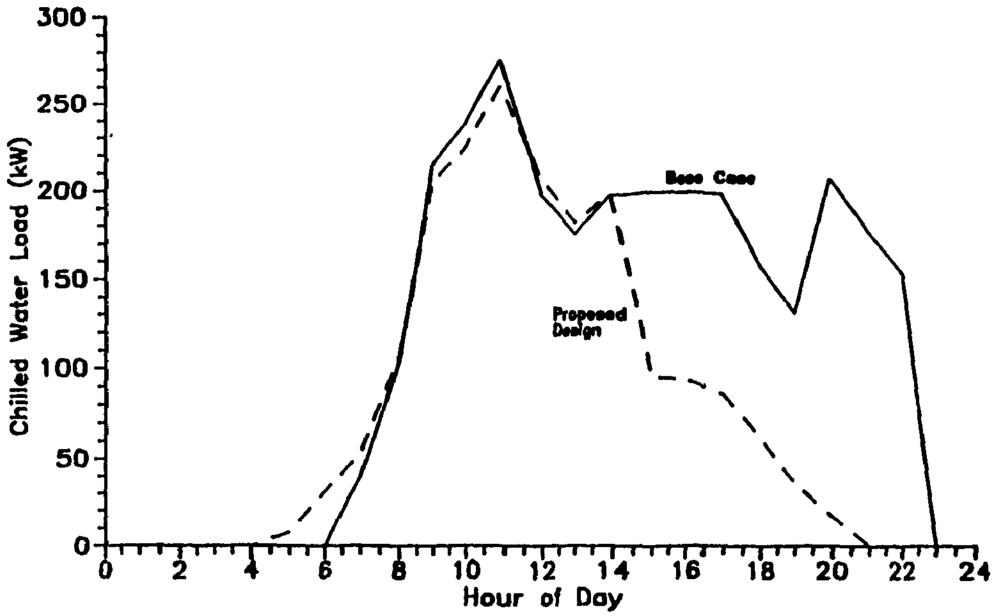

Figure 3.18 Interior zone chilled water load for a hot summer day.
Base Case: Peak=276.0 kW, Total=2869 kWh
Proposed Design: Peak=260.8 kW, Total=1866 kWh

The previous results indicate the potential of energy savings is established by allowing the temperature to drift in the occupied space. To verify the thermal comfort of the occupants, the TCM program presented and validated earlier in this chapter is utilized to predict the occupant response. The occupants are assumed to be wearing typical summer clothing ensembles (CLO=0.5), with the ambient environment at 50% relative humidity and air velocity in the occupied space at about 0.1 m/s.

Assuming the temperature remains constant at 24.6°C for the base case design from 09:00 to 18:00 hours (Fig. 3.16), the thermal sensation response of the building occupants illustrated in Figure 3.19 is about 0.3. As the temperature in the space becomes lower after 18:00 hours, the magnitude of the thermal response of the occupants toward the warm thermal sensation will decrease.

The proposed design is assumed to keep the temperature relatively constant at 25.1°C from 09:00 to 15:00 hours. During this period the thermal sensation response of the occupants is 0.50. When the temperature in the space is then allowed to drift to 27°C, the TCM program predicts the average thermal sensation for the building occupants to be approximately 1.0.

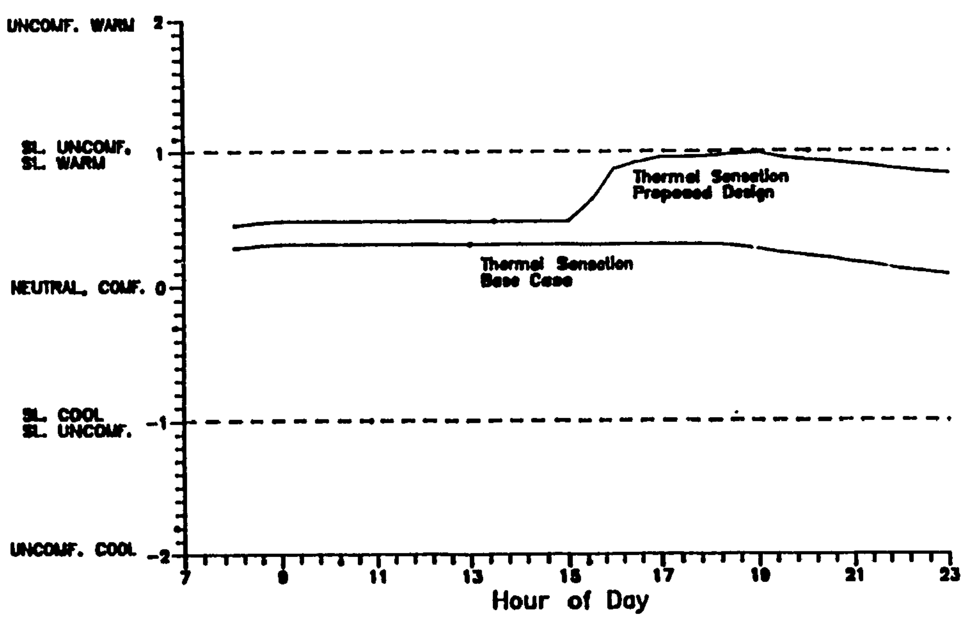

Figure 3.19 Predicted thermal sensation response of building occupants in the interior zone for a hot summer day.

A thermal sensation value of 1.00 represents the upper limit of warm thermal comfort (i.e. 80% thermal acceptability). Since this limit is not exceeded, the proposed design can be accepted.

As previously stated, A.P. Gagges's experimental work confirmed that skin temperature is a good indicator of thermal sensation and comfort in cold environments. Under conditions where sweating occurs, Gagge indicated skin wettedness is a better indicator of discomfort than skin temperature.

Figure 3.20 illustrates the thermal discomfort response of the building occupants to the similar environment (Fig. 3.16).

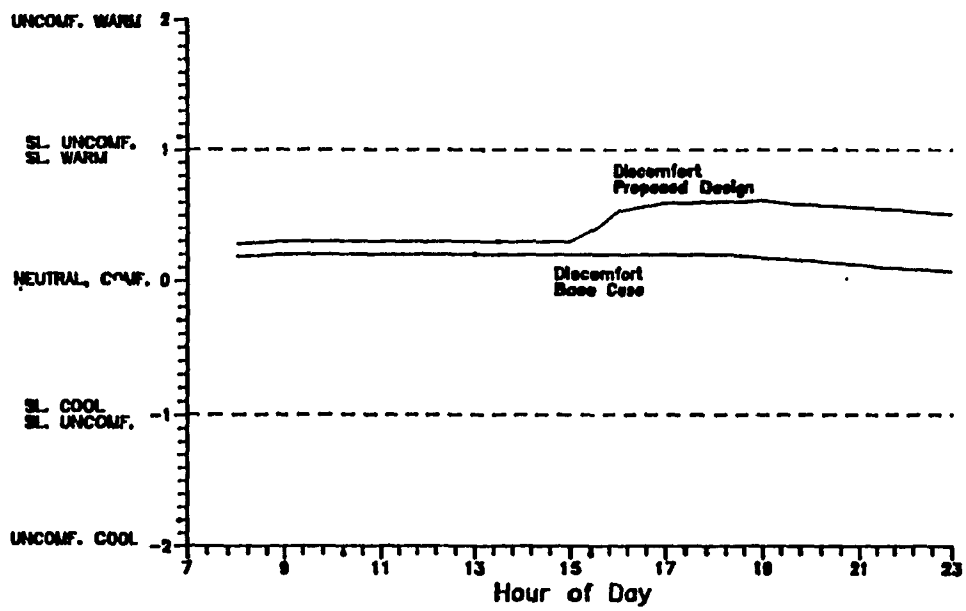

Figure 3.20 Predicted discomfort response of building occupants in the interior zone for a hot summer day.

The discomfort response of the occupants to the base case environment in Figure 3.20 is about 0.2. For the proposed design, the discomfort response to the ambient environment before the temperature drift is 0.3. After the allowed temperature drift, the predicted discomfort response to an ambient temperature of 27°C is only 0.6.

3.6.1.b Average Summer Day

The daily pattern of energy use for the base case and the proposed design were further studied for an average summer day in July in Montréal (high=26.2°C, low=14.0°C).

Interior zone temperatures for an average summer day are illustrated in Figure 3.21. The space temperature for the proposed design is once again allowed to drift after 15:00 hours to about 27°C. The potential for energy conservation in the proposed design is compared to the base case, where the temperature profile for the base case remains relatively constant throughout the occupied period.

Analysis of the temperature profiles shows that the average summer day (Fig. 3.21) and the hot summer day (Fig. 3.16) are very similar, although the interior zone for the base case and proposed design is slightly warmer (0.1°C) during the hot summer day for the comparable period of time.

The space cooling load profile for the average summer day (Fig. 3.22) is also similar to the hot summer day pattern (Fig. 3.17). For the average summer day, the total cooling

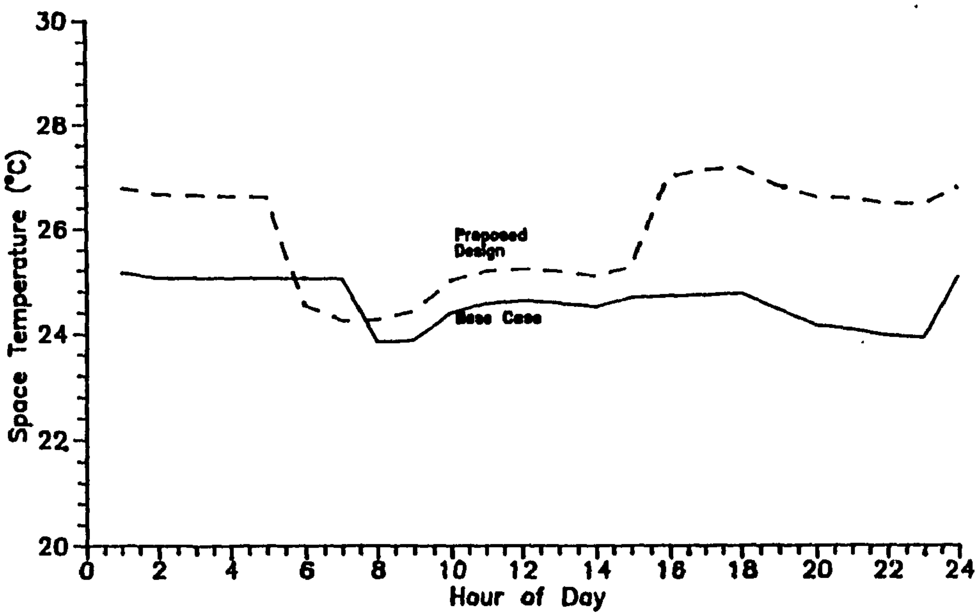

Figure 3.21 Interior zone space temperature for an average summer day.

load for the base case is 109.8 kWh, which is 3.9% higher than the proposed design (105.5 kWh). The permitted drift of the space temperature after 15:00 hours for the proposed design reduces the space load when compared to the base case for the same period of time. However, due to the overnight increase in space temperature for the proposed design, the cooling system as previously mentioned is required to start-up two hours earlier than the base case, thus increasing the early morning space cooling load.

The peak space cooling load which occurs at 17:00 hours for the base case is 8.8 kW. For the proposed design, the peak space cooling load which occurs 3 hours earlier is 9.8 kW, or 11.5% more than the base case on an average summer day.

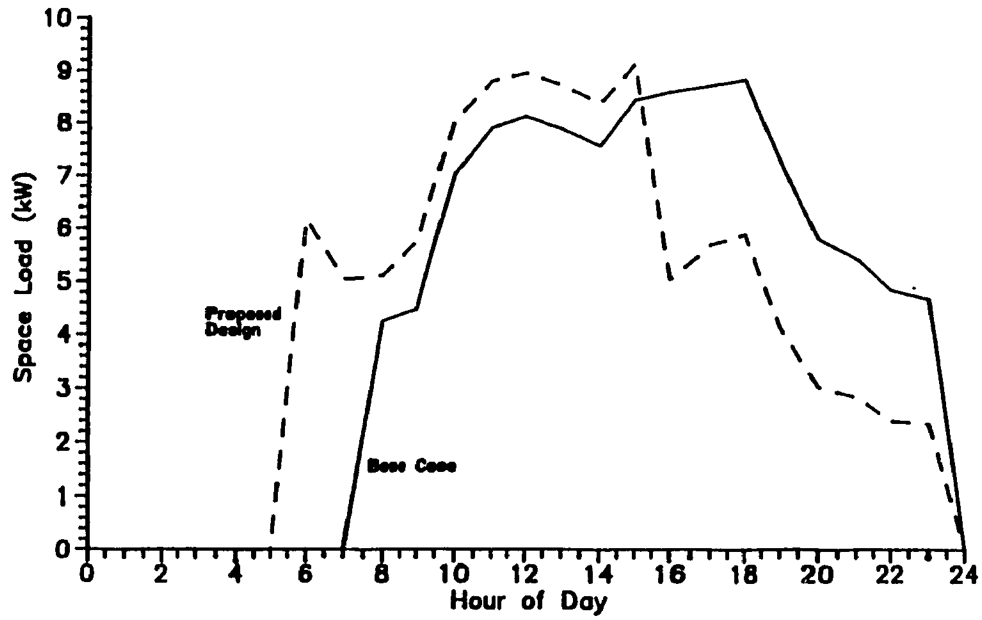

Figure 3.22 Interior Zone Space Cooling Load for an average summer day.
Base Case: Peak=8.8kW, Total=109.8kWh,
Proposed Design: Peak=9.8kW, Total=105.5kWh.

The chilled water load for the interior zones on an average summer day is shown in Figure 3.23. Chilled water use for the base case and the proposed design are almost identical until 15:00. After this time, when the space temperature is allowed to increase in the zone to 27°C, the chilled water consumption for the proposed design decreases. Daily chilled water use for the proposed design is reduced 38.6%, from 941.1 to 578.0 kWh as compared to the base case.

The peak chilled water demand for the interior zones of the base case and reference building are virtually equivalent.

The base case chilled water peak demand is 134.5 kW at 15:00 hours. The peak demand for the proposed design is 137.2 kW (2.0% more than the base case) at 14:00 hours.

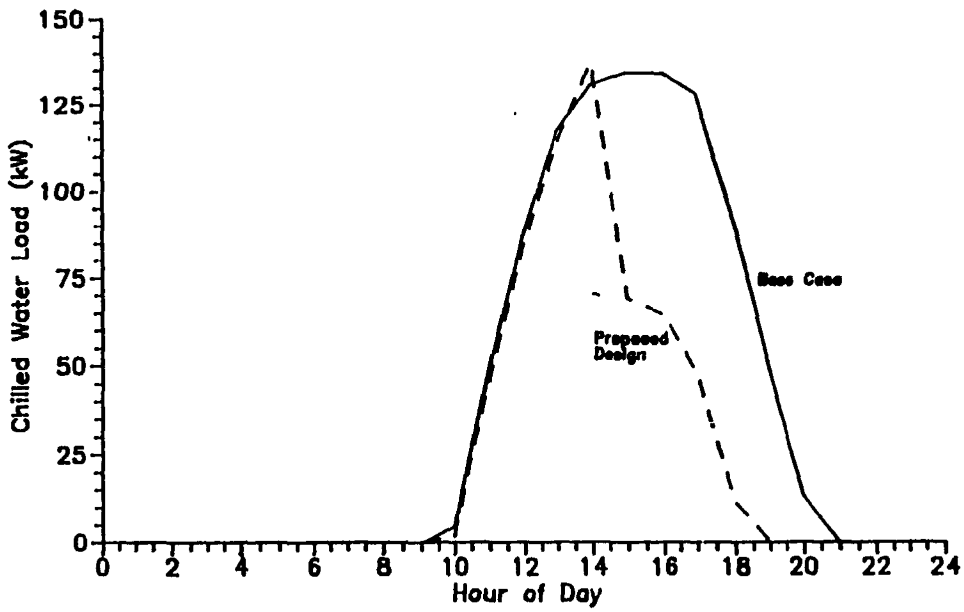

Figure 3.23 Interior zone chilled water load for an average summer day.
Base Case: Peak=134.5kW, Total=941.1kWh,
Proposed Design: Peak=137.2kW, Total=578.0kWh.

The daily chilled water use profile for the base case and proposed design demonstrate a 67 and 69% reduction in chilled water consumption in order to maintain the space temperature for an average summer day as compared to a hot summer day (Fig. 3.18).

Furthermore, peak loads for the base case and proposed design are approximately 51 and 47% lower on an average summer day as compared to a hot summer day.

Thermal sensation predictions for occupant response in the interior zone bv the TCM program for the base case and proposed design are illustrated in Figure 3.24. Thermal sensation responses to the base case temperature profile (assumed to be constant from 08:00 - 18:00 hrs) are well within acceptable comfort limits (0.28). Occupant response to the proposed design are also quite acceptable (0.48) before the permitted temperature drift. The predicted thermal sensation of the building occupants by the TCM program to the allowed temperature drift remained within acceptable limits (80%) at about a 0.95 discomfort level (Fig. 3.24).

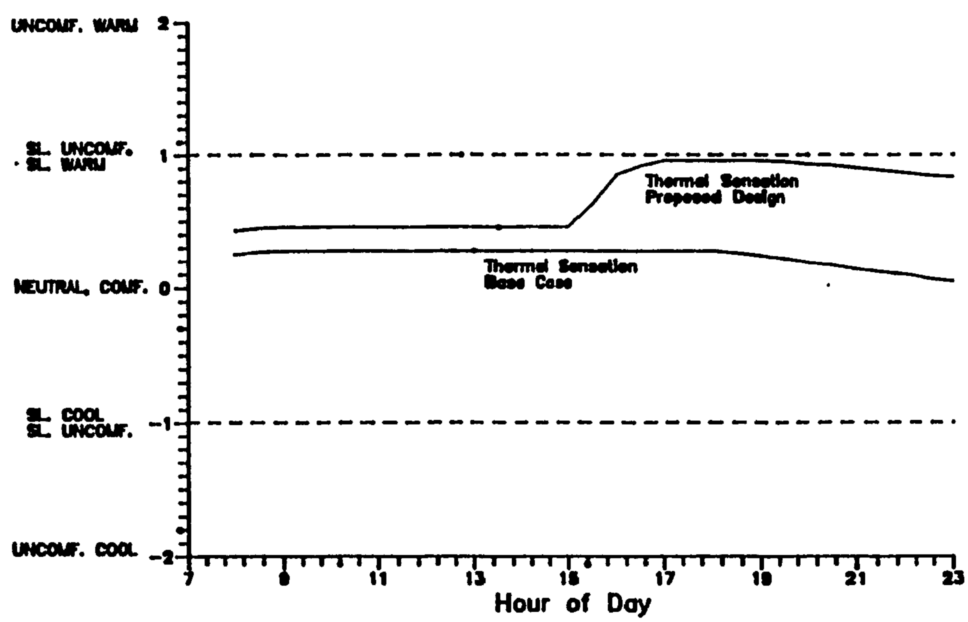

Figure 3.24 **Predicted thermal sensation response of building occupants in the interior zone for an average summer day.**

Discomfort predictions to the ambient environment indicate more favourable responses to the base case and the proposed design (Fig. 3.25). The discomfort level for the base case is about 0.18 from 08:00 to 18:00 hours, followed by a slight decrease in the magnitude of the discomfort level owing to the drop in space temperature after 18:00 hours. The discomfort level for the proposed design increased from 0.29 before the temperature drift to 0.60 following the temperature drift.

The pattern of predicted thermal sensation and discomfort responses to the base case and the proposed design showed little difference between average and hot summer days. Predictions by the TCM program for thermal sensation and

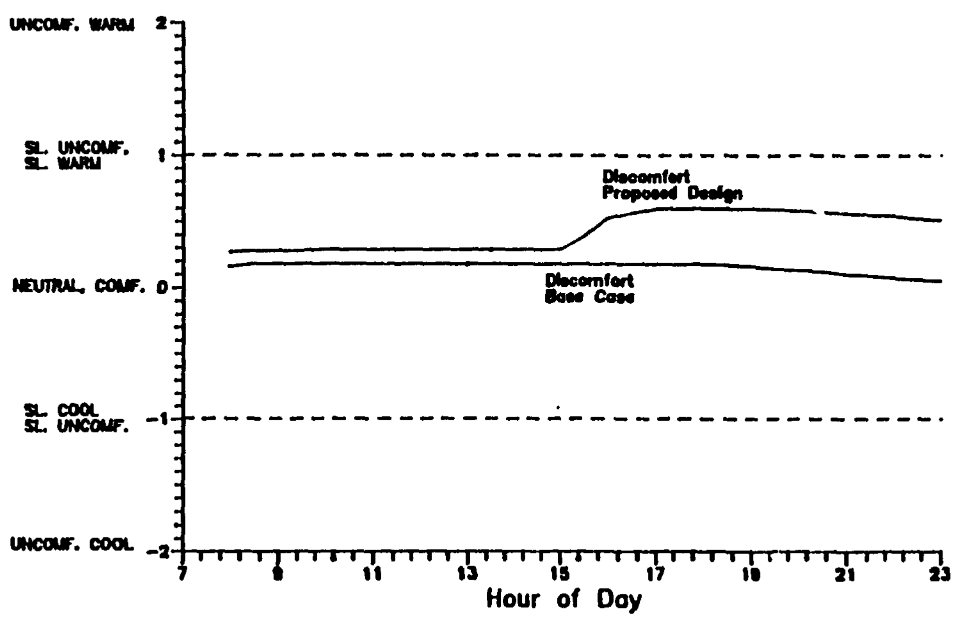

Figure 3.25 **Predicted discomfort response of building occupants in the interior zone for an average summer day.**

discomfort level responses in the interior zone were generally displaced slightly to the warmer region for a hot summer day.

3.6.2 Summer Analysis of Chilled Water Consumption

In this section, the analysis is now carried out for an entire summer season (June 1st to September 31st) to evaluate the peak demand and chilled water consumption.

The average monthly peak demand (Fig. 3.26) is reduced by 2.0 to 7%, when the temperature in the space is allowed to drift within thermally acceptable limits. The energy consumption for chilled water is reduced by 34 to 40% (Fig. 3.27).

Although one of the objectives in this study was to determine the potential for energy conservation during the cooling season for interior zones, perimeter zones also demonstrated significant reductions in chilled water use for the daily and monthly cooling periods of the proposed design.

Table 3.4 displays the space load for a perimeter zone facing west and the chilled water load for all perimeter zones during an average summer day.

Peak chilled water demand for the perimeter zones during the summer months is illustrated in Figure 3.28. It is interesting to observe for two of the summer months (June & August), the peak demand partially increased.

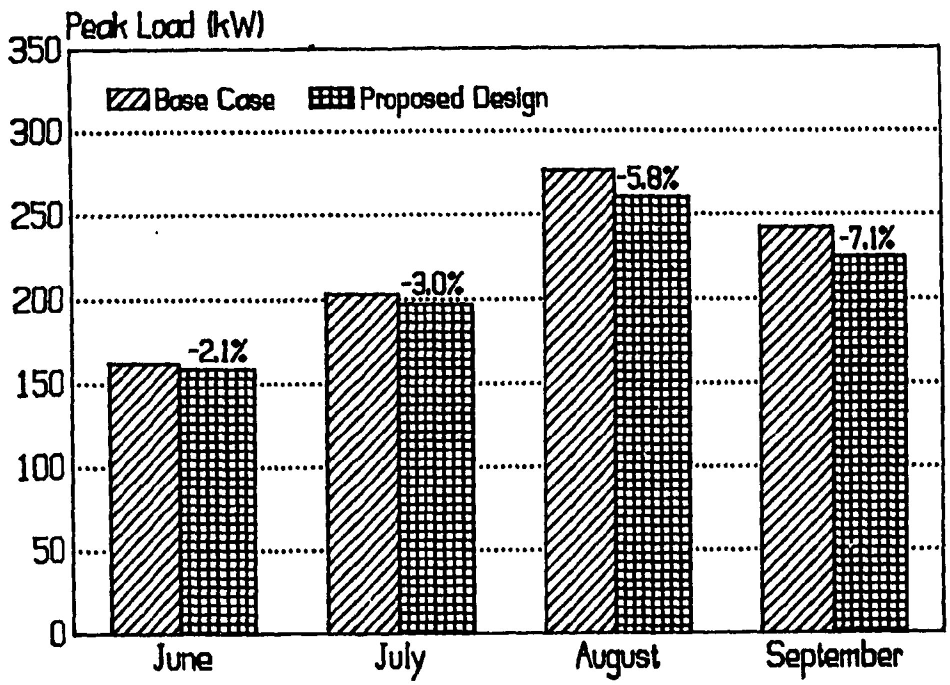

Figure 3.26 **Monthly Peak Chilled Water Demand for Interior Zones**

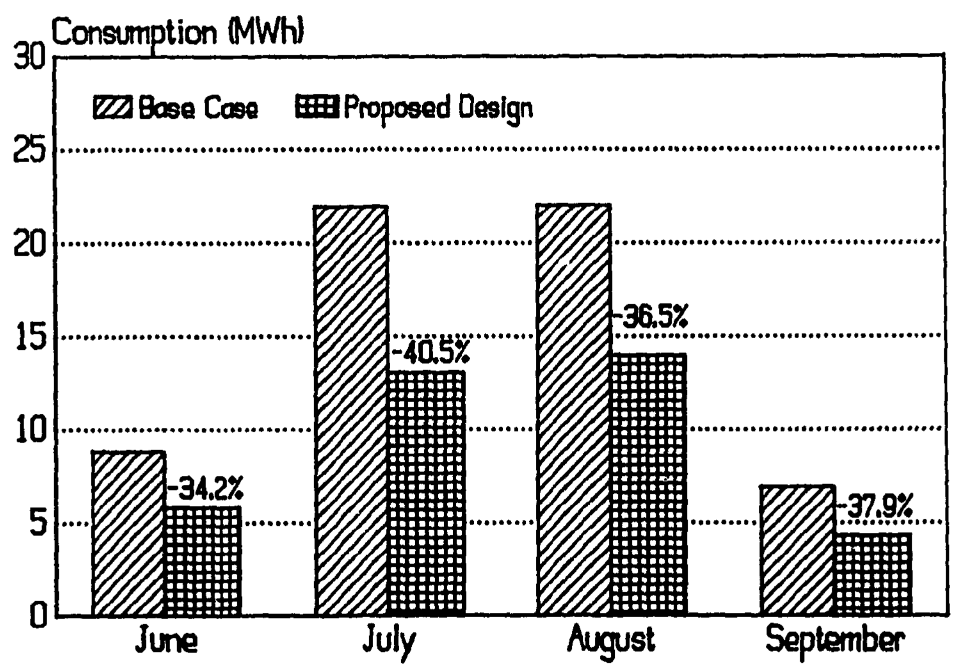

Figure 3.27 **Monthly Chilled Water Consumption for Interior Zones**

Table 3.4 Loads for perimeter zone in the reference building

	Base Case	Proposed Design	Percent Difference
Space Load			
Peak (kW)	8.088	6.335	-21.7
Total (kWh)	82.760	76.380	-7.7
Chilled Water Load			
Peak (kW)	339.7	342.6	+0.8
Total (kWh)	3512.0	2580.0	-26.5

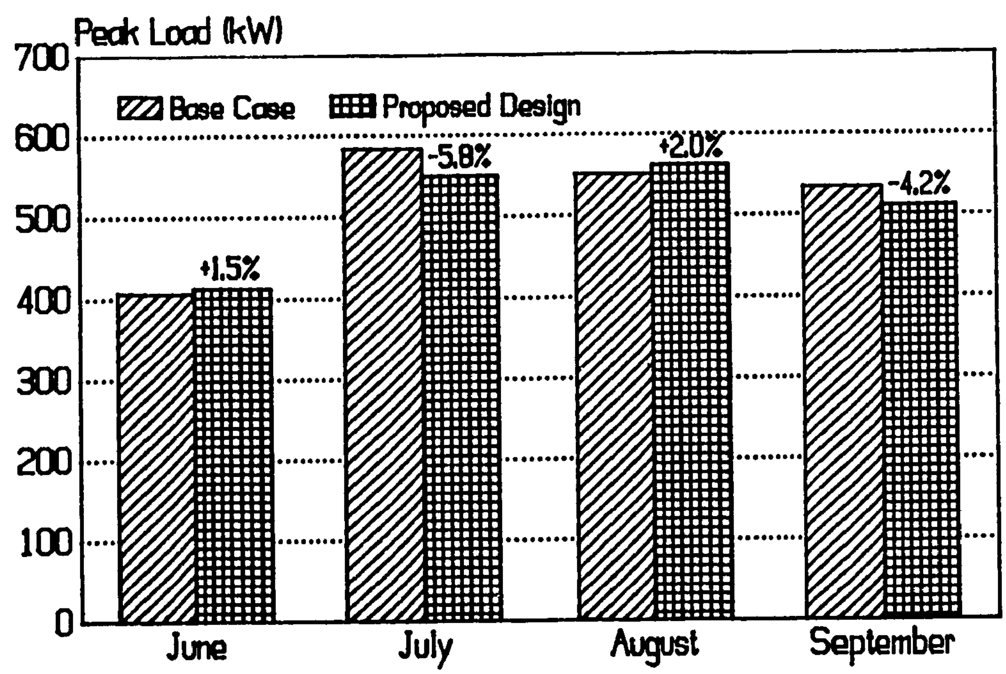

Figure 3.28 Monthly peak chilled water demand for perimeter zones

This may be attributed to the following reasons:

1) the overnight space temperatures in the perimeter zones are higher for the proposed design, and

2) several of the perimeter zones encounter peak demands early in the morning.

Since the proposed design is intended to reduce the peak chilled water demand in the late afternoon (after 15:00 hrs) for perimeter zones, the combination of the previously mentioned possibilities would produce a slightly larger peak demand on the system during the early morning hours.

The monthly chilled water consumption for the summer period is reduced by 20 to 26% for the proposed design as compared to the base case for perimeter zones in Figure 3.29.

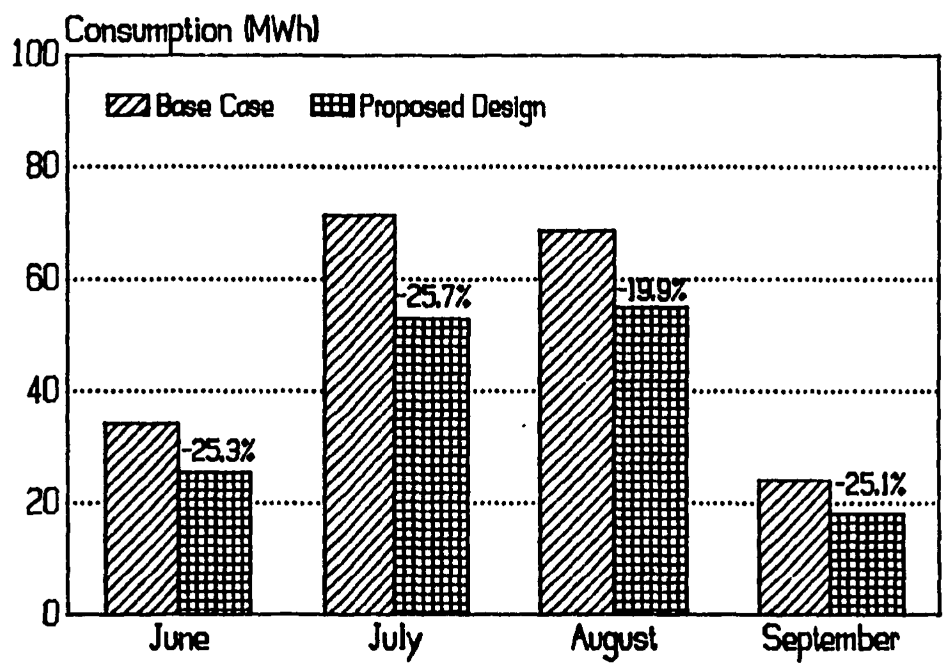

Figure 3.29 Monthly chilled water consumption for perimeter zones

3.6.3 Energy Consumption

Table 3.5 specifies the energy consumption for total heating (hot water use), total cooling (chilled water use), and electricity during the four month summer season for the base case and the proposed design of the reference building.

Table 3.5 Seasonal energy consumption per component

System Load	Base Case	Proposed Design	Difference
Heating (kWh)			
Perimeter	4 379	8 727	+ 4 348
Interior	44	338	+ 294
Cooling (kWh)			
Perimeter	198 300	151 600	- 46 700
Interior	59 700	37 150	- 22 550
Electricity (kWh)			
Perimeter	124 700	126 500	+ 1 800
Interior	136 700	141 900	+ 5 200
Energy Budget for All Systems (kWh/m^2)	58.28	51.89	- 11.0%

As indicated in the previous section, the cooling load for the perimeter and interior zones is substantially reduced with the allowed temperature drift for the proposed design in the reference building.

Electrical consumption increased approximately 2.7% for the proposed design. Since the HVAC system in the proposed design was scheduled to start 2 hours earlier than the base case, the fans would consequently operate for a longer period of time, thus increasing electrical use.

The energy to run auxiliary equipment for the perimeter and interior zones increased with the proposed design, which in turn increased the electrical consumption.

3.6.4 Improper HVAC Design will increase Energy Consumption

BLAST simulations also demonstrated proper control of the HVAC system is necessary to achieve actual energy savings. Results which indicate space cooling load savings during an accepted temperature drift or ramp does not necessarily indicate energy savings in large office buildings. In some circumstances if the temperature in the space is allowed to drift, chilled water demand and consumption may increase since the HVAC system is not appropriately designed for this conservation measure.

For example, the proposed design indicated a reduction in space cooling load (Fig. 3.17), when the ambient temperature was allowed to drift after 15:00 hours (Fig. 3.16) during a hot summer day. Correspondingly, for the same period of time, chilled water consumption also decreased (Fig. 3.18) as compared to the base case.

If however, the discriminator control (which resets the cold deck temperature) for the HVAC system is replaced by a fixed set-point control then the chilled water demand and consumption will increase for the proposed design (Fig. 3.30), although temperature and space load profiles will remain the same as in Figures 3.16 and 3.17.

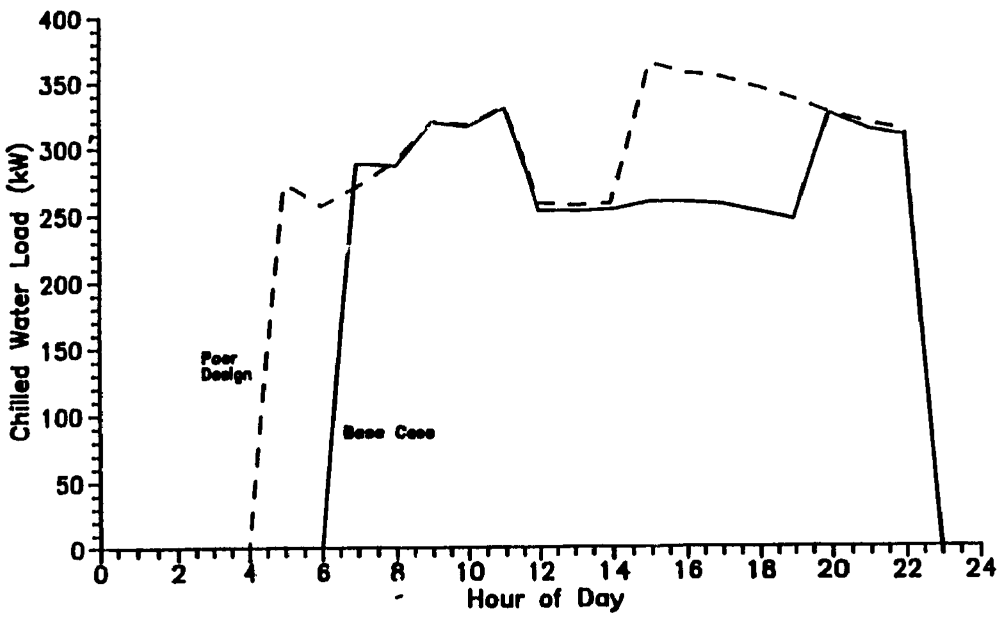

Figure 3.30 **Interior zone chilled water load for poor HVAC design for a hot summer day.**
Base Case: Peak=329.8 kW, Total=4511 kWh
Poor Design: Peak=363.9 kW, Total=5537 kWh

Chilled water consumption for the inappropriately designed HVAC system increased by 22% while peak demand increased 10%, as compared to the base case during the allowed temperature drift (15:00 -23:00 hrs) on a hot summer day.

Similarly, for an average summer day, chilled water consumption increased for the proposed design over the base case for an inappropriately designed HVAC system (Fig. 3.31). Space temperatures and cooling loads for this design are identical to Figures 3.21 and 3.22. As previously indicated in Figure 3.22, the space cooling load decreased during the allowed temperature drift for the proposed design as compared to the base case.

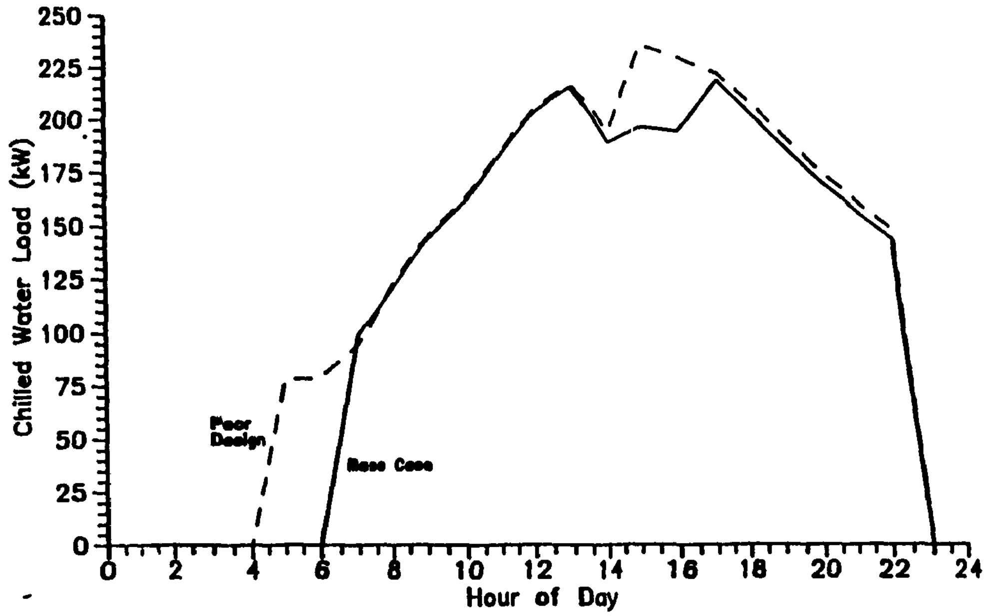

Figure 3.31 **Interior zone chilled water load for poor HVAC Design for an average summer day.**
Base Case: Peak=218.8 kW, Total=2786 kWh
Poor Design: Peak=236.1 kW, Total=3053 kWh

However due to the improper HVAC system design, chilled water consumption increased 6.9% and peak demand increased 7.9% when the temperature was permitted to increase in the space after 15:00 hours .

3.7 CONCLUSIONS

For purposes of energy and cost savings, it is sometimes necessary to control environments to conditions that deviate from those of optimum comfort but are still acceptable to a majority of occupants.

A Transient Comfort Model (TCM) micro-computer program was developed based primarily on algorithms presented by

ASHRAE Fundamentals and also other publications to predict the thermal sensations and discomfort levels of building occupants. The findings indicate with faster rates of temperature change (i.e. 1.0, 1.5, and 2.0 °C/hr) the acceptable deviations from neutral to slightly cool and warm sensations are larger than a steady-state and 0.5°C/hr rate of temperature change.

Application of acceptable temperature drifts as a mode of energy conservation in office buildings in Montréal confirmed the potential for significant energy savings. Permitting the temperature to increase in the space by 2°C in summer after a certain specified time, reduced the chilled water consumption for interior zones during the summer cooling season by approximately 38% and the monthly peak loads an average 4.5%.

Further simulations revealed space cooling load savings due to a temperature drift or ramp does not necessarily indicate actual energy conservation. Modifications to the HVAC system control is necessary to achieve real energy savings. For one such circumstance, analysis of an applied temperature drift for an improperly designed HVAC system increased the system's peak cooling demand and total consumption by 10 and 22%, while the space cooling load was presented to decrease for the same period of time.

CHAPTER 4

ANALYSIS OF ENERGY-EFFICIENCY OF HVAC SYSTEMS USED IN OFFICE BUILDINGS

4.1 INTRODUCTION

Many buildings have the potential for energy savings through various energy conservation measures. However, the energy consumption of a building is a complex function of numerous interrelated processes and is therefore difficult to determine the conservation measures that are most effective to a building. In the design of an energy conscious building, the most accurate means of evaluating the effect of the various factors on the energy performance is the computer simulation of the building, its occupancy, systems and components.

Computer modelling enables the designer to compare the products performance with target values in terms of cost and energy. Modelling further evaluates the potential of energy savings and tests the sensitivity of energy consumption to specific energy conservation measures. Once these conservation measures are evaluated, the selection of the most appropriate design strategies are implemented to optimize energy consumption and cost.

Cleary and Schuldt [59] determined the optimal thermal performance of several energy conservation measures for two office buildings located in Seattle. The DOE2.1B computer simulation program performed an analysis of several energy conservation measures. The approved measures were then implemented into the actual buildings, and later the predicted energy savings were compared with actual savings (Table 4.1). They found small differences and suggested they are mainly due to building schedules which did not conform to the averages used in the simulations.

Table 4.1 Comparison of predicted versus actual energy retrofit [59]

	Consumption before retrofit kWh/m^2 yr	Saving after conservation retrofit	
		Predicted	Actual
Building 1			
Lighting	134.7	45%	44%
HVAC	69.4	9%	9%
Building 2			
Lighting	75.4	32%	21%
HVAC	66.2	33%	29%

Nall and Crawley [60] mentioned that among the major energy related decisions that are made during the schematic design phase of an office building is the selection of the type of mechanical systems. Using a building energy simulation program, they compared the energy performance of several HVAC system alternatives in Cleveland (Table 4.2). Based on the annual energy efficiency of the various HVAC systems, Nall and Crawley concluded a VAV induction system providing air for the interior spaces and a 4-pipe fancoil system along the perimeter zones (alternative 3) along with double bundled chiller, demonstrated to have the best annual

Table 4.2 HVAC system: Comparison of energy efficiency [60]

HVAC System	Consumption kWh/m^2 yr	Percent Difference
Alternative 1: Int - VAV induction, Ext - 4 pipe fancoil, gas boiler, centrifugal chiller	176.3	---
Alternative 2: Int - VAV induction, Ext - VAV with baseboard heat, gas boiler, open drive centrifugal chiller	185.6	5.3%
Alternative 3: Int - VAV induction, Ext - 4 pipe fancoil system, gas boiler, double bundled chiller	167.4	-5.0%
Alternative 4: Carrier dual conduit system, Int - VAV Ext - Constant volume outside temperature reset, gas boiler, centrifugal chiller	191.2	8.4%
Alternative 5: Constant volume reheat system, gas boiler, double bundled chiller	306.2	73.7%

energy performance for an office building.

A research project conducted by Battelle Pacific Northwest Laboratories [61], investigated some key design strategies which contribute to substantial reductions in the annual energy consumptions in 22 large and small office buildings in the United States. The design effort concentrated on optimizing thermal gains and losses through building orientation, surface-to-volume ratio, envelope and lighting. Nearly all the redesigns reduced the lighting capacity, and installed more energy efficient HVAC systems. Variable air volume systems and heat pumps were placed in large and small office buildings respectively. Redesigns of small office buildings indicated a 50% average reduction in annual energy use and an average 42% annual energy savings in larger office buildings.

Bourassa et al. [4] performed the simulation of four existing representative office buildings in Canada using the Meriwether ESA computer programs. Results of the various simulations indicated reductions of 44 to 50% were obtained through the application of "No Cost" energy conservation measures. Application of "Minor Cost" redesigns provided further savings leading to a total savings in the order of 60% of the overall annual energy consumption.

Jordan [62] compared the energy consumption of central air-handling units with that of individual units located on each floor. The comparison, which was performed using DOE and TRACE programs, involved office buildings with variable air volume systems. Their findings suggested central systems consume less energy (0.7 to 17.9%) than local systems.

The objectives of this chapter are:

- to evaluate the design energy performance of office buildings in Montréal following ASHRAE Standard 90.1,

- to evaluate different energy conservation measures adopted to these buildings,
- to improve the energy performance of the reference building.

While there are numerous energy saving opportunities to optimize an office building's energy performance and cost, it is beyond the scope of this research to present all possible energy conservation measures.

4.2 BUILDING ENERGY SYSTEMS ANALYSIS

The Buildings Energy Systems Analysis (BESA) program developed by Public Works Canada is used to evaluate the energy performance of the reference building. The program can assist architects and engineers simulate buildings with up to 25 zones, served by up to 5 secondary systems. The program supplies to the designer a selection from 52 energy conservation measures (ECM's) in order to evaluate the potential reduction of energy use and operating cost. Optimization of 13 design ECM's is further provided through use of parametric analysis, which enables the designer to determine the sensitivity of building energy and loads to changes in the particular conservation measure.

4.2.1 Algorithms for Peak Zone Loads

Peak zone loads are determined from the design weather data for 24 hours of a typical day of each month of the year.

Peak heating load

Peak heating loads are calculated from the sum of the following heating load components [63]:

i) Heat flow through the building envelope

$$q = UA\,(T_O - T_S)$$

where:

- q = heating load due to transmission, W
- U = overall heat transfer coefficient, $W/m^{2\circ}C$
- A = surface area of envelope, m^2
- T_O = outdoor design temperature, $^{\circ}C$
- T_S = space heating set-point temperature, $^{\circ}C$

ii) Heat flow through floors

$$q = UA\,(T_O - T_S)$$

where:

- q = above-grade floor load, W
- U = above-grade floor U-value, $W/m^{2\circ}C$

and,

$$q = P \cdot LF$$

where:

- q = on-grade floor load, W
- P = surface area, m^2
- LF = heat loss factor, W/m^2

iii) Infiltration Loads

$$q_{sens} = \dot{m} c_p\,(T_o - T_s)\,F$$

$$q_{lat} = \dot{m} h_v\,(W_o - W_s)\,F$$

where:

q_{sens} = sensible infiltration load, W
q_{lat} = latent infiltration load, W
$\dot{m}$ = mass flow rate, kg/s
c_p = specific heat of air, J/kg°C
h_v = latent heat of vaporization, J/kg
W_o = humidity ratio of outdoor air
W_s = humidity ratio of indoor air
F = monthly infiltration factor

Peak cooling load

The CLTD method is used to determine zone cooling loads. The peak zone cooling load is the maximum of the total hourly loads calculated from the sum of the following heat flows [63]:

i) heat flow through building envelope

$$q = UA \cdot CLTD \cdot f$$

where:

q = cooling load due to transmission, W
U = heat transfer coefficient, $W/m^2 {}^\circ C$
A = surface area, m^2
$CLTD$ = cooling load temperature difference, °C
f = ventilation factor

ii) Heat flow through floor

$$q = UA\,(T_O - T_R)$$

where:

q = cooling load through floor, W
T_O = outdoor temperature, °C
T_R = cooling set-point temperature, °C

iii) Infiltration loads

$$q_{sens} = \dot{m} c_p (T_O - T_R) F$$

$$q_{lat} = \dot{m} h_v (W_O - W_R) F$$

where:

q_{sens} = sensible infiltration load, W
q_{lat} = latent infiltration load, W
$\dot{m}$ = mass flow rate, kg/s
c_p = specific heat of air, J/kg°C
h_v = latent heat of vaporization, J/kg
W_o = humidity ratio of outdoor air
W_R = humidity ratio of indoor air
F = monthly infiltration factor

iv) Solar Heat Gains

$$q = A_G \cdot MSHFG \cdot CLF \cdot SC \cdot SLT$$

where:

q = solar heat gains, W
A_G = glazing area, m^2
MSHGF = maximum solar heat gain factor, W/m^2
CLF = cooling load factor
SC = shading coefficient
SLT = sunlit ratio

v) Heat flow between zones

$$q = UA (T_A - T_R)$$

where:

q = heat flow through internal partitions, W
U = overall heat transfer coefficient of partition, $W/m^2{}^\circ C$
A = surface area of partition, m^2
T_A = average temperature of adjacent space, °C
T_R = cooling set-point temperature, °C

vi) Internal heat gains

- People

$$q_{sens} = N_P \cdot Q_s \cdot CLF_P \cdot F_P$$

$$q_{lat} = N_P \cdot Q_l \cdot F_P$$

- Lights

$$q = BF \cdot Q_L \cdot CLF_L \cdot F_L$$

- Equipment

$$q = Q_E \cdot CLF_E \cdot F_E$$

where:

N_P = number of people
Q_s, Q_l = sensible and latent heat gain per person, W
Q_L = lighting level, W/m^2
Q_E = equipment load level, W/m^2
CLF = cooling load factors for people, lights and equipment
BF = ballast factor
F = part usage factor of people, lights and equipment for each hour

4.2.2 Annual Energy Consumption

The annual energy consumption is determined as follows [63]:

$$E = \frac{1}{1000} \sum_{m=1}^{12} \sum_{sb}^{eb} (q_O h_O + q_U h_U)$$

where:

E = annual energy consumption, kWh
q_O = plant diversified loads during occupied period, W
h_O = number of hours of occurrence of each temperature bin, during the occupied hours
q_U = plant diversified loads during unoccupied period, W
h_U = number of hours of occurrence of each temperature bin, during the unoccupied hours

$\sum_{sb}^{eb}$ = summation from starting bin (sb) to ending bin (eb) over all temperatures

$\sum_{m=1}^{12}$ = summation over all months of the year

4.3 REFERENCE BUILDING

The base case reference building which is designed in accordance with the Energy Cost Budget Method [20], and the Québec law concerning energy conservation in new buildings [19] is similar to the building presented in chapter 2 with only minor modifications to the HVAC system.

4.3.1 Building Description

A general description of the reference building is outlined below:

Orientation and Shape

- The reference building is 10 stories high with dimensions 30m by 30m (total floor area = 9000 m^2).

Thermal Zones

- One interior and four perimeter zones are defined for each floor of the reference building (Fig. 4.2) [20].

Internal Loads

- Occupancy = 7 people / 100 m^2 [64]
- Lighting = 22 W/m^2 [19].
- Equipment = 8 W/m^2 [20].

- Schedules for occupancy, lighting and equipment are similar to schedules previously presented in section 2.4.1 for the reference building simulated by BLAST.

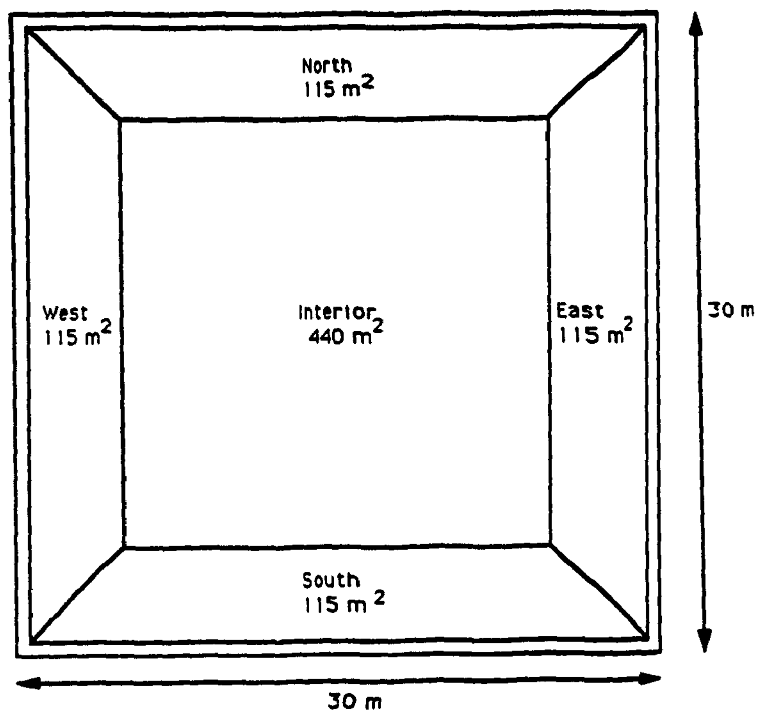

Figure 4.1 Zone description of reference building

<u>Building Envelope</u>

- Insulated spandrel glass wall construction with U=0.313 W/m^2°C.

- Flat masonry roof with built-up roofing with U=0.204 W/m^2°C.

- The solar absorptivity of opaque walls and roof is 0.70, and the ground reflectivity is 0.20 [20].

- Double-glazed windows with U=2.22 W/m^2°C, and shading coefficient of 0.60. Glazing to wall area ratio is 31%, obtained from 15% of gross floor area [19].

- Infiltration rate is 0.193 $L/s/m^2$ of the gross exterior wall [20]. Infiltration shall only occur for perimeter zones while the HVAC system is OFF.

HVAC Systems and Equipment

For the reference building, central VAV with perimeter reheat system is recommended [20].

- Two VAV systems are designed for the building:
  VAV 1 - serving floors 1 through 5,
  VAV 2 - serving floors 6 through 10.

- Operating hours: 7:00 to 23:00 hrs, weekdays.

- Ventilation rate = 10 L/s/person.

- Space heating temperature is set at 21.7 °C, space cooling temperature is set at 24 °C, and setback temperature is 13 °C.

- Centrifugal chiller with COP = 5.0.

- Hot water boiler using natural gas energy supply with a combined impeller and motor efficiency of 60%.

- Dry-bulb economizer system.

Energy Costs

Electrical rate structure for the whole year of the reference building is based on the general service rate structure (Rate "M") for office buildings in Montréal, in 1990 [65].

Demand Charges: 6.63 $/kW

Energy Charges:

	kWh	$/kWh
First	120	0.0488
Next	78000	0.0395
Balance		0.0255

Gas Prices [66] : 0.265 $\$/m^3$

Oil Prices [67] : 0.300 $/L

An initial simulation run is performed using the BESA program to:

a) verify the supply air flow rates at the design conditions according to ASHRAE Standards 90.1-1989 [20],

b) determine the minimum circulation air flow rates for VAV systems,

c) obtain heating and cooling plant loads to estimate auxiliary loads for the system (i.e. pumps), and

d) to determine the capacity and total pressure requirements of the supply and return fans,

ASHRAE Standard 90.1 [20] indicates, the minimum circulation air flow rate to a conditioned zone at design conditions for VAV systems shall be greater than 4.5 air changes per hour. Thus, initial peak supply air flow rates for North and interior zones are modified to comply with this criteria (Table 4.3).

During occupied hours, minimum circulation air flow rates for VAV systems must be conserved to ensure acceptable indoor air quality for the occupants. The minimum air flow rate for the separate zones shall be the maximum value of the following [20]:

$$\text{Minimum supply} = \max \begin{cases} 30\% \text{ maximum air supply} \\ 10 \;\; L/s/person \\ 2 \;\; L/s/m^2 \text{ floor area} \end{cases}$$

The minimum supply air flow rates for each zone is presented in BESA as a percentage of the peak supply rate to the corresponding zone (Table 4.3).

Table 4.3 Maximum and minimum supply air flow rates

Zones	initial BESA values		adopted values		Minimum / Maximum %
	L/s	ACH	L/s	ACH	
North	409	3.6	520	4.5	44
South	896	7.8	896	7.8	30
East	834	7.3	834	7.3	30
West	914	8.0	914	8.0	30
Interior	859	2.0	2000	4.5	30

Centrifugal fans are selected to circulate and evacuate conditioned air throughout the building. The supply and exhaust duct system layout for a typical floor in the reference building is illustrated in Figure 4.2.

The capacity of the supply or exhaust fans is determined from [68]:

$$FP = \frac{AFR * \Delta P}{\eta}$$

where:
- FP = fan power, in W
- AFR = supply or exhaust air flow rates, in L/s
- Δp = total pressure losses, in Pa
- η = efficiency of centrifugal fans, 70%

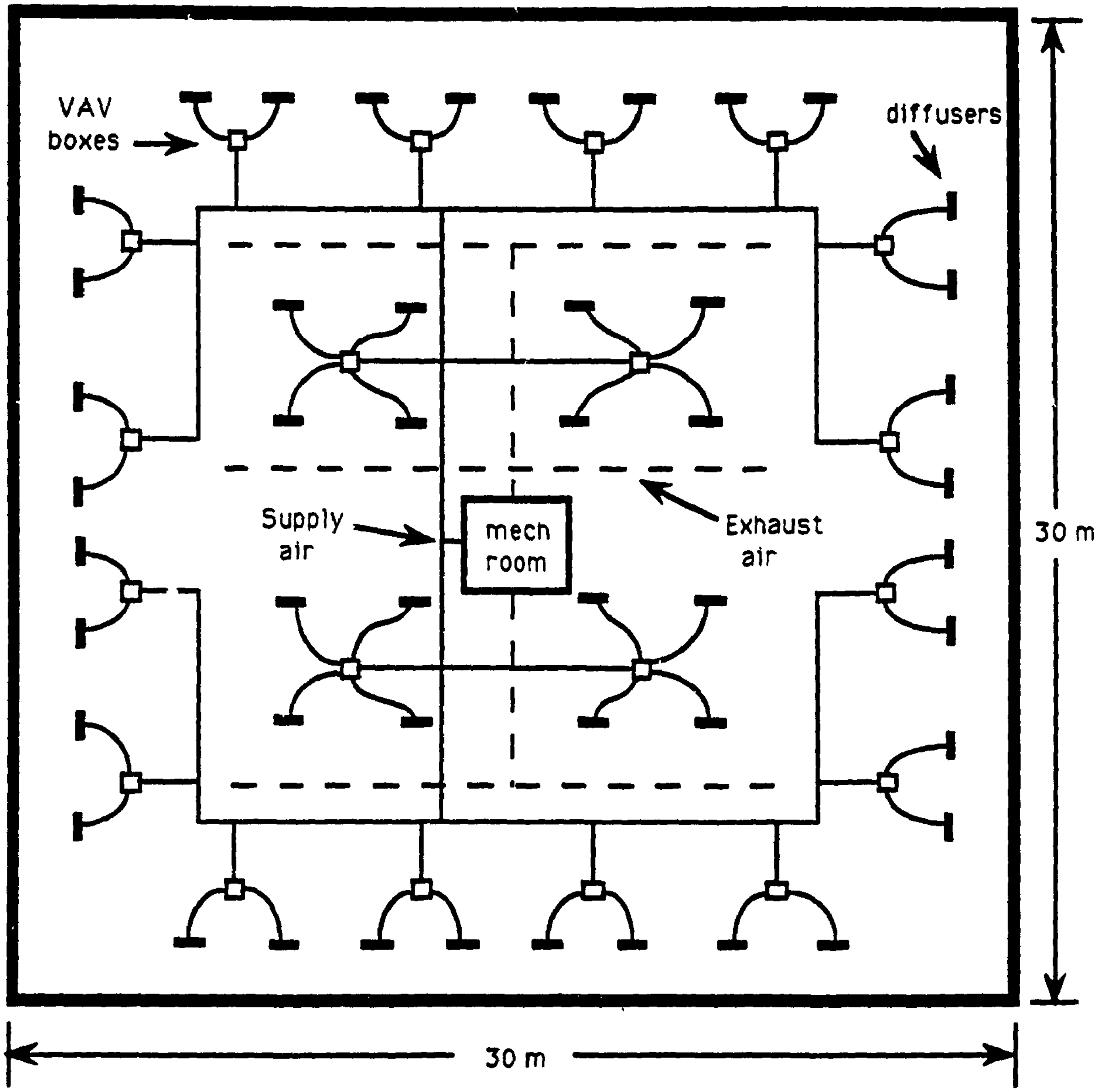

Figure 4.2 Duct system layout per floor of reference building

Total pressure losses for the supply and exhaust fans are estimated using the equal friction method (Table 4.4). With a known air flow rate, this method establishes the duct size and the lost pressure per unit length. The equal friction method is used extensively in design of low velocity duct systems since it gradually reduces the air velocity from fan to outlet, thereby reducing noise problems.

Table 4.4 System pressure losses and fan capacities

	Mechanical Room 1		Mechanical Room 2	
	Supply	Exhaust	Supply	Exhaust
Air Handling Units	1.813		1.570	
Main Shaft	0.177	0.400	0.077	0.402
Ducts	0.653	0.291	0.653	0.291
Total:				
inch of water	2.643	0.691	2.300	0.693
Pa	658	172	573	172
Fan Capacity:				
Hp	20.4	5.3	17.7	5.3
kW	15.2	4.0	13.3	4.0

Primary plant loads, that is the summation of loads of all cooling or heating coils, calculated by the program for the reference building are:

- Cooling plant load = 844.8 kW
- Heating plant load = 202.0 kW

The auxiliary loads for the primary plant are evaluated as follows [68]:

Chilled water pump:

$$FR = \frac{Q_{cool}}{4.19 \cdot \Delta T}$$

where:

- FR = water flow rate, in L/s
- Q_{cool} = cooling plant load, in kW
- ΔT = temperature rise, 6.7°C [20]

$$PP = \frac{FR \cdot \Delta P}{\eta}$$

where:

- PP = chilled water pump power, in W
- ΔP = head losses, in kPa
- η = combined impellar & motor efficiency, 65% [20]

Condenser water pump:

$$FR = \frac{Q_{cool}}{4.19 \cdot \Delta T}$$

where:

- ΔT = temperature rise, 5.5°C [20]

$$PP = \frac{FR \cdot \Delta P}{\eta}$$

where:

- PP = condenser water pump power, in W
- ΔP = head losses, in kPa
- η = combined impeller & motor efficiency, 60% [20]

Hot water pump:

$$FR = \frac{Q_{heat}}{4.19 \cdot \Delta T}$$

where:
- FR = water flow rate, in L/s
- Q_{heat} = heating plant load, in kW
- ΔT = temperature rise, 16.7°C [20]

$$PP = \frac{FR \cdot \Delta P}{\eta}$$

where:
- PP = hot water pump power, in W
- ΔP = head losses, in kPa
- η = combined impeller & motor efficiency, 60% [20]

4.3.2 Computer Simulation of the Reference Building

Table 4.5 lists the peak zone loads for the reference building as determined by BESA.

Table 4.5 Peak zone loads for reference building

Zone	Cooling kW	Heating kW
Intermediate:		
North	5	5
South	12	5
East	11	5
West	12	5
Interior	11	0
Top Floor:		
North	5	6
South	12	6
East	11	6
West	12	6
Interior	11	4

The yearly energy cost of the reference building (base case) determined by BESA is $\$8.66/m^2$ yr. Electrical consumption and demand represent 48 and 39% of the yearly operating cost, with 13% of the cost attributed to gas consumption.

The annual energy consumption for the building is 163.3 kWh/m^2 yr. The lighting systems consumed the largest portion of the yearly energy use (41%), followed by heating (33%), equipment (12%), cooling (7%), fans (4%) and auxiliary energy use (2%).

For comparison, the lowest annual energy use and cost found among the of 67 office buildings surveyed in Montréal (Chapter 1) was 251.4 kWh/m^2 and 9.14 $\$/m^2$. Thus, one can conclude either ASHRAE Standard 90.1-1989 is too conservative in its guidelines for energy efficient buildings, or the predicted energy performance given by BESA is low. Nall and Crawley [60] stated "... energy consumption estimates made with building simulation tools will tend to be low, if only because occasional lapses in standard operating procedures in the building will increase consumption. The simulation assumes that operating procedures are followed perfectly".

4.3.3 Initial Cost of HVAC System

Initial material and labour cost of the HVAC system of the reference building is estimated based on the Hanscomb catalogue [35] and the Means Mechanical Cost Data [69] (Table 4.6).

Table 4.6 Initial Cost of HVAC System

Component	Cost $
Central Air Handling Units roof & 6^{th} floor	53 800
Supply & Exhaust ducts, louvers, dampers & insulation	318 400
Control (VAV) Boxes, with reheat	75 500
Linear Slot Diffusers and Return Air Grilles	39 250
Gas fired hot water boiler, capacity 202 kW	98 700
Air Conditioning, chiller + cooling tower capacity 845 kW	822 000
Total	**1 407 650**
Total/floor area ($\$/m^2$)	**156.40**

For comparison, Hanscomb lists the initial cost of an HVAC system for a medium sized office building in Montréal to be 123.57 $\$/m^2$.

4.4 ENERGY CONSERVATION MEASURES

Energy conservation measures are alternatives applied to the existing building to reduce annual energy use and cost. To meet the objectives of this chapter, the following design procedures are followed to optimize the energy performance of the reference building:

1) Incremental Design Change Method:

When a designer uses this approach, he modifies the values of some parameters within the same HVAC system in order to improve the energy performance of the building. Some examples of building parameters may include, zone heating and cooling set-point temperatures, ventilation rates, and envelope thermal transmittance values.

2) Non-Incremental Design Change Method:

This approach proposes a totally new design of the initial building model, such as a different HVAC system.

The subsequent design parameters were considerably reduced or eliminated to determine the maximum variation of the energy performance that can be obtained for the reference building.

i) Thermal transmittance of building envelope:
U-wall (reduced from 0.313 to 0.06 $W/m^{2o}C$),
U-roof (0.204 → 0.06 $W/m^{2o}C$),
U-glaz (2.22 → 1.06 $W/m^{2o}C$)

ii) Air infiltration:
During unoccupied hours (0.183 → 0.0 ACH)

iii) Shading coefficient (0.6 → 0.0)

iv) Internal loads:
Lighting (22.0 → 0.0 W/m^2),
Equipment (8.0 → 0.0 W/m^2)

Elimination of internal loads produced the largest cost savings of 50.6% (Fig. 4.3). By comparison, improvement of the building envelope reduced the energy costs only 7.8%. Thus, the yearly energy costs for the reference building is dominated by internal loads and any improvement in the energy cost profile of the building should concentrate on minimizing these loads.

An analysis of the change in energy consumption with the elimination of the same parameters showed a different trend (Fig. 4.4). The largest reduction of the yearly energy consumption occurred when the overall U-value of the building envelope was improved and infiltration losses eliminated. This set of ECM's improved the original energy performance of the reference building by 22.2%. When the internal heat gains are eliminated, the energy savings are about 10.7%.

Since the final decision is based mainly on the energy cost as recommended by ASHRAE Standard 90.1-1989, Energy Cost Budget Method, the building envelope is considered to be well designed, and energy simulations are performed towards reducing internal heat gains and improving the performance of the HVAC system.

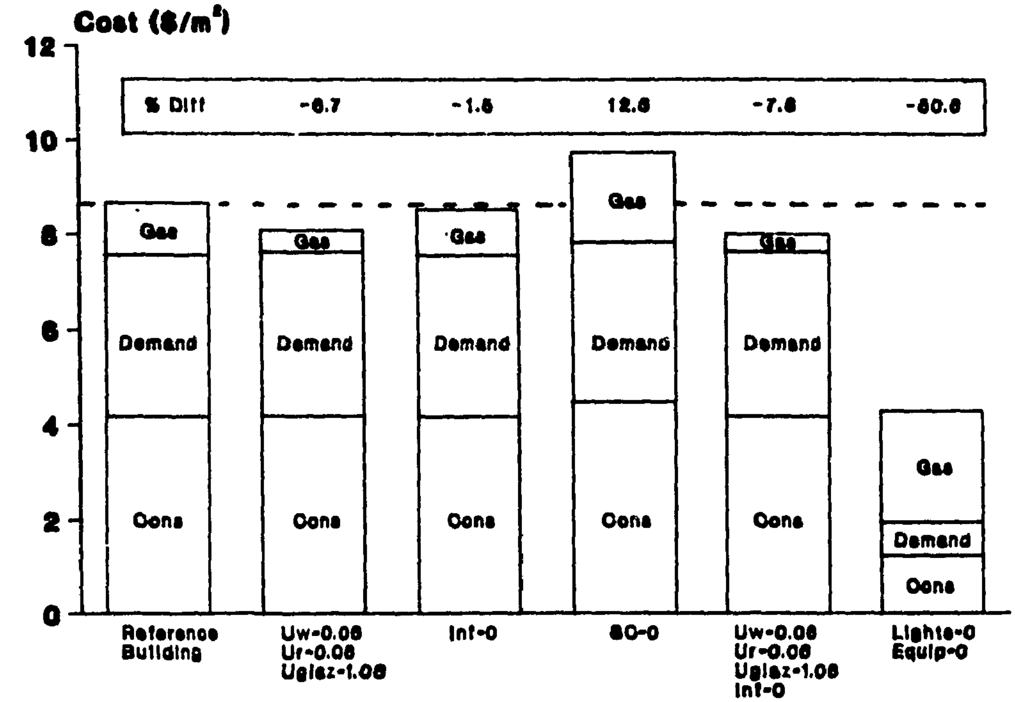

Figure 4.3 Yearly energy cost profiles for the reference building

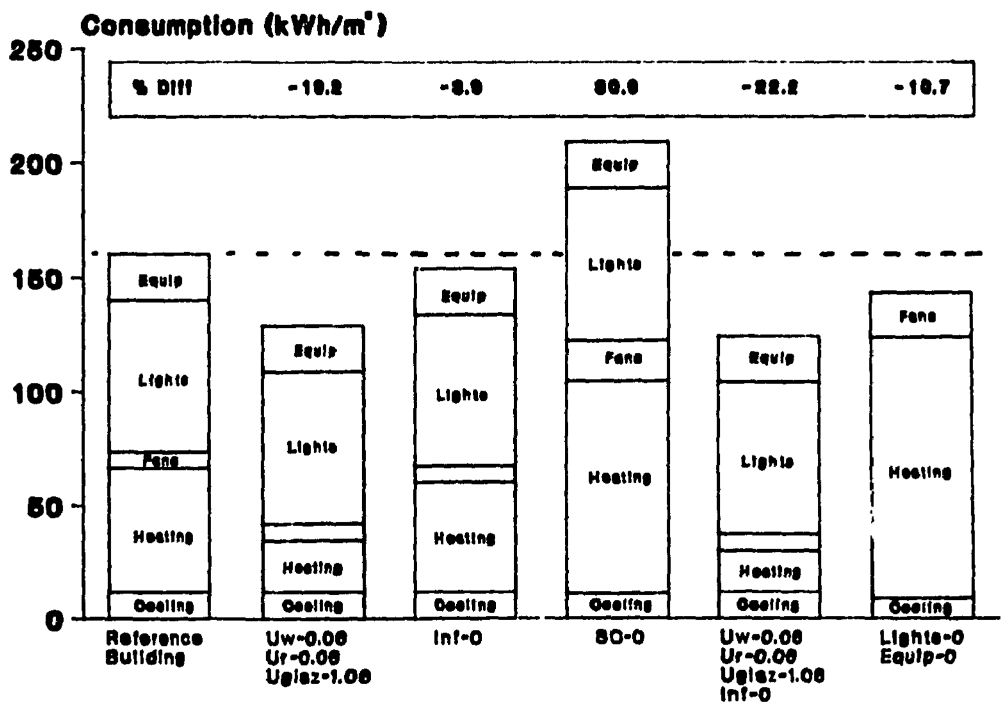

Figure 4.4 Yearly energy consumption profiles for the reference building

Figure 4.5 shows the reduction of the yearly operating cost for several energy conservation measures for the reference building. In order to examine the maximum cost savings of the central plant, the auxiliary loads are eliminated and a chiller COP value of 10 is simulated. This measure reduced the reference building operating costs by 7%, from 8.66 to 8.05 $\$/m^2$ yr. Measures to analyze the potential savings of the VAV systems included eliminating the fan loads and increasing the supply air temperature from 13°C to 18°C. Each of these measures separately reduced the yearly operating costs by 8 and 11% respectively.

For interest, the largest reduction in the annual energy consumption of the reference building for the same measures is observed when the supply air temperature is raised to 18°C (Fig. 4.6). Energy savings for this measure reduced the annual cooling load from 11.91 to 5.31 kWh/m^2 yr, and the annual heating load from 54.52 to 36.3 kWh/m^2 yr. The overall annual energy use decreased 16.8%, when the supply air temperature is raised by 5°C.

The energy source for the base case is electricity and natural gas. By using only electricity the yearly operating costs are increased from 8.66 to 9.35 $\$/m^2$ yr (Fig. 4.7). A combined electricity and oil supply raised operating costs to 9.07 $\$/m^2$ yr for the reference building.

As previously indicated, two VAV systems supply air in the reference building. System 1 supplies conditioned air to

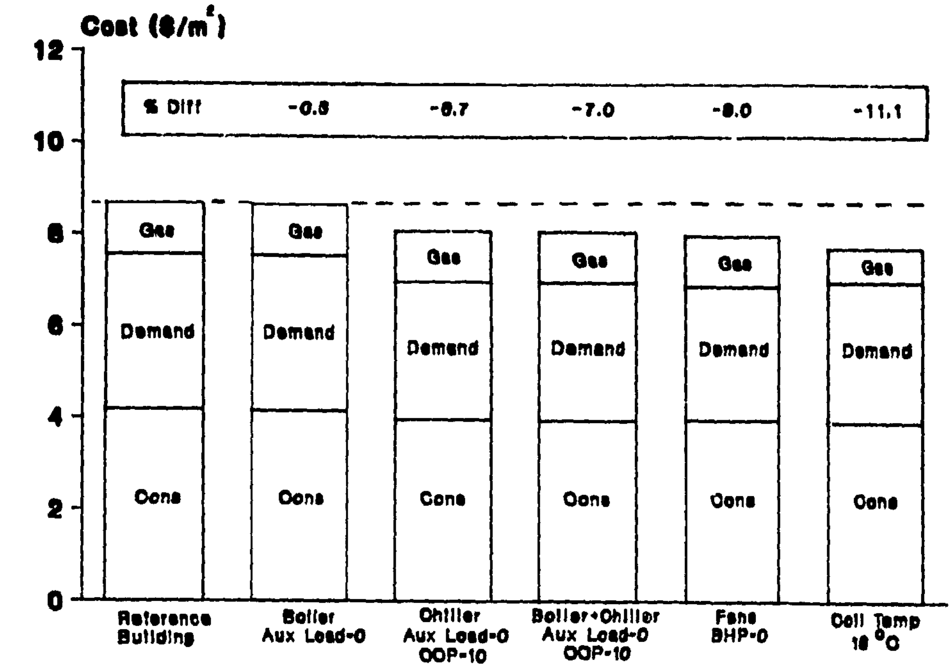

Figure 4.5 **Yearly energy cost profiles for reference building with VAV systems**

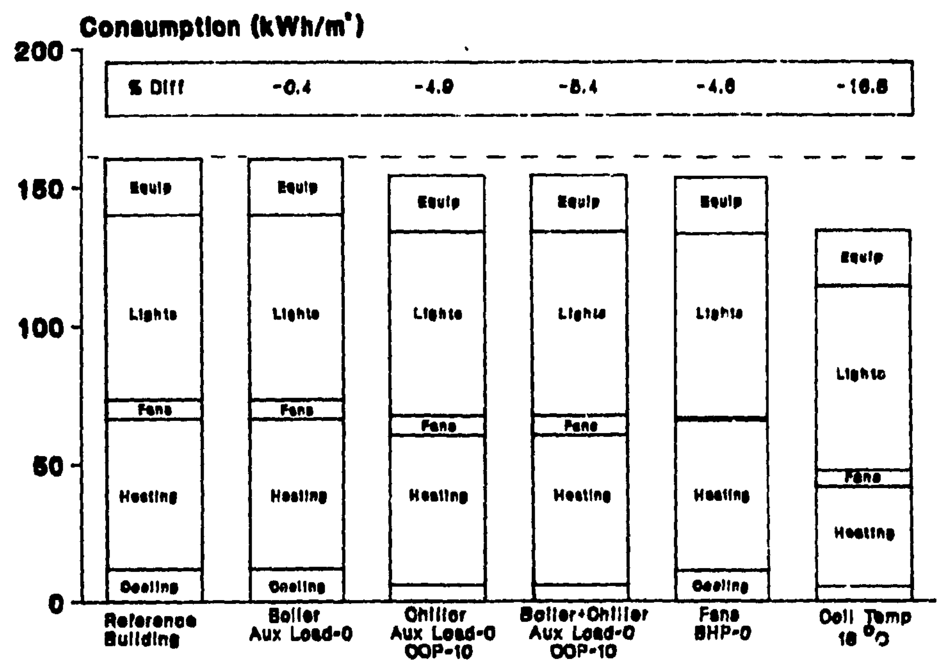

Figure 4.6 **Yearly energy consumption profiles for reference building with VAV systems**

floors 1 through 5, and system 2 supplies air to floor 6 through 10. An alternative arrangement is simulated by having one VAV system supplying air to the perimeter zones and one system supplying air to the interior zones. This design reduced yearly operating costs from 8.66 to 8.54 $\$/m^2$ yr (Fig. 4.7).

Multiple VAV systems to condition air for every two floors of the building slightly increased energy costs by 0.5%. Energy consumption profiles for the various VAV system designs are illustrated in Figure 4.8.

Non-incremental design changes such as locating induction units along the perimeter zones with a VAV system supplying air to the interior zones increased energy cost by 26.3% (Fig. 4.9), and energy consumption by 68.9% (Fig. 4.10). This arrangement considerably increased the heating energy consumption from 54.52 to 162.0 kWh/m^2 yr. Consequently, gas costs tripled from 1.11 to 3.30 $\$/m^2$ yr. ECM simulations for the induction/VAV arrangement such as eliminating auxiliary loads, increasing the chiller COP and supply temperature, still maintained energy costs by more than 20% over the initial reference building design.

Using electricity as a single source of energy for the induction/VAV arrangement increased operating costs by 67.2% over the reference building and 32.4% as compared to the induction/VAV system with electricity and gas energy supply. Similarly, an electricity and oil fuel supply for the

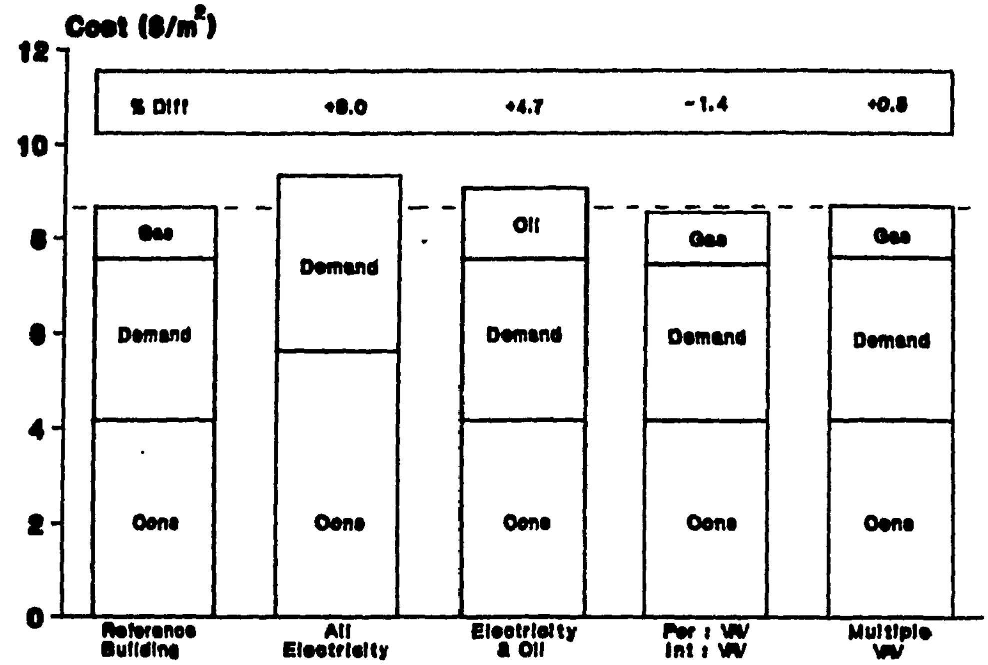

Figure 4.7 Yearly energy cost profiles for reference building with VAV systems

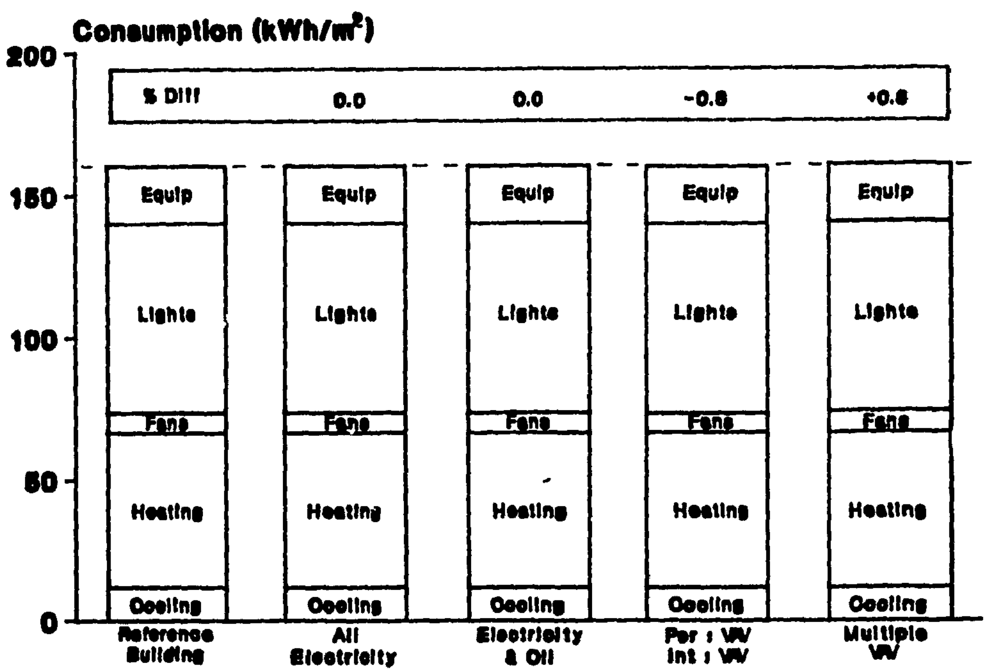

Figure 4.8 Yearly energy consumption profiles for reference building with VAV systems

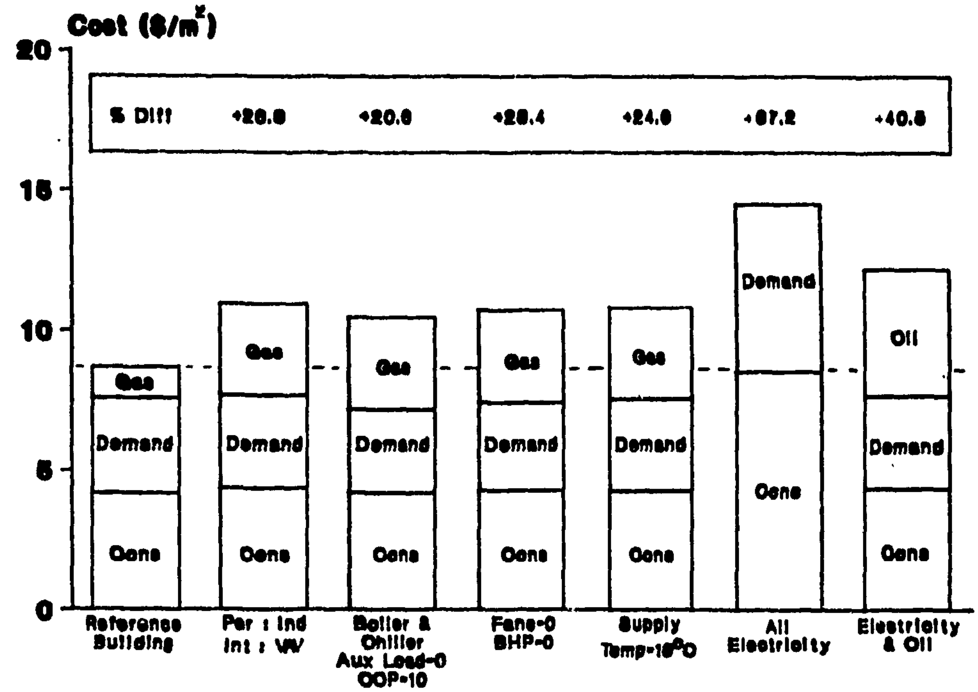

Figure 4.9 Yearly energy cost profiles for reference building with Induction & VAV systems

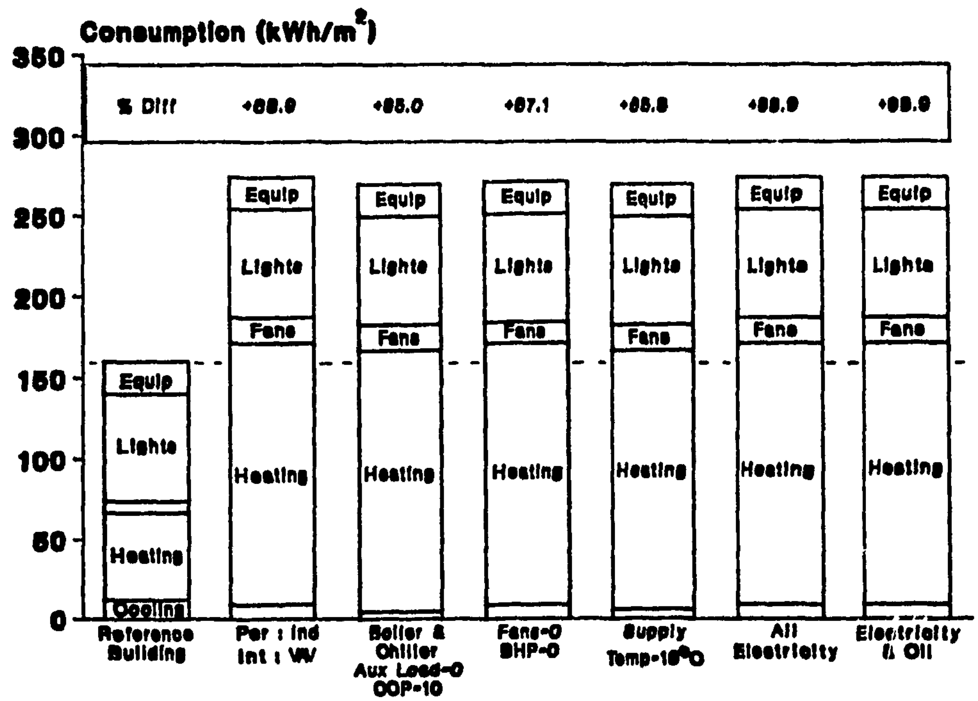

Figure 4.10 Yearly energy consumption profiles for reference building with Induction & VAV systems

induction/VAV arrangement raised operating costs 40.5% above the base case reference building.

Replacement of the VAV system in the reference building with a water loop heat pump increased electrical consumption, demand and gas consumption by a combined 42.5% annually (Fig. 4.11) as determined by BESA.

Elimination of the fan and pump loads, with a cooling and heating COP value of 10 for the heat pump system still managed to increase the energy costs by 7.7% (Fig. 4.12) as compared to the VAV system for the reference building. Removal of the preheat coil for the water loop heat pump system decreased energy cost by 4.9%, but remained 32.4% above the reference building. The operation of heat pumps during setback instead of the unitary electric heaters further increased consumption and demand costs by 5.8% over the initial heat pump design.

The annual energy consumption for the water loop heat pump illustrated in Figure 4.13 is 248.6 kWh/m^2 yr, 52.2% more than the reference building. The energy use of the water loop heat pump system without fan and pump loads, and a plant COP of 10 still remained 21.4% above the reference building (Fig. 4.14).

For comparison, a reverse cycle heat pump arrangement with booster in series has an annual operating cost of 10.23 \$/m^2 yr, or 18.1% above the reference building (Fig. 4.15) but 20.6% less than the water loop heat pump system. Various measures to improve the efficiency of the reverse cycle heat

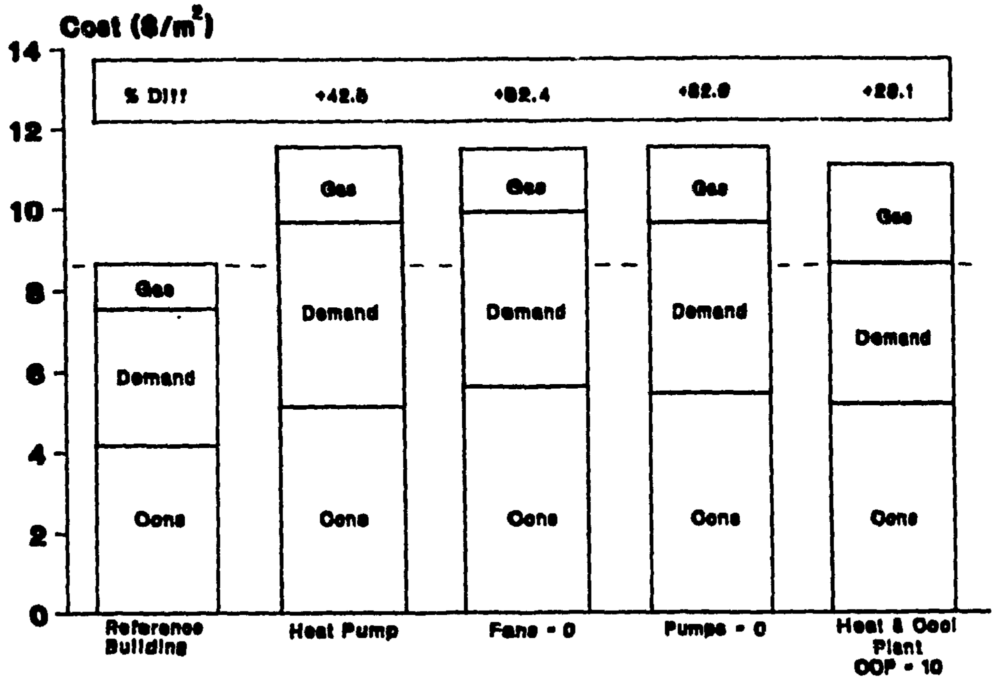

Figure 4.11 Yearly energy cost profiles for reference building with water loop heat pump system

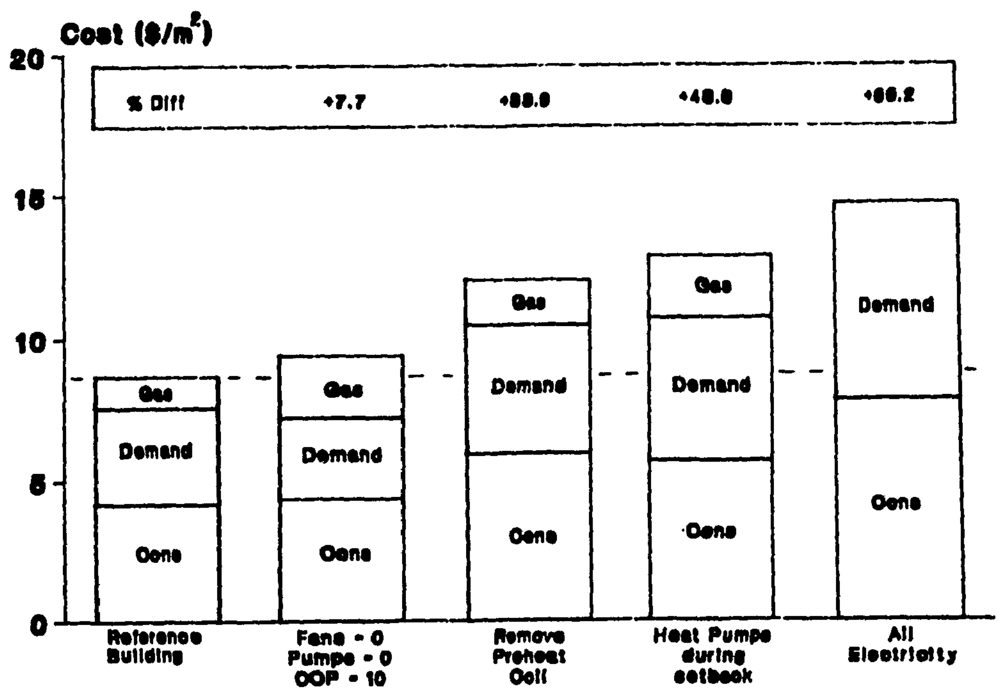

Figure 4.12 Yearly energy cost profiles for reference building with water loop heat pump system

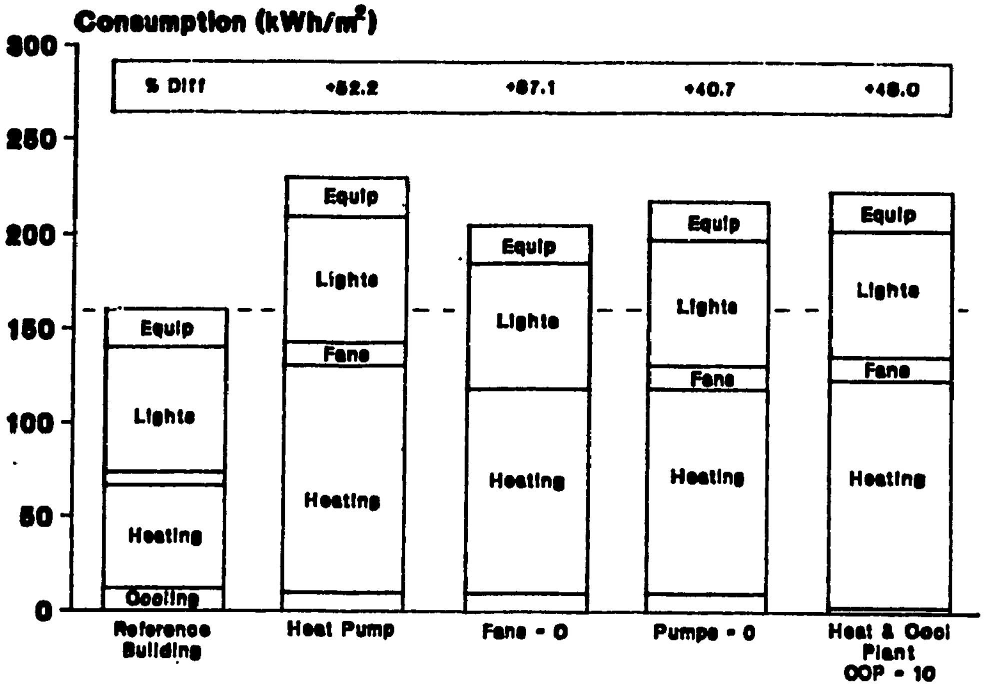

Figure 4.13 Yearly energy consumption profiles for reference building with water loop heat pump system

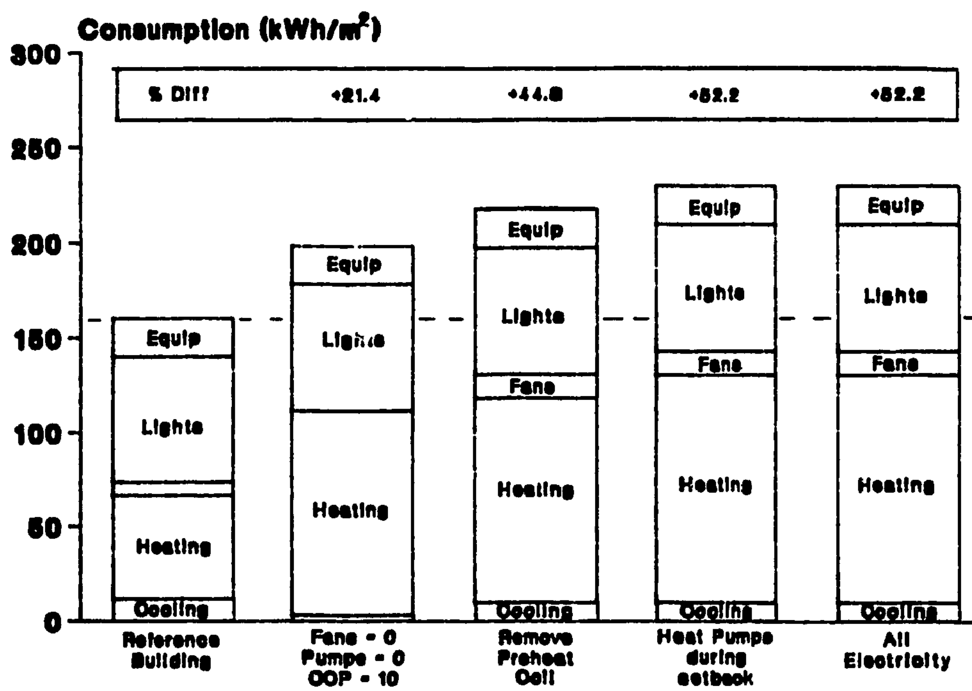

Figure 4.14 Yearly energy consumption profiles for reference building with water loop heat pump system

pump system such as improving the COP reduced fuel costs, but remained 3.1% above the reference building design.

The energy consumption for the reverse cycle heat pump is 199.4 kWh/m^2, which is 24.7% less than the water loop heat pump system. However, as illustrated in Figure 4.16, the reverse cycle heat pump consumes 22.1% more annual energy than the reference building.

In summary, elimination of lighting and equipment loads produced the largest cost savings (50.6%) for the reference building. The second largest cost savings (11.1%) resulted from raising the supply air temperature from 13 to 18°C.

Non-incremental design changes such as replacing the reference building's VAV system with a combined induction/VAV arrangement increased annual operating costs by 26.3%. Water loop and reverse cycle heat pump systems also increased the annual operating costs of the reference building by 42.5% and 18.1% respectively.

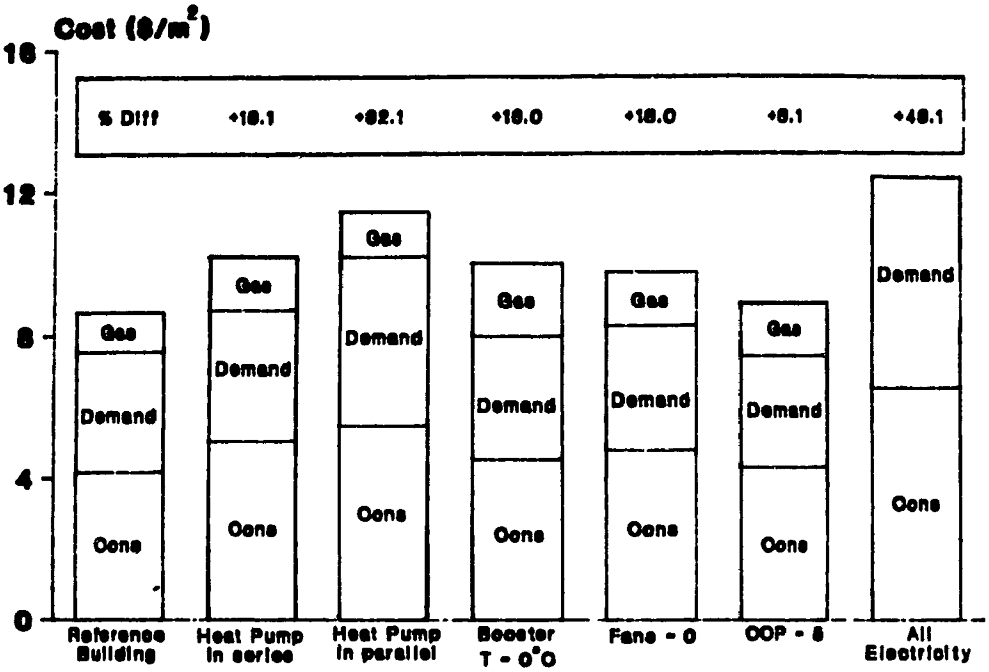

Figure 4.15 -early energy cost profiles for reference building with reverse cycle heat pump system

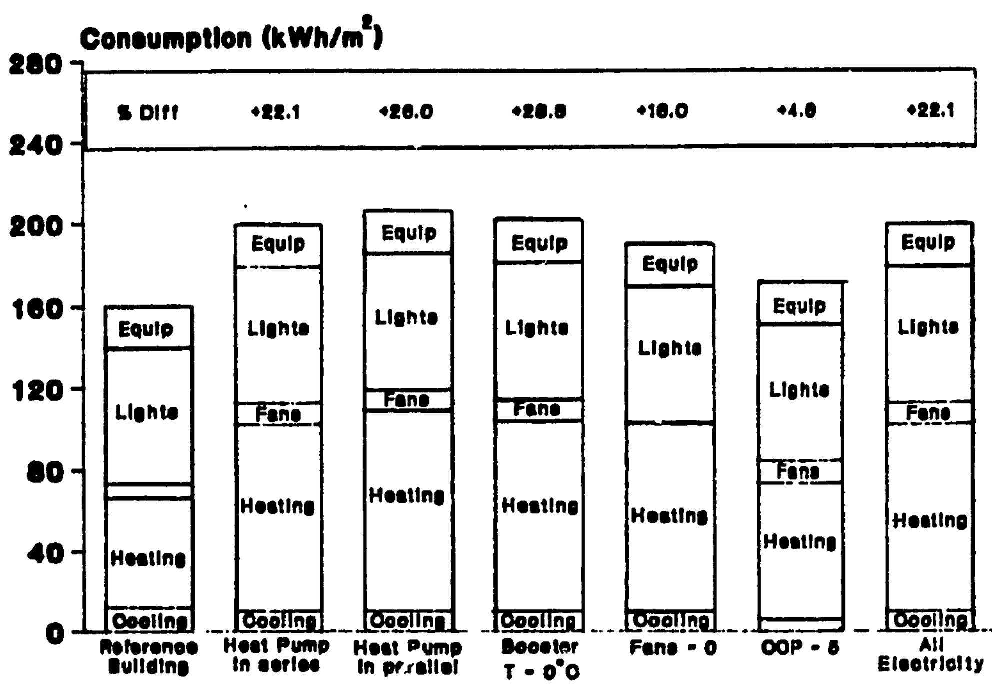

Figure 4.16 Yearly energy consumptio profiles reference building with rse cycle heat pump system

4.5 PROPOSED DESIGN

In this section some energy conservation measures are selected and implemented based on the previous analysis.

4.5.1 Lighting Load

As a building becomes more energy efficient, the major targets of opportunity can shift. Typically, lighting energy strategies become more important. Wong-Kcomt et al. [70] indicated the energy efficient fluorescent lighting fixtures can reduce power and energy by 33 to 50%. Additionally, cost savings can range from 30 to 50% of the actual lighting energy costs.

The initial proposed design recommends installation of high efficiency lighting fixtures with an installed capacity of 15 W/m^2, while maintaining the same lighting level.

This approach reduced operating costs by 14% from 8.66 to 7.45 $\$/m^2$ yr, which is composed of 46% electrical consumption, 36% electrical demand and 18% gas consumption. The annual energy consumption is reduced by 6.2%, from 163.3 to 153.1 kWh/m^2 yr. The heating component consumed the largest proportion of energy at 43%, followed by lighting (30%), equipment (13%), cooling (7%), fans (5%) and auxiliary (2%).

4.5.2 Supply Temperature

In many situations, supply temperature is significantly lower than that which is required to condition a space. Consequently, to avoid over cooling, the supply air must then be reheated or mixed with warm air to give the required supply air temperatures. Thus, this approach increases energy cost due to the added conditioning process for the supply air.

The supply temperature for the reference building is proposed to be raised from 13°C to 15°C for all zones.

Yearly operating costs for this proposed design is 8.45 $\$/m^2$ yr, or 2.4% less than the reference building annual costs. Electrical consumption costs are 48% of the total, followed by demand at 40% and gas consumption at 12%. The energy consumption is 154.4 kWh/m^2 yr, or 5.3% less than the reference building. The energy component profile is comprised of 6% cooling, 31% heating, 43% lighting, 13% equipment, 5% fans and 2% auxiliary loads.

4.5.3 Combined ECM's

The final design uses efficient lighting fixtures (15 W/m^2), higher supply temperature (15°C) and two VAV systems separately supplying conditioned air to the interior and perimeter zones.

These measures reduced annual operating costs by 20.2%, from 8.66 to 6.91 $\$/m^2$ yr for the proposed design (Fig. 4.17). Similarly, the energy consumption for the proposed design is 16.6% lower, from 163.3 to 136.1 kWh/m^2 yr (Fig. 4.18).

Initial material and labour installation cost comparisons for the HVAC systems in the reference building and proposed design are listed in Table 4.7. Increased costs for the air handling units and the duct system in the proposed design are

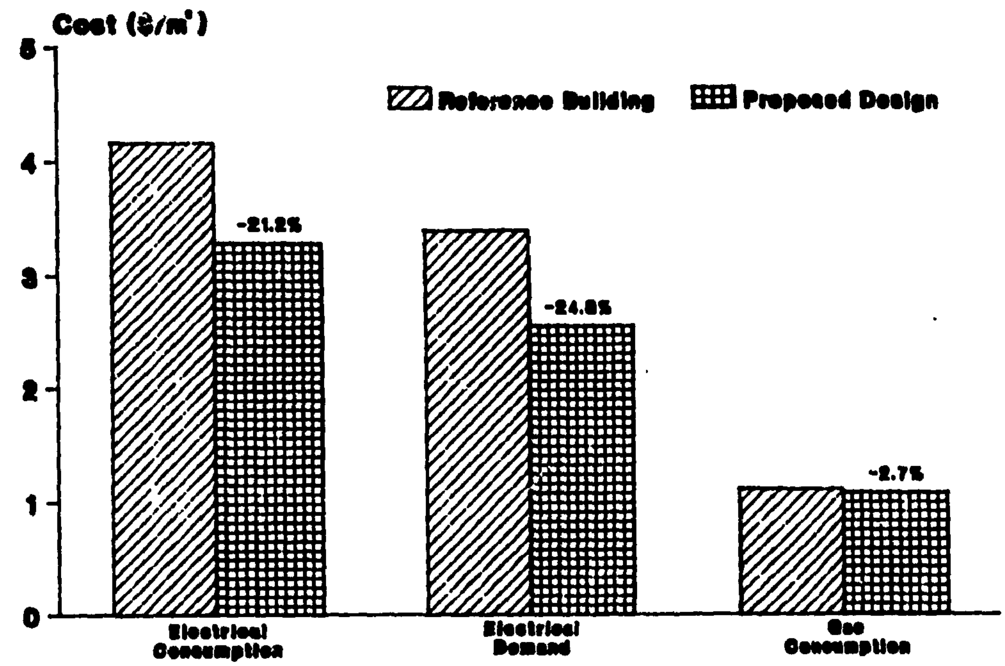

Figure 4.17 **Operating cost comparisons for reference building versus proposed design**

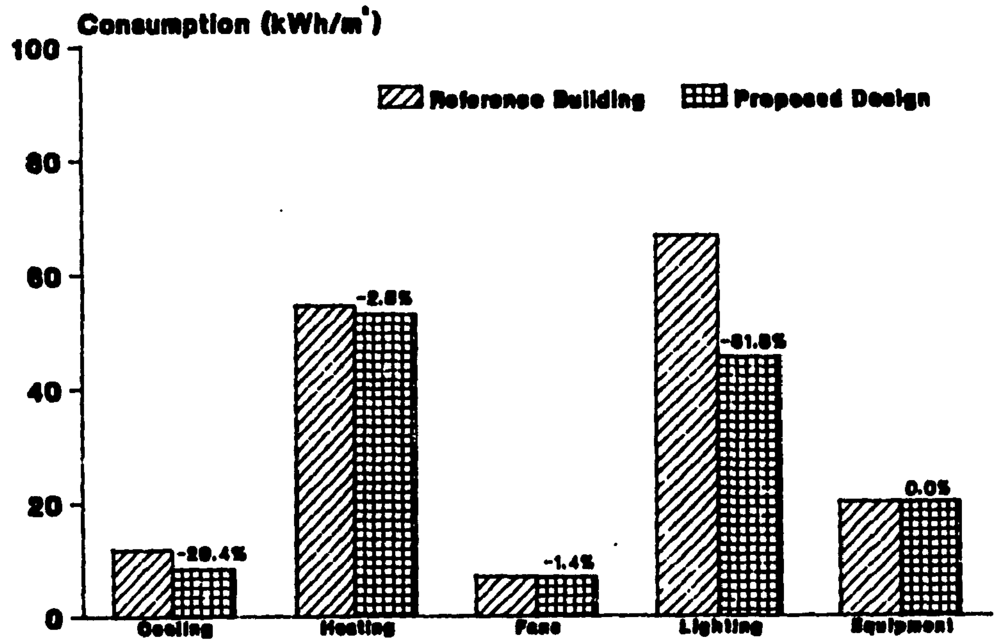

Figure 4.18 **Energy use comparisons for reference building versus proposed design**

attributed to a larger air flow rate. Since the supply air temperature in the proposed design is 2°C higher than the reference building, this will require larger quantities of air to maintain space temperatures within specified limits.

Table 4.7 Initial cost comparisons of reference building versus proposed design

Component	Reference Building	Proposed Design	% Diff.
Central Air Handling Units	53 800	68 300	+27.0
Supply & Exhaust ducts	318 400	354 700	+11.4
Control (VAV) Boxes, with reheat	75 500	75 500	0.0
Diffusers & return air grilles	39 250	39 250	0.0
Heating Plant (boiler)	98 700	98 700	0.0
Air Conditioning, chiller & cooling tower	822 000	700 500	-14.5
Total	**1 407 650**	**1 336 950**	**-5.0**
Total/floor area ($/m^2)	**156.40**	**148.55**	

The total initial cost for the proposed design is 5% lower than for the reference building. The decrease in the total initial cost is attributed to a lower cost for the air conditioning system. Lower internal heat gains due to the reduced lighting load (22 → 15 W/m^2) in the proposed design decreased the required cooling plant load from 845 to 720 kW (-14.8%). The central heating plant load remained the same at 202 kW for the two buildings.

The life cycle costs for the two buildings can be compared using the economic approach presented in chapter 2 (section 5). Present worth values for the two buildings at an assumed interest rate (i=12%) and escalation rate (j=10%) for a 25 year amortization period (n) are:

Present worth (reference building) = $ 2 966 830

Present worth (proposed design) = $ 2 581 330

The comparison indicates a reduction of 13% in the life cycle cost which can be achieved with the proposed design for an office building located in Montréal.

4.6 CONCLUSIONS

The annual operating cost for the reference building is dominated by the internal loads. Elimination of internal loads resulted in a 50.6% annual cost saving. Comparatively, potential savings due to the maximum possible reduction in external loads are only 7.8% of the annual operating costs.

The most cost-effective way to provide building air circulation for heating, cooling and ventilation in the reference building is through the use of a variable air volume system. The annual operating cost for a VAV system represents approximately 60% of the operating cost for an induction system, and an average 77% for water loop and reverse cycle heat pump systems.

The proposed design considered:

a) installing high efficiency lighting fixtures,

b) increasing the supply air temperature, and

c) selecting two VAV systems to supply conditioned air to the interior and perimeter zones separately.

These measures resulted in reduction of the annual energy consumption and cost of 16.6% and 20.2% respectively, for an office building in Montréal.

CHAPTER 5

NEW DESIGN OUTDOOR TEMPERATURES FOR SIZING HVAC SYSTEMS IN MONTRÉAL

5.1 INTRODUCTION

One of the main functions of a building is to provide its occupants with a thermally comfortable indoor environment even under extreme outdoor conditions. However, it is in the interest of the owner/manager to minimize the initial and operating costs of such environmental conditioning systems. Therefore, the initial step to properly design and size heating and cooling systems is to select outdoor design weather data. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) along with various other professional societies and companies have published design weather data for various climatic regions in the United States and Canada. The methodology for assessing the design weather data is based on the principle of accepting a low risk that the extreme outdoor temperatures exceed the design values. Usually, the risk is expressed as a percentage of the total number of hours during the heating or cooling season when the climatic conditions exceed the design conditions.

ASHRAE's Handbook of Fundamentals published the design weather data for numerous cities across North America [71] based on the compilation of hourly weather data for a 15-year period of record (1957-1971). Design outdoor temperatures

(DOT) for winter and summer seasons in Montréal, Canada, were calculated using this period of record.

For Canadian cities, ASHRAE determined the design outdoor temperature in January (for heating) and in July (for cooling), assuming that the most severe weather conditions will occur during these two months. Thus in Montréal, for a 99% frequency the designer will accept a risk of 1% to have the outdoor temperature lower than -27°C (Table 5.1). Since in January the total number of hours is 744, the designer accepts that the outside temperature can drop below -27°C for 7.4 hours during the month. For the cooling season, levels of 1% and 2.5% characterize the frequency of temperatures above the design values. Therefore, for frequency levels of 1% and 2.5%, the designer will accept the outside temperature to be greater than the DOT for 7.4 and 18.6 hours respectively in the month of July.

Table 5.1 Design weather data for Montréal as recommended by ASHRAE [71]

Winter (DOT)		Summer (DOT)	
99%	97.5%	1%	2.5%
-27°C	-23°C	31°C	29°C

Several other sources also recommended the design outdoor temperatures for sizing HVAC systems in Montréal (Table 5.2).

Table 5.2 Design outdoor temperatures for Montréal

Source	Summer	Winter
Carrier [72]	32°C	---
CIBSE [73]	32°C	-23°C
National Building Code [74]	30°C	-23°C
Québec Law [19]	---	-23°C

However, the recommended values in Table 5.2 neglect to consider the duration of temperatures and the thermal inertia of a building, which can offset the effects of extreme weather conditions over relatively short periods of time.

The consequence of the traditional design procedure quite often leads to over-sizing of mechanical systems, diminishing its efficiency due to the part load operation, and logically producing higher initial and operating costs for the systems.

New approaches were developed to define the design weather data for heating and cooling systems. These approaches explored the impact of the duration of extreme temperatures and the effect of the building thermal inertia on the design weather data for winter and summer.

Snelling [75] studied the duration of time that design temperature values were equalled and exceeded in summer and winter, using durations from one to eight hours and a risk of 1%, 2.5% and 5%. He indicated the ASHRAE summer design temperature determined for durations of one or more hours for Belleville, Illinois at 2.5% risk is 33°C, which was also established in his analysis. However, Snelling revealed for durations of six hours or more at 33°C, the actual risk was only 1.8% for such an event to occur. Similarly, the ASHRAE design temperature in winter for durations of one or more hours at 97.5% risk is -14°C. Once more, he indicated for durations of six hours or more at -14°C, the actual risk was 97.7% for such an occurrence. Thus, he concluded the frequency when design values are surpassed by constant temperature durations of six or more hours, is less than the frequency by durations of one or more hours.

Richard [76] attempted to define new design outdoor temperature values for a risk of 2.5% in summer and winter taking into account the duration of specified extreme temperatures and the thermal inertia of buildings. Table 5.3 shows the corresponding average number of occurrences per season of a specific temperature in Washington D.C.. The last column of Table 5.3 gives the average number of hours per season that the temperature in column 1 is equalled or exceeded for a duration of 6 hours or longer. For example, if the thermal inertia of a building is 6 hours and a risk level of 2.5% is accepted (which represents 75 hours over the cooling season: June - September), one would then select 31.1°C as the design value; whereas the corresponding design dry-bulb temperature listed in ASHRAE Fundamentals for Washington is 32.8°C. Columns 2 through 7 in Table 5.3 also illustrate the longer the duration for a specific temperature, the lower the frequency for such an event to occur.

Table 5.3 Average occurrences per season of durations greater than threshold temperatures [76]. (15-year weather data for Washington D.C.)

Threshold Temp. °C	Duration						Average # hours >6
	1	2	3	4	5	6	
36.7	0.1	0.0	0.0	0.1	0.0	0.0	0.0
36.1	0.2	0.1	0.0	0.1	0.0	0.0	0.0
35.6	0.4	0.2	0.0	0.1	0.1	0.0	0.0
35.0	0.7	0.3	0.4	0.0	0.2	0.0	0.5
34.4	0.9	0.5	0.4	0.4	0.3	0.1	1.5
33.9	1.7	0.6	1.0	0.5	0.4	0.4	4.7
33.3	2.5	1.5	1.0	0.9	0.8	0.5	8.8
32.8	3.9	1.9	1.4	1.1	1.6	1.1	18.0
32.2	5.2	3.1	1.9	1.4	1.7	1.2	29.0
31.7	5.9	4.2	3.4	1.8	3.3	2.2	48.9
31.1	6.7	3.6	2.7	3.0	3.8	2.8	71.4
30.6	6.4	4.4	3.3	3.3	4.8	3.5	108.1

Berg-Hallberg [77] and Peterson [78] suggested that the two most important factors in sizing HVAC systems are the design outdoor temperatures and the thermal characteristics of the building. Peterson stated that most heating systems are quite often unnecessarily oversized. Therefore, they defined a new design outdoor temperature (T_D) as a function of:

1) extreme outdoor temperature (T_E), expressed as the average daily temperature,
2) time constant of the building (τ_b), in hours

3) duration of extreme outdoor temperature (i), in days

4) acceptable change in indoor temperature (ΔT_R), in °C

$$T_D = T_E + \frac{\Delta T_R}{1-\exp(-i/\tau_b)} \tag{5.1}$$

The results presented by Berg-Hallberg (Table 5.4) show that the new design outdoor temperatures are higher than those in the Swedish building code, thus designers/engineers can reduce the initial size of heating systems.

Table 5.4 Design outdoor temperature in Sweden [77]

City	Berg-Hallberg		Swedish Code	
	Light Structure $25<\tau_b<80$h	Heavy Structure $80<\tau_b<300$h	Light Structure	Heavy Structure
Göteborg	$-17<T_D<-14$°C	$-14<T_D<-9$°C	-18°C	-15°C
Stockholm	$-18<T_D<-16$°C	$-16<T_D<-11$°C	-18°C	-17°C
Härnösand	$-22<T_D<-21$°C	$-21<T_D<-18$°C	-23°C	-21°C

5.2 METHODOLOGY

This section presents the methodology used to develop the new design weather data for HVAC systems in Montréal, based on statistical analysis of hourly temperatures over a 15 year period of record (1974-1988).

The method is primarily based on the Berg-Hallberg model with some modifications to consider the duration period and the extreme outdoor temperature in hours rather than days.

Figure 5.1 shows the relationship between outdoor and indoor temperatures. When the outdoor temperature drops from the design value T_D to the extreme design temperature T_E, the indoor temperature decreases throughout the duration (i). The maximum difference between T_D and T_E is selected in such a way that the maximum variation of the indoor temperature will not exceed the accepted change in indoor temperature (ΔT_R=1.5 °C) throughout the duration (i). When the outdoor temperature returns to the design value, the indoor temperature will rise to the specified room temperature.

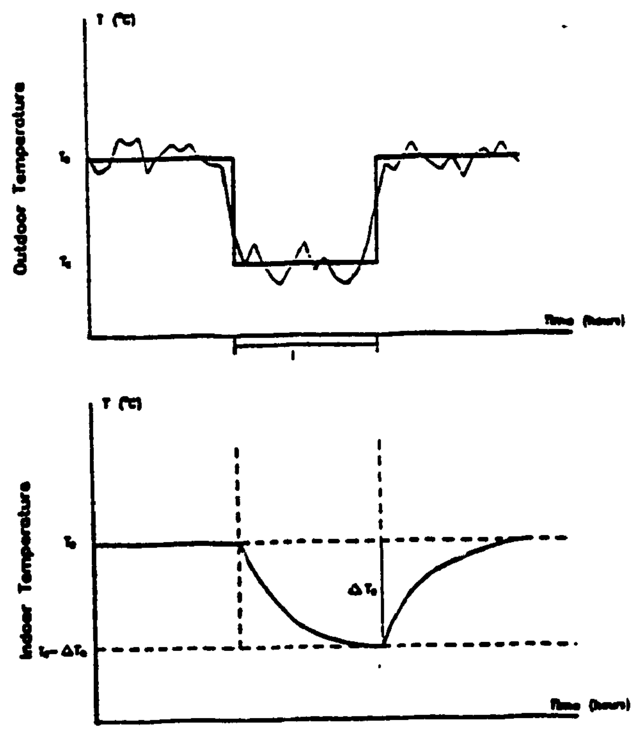

Figure 5.1 **Indoor and outdoor temperatures versus time [77]**

Richard [76] emphasized the necessity to have measurements 15 years or more to accurately determine extreme outdoor temperatures and insure relatively small variance about the mean.

In this analysis, the hourly dry-bulb and wet-bulb temperatures measured at Dorval airport between 1974 and 1988 provided by Environment Canada were used. The design weather data for the Canadian cities recommended by ASHRAE were based only on the records for the months of January and July, instead of the normal three month period (Dec-Feb & June-Aug) used for the U.S. cities.

The analysis of the recent weather data (1974-1988) supports the previous approach used by ASHRAE. Figures 5.2 and 5.3 illustrate the total number of monthly occurrences for successive five-day intervals during the 15 year period for which the temperature exceeded the design weather data in Montréal (29°C in summer and -23°C in winter). During the summer season, July is observed to have the highest frequency of severe outdoor temperatures and therefore summer design temperatures should be based on this month. Similarly, January was selected to evaluate winter design values.

Figures 5.4 and 5.5 show the average dry-bulb temperature in July and January for each year of analysis, and the overall 15 year average dry-bulb temperature for the two months. As one can notice there is a larger fluctuation of the average temperature in January from year to year than in July. Thus,

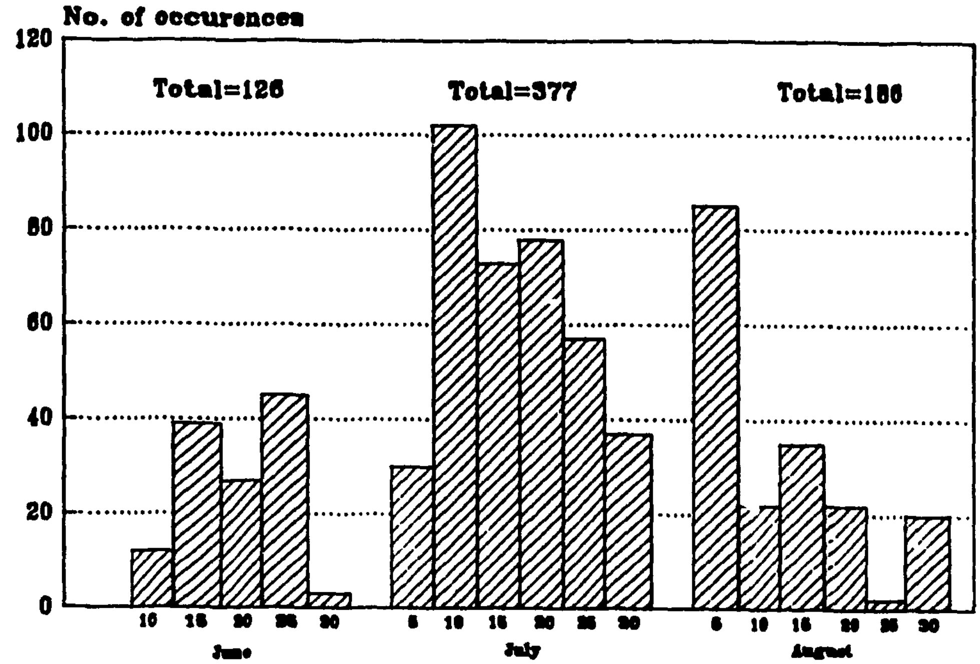

Figure 5.2 Total number of hours when the outdoor temperature is greater than 29°C in summer in Montréal, during 15-year period

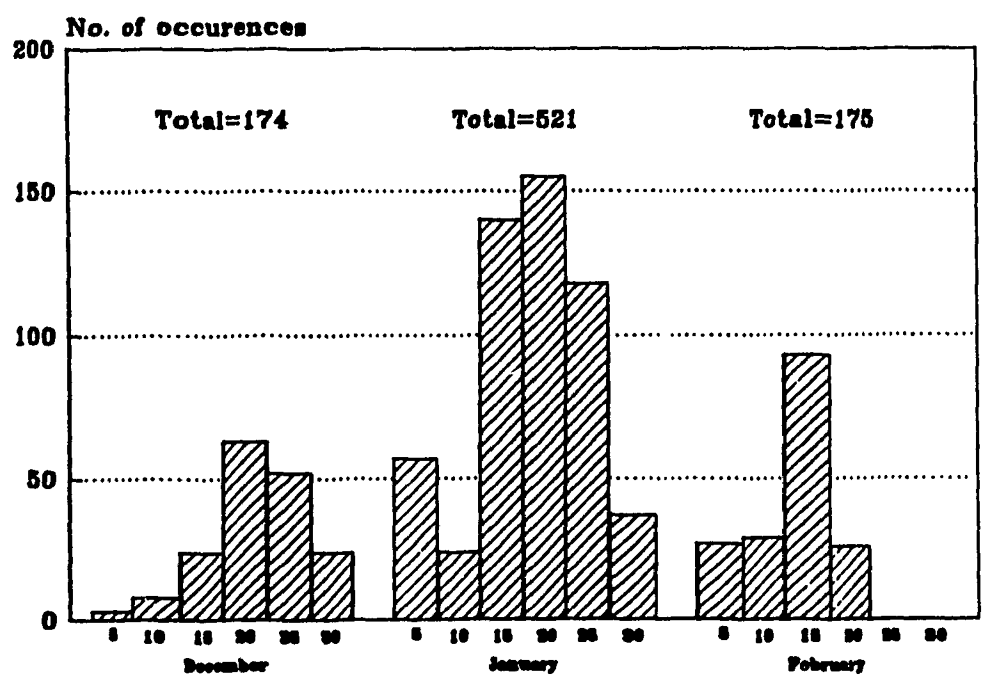

Figure 5.3 Total number of hours when the outdoor temperature is less than -23°C in winter in Montréal, during 15-year period

due to the larger values of the standard deviation and flatness index (std. deviation/average) in January, this study recommends accepting a lower risk level for design temperatures in winter (99%) than in summer (2.5%). It should be noted that ASHRAE Standard 90.1-1989 also recommends using the same risk levels for sizing of HVAC systems.

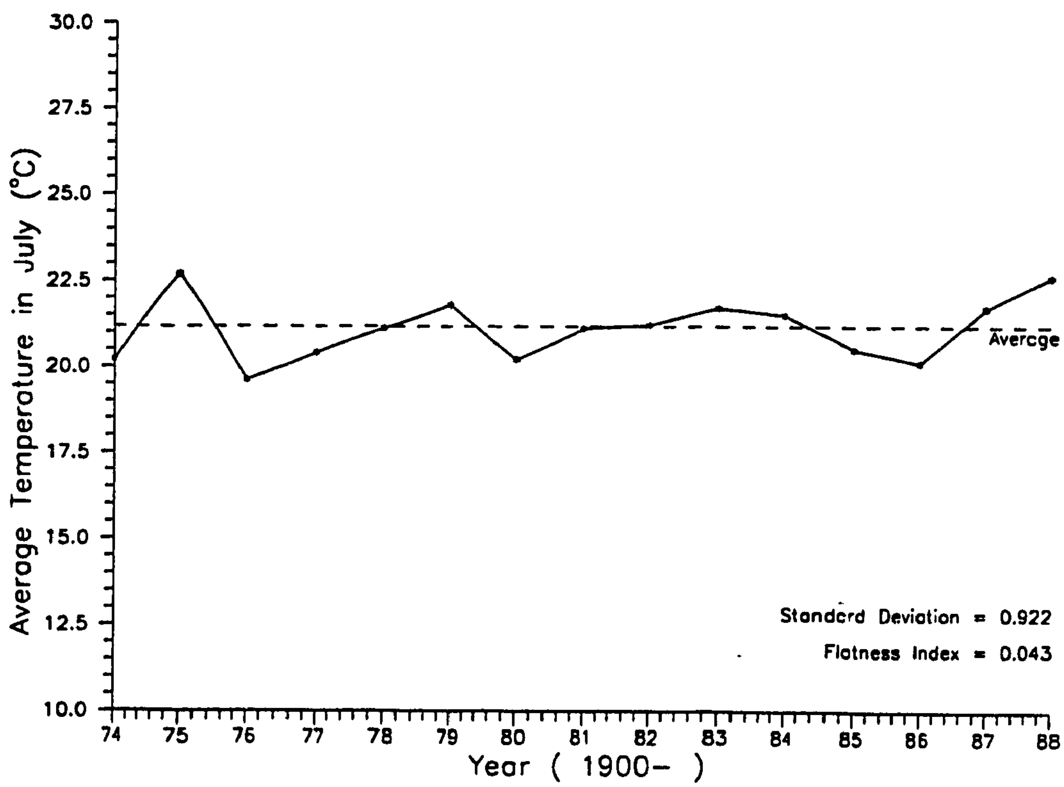

Figure 5.4 Variation of the monthly average dry-bulb temperature in July

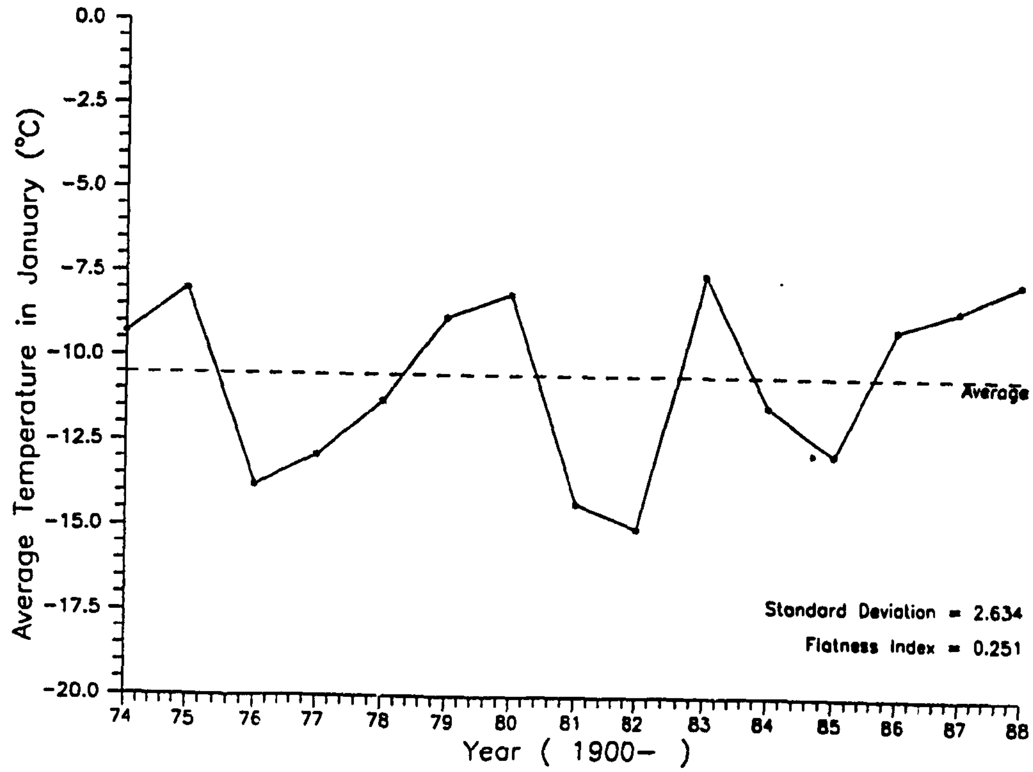

Figure 5.5 Variation of the monthly average dry-bulb temperature in January

Table 5.5 shows the average number of occurrences in the 15 year period, when the dry-bulb temperature remained relatively constant within a 1°C change (i.e. 22 ±0.5°C) for the specified length of duration. As one can observe, the outdoor temperatures in January are more stable and do not change from hour-to-hour as frequently as temperatures in July. For instance, the number of occurrences that the outdoor temperature in July remained within a 1°C range for a duration of 5 hours is 10, whereas the number of occurrences in January is 27.

Table 5.5 Yearly number of occurrences for a specified duration in Montréal, as an average of 15-year period (1974-1988)

Month	Duration 'i' (hours)											
	1	2	3	4	5	6	7	8	9	10	11	12
July	484	158	59	25	10	4	2	1	0.5	0.3	0.2	0.1
January	374	169	81	43	27	17	11	7	5.0	3.0	2.0	1.5

As Richard [76] noticed (Table 5.3), the results from Table 5.5 indicate the longer the duration for a specific temperature, the lower the frequency of occurrence.

5.3 RESULTS

To develop the required design weather data, a new term defined as "duration design temperature" (T_{DD}) is presented. The duration design temperature represents the extreme outdoor temperature (T_E) for a given duration (i) expressed in hours rather than days as described in equation 5.1.

This section presents the proposed design weather data for continuous 24-hour operation of an HVAC system, and those for 14-hour operation which can be applied to commercial building systems such as office buildings. Finally, the impact of the proposed data on the size of the cooling and heating plant is evaluated for a reference office building.

5.3.1 Design Outdoor Temperature (24 hour period)

Design temperatures developed in this section are determined assuming a continuous 24 hour operation of the HVAC system in January and July.

Figure 5.6 shows the linear relationship between duration (i) in summer at a risk level of 1% and the corresponding duration design temperature. It is observed from this figure that for durations up to 5 hours, the duration design temperature is approximately equal to the ASHRAE design value. However, for durations longer than 5 hours, there is an appreciable difference in duration design temperatures and the corresponding ASHRAE value. For instance, the duration design temperature for summer duration of 6 hours is 29°C, and an 8 hour duration corresponds to a design temperature of about 25°C, while the ASHRAE design value remains constant at a selected 31°C regardless of the temperature duration.

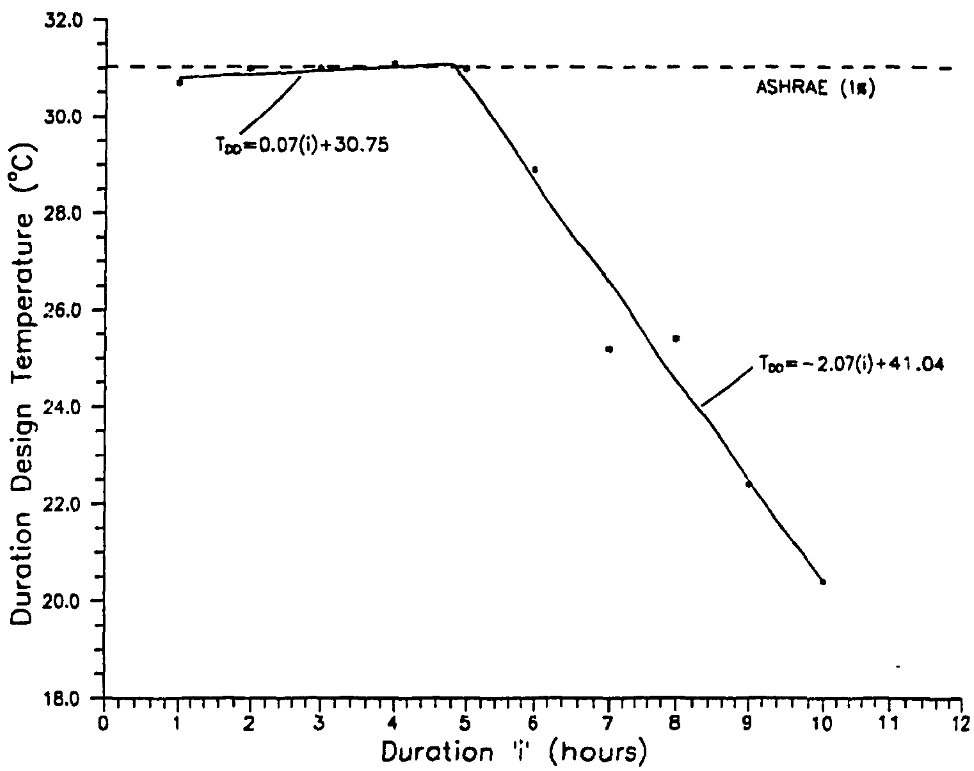

Figure 5.6 **Duration design temperature for a 24 hour period in summer at 1%**

Similarly, Figure 5.7 shows the relationship between summer duration design temperature and duration of observed outdoor temperatures at a risk level of 2.5%. The duration design temperature for durations up to 5 hours are only a little above the design weather value recommended by ASHRAE for Montréal. However for durations above 5 hours, the designer may select progressively lower design temperatures for longer periods of duration.

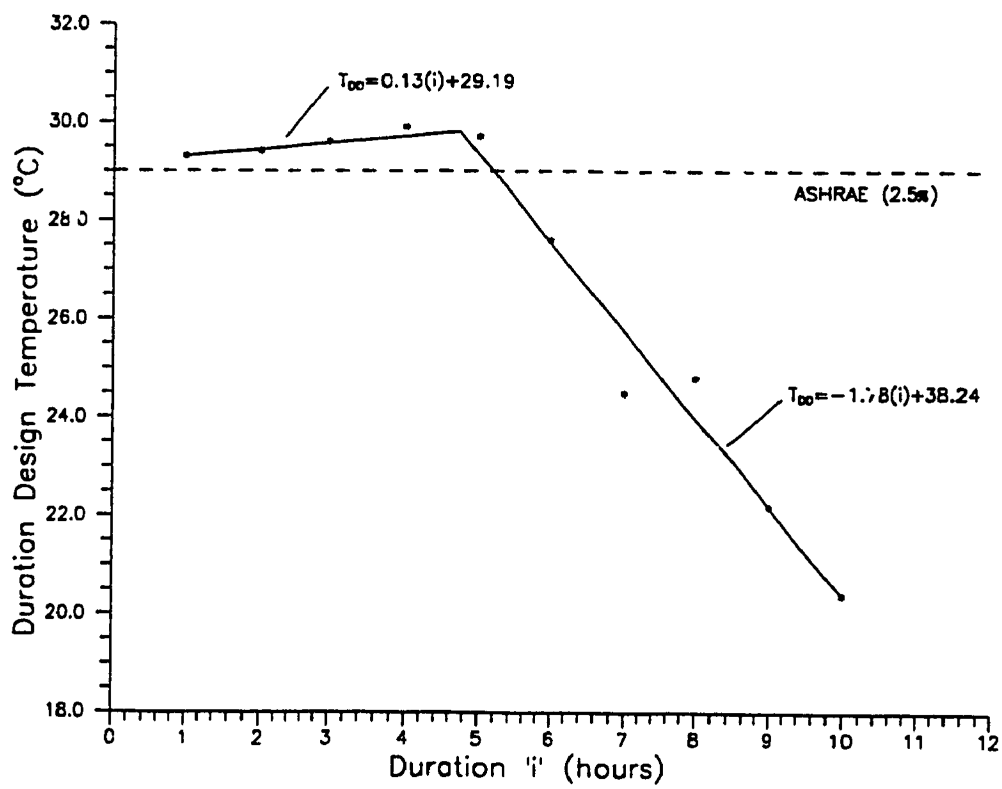

Figure 5.7 **Duration design temperature for a 24 hour period in summer at 2.5%**

Figures 5.8 and 5.9 show the duration design temperatures in winter for associated risk levels of 99% and 97.5%.

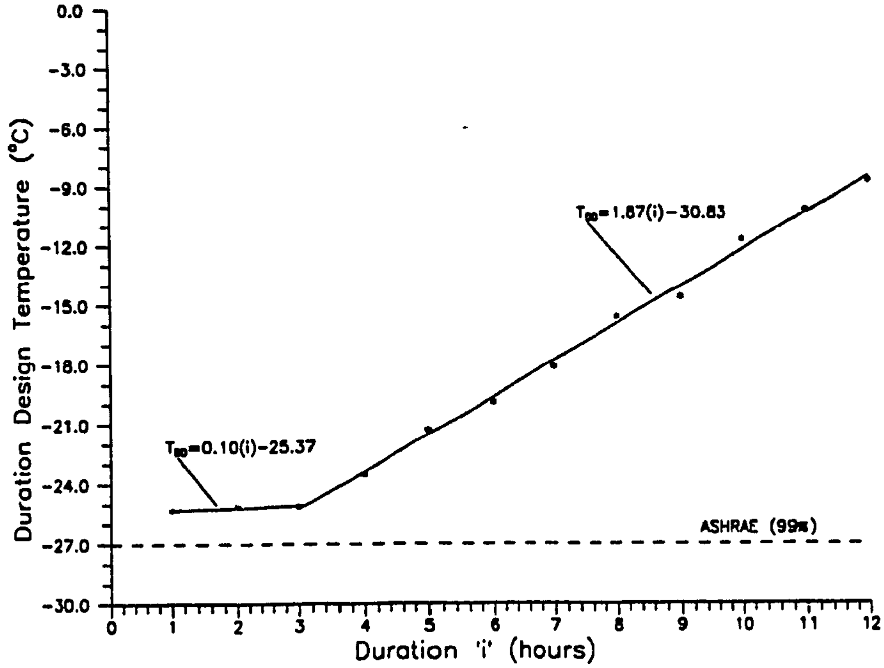

Figure 5.8 **Duration design temperature for a 24 hour period in winter at 99%**

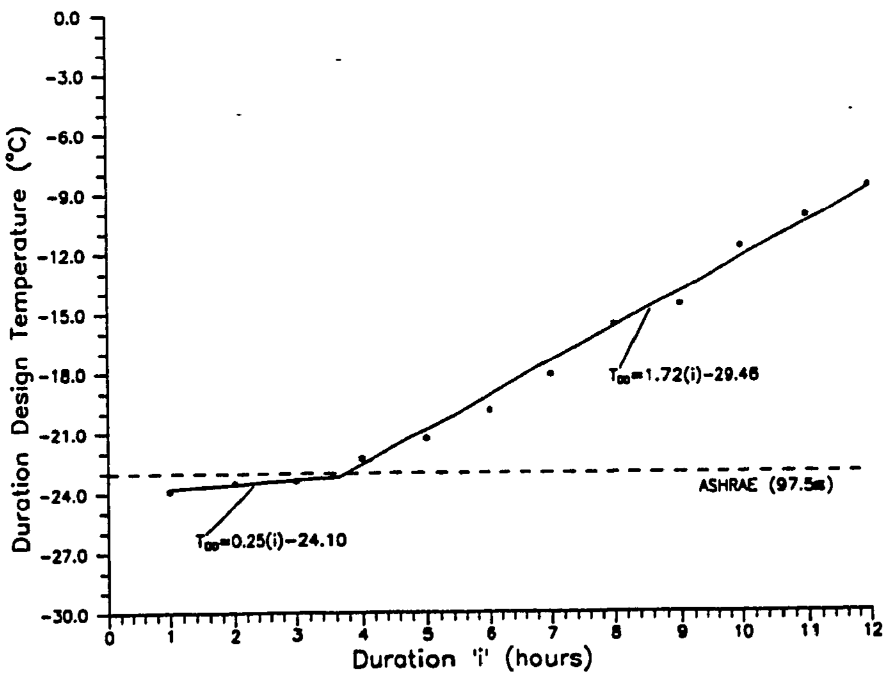

Figure 5.9 **Duration design temperature for a 24 hour period in winter at 97.5%**

In Figure 5.8 the duration design temperature for durations up to 3 hours is slightly higher than the ASHRAE design value. Nevertheless, it is once again important to observe that the duration design temperature becomes moderately higher as the duration of outdoor temperatures increase. For example, at a duration of 4 hours the design temperature is -23°C, while at a duration of 10 hours the duration design temperature is -12°C. These can be compared to the ASHRAE value of -27°C at the same level of risk.

The small difference between the duration design temperature (-25.3°C) for one hour and the ASHRAE value (-27°C) observed in Figure 5.8 can be attributed to the general warming of the atmosphere, between the first period of record (1957-71) used by ASHRAE and the period used in this analysis (1974-88).

Comparatively, Figure 5.9 illustrates that for a risk level of 97.5%, the duration design temperature is similar to ASHRAE's value for durations up to 4 hours. However, for durations above 4 hours, the design temperature becomes warmer as the duration increases. Thus, for relatively short periods of duration (< 4 hrs), the duration design temperature values in winter are similar to those recommended by ASHRAE. For extended periods of duration, the designer can accept progressively higher duration design temperatures for longer duration periods while continuing to maintain the same risk level.

Figures 5.10 through 5.13 illustrate the design outdoor temperature values in Montréal developed by integrating the new duration design temperature (T_{DD}) in hours, instead of T_E expressed in days in equation 5.1, and the time constant of the building (τ_b). Figure 5.10 shows the design outdoor temperatures in summer at a risk level of 1%, while temperatures corresponding to a risk of 2.5% are given in Figure 5.11. Figures 5.12 and 5.13 represent the design outdoor temperatures in winter at risk levels of 99% and 97.5%.

One can notice a significant difference between the design outdoor temperature values evaluated in this study for January and July, and the recommended ASHRAE values: subsequently the magnitude of the variation is more apparent when the duration period is larger. For instance, in Figure 5.13 the design outdoor temperature value at a duration of 3 hours and a time constant equal to the duration (i/τ_b=1.0) is -21.2^{o}C, while the corresponding ASHRAE value is -23^{o}C. Additionally, at a duration of 6 hours and similar duration/time constant ratio, the design outdoor temperature is -16.5^{o}C.

The design outdoor temperatures corresponding to the ratio i/τ_b equal to 1.0 or 0.5 are very conservative, as the time constant of the building can take values displayed in Table 5.6.

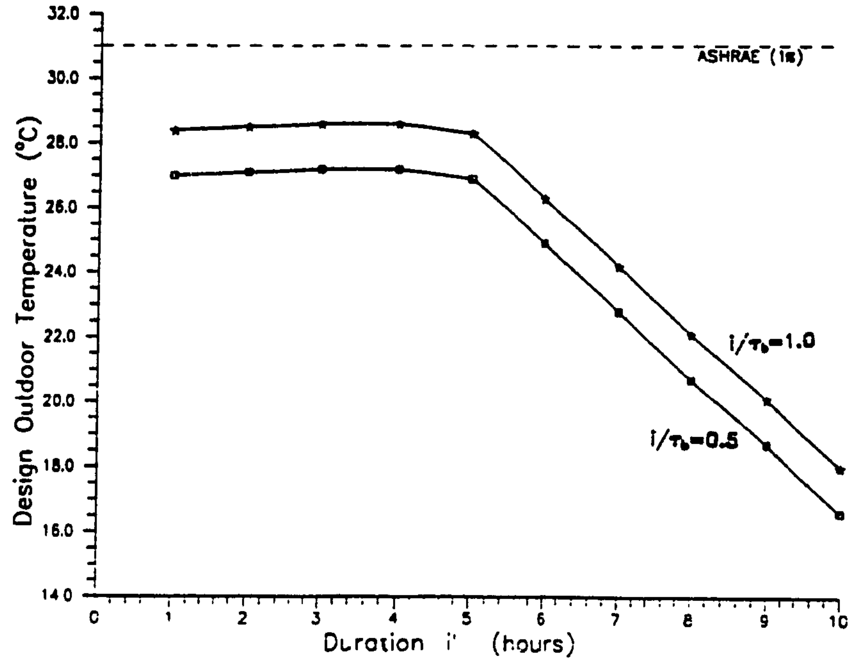

Figure 5.10 **Design outdoor temperature for a 24 hour period in summer at 1%**

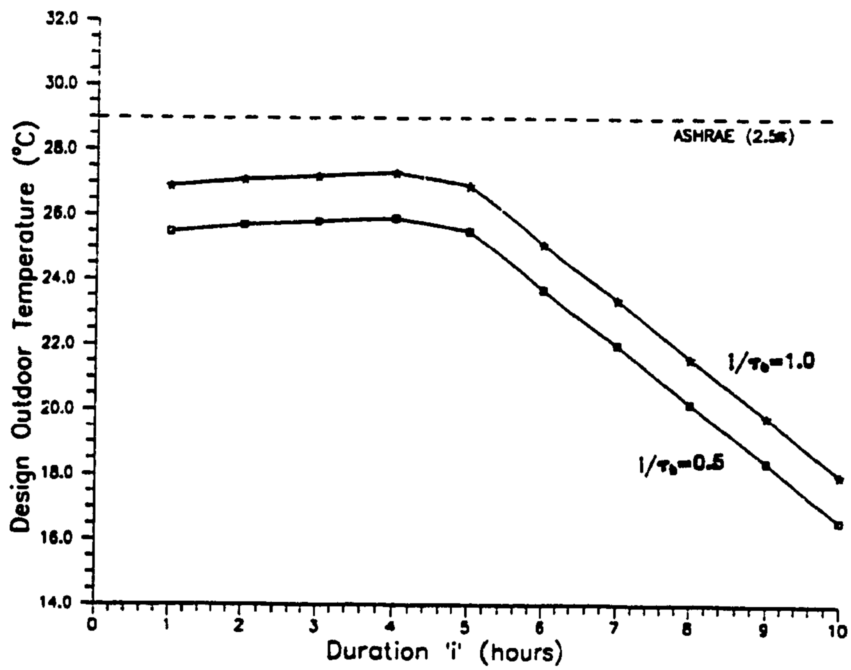

Figure 5.11 **Design outdoor temperature for a 24 hour period in summer at 2.5%**

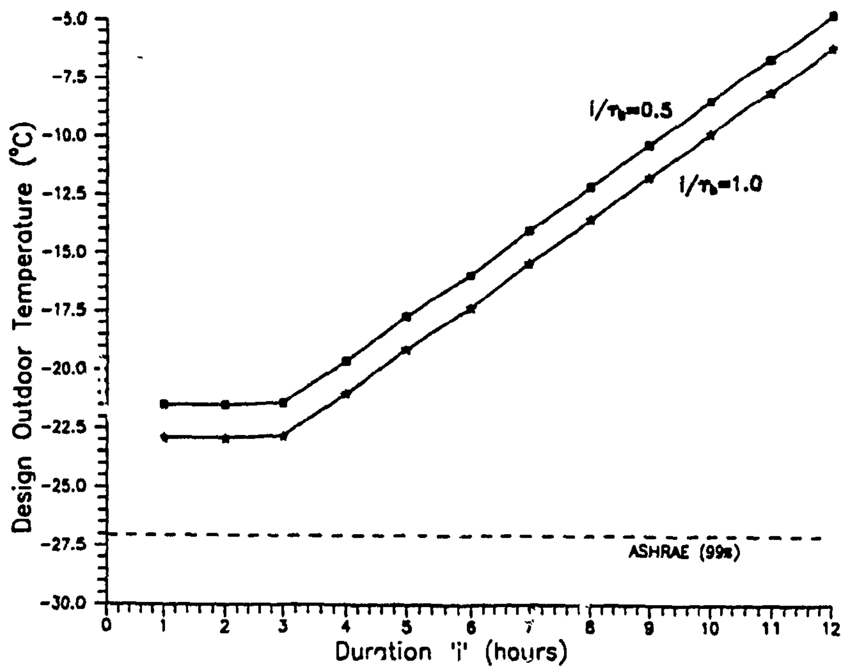

Figure 5.12 Design outdoor temperature for a 24 hour period in winter at 99%

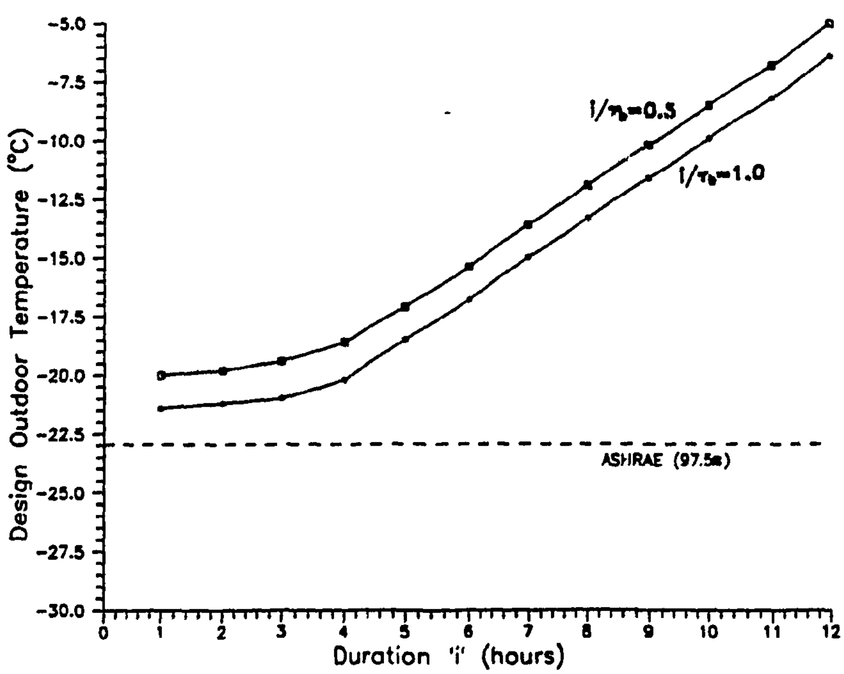

Figure 5.13 Design outdoor temperature for a 24 hour period in winter at 97.5%

Table 5.6 Time constant values for buildings [77]

Type of Building	τ_b (hours)
light	24
medium	48-60
heavy	96

5.3.2 Design Outdoor Temperature (14 hour period)

Office buildings need to provide a thermally comfortable working environment between 08:00-22:00 hours (18:00-22:00 hours for building maintenance personnel). However, the majority of heating systems in office buildings are unnecessarily oversized since they are designed to meet maximum thermal loads during unoccupied hours (22:00-08:00), when extreme outdoor temperatures frequently occur. Therefore, the following section will define January design outdoor temperatures based on a 14-hour period (08:00-22:00) of operation for an HVAC system.

Figures 5.14 and 5.15 illustrate the January duration design temperatures at risk levels of 99% and 97.5% for a 14 hour period. The general shape of these curves are comparable to curves obtained in section 5.3.1 (Fig. 5.8 & 5.9) for a 24 hour period. However, the duration design temperatures T_{DD} in Figures 5.14 and 5.15 for each corresponding duration (i) are higher than the duration design temperatures for similar durations in Figures 5.8 and 5.9. Further, as duration (i)

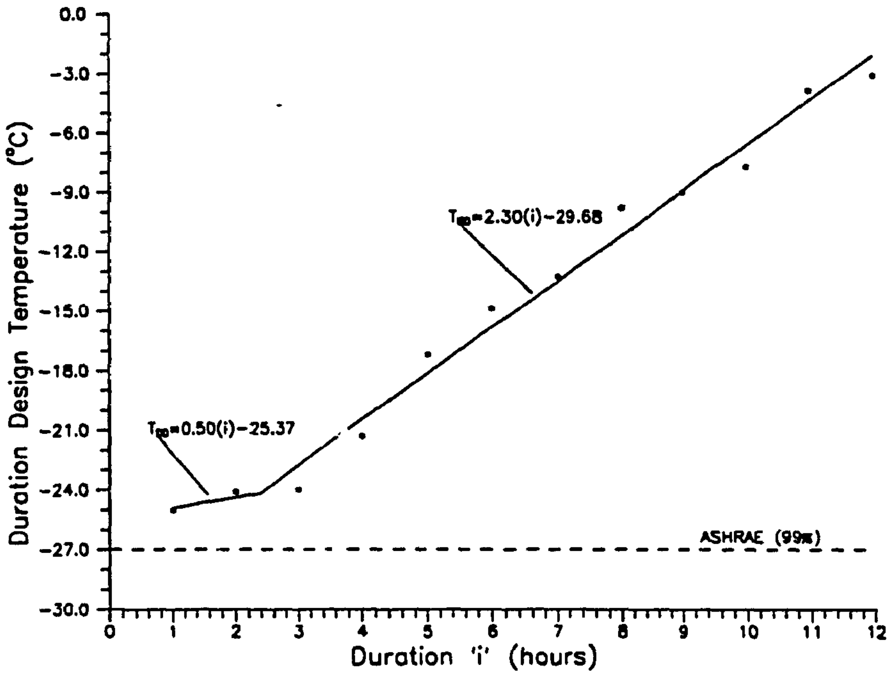

Figure 5.14 **Duration design temperature for a 14 hour period in winter at 99%**

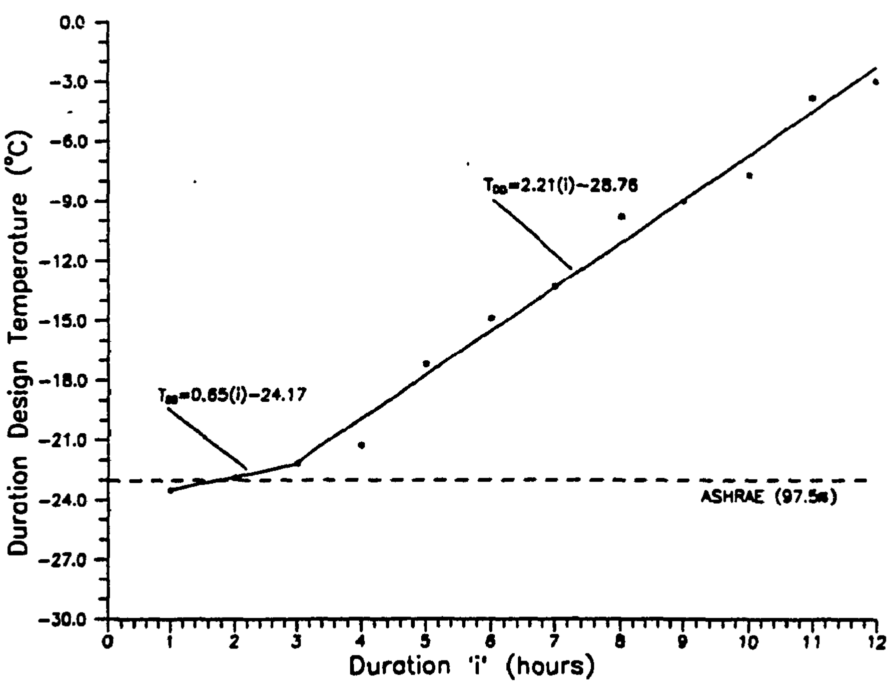

Figure 5.15 **Duration design temperature for a 14 hour period in winter at 97.5%**

increases for frequency levels of 99% and 97.5%, the rate of increase of the T_{DD} evaluated during the 14 hour period becomes larger than the T_{DD} rate of increase for the 24 hour period. For example, the T_{DD} rate of increase in Figure 5.14 and 5.15 for durations above 3 hours are 2.30°C/hr and 2.21°C/hr, whereas the T_{DD} rate of increase shown in Figures 5.8 and 5.9 are 1.87°C/hr and 1.72°C/hr respectively. This suggests that extreme cold temperatures and durations of cold temperatures in January are observed to occur more frequently at night between 22:00-08:00 hours. Therefore, heating systems in office buildings need not be sized for a 24 hour period. Rather a 14 hour period would suffice, since the heating loads in the office building during occupied hours for prescribed risk levels will be satisfied.

Figures 5.16 and 5.17 represent the January design outdoor temperatures T_D determined from equation 5.1 using duration design temperatures T_{DD} evaluated for a 14 hour period.

Design outdoor temperature values in Figures 5.16 and 5.17 are higher than T_D values in Figures 5.12 and 5.13 (24 hour period) for similar durations and ratios i/τ_b. For instance, Figure 5.18 shows the design outdoor temperature for a 2.5% risk in January for a 14-hour period is higher then the design outdoor temperature for a 24-hour period at i/τ_b ratio equal to 1.

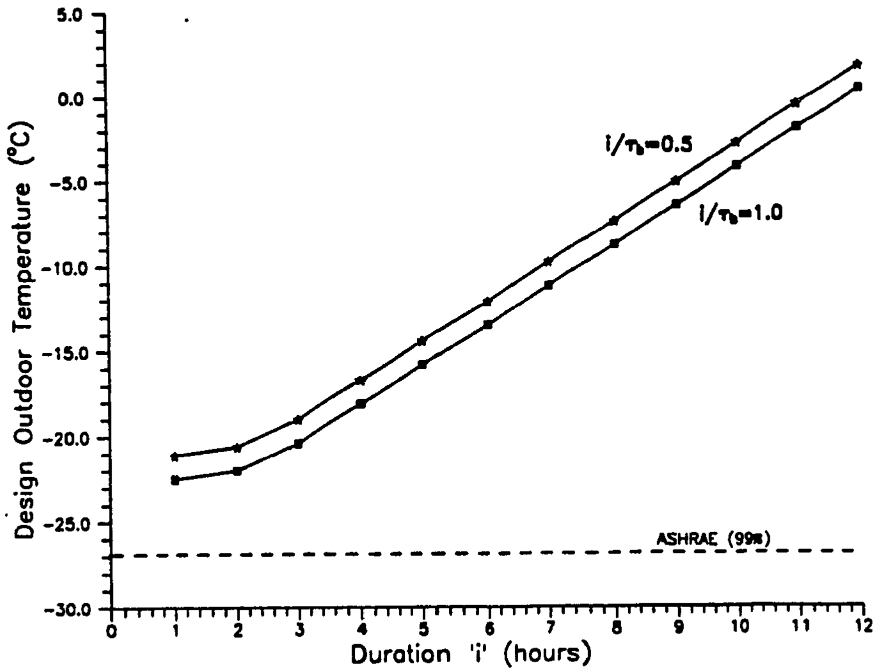

Figure 5.16 **Design outdoor temperature for a 14 hour period in winter at 99%**

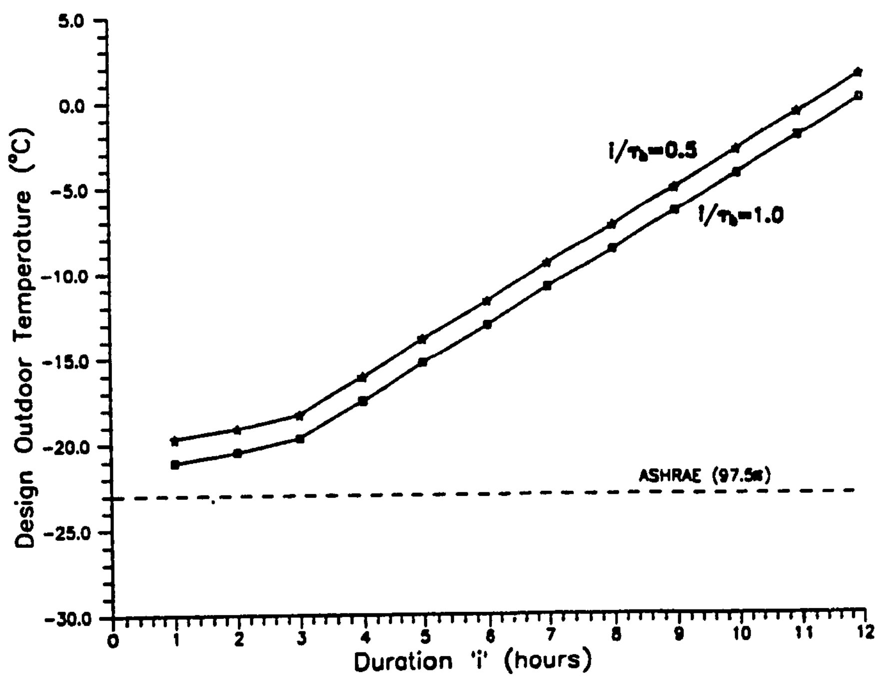

Figure 5.17 **Design outdoor temperature for a 14 hour period in winter at 97.5%**

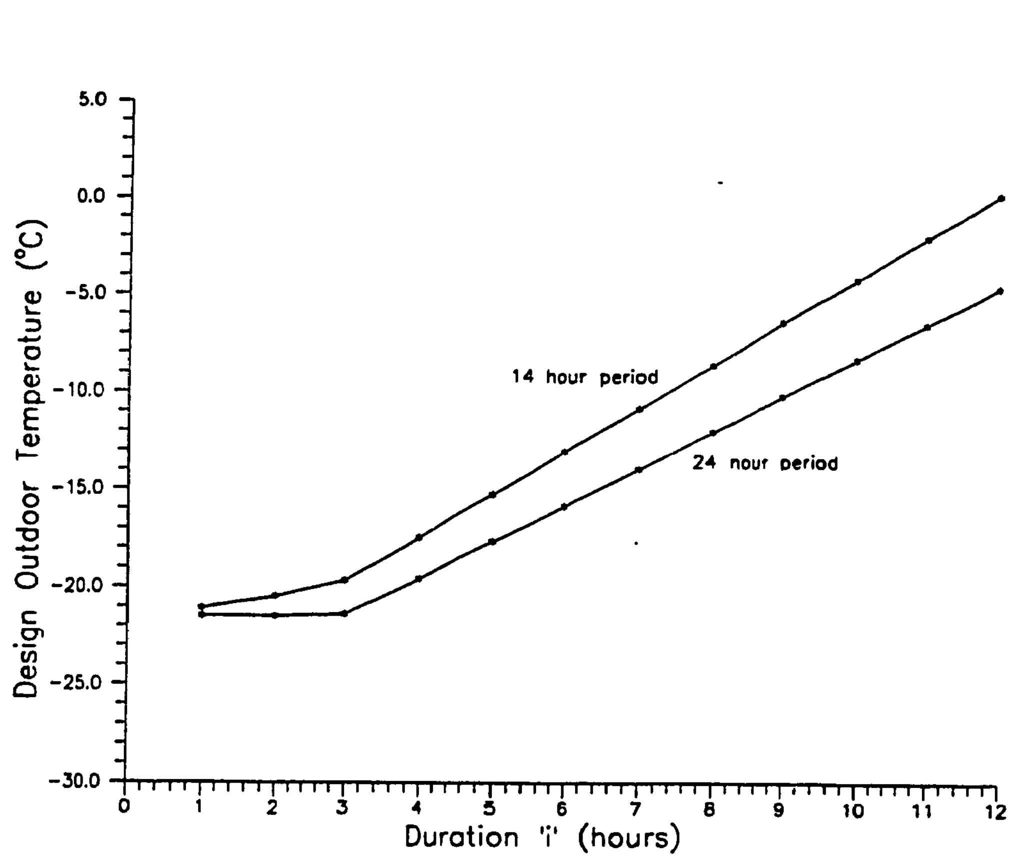

Figure 5.18 **Comparison of design outdoor temperature based on a 24 versus 14 hour period in winter at 97.5%**

Thus, a decrease in the size of heating systems using the 14 hour period is justified, since thermal comfort within the working environment is maintained for accepted risk levels during occupied hours.

Evaluation for July design outdoor temperatures for a similar 14 hour period (08:00-22:00 hours) is not required since recorded maximum daily temperatures in July normally occur early in the afternoon (approximately 14:00 - 15:00 hours).

5.3.3 Plant Sizing with New Design Outdoor Temperatures

The building energy systems analysis program (BESA) described in Chapter 4 was used to evaluate the consequences of new design outdoor temperatures on the plant size of the reference office building, outlined in Chapter 4.

The central plant size of the reference building simulated by BESA according to the ASHRAE and new design outdoor temperatures are displayed in Table 5.7. As the design temperature in winter becomes higher due to the effects of duration (i) and time constant (τ_b) of the building, the heating plant size is reduced. For instance, the heating plant size according to the ASHRAE design temperature of -27°C is 227.3 kW, whereas the heating plant size corresponding to the new design outdoor temperature of -23°C for a 24 hour period at a duration of 1 hour and i/τ_b ratio of 1 is 9.8% less. Similarly, if a new design outdoor temperature of -16°C is selected using a duration of 6 hours and i/τ_b ratio of 0.5 for the building, then the heating plant size can be further reduced as compared to the ASHRAE design data by about 25%.

The cooling plant size of the reference building can also be reduced within the range of 2.8 to 8.1% (21.3 - 61.6 kW) as compared to the results based on ASHRAE data, if the new design outdoor temperature in summer is considered.

Table 5.7 Effect of the new design outdoor temperatures on the size of heating/cooling plant of an office building

		i/τ_b=1.0				i/τ_b=0.5			
		i=1 hour		i=6 hour		i=1 hour		i=6 hour	
	ASHRAE	24 hour	14 hour	24 hour	14 hour	24 hour	14 hour	24 hour	14 hour
Design Temperature	°C	°C	°C	°C	°C	°C	°C	°C	°C
Summer (2.5%)	29	27	27	25	25	26	26	24	24
Winter (99 %)	-27	-23	-23	-17	-14	-22	-21	-16	-12
Plant Load	kW	%	%	%	%	%	%	%	%
Cooling	760.0	-2.8	-2.8	-5.7	-5.7	-5.1	-5.1	-8.1	-8.1
Heating	227.3	-9.8	-9.8	-22.2	-22.2	-11.1	-13.6	-24.7	-33.3

5.4 CONCLUSIONS

Efficient design of a building's mechanical system involves proper selection of design weather data. The existing methodology for developing the design weather data is based on the principle of accepting a low risk that the extreme outdoor temperatures exceed the design values. Usually, the risk is expressed as a percentage of the total number of hours during the heating or cooling season. However, this approach neglects to consider the duration of outdoor temperatures and the thermal characteristics of the building which can effectively reduce the impact of extreme weather conditions for sufficient periods of time.

A new approach combines the duration of temperatures and the time constant of a building. Results from this study show definite improvements for summer and winter design values while still maintaining the same level of risk. For instance, if the designer considers a duration of 6 hours at a risk level of 2.5% in summer, the new design outdoor temperature in Montréal can be 25°C for light buildings or 24°C for heavier buildings, while the comparable ASHRAE design value for a similar level of risk is 29°C. Similarly in winter for a design risk level of 99%, design outdoor temperature values in Montréal can be -17°C for light buildings and -16°C for heavier buildings, whereas the corresponding ASHRAE design weather value in winter for an accepted risk level of 99% is -27°C.

Integrating the duration of temperatures and the thermal characteristics of a building will reduce the size of the central plant and also improve the efficiency of the system at part load. Central plant simulations using a building energy analysis program demonstrated selection of the new design outdoor temperatures can reduce the cooling and heating plant sizes by up to 8 and 33% respectively, thereby lowering the initial purchase cost of the mechanical system in the building.

CHAPTER 6

DATABASE OF BUILDING ENERGY SIMULATIONS

6.1 INTRODUCTION

A database containing the building design parameters and the corresponding annual energy performance predicted by the BLAST and BESA building energy analysis programs introduced in Chapters 2 and 4 is developed and presented in this section.

The main objective of the database is to assist architects and engineers in the preliminary design phase of an office building in Montréal. For example, the architect may wish to observe the effect of glazing areas and shading coefficients on the energy performance of the building, or the engineer may want to investigate the variation of the annual energy consumption due to the amount of fresh air supplied in the building. Coincidentally, the creation of the database will lay the foundations of a database structure file which will in-turn allow further simulations and/or different building types such as residential and industrial to be incorporated into the database. In addition, future possibilities may include linkage between computer simulations of the annual energy performance and the actual energy performance of a building. For instance, a database containing the energy performance of the buildings surveyed in Montréal in 1989 (Chapter 1) can be compared to computer simulations of buildings with similar design parameters.

6.2 COMPUTER DATABASE

The dBASE IV program developed by ASHTON-TATE [79] is an excellent database-management system which permits the architect/engineer to access and manipulate data in order to generate a list according to the needs of the user.

6.2.1 Building Parameters

A total of 529 simulations performed by BLAST (480) and BESA (49) are entered into the database. The database structure contains several prominent indices that define the building and the parameters that might modify the annual energy performance of the building. Each building parameter is described under a field name which can be defined as either character or numeric:

Field Name	Description
PROGRAM	- simulation program: "BLAST" or "BESA"
AREA	- total floor area of the building, in m^2
FLOORS	- number of floors in the building,
CONFIGURE	- configuration of the building: "SQUARE" = 30 x 30m "RECTANGLE" = 40 x 22.5m
ORIENTAT	- glazing orientation of the building: "NSEW" = North, South, East, West "NS" = North, South "EW" = East, West
GLAZING	- ratio of glazing area to exterior surface area, in percent
UEQV	- equivalent U-value for the entire building envelope, in $W/m^2\,^{\circ}C$

SC - shading coefficient,

HVAC - HVAC system type:
"VAV" = variable air volume
"IND" = VAV (interior), induction (perimeter)
"WLHP" = water loop heat pump
"RCHP" = reverse cycle heat pump

LOCATION - location of the HVAC system:
"CENTRAL" = serving perimeter and interior zones
"PERINT" = serving perimeter and interior zones separately
"MULTIPLE" = one system per floor

PEOPLE - number of people per unit area, people/m^2

LIGHTS - lighting load, in W/m^2

EQUIPMENT - equipment load, in W/m^2

INFIL - infiltration rate, ACH

OA - ventilation rate, in L/s/m^2

SAV - supply air volume, in L/s/m^2

SAT - supply air temperature, in °C

DISC - discriminator control:
"YES" or "NO"

ECONO - economizer type:
"NO" = no economizer
"WET" = enthalpy economizer
"DRY" = dry-bulb economizer

FAN - fan power, in W/L/s

COP - coefficient of performance of the chiller,

FUELTYPE - type of fuel supply:
"ELEC" = electricity
"GASELEC" = gas and electricity
"OILELEC" = oil and electricity

ENERGY - annual energy consumption, in kWh/m^2

COOLE - percentage of cooling energy from the annual energy consumption, HEATE - percentage of heating energy from the annual energy consumption,

ELECE - percentage of energy for fans, lighting and equipment from the annual electrical consumption,

COST - annual energy cost, in $\$/m^2$

ELECC - percentage of electrical cost from annual cost,

FUELC - percentage of oil or gas cost from annual cost.

6.2.2 Searching and Listing Information

The query screen in dBASE IV is a comprehensive tool which enables the user to access specific information about buildings. For instance, suppose that the architect / engineer wants to study the energy performance of certain design parameters. The user identifies the key design parameters in the top half of the "file skeleton" in the query-design work surface (for example, simulations performed by BLAST, with building dimensions 30x30m and 30% glazing on all 4 facades):

PROGRAM	CONFIGURE	ORIENTAT	GLAZING
"BLAST"	"SQUARE"	"NSEW"	30

The user then uses the "view skeleton" which appears in the bottom half of the query-design work surface, to observe only the energy performance of the building with the previously mentioned parameters (i.e. the annual energy consumption and the percentage of cooling, heating and electrical requirement, also the annual energy cost with the percentage of electricity and fuel):

ENERGY	**COOLE**	**HEATE**	**ELECE**	**COST**	**ELECC**	**FUELC**
244.5	10.6	61.4	28.0	8.66	54.1	45.9
234.2	11.2	59.4	29.4	8.40	56.2	43.8
220.9	12.4	56.1	31.5	8.10	59.4	40.6
218.1	13.5	53.7	32.8	8.11	61.8	38.2
286.0	9.2	66.7	24.1	9.78	48.2	51.8
275.5	9.6	65.3	25.1	9.51	49.9	50.1
260.6	10.4	62.8	26.8	9.15	52.6	47.4
246.3	11.8	59.3	28.9	8.84	56.2	43.8
299.3	8.7	68.2	23.1	10.14	46.7	53.3
287.9	9.2	66.7	24.1	9.84	48.3	51.7
273.6	10.0	64.5	25.5	9.49	50.7	49.3
258.3	11.2	61.2	27.6	9.16	54.2	45.8

The architect/engineer may then compare these results obtained for a square building (30x30m), to a building with dimensions 40 x 22.5m, (or he can ask for the average values):

PROGRAM	**CONFIGURE**	**ORIENTAT**	**GLAZING**
"BLAST"	"RECTANGLE"	"NSEW"	30

ENERGY	**COOLE**	**HEATE**	**ELECE**	**COST**	**ELECC**	**FUELC**
248.0	10.5	61.9	27.6	8.75	53.5	46.5
235.0	11.3	59.5	29.2	8.42	56.0	44.0
219.9	12.4	56.0	31.6	8.06	59.5	40.5
215.1	13.5	53.4	33.1	8.02	62.0	38.0
290.9	9.0	67.3	23.7	9.89	47.6	52.4
279.0	9.4	65.8	24.8	9.59	49.4	50.6
261.5	10.4	63.0	26.6	9.15	52.4	47.6
243.9	11.7	59.2	29.1	8.75	56.3	43.7
303.7	8.6	68.6	22.8	10.23	46.1	53.9
291.4	9.1	67.1	23.8	9.91	47.8	52.2
274.2	9.9	64.7	25.4	9.48	50.5	49.5
255.3	11.1	61.1	27.8	9.05	54.4	45.6

6.3 CONCLUSIONS

A database containing the building energy simulations performed by BLAST and BESA in this thesis was created using the dBASE IV program. The purpose of the database is to enable the architect / engineer to study the effect of certain design parameters on the annual energy performance of the building. Furthermore, the database provides the basic structure file necessary to incorporate further simulations of commercial buildings, as well as residential and industrial type buildings in Montréal (or of any other location).

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

In 1989, a research was carried out between May and October by an investigating team (including the author of this thesis) at the Centre of Building Studies, Concordia University, in collaboration with le Bureau de l'Éfficacité Énergétique du Québec and the Montréal Downtown Energy Forum programme. The main objective of the study was to analyze the pattern of energy use in office buildings in Montréal. The study demonstrated that 88% of the buildings surveyed had an annual energy budget higher than recommended target levels of 200-270 kWh/m^2 yr. Further, since the fall of oil prices in 1986 to $12.00 a barrel U.S., energy consumption in newer office buildings has increased at an annual rate of 12%, thus making these buildings quite vulnerable to present day oil price fluctuations (i.e. Gulf Crisis in 1990).

One of the main factors observed to contribute to the annual energy cost and consumption profile in the building survey is the glazing area. The average annual energy use increased by 95% in buildings, when the glazing to wall area percentage increased from 20 to 70%. In comparison, the lowest annual operating costs are observed for buildings with corresponding glazing areas between 35 and 40%.

ASHRAE Standard 90.1-1989, "Energy efficient design of new buildings except low-rise residential buildings" prescribes maximum permissible glazing areas for buildings throughout the United States. Research was performed in this thesis to develop similar optimum glazing areas in office buildings in Montréal, based on energy consumption and life cycle costs. These results indicate that based on energy performance, the optimum glazing areas are slightly higher in office buildings in Montréal (average 6.7%), than the ASHRAE design values for northern cities in the United States. Furthermore, based on life cycle costing, optimum glazing areas in office buildings can have twice the amount of glazing area as compared to corresponding ASHRAE guidelines.

Simulation of applied temperature drifts in the indoor working environment in buildings was performed to investigate the potential of energy conservation. A transient comfort model developed in Chapter 3 predicted the response of occupants to the applied temperature drifts. Results indicated that with acceptable temperature drifts of up to 2°C/hr in summer, the total system's cooling load was reduced by about 38% and the monthly peak cooling loads by 4.5%.

Building energy system's analysis demonstrated the most cost-effective way to provide the heating, cooling and ventilation needs for an office building in Montréal is through the application of a variable air volume system. The design of a VAV system for the reference building in Chapter 4 proved to be 40% more cost efficient than a combined VAV and induction system, and an average 23% more efficient than heat pump systems. Further, installation of high efficiency lighting fixtures and reset of supply air temperature resulted in annual cost and energy savings of 20.2 and 16.6% respectively.

In Chapter 5, a new approach was introduced which combines the duration of outdoor temperatures and the building thermal inertia. This approach enables the designer to reduce the size of the central plant, and improve its efficiency, while maintaining the same level of risk that the design outdoor temperatures would not be exceeded. Thus, it reduces the initial and operating costs of the mechanical systems in the building.

A database was created which contains the simulations performed for the reference building in the previous chapters. The database can assist architects and/or engineers in the conceptual design of building envelopes and mechanical systems.

7.2 RECOMMENDATIONS

To further enhance the results of the present study:

i) Additional analysis is recommended in order to examine the abundant data collected from the building survey, and to find subsequent building parameters contributing to energy use in buildings,

ii) Develop optimum glazing areas for some other reference buildings such as small office buildings or other types of HVAC systems,

iii) Additional validation of the transient comfort model to determine the potential of energy savings for allowed indoor temperature drifts in winter, and then to evaluate the best strategy for different types of HVAC systems in large office buildings.

iv) Development of a database which can link the simulation structure of the database to the actual building survey structure, and then to add further simulations of different types of buildings and HVAC systems to the existing database.

REFERENCES

1. Statistics Canada, "Quarterly report on energy supply-demand in Canada", Statistics Canada, Industry Division Energy Section. Catalogue 57-003 Quarterly, August 1990, Volume 14, Number 4.

2. "Canada inefficient in energy use, agency says", The Gazette, Montréal June 17, 1985.

3. "What a waste", The Gazette, Montréal October 20, 1990.

4. Bourassa, G.F., Latta J.K., Thompson, A.J., Housch, S. and Monteyne, R., "Energy Budgets for office buildings", Building Research and Practice 1981, Volume 9, Number 4.

5. Elmahdy, A.H., "Low-energy office buildings", Proceedings of the W67 Symposium held at the Division of Building Research, National Research Council of Canada, Ottawa, May 16, 1984.

6. Loftness, V. and Crenshaw, R., "The refinement of descriptive indices critical to improving the thermal performance of whole buildings", Buildings Thermal Envelope Coordinating Council (BTECC). Thermal Performance of the Exterior Envelopes of Buildings III, December 2-5, 1985.

7. Zmeureanu, R., "Energy Consumption in Office Buildings", Downtown Energy Forum 1987, Volume 1, Number 1.

8. Zmeureanu, R., "Energy Consumption in Montréal", Downtown Energy Forum 1989, Volume 3, Number 1.

9. Bevington, R. and Rosenfeld, A.H., "Energy for Buildings and Homes", Scientific American 1990, Volume 263, Number 3.

10. EIA. 1986, "Non-residential buildings energy consumption survey: Commercial buildings consumption and expenditures 1983", DOE/EIA-0318 (83). Washington, D.C.: U.S. Department of Energy/Energy Information Administration.

11. Piette, M., Wall, L.W. and Gardiner, B.L., "Measured Performance", ASHRAE Journal 1986, Volume 28, Number 1.

12. Spielvogel, L.G., "Energy Performance Data", ASHRAE Journal 1990, Volume 22, Number 1.

REFERENCES

13. "A baseline for energy design", Battelle Pacific Northwest Laboratory/U.S. Department of Energy, Progressive Architecture, 63(4), April 1982a.

14. "Energy design of office buildings", Battelle Pacific Northwest Laboratory/U.S. Department of Energy, Progressive Architecture, 63(6), June 1982b.

15. Brodrick, J.R., Crawley, D.B. and Briggs, R.S., "A new approach to buildings and energy analysis", ASHRAE Journal 1990, Volume 32, Number 8.

16. Zmeureanu, R., Fazio, P., Doramajian, A. and Noce, L., "Energy Performance of Office Buildings in Montreal in 1988", Bureau de l'Éfficacité Énergétique. Ministère de l'energie et des ressources, Gouvernement du Québec, 1989.

17. "Montreal Office Space Directory 1989", Published for the Building Owners' and Managers' Association of Montreal Inc. Canam Publications Ltd.

18. Elder, J. and Tibbott, R.L., "Do People Like Energy-Saving Offices?", Building Research and Practice 1981, September/October.

19. "An Act Respecting the Conservation of Energy in Buildings. R.S.Q.", Chap. E-1.1, Quebec 1984.

20. ASHRAE 1989, ASHRAE Standard 90.1A, "Energy Efficient Design of New Buildings Except Low-Rise Residential Buildings", Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers Inc.

21. Rudoy, W. and Duran, F., "Effect of Building Envelope Parameters on Annual Heating/Cooling Load", ASHRAE Journal 1975, Volume 17, Number 7.

22. Granit, M. and Möller, I., "Building Shape and Energy Demands", Building Research and Practice 1981, January/February.

23. Brotherton, T.M., Kreider, J.F., Claridge, D.E. and Norford, L.K., "A Multiclimate Comparison of the Simplified ASHRAE Building Consumption Model with DOE-2 Results", ASHRAE Transactions 1987, Volume 93, Part 2.

REFERENCES

24. Turiel, I., Boschen. R., Seedall, M. and Levine, M., "Simplified Energy Analysis Methodology for Commercial Buildings", Energy and Buildings 1984, 6.

25. Johnson, C.A., Besant, R.W., and Schoenau, G.J., "Economic Preferred Window Orientation and Optimum Fenestration Design Of a Non-Daylit and a Daylit Large Office Building For Different Climatic Conditions and Different Billing Structures", ASHRAE Transactions 1990, Volume 96, Part 1.

26. Crawley, D.B., "Envelope Strategies for a Corporate Headquarters Office Building", ASHRAE Journal 1985, Volume 27, Number 4.

27. Johnson, C.A., Besant, R.W. and Schoenau, G.J., "An Economic Parametric Analysis of the Thermal Design of a Large Office Building Under Different Climatic Zones and Different Billing Schedules", ASHRAE Transactions 1989, Volume 95, Part 1.

28. ASHRAE 1980, ASHRAE Standard 90.A, "Energy Conservation in New Building Design", Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers Inc.

29. Crawley, D.B. and Briggs, R.S., "Standard 90, The Value - Extensive Computer Simulation testing Demonstrates Energy Conservation Impact on Buildings by Proposed Standard 90.1", ASHRAE Journal 1985, Volume 27, Number 11.

30. Hittle, D.C., "BLAST, The Building Load Analysis and Systems Thermodynamics Program, Vol. 1: User's Manual", U.S. Army Construction Engineering Research Laboratory, Champaign, Illinois, December 1977.

31. Youill, G.K., "Verification of the BLAST Computer Program for Houses, A Research Report", Energy, Mines and Resources Canada, November 1983. Buildings Energy Technology Transfer (BETT), Publication Number 83.05.

32. Yuill, G.K. and Phillips, E.G., "Comparison of BlAST Program Predictions with the Energy Consumption of Two Buildings", ASHRAE Transactions 1981, Volume 87.

REFERENCES

33. Fazio, P. and Zmeureanu, R., "Energy Analysis in Buildings Through Computerized Techniques", 1989, Centre of Building Studies, Concordia University, Montréal.

34. ASHRAE 1980, ASHRAE Handbook - 1980 Systems. Chapter 45, Life Cycle Costs. Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers Inc.

35. Hanscomb's "Yardsticks for Costing", 1989, Southam Business Information and Communications Group Inc., Don Mills, Ont.

36. Hayter, R.B., "Comfort education for energy conservation", ASHRAE Transaction 1987, Volume 93, Part 1.

37. McNall, P.E., Pierce, E.T. and Barnett, J.P., "Control strategies for energy conservation", Energy Conservation Strategies in Buildings, 1978. Edited by Stolwijk, John B. Pierce Foundation.

38. Fleming, W.S., "Energy conservation: an investigation of the thermal comfort alternative", ASHRAE Transaction 1979, Volume 85, Part 2.

39. ASHRAE 1975, ANSI/ASHRAE Standard 90-1975, "Energy Conservation in New Building Design", Atlanta: American Society of Heating, Refrigerating and Air- Conditioning Engineers Inc.

40. ASHRAE 1981. ANSI/ASHRAE Standard 55-81. "Thermal environmental conditions for human occupancy", Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

41. Nelson, T.M., Nilsson, T.H. and Hopkins, G.W., "Thermal Comfort: Advantages and Deviations", ASHRAE Transaction 1987, Volume 93, Part 1.

42. Nevins, R.G., "Energy: Conservation strategies and human comfort", ASHRAE Journal 1975, April.

43. Berglund, L.G., "Control and simulation of thermal comfort", Proceedings of the workshop of HVAC controls modelling and simulation. Georgia Institute of Technology 1984, February 2-3.

REFERENCES

44. Schiller, G.E. and Arens, E.A., "Thermal comfort in office buildings", ASHRAE Journal 1988, Volume 30, Number 10.

45. Schiller, G.E., Arens, E.A., Bauman, F.S., Benton, C., Fountain, M. and Doherty, T., "A field study of thermal environments and comfort in office buildings", ASHRAE Transaction 1988, Volume 94, Part 2.

46. Griffiths, I.D. and McIntyre, D.A., "Sensitivity to temporal variations in thermal conditions", Ergonomics 1974, 17(4),

47. McIntyre, D.A. and Griffiths, I.D., "Changing temperatures and comfort", Building Service Engineering 1974, 42(8).

48. Berglund, L.G. and Gonzalez, R.R., "Application of acceptable temperature drifts to built environment as a mode of energy conservation", ASHRAE Transaction 1978, Volume 84, Part 1.

49. Berglund, L.G. and Gonzalez, R.R., "Occupant acceptability of eight-hour-long temperature ramps in the summer at low and high humidities", ASHRAE Transaction 1978, Volume 84, Part 2.

50. Berglund, L.G., "Thermal Acceptability", ASHRAE Transaction 1979, Volume 85, Part 2.

51. Rohles, F.H., Hayter, R.B. and Berglund, L.G., "Comfort and cold and warm discomfort during summer and winter in northern and southern United States", ASHRAE Transaction 1977, Volume 83, Part 1.

52. Hensen, J.L.M., "Literature Review on Thermal Comfort in Transient Conditions", Building and Environment, 1990.

53. Gagge, A.P., Stolwijk, J.A.J., and Nishi, Y. "An effective temperature scale based on a simple model of human physiological regulator response". ASHRAE Transactions, 70, 1970

54. Berglund, L., "Mathematical models for predicting the thermal comfort response of building occupants", ASHRAE Transaction 1978, Volume 84, Part 1.

REFERENCES

55. Doherty, T.J. and Arens, E., "Evaluation of physiological bases of thermal comfort models", ASHRAE Transaction 1988, Volume 94, Part 1.

56. ASHRAE 1989, ASHRAE Fundamentals Volume. Chapter 8: "Physiological Principles, Comfort, and Health". Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

57. Rohles, F.H., Hayter, R. and Milliken, G., "Effective Temperature (ET*) as a Predictor of Thermal Comfort", ASHRAE Transactions 1975, Volume 81, Part 2.

58. Gagge, A.P., Fobelets, A.P. and Berglund, L.G., "A standard predictive index of human response to the thermal environment", ASHRAE Transaction 1986, Volume 92, Part 2B.

59. Cleary, C.M. and Schuldt, M.A., "Predicted vs. Actual Conservation Opportunities in Commercial Buildings: Lessons learned from measured energy performance", ASHRAE Transaction 1989, Volume 95, Part 2.

60. Nall, D.H. and Crawley D.B., "Energy Simulation in the Building Design Process", ASHRAE Journal, 1983, Volume 25, Number 11.

61. "Energy Design of Office Buildings", Battelle Pacific Northwest Laboratories. Progressive Architecture, 1982b, Volume 632, Number 6.

62. Jordan, C., "Central vs. local HVAC fan systems for highrise office buildings", ASHRAE Journal 1989, Volume 31, Number 9.

63. BESA (Building Energy Systems Analysis). Retrofit V2.0. Developed by: Canadaplan Group Inc., Hamilton, Ontario, Canada and Ferriera, Kalazinsky & Assoc., Norton, MA. U.S.A., under contract with Public Works Canada, 1987.

64. ASHRAE 1989, ASHRAE Standard 62, "Ventilation for Acceptable Indoor Air Quality", Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers Inc.

REFERENCES

65. Règlement No. 499 D'Hydro-Québec 1990, Etablissant les tarifs d'électricité et les conditions de leur application.

66. Gaz Metropolitan, price quote by phone on June 15, 1990, Montréal, Québec.

67. Texaco Canada, price quote by phone on June 15, 1990, Montréal, Québec.

68. Mechanical Conversion Handbook for Mechanical Engineers in the Building Industry, 1984, Public Works Canada.

69. Means Mechanical Cost Data, 1990, 13th Edition. R.S. Means Company Inc.. Construction Consultants & Publishers. Kingston MA.

70. Wong-Kcomt, J.B., Turner,W.G., Hung, S. and King, W.R., "New Lighting Options for State Buildings", Energy Engineering, 1990, Volume 87, Number 1.

71. ASHRAE 1989, ASHRAE Fundamentals Volume, Chapter 24: "Weather Data and Design Considerations". Atlanta: American Society of Heating, Refrigerating and Air-Condition Engineers, Inc.

72. Handbook of Air-Conditioning System Design, Carrier Air-Conditioning Company, McGraw-Hill Book Company, 1965.

73. The Chartered Institute of Building Services Engineers, "Design Data", 1986, Volume A, Table A2.22.

74. Supplément du Code National du Bâtiment du Canada, 1985.

75. Snelling, H.J., "Duration Study for Heating and Air-Conditioning Design Temperatures", ASHRAE Journal, May 1985.

76. Richard, O.E., "Evaluating Design Temperatures for HVAC Applications in Extreme Climates", ASHRAE Transactions 1982, Volume 88, Part 1.

77. Berg-Hallberg, E.M., "Design Outdoor Temperature for Buildings in Sweden", KTH, Stockholm, 1983:1, Volume 13.

78. Peterson, F., "Design Outdoor Temperature - A New Concept", KTH, Stockholm, 1986:1, Volume 16.

REFERENCES

79. "Installing dBASE IV Developer's Edition", ASHTON-TATE, Torrance, California, 1990.