RESEARCH REPORT

Monitored Performance of an Innovative Multi-Unit Residential Building: Final Report

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MONITORED PERFORMANCE OF AN INNOVATIVE MULTI-UNIT RESIDENTIAL BUILDING

FINAL REPORT

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ABSTRACT

A research project was undertaken to investigate a wide variety of aspects in an innovative condominium building in Dundas, Ontario. The 48 unit, 6 storey building was designed to use 35% less energy than a similar building designed to just meet the MNECB. The research project was set up to determine the potential for meeting a reasonable air sealing specification though detailing, training of trades, site inspection, testing, corrective action and retesting.

Many innovative features were included in the building design. Several were included in the research project. These included:

- indoor air quality
- ventilation effectiveness
- building energy performance
- heating appliance energy performance
- building water consumption
- heat, air and moisture transfer through the walls

A quantitative analysis of the performance of these areas is presented. The benefits and shortcomings in each area are examined.

ACKNOWLEDGEMENTS

The authors wish to thank the following individuals and organizations.

Mr. Richard Leibtag of Urban Horse Developments for making this project possible by having the foresight to build such an innovative building.

The condominium owners who agreed to allow monitoring of their suites.

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Mr. Tony Wood of Can-Am Air Leakage Control for his assistance with air leakage testing at the building.

EXECUTIVE SUMMARY

The innovative condominium in Dundas, Ontario was designed around the four main goals of the IDEAS Challenge and C-2000 programs. These include envelope durability, energy efficiency, indoor air quality and mechanical ventilation, and environmental and resource conservation. The building was designed to have energy consumption 35% lower than a similar building designed to meet the MNECB. The thermal comfort and indoor air quality were also expected to be better than that in typical apartment buildings. Improved building features include

- an airtight and well-insulated building envelope using both EIFS and brick veneer cladding
- combo space/water heating systems using the water heater connected to and air handler
- individual in-suite HRVs
- water efficient appliances and fixtures
- energy-efficient appliances, lighting etc.

The building was constructed during 1998 and 1999 with occupancy in the summer of 2000.

To better understand the operation of the building a comprehensive monitoring and evaluation program was undertaken. The monitoring program consisted of one-time measurements of envelope airtightness, indoor air quality, ventilation system performance and air movement. A PC-based data acquisition system was installed. Performance monitoring included the heating systems, building envelope, and ventilation systems. Monitoring was undertaken to understand long-term system performance, indoor air quality and overall energy performance. Short-term testing was also undertaken to investigate building air tightness and indoor air quality issues.

Blower door testing showed that that building air tightness targets were essentially reached. The wall systems are relatively airtight and their performance shows no real dependence on indoor/outdoor pressure differences. Temperature and humidity measurements indicate that the wall systems are functioning well with no indication of moisture buildup or condensation in the walls.

The seasonal efficiency of the combo space/water heating systems ranged from 35 to 45%. These efficiencies are below the water heater energy factor of 0.58. Combo-system efficiency appeared to have been compromised by a lack of burner set-up during installation and by tank standby losses.

Despite low equipment efficiency, the monitored building heating energy and electricity consumption is 137 kWh_e. This exceeds the target of 35% total energy use reduction relative to the MNECB. There is a wide variation in energy use between suites depending on HRV operation, thermostat set-point, occupancy patterns and heating equipment efficiency. Water consumption is 0.5 $m^3/m^2/yr$, approximately 25% that of other apartment buildings.

Tracer gas measurements indicated that the suites are well ventilated and there is little suite-to-suite and corridor-to-suite air movement. Although some garage air is entering the central corridors, the ventilation systems in the corridors, garage and individual suites and the weather stripping of suite doors are effective in limiting garage pollutants from entering in the suites. Readings of formaldehyde, respirable particulates and VOCs in one suite were within Heath Canada guidelines, showing excellent indoor air quality can be achieved with proper construction and ventilation techniques.

The average outdoor air ventilation rate is 0.29 ACH with the HRV operating and 0.39 ACH when the HRV and the central air handler are operating, showing good overall ventilation. Room readings showed good distribution to each room regardless of fan operating strategy. It appears that, with proper ducting design, the HRV can distribute ventilation air throughout the suites (without continuous operation of the central air handler). The building shell is tight with a natural ventilation rate through the envelope of only 0.06 ACH.

In summary, the building is performing very well. The design concept of an airtight, well insulated envelope, in-suite HRVs and building compartmentalization appear to be working as expected. However, the combo heating systems, high-efficiency furnace and mid-efficiency central boiler are performing below their laboratory-certified ratings.

RÉSUMÉ

L'immeuble en copropriété innovateur de Dundas, en Ontario, a été conçu en fonction des quatre grands objectifs du Défi IDÉES et du programme C-2000, à savoir la durabilité de l'enveloppe, l'efficacité énergétique, la qualité de l'air intérieur et la ventilation mécanique de même que la préservation de l'environnement et des ressources. Ce bâtiment devait avoir une consommation d'énergie de 35 % inférieure à celle d'un bâtiment similaire conforme aux normes du Code modèle national de l'énergie pour les bâtiments (CMNÉB). Le confort thermique et la qualité de l'air intérieur devaient aussi être supérieurs à ceux d'immeubles d'appartements typiques. C'est pourquoi le bâtiment possède les caractéristiques évoluées suivantes :

- une enveloppe étanche à l'air et bien isolée grâce à un système d'isolation des façades avec enduit (SIFE) et à un placage de brique
- une installation combinée de chauffage de l'eau et des locaux faisant appel à un chauffe-eau raccordé à un appareil de traitement de l'air
- des ventilateurs-récupérateurs de chaleur dans chaque logement
- des appareils de plomberie à faible consommation d'eau
- des électroménagers et des appareils d'éclairage éconergétiques

Le bâtiment a été construit en 1998 et 1999, et les occupants y ont emménagé au cours de l'été 2000.

Pour mieux comprendre le fonctionnement de tous les éléments du bâtiment, on a mis au point un programme complet de surveillance et d'évaluation. C'est ainsi qu'on a procédé à des mesures ponctuelles de l'étanchéité à l'air de l'enveloppe, de la qualité de l'air intérieur, de la performance de l'installation de ventilation et du mouvement de l'air. On a aussi mis en place un système d'acquisition de données tournant sur ordinateur personnel. Le contrôle de la performance a porté sur les installations de chauffage, l'enveloppe du bâtiment et la ventilation. Cette surveillance a servi à comprendre la performance à long terme des installations et assemblages, la qualité de l'air intérieur et le rendement énergétique global. De plus, on a effectué des essais à court terme pour connaître l'étanchéité à l'air du bâtiment ainsi que la qualité de l'air dans les logements.

Un test d'infiltrométrie a montré que les objectifs d'étanchéité à l'air fixés avaient essentiellement été atteints. Les assemblages muraux se sont avérés relativement étanches et leur performance n'a pas semblé être tributaire des différences de pression entre l'intérieur et l'extérieur. Les mesures de la température et de l'humidité ont révélé que les assemblages muraux s'acquittent bien de leur fonction sans montrer de signe d'accumulation d'humidité ou de condensation interne.

L'efficacité saisonnière de l'installation combinée de chauffage de l'eau et des locaux variait de 35 à 45 %. Ces chiffres sont inférieurs au facteur énergétique de 0,58 du chauffe-eau. L'efficacité de l'installation combinée semble avoir été compromise parce que le brûleur n'avait pas été réglé au moment de la mise en place et à cause des pertes de chaleur par la paroi du chauffe-eau.

Malgré la faible efficacité de l'équipement, on a pu obtenir une consommation d'énergie de chauffage et d'électricité de 137 kWh_e pour le bâtiment mis à l'essai. Cette valeur dépasse l'objectif de réduction de 35 % de l'utilisation totale d'énergie par rapport au CMNÉB. La consommation d'énergie varie beaucoup d'un logement à l'autre selon l'utilisation des ventilateurs-récupérateurs de chaleur, la température de consigne des thermostats, les habitudes des occupants et l'efficacité de l'équipement de chauffage. La consommation d'eau est de 0,5 m^3/m^2/an, soit environ 25 % de ce que l'on constate dans les autres immeubles d'appartements.

Les mesures prises au moyen d'un gaz traceur portent à croire que les logements sont bien ventilés et que les mouvements d'air entre les appartements, et entre les corridors et les appartements, sont faibles. Bien qu'un certain volume d'air provenant du garage s'infiltre dans les corridors centraux, les dispositifs de ventilation dans les corridors, le garage et les logements individuels, ainsi que le calfeutrage des portes des appartements, parviennent à limiter l'infiltration des polluants dans les logements. Les concentrations de formaldéhyde, de particules inhalables et de composés organiques volatils dans un logement étaient conformes aux directives de Santé Canada à ce sujet. Il est donc possible d'atteindre une excellente qualité de l'air intérieur lorsqu'on a recours à des techniques appropriées de construction et de ventilation.

Le taux moyen de renouvellement d'air est de 0,29 lorsque le ventilateur-récupérateur de chaleur fonctionne et de 0,39 lorsque le ventilateur-récupérateur de chaleur et l'appareil central de traitement de l'air sont en marche, ce qui montre que la ventilation s'avère bonne dans l'ensemble. Les lectures prises dans les pièces ont révélé une bonne distribution de l'air dans chaque pièce peu importe la façon dont la ventilation avait été utilisée. Il semble qu'une bonne conception du réseau de conduits permette au ventilateur-récupérateur de chaleur de distribuer l'air de ventilation dans tous les logements (sans pour autant que l'appareil central de traitement de l'air fonctionne en continu). L'enveloppe du bâtiment est très étanche puisqu'elle affiche un taux de ventilation naturelle d'à peine 0,06.

En résumé, ce bâtiment offre un excellent rendement. Le concept d'une enveloppe étanche à l'air et bien isolée et de logements dotés de ventilateurs-récupérateurs de chaleur dans un bâtiment compartimenté semble donner les résultats escomptés. Néanmoins, l'installation de chauffage combinée, le générateur de chaleur à haute efficacité et la chaudière centrale à efficacité moyenne donnent un rendement inférieur à leurs cotes de certification en laboratoire.

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Table of Contents

Abstract ii

Acknowledgements iii

Executive Summary iv

Table of Contents vi

List of Figures ix

List of Tables xi

1. INTRODUCTION 1

- 1.1 Background 1
- 1.2 Overview of Building Design 2
- 1.3 Overview of Monitoring Program 9

2. BUILDING ENVELOPE AIRTIGHTNESS 12

- 2.1 Overview 12
  - Stakeholder and Contractor Education 13
  - Air Leakage Testing 13
- 2.2 Envelope Design 14
  - Original Envelope Design 14
  - Changes to the Original Design 17
- 2.3 Representative Wall Air Leakage Test 19
  - Purpose 19
  - Test Procedure 19
  - Test Conditions 22
  - Analysis and Results 22
  - Leakage Locations 23
- 2.4 Individual Suite Test 26
  - Purpose 26
  - Test Procedure 26
  - Test Conditions 28
  - Results and Analysis 29
  - Possible Sources of Error 30
  - Interpretation of Results 30
  - Air Leakage Location Identification 31
- 2.5 Whole Building Air Leakage Test 33
  - Purpose 33
  - Test Procedure 33
  - Test Conditions 35

Analysis and Results 36
2.6 Conclusions 37

3. HEAT, AIR AND MOISTURE TRANSPORT in the BUILDING ENVELOPE 39
3.1 Wall Systems 39
3.2 Monitoring Approach 42
Monitoring of the Brick Veneer Wall 42
Monitored Weather Conditions 43
3.3 Monitoring Results 43
Temperature Performance 43
Moisture Accumulation in the Walls 48

4. HEATING SYSTEM PERFORMANCE 49
4.1 Description of Heating Systems 49
Combo-Systems 49
Independent Furnace/Water Heating Systems 50
Central Common Area System 50
4.2 Monitoring System 51
4.3 Monitoring Results 52
Combustion Efficiency Results 52
Heating Loads 54
Heating System Monitored Results 55

5. VENTILATION AND INDOOR AIR QUALITY 61
5.1 Ventilation Design for IAQ 61
5.2 Indoor Air Quality Testing 64
5.3 Ventilation Testing Results 71
5.4 Long-Term Testing Results 78
Temperature 78

6. ANNUAL ENERGY CONSUMPTION 82
6.1 Overview 82
6.2 Energy Consumption 83
Electricity 83
Natural Gas 86
Total Building Energy Consumption 88
6.3 Water Consumption 91

7. CONCLUSIONS 92
Building Air Tightness 92
Heat, Air and Moisture Transport in Walls 92
Heating System Performance 93
Ventilation and Indoor Air Quality 93

Annual Energy Consumption.. 94

8. REFERENCES 95

Appendix A. List of Sensors

Appendix B. Air Sealing Objectives and Strategies Presentation

List of Figures

Figure 1.1: The Innovative Condominium in Dundas, Ontario 1
Figure 1.2: Thermally-Broken Balcony Support Detail 5
Figure 1.3: Photograph of Pre-Cast Balconies 5
Figure 2.1: As-Designed Window Sealing Detail – Brick Veneer Wall 15
Figure 2.2: As-Designed Window Sealing Detail – EIFS Wall....................................... 15
Figure 2.3: As-Designed Wall Intersection Detail – Brick Veneer and EIFS.................. 16
Figure 2.4: As-Built Window Sealing Detail – Brick Veneer Wall 18
Figure 2.5: As-Built Window Sealing Detail – EIFS Wall.. 19
Figure 2.6: Leakage Locations Identified in Representative Wall 21
Figure 2.7: Temporary Polyethylene Wall with Perimeter Taped 22
Figure 2.8: Air Leakage Found at King Studs 25
Figure 2.9: Hole Left Unsealed When Brick Tie Relocated 25
Figure 2.10: Leakage Location Identified in Representative Suite 28
Figure 2.11: Wiring Passing Through Floor Slab Left Unsealed 32
Figure 2.12: Drywall Compound for Smoke Control Falls Off Electrical Box 33
Figure 2.13: Blower Doors Locations for Whole Building Depressurization Testing 35
Figure 3.1: Instrument Locations In Brick Veneer Wall 40
Figure 3.2: Instrumentation Locations for Sixth Floor EIFS Wall................................... 41
Figure 3.3: Instrument Locations for Fourth Floor EIFS Wall 41
Figure 3.4: Temperatures Across Brick Wall on a Cold Day 44
Figure 3.5: Temperatures Across an EIFS Wall on a Cold Day 45
Figure 3.6: Theoretical and Monitored Temperature Index for a Brick-clad Wall............ 46
Figure 3.7: Theoretical And Monitored Temperature Index for an EIFS Wall 46
Figure 4.1: Combo-System Monitoring Schematic 52
Figure 4.2: Monitored Efficiency for Three Water Heaters 57
Figure 5.1: Typical Suite Ventilation System Schematic... 62
Figure 5.2: PFT Equipment Layout for Whole Building Testing 66
Figure 5.3: Equipment Layout for SF_6 Testing 68
Figure 5.4: PFT Equipment Layout for In-Suite Testing.. 69
Figure 5.5: Equipment Layout for Suite IAQ Testing 70
Figure 5.6: PFT Test Results for Vertical Air Movement Within Building........................ 72
Figure 5.7: PFT Test Results for Horizontal Air Movement on First Floor 73
Figure 5.8: PFT Test Results for Horizontal Air Movement on First Floor 74

Figure 5.9: Monitored Temperatures in Three Suites 79
Figure 5.10: Monitored Relative Humidity in Three Suites 81
Figure 6.1: Daily Average Suite Electricity Consumption 84
Figure 6.2: Variation in Suite Electricity Consumption 85
Figure 6.3: Common Area Daily Average Electricity Consumption 86
Figure 6.4: Daily Average Suite Natural Gas Consumption 87
Figure 6.5: Variation in Daily Average Natural Gas Consumption 87
Figure 6.6: Comparison of Monitored and Simulated Energy Consumption 89
Figure 6.7: Building Energy End-Use Breakdown from EE4 Model 90

List of Tables

Table 1.1: Building Design vs. MNECB Reference Building 3

Table 2.1: Air-Tightness Results for Representative Wall Test 23

Table 2.2: Air-Tightness Results for Representative Suite 29

Table 2.3: Test Results for Whole Building Depressurization Test 36

Table 2.4: Adjusted Air-Tightness Results for Three Tests 38

Table 4.1: Combustion Efficiency Test Results for Four Appliances 53

Table 4.2: Monitored Operating Parameters for Three Suites 55

Table 4.3: Monitored Performance Parameters for Five Appliances 56

Table 4.4: Performance Comparison: Combo-System to Separate Appliances 60

Table 5.1: Results Summary for Building Air Movement 75

Table 5.2: Results Summary for SF_6 Tracer Gas Testing 76

Table 5.3: Results Summary for Indoor Air Quality Testing 78

Table 5.4: Monitored Indoor Temperatures for Five Locations 78

Table 5.5: Monitored Relative Humidity for Five Locations 80

Table 5.6: Monitored CO_2 Levels for Four Locations 81

Table 6.1: Monitored Building Energy Consumption 88

1. INTRODUCTION

1.1 Background

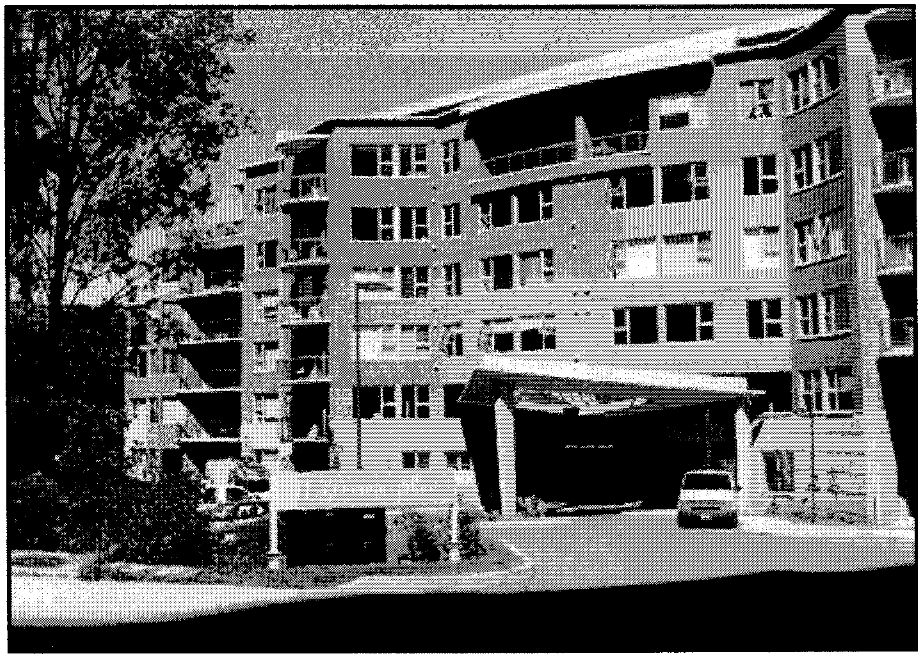

Figure 1.1: The Innovative Condominium in Dundas, Ontario

The innovative condominium building in Dundas, Ontario was designed around the environmental and energy goals of the IDEAS Challenge/C-2000 programs [CMHC, 2000, NRCan, 2000]. The building was designed to have 35% lower energy consumption than a similar building designed to the Model National Energy Code for Buildings (MNECB) [NRC, 1997]. Thermal comfort and indoor air quality were also expected to be better than that in typical apartment buildings due to improved building features including:

- an airtight and well-insulated envelope
- natural gas-fired combo space/water heating systems
- individual in-suite heat recovery ventilators (HRVs)
- energy-efficient lighting

The building was designed in 1997 and construction began in 1998. The first occupants moved into the building during the summer of 2000 and the building was fully occupied by the end of 2000. A research project was undertaken to monitor and assess five aspects of the building's performance:

- airtightness of building envelope
- heat, air and moisture transport in the building envelope
- performance of various space and water heating systems
- effectiveness of the building ventilation systems in achieving good indoor air quality
- overall energy and water consumption

A variety of techniques were used to assess the building performance:

- one-time blower door tests
- short-term tracer gas tests
- monthly suite meter readings
- a comprehensive data acquisition system to collect and store one-year's data

This report describes the monitoring methodology and results. Where possible, the performance of the innovative condominium in Dundas, Ontario is compared to the performance of typical Canadian apartment buildings. Sections 2 through 6 present this information for the five aspects of the building studied.

1.2 Overview of Building Design

This innovative condominium brings high-quality design and construction to the speculative condominium market. This building is the first phase of a larger development located on a 0.5 hectare abandoned industrial site in the centre of Dundas, Ontario. The building envelope details were designed to provide innovative solutions to heat, air and moisture movement deficiencies common in multi-storey residential buildings. The high-performance design was engineered to reduce operating costs by 35% when compared with current good practice in multi-unit residential construction. There were additional design goals beyond energy efficiency:

- longer building life
- lower maintenance requirements
- exceptional occupant comfort, health and safety

The building is an 8,300 m^2, 6-storey concrete structure above a 2,000 m^2 partially buried parking garage. The 1,820 m^2 common areas include a community room with kitchen facility and outdoor terrace, hot tub and shower room, games/meeting room, exercise room and guest suite. The residential suites average about 140 m^2 each and are a mix of one- and two-bedroom units. Most of the residents are seniors; all suites have only one or two occupants.

Table 1.1 provides a summary of design values for building shell components, the HVAC system and lighting for the innovative condominium as compared to model national energy code for buildings (MNECB) requirements. The Reference Building is the building that would have been built if the condominium were designed to just meet the minimum requirements of the MNECB.

Table 1.1: Building Design vs. MNECB Reference Building

	Innovative Condominium	MNECB Reference Building
Outdoor Air, suites	0.35 ACH	0.35 ACH
Fenestration U-value (W/m^2°C)	1.6	3 4
Opaque Wall U-value (W/m^2°C)	0.32	0.55
Roof U-value (W/m^2°C)	0.23	0.47
Ground Floor Insulation (m^2°C/W)	3.57	2.13
HVAC System	Suites: natural gas water heater for space and hot water (E_t=80%), 4-pipe fan coil with ECM blower motor, served by central water-cooled screw chiller (design COP=4.3), HRVs with 65% effectiveness Common area: central gas-fired boiler (E_t=84%)	Suites and common area: 4-pipe fan coil served by central water-cooled screw chiller (COP=3.8) and gas-fired hot water boiler (E_t=80%), central gas-fired make-up air unit with individual exhaust fans
Lighting power density, suites	9 W/m^2	9 W/m^2
Lighting power density, common areas	6.1 W/m^2	9 1 W/m^2
Lighting controls	Occupancy sensors in parking garage	Manual switching

Building Envelope

Exterior and interior walls were constructed with steel stud framing that is lightweight and results in a relatively thin wall (maximizing usable floor area), inexpensive material costs per unit of wall area, and low installation costs. Approximately half the exterior wall area is brick veneer and half is an exterior wall insulation and finish system (EIFS). High levels of insulation were achieved using urethane and polystyrene foam insulation over the entire exterior of the building. Continuous exterior insulation eliminated thermal bridging at wall studs and floor slabs. Additional insulating value was obtained by filling the 90 mm steel stud cavity with fibreglass batts. The average wall insulation value is RSI 3.12 (R18) including the thermal bridging at the steel studs. The concrete roof slab is covered with semi-rigid mineral fibre insulation having a minimum RSI 4.35 (R24) at any point on the roof. Fibre insulation was tapered so that the roof deck could be sloped toward the roof drains. Typically the RSI-value would be reduced to below the specified value wherever the insulation was tapered.

The thermal integrity of the envelope was further maintained by innovative design at sites that are normally significant thermal bridges. Two examples are of particular interest:

- shelf angles supporting the brick veneer were moved outboard of the exterior insulation
- balcony slabs were hung from insulated shelf angles, disconnecting the balcony slab from the floor slab (Figure 1.2 and 1.3)

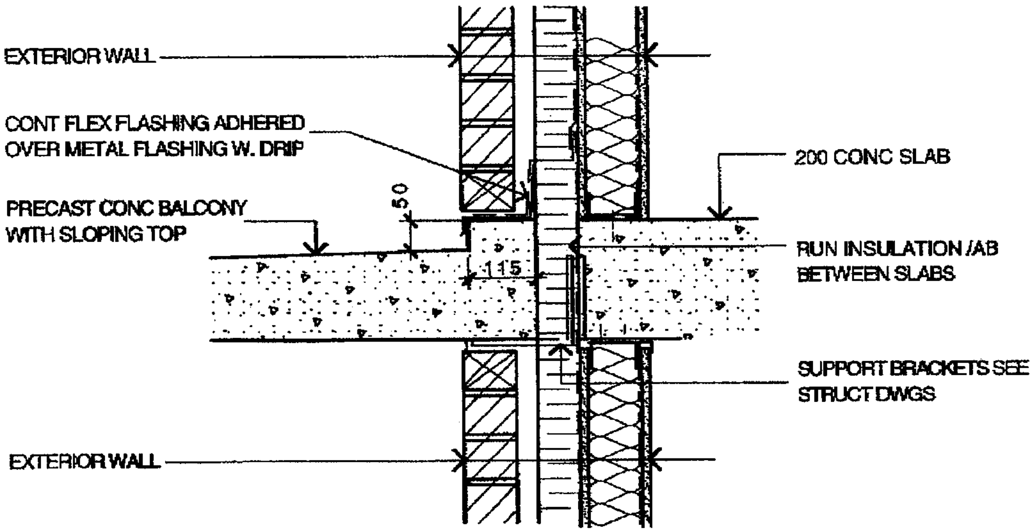

Figure 1.2: Thermally-Broken Balcony Support Detail

Figure 1.3: Photograph of Pre-Cast Balconies

A gypsum-board air barrier system was placed outside of the steel studs to control air movement. Joints in the gypsum board were sealed with either sheathing tape or foamed-in-place insulation. The vapour retarder, which controls moisture movement, is formed by the foam insulation outside of the fiberglass insulation. Simulations using CMHC's computerized heat, air, and moisture transfer analysis program EMPTIED [CMHC, 1998] showed that condensation would not occur because the temperature at the plane of the vapour retarder was always above the dew point temperature of indoor air. The integrity of the air barrier/vapour retarder was maintained by close attention to construction details. Vapour impervious materials were used to seal rough openings around exterior penetrations such as windows, doors and duct sleeves. The building trades were given training, construction details, and directions on proper sealing of holes for services penetrating exterior walls.

Water penetration from the exterior is controlled through a variety of measures. The brick veneer finish was designed and constructed using the principles of a pressure equalized rainscreen. Air pressure equalization between the front and back of the brick veneer eliminates a major driving force that can carry water into the envelope. It was important to ensure any water breaching the building brick façade be effectively carried back to the building exterior; therefore, flashing details were given special consideration.

The EIFS system was installed as a face-sealed system to protect against water penetration. Flashing and caulking details that ensure water does not get behind the EIFS face were important.

Careful consideration was given to both energy efficiency and thermal comfort in the selection of the windows and sliding glass doors. All are double-glazed units incorporating six important features:

- spectrally-selective coating to reduce overheating in summer
- low-e coating and argon gas fill to increase heat retention in winter
- high-performance fiberglass frames
- insulating edge-spacers
- exceptionally airtight construction in both the fixed and the operable configurations

The overall window U-value is a low 1.61 W/(m^2 °C), in contrast to the MNECB requirement of 3.2 W/(m^2 °C). The combination of high-performance windows, high wall-insulation levels and low air leakage results in quieter suites, warmer exterior wall surfaces and reduced drafts compared to conventional construction practices.

Consequently, perimeter heating is not required to maintain acceptable levels of thermal comfort and construction costs are reduced.

Two problems associated with parking garages in multi-unit residential buildings are cold floors above the parking garage and the need to provide freeze protection for water services running at garage ceiling level. Both problems were avoided at this innovative condominium by installing an insulated ceiling (RSI 3.57/ R20) under the pipes and by installing minimal heating into the cavity created immediately under the floor. This arrangement keeps the floors above the parking garage warm while the pipes are protected from freezing without significant heat loss to the garage.

Heating and Cooling Systems

Five design goals were set for the heating and cooling systems:

- to minimize space heating and cooling loads
- to minimize installation and operating costs
- to minimize equipment space requirements
- to provide for individual environmental control
- to allow for individual suite billing

A combination water/space heating system (combo-system) was installed in most suites in a small utility/laundry room. The system consists of a heating source (a natural gas-fired power-vented water heater) and a heat distribution system (an air-handler connected to a supply and return air duct system). The air-handler contains a hot water coil, a chilled water coil connected to the central chiller, and an energy-efficient electronically commutated motor (ECM) to drive the fan. Water heater tank sizes are based on the floor area of the suite. The larger, top floor units have 190-litre tanks and all other suites have 151-litre tanks. Heating, cooling and ventilation air is ducted to each room from the unit. To reduce electrical operating costs, the blower operates only when heating or cooling is required.

Due to heat load considerations, the two largest penthouse suites each have a condensing gas-fired furnace and stand-alone gas-fired water heater. A 150-kW mid-efficiency (84%) central gas-fired boiler provides heating for building common areas.

A central 262-kW (75 Ton) water-cooled chiller located in the penthouse mechanical room provides chilled water for air conditioning. This is the only central mechanical system serving the whole building. Energy-efficient features were specified for the chiller. Two of these features are:

- digital control to maximize the benefits of advantageous outdoor weather conditions
- variable-speed cooling tower fans and pumps to minimize electricity use

Air conditioning is provided in each suite by a 7-kW (2 Ton) chilled water coil in the combo-system's air-handler. The variation in load between suites was small and allowed a single size coil to be used in all but the two penthouse suites.

The typical or base system for a building of this type is a four-pipe fan coil served by central water-cooled screw chiller with a COP of 3.8 and a gas-fired hot water boiler with a thermal efficiency of 80%.

Ventilation Systems

Heat recovery ventilators (HRVs) are used throughout the building to provide continuous ventilation air while minimizing energy costs. An HRV is installed in the utility/mechanical room of each suite. All HRVs provide a continuous flow of 30 L/s (60 cfm) increasing to 60 L/s (120 cfm) when activated by a push button in the bathrooms. The supply air duct of the HRV is connected to the air-handler's supply duct. This arrangement allows the space conditioning ductwork to distribute outdoor ventilation air throughout the suite. Exhaust air is ducted separately from washrooms and laundry to the HRV. When the main air-handler fan is off, only the HRV fan is used to distribute ventilation air. The air-handler fan comes on when there is a call for heating or cooling. A deflector, used to create a venturi in the air handler supply duct, ensures that the HRV supply fan is not overpowered, thereby reducing ventilation flow during heating or cooling operation.

Each suite has an individual combustion air supply duct for the water heater and other combustion appliances, and make-up air for the range hood. Nine vent shafts scattered throughout the building carry flues from multiple appliances to the roof. Individual plastic (ABS) vent pipes from each water heater run up the vent shaft. A 150-mm diameter galvanized vent riser allows venting of multiple clothes dryers within each stack. A thermostatically operated fan at the top of the galvanized vent riser induces a draft whenever any clothes dryers operate. Some appliances on the sixth floor are vented directly through the roof. The range hood and HRV in each suite exhausts individually to the outdoors at the exterior wall.

A central HRV supplies 330 L/s (700 cfm) of fresh air to the common corridor on each floor and exhausts continuously through the garbage chute on each floor. Air is also drawn from the garbage room at the bottom of the shaft. Supply air from the HRV induces slightly positive corridor pressurization. A second large HRV provides conditioned outdoor air to, and exhaust from, the ground floor spa and shower rooms.

Typically, the base ventilation system for a multi-storey condominium building would be a gas-fired make-up air unit to pressurize the halls. Individual range hoods and individual or central bathroom exhaust would be used to ventilate the suites.

Lighting

This building was designed to use 30% less lighting power than a similar building designed to meet the Model National Energy Code for Buildings. Savings are achieved through a combination of high efficiency lamps, lighting controls, and good design for appropriate illumination levels. Compact fluorescent and T-8 fluorescent fixtures with electronic ballasts are used in the corridors. High-pressure sodium fixtures provide base-level lighting in the underground parking garage.

Water

Domestic water is supplied through a common meter serving the entire building. Suites are not individually sub-metered for water use. The local plumbing code mandates low-flow, 6.0 L/flush (1.6 gal/flush) toilets. These are currently the lowest water use toilets that are available off the shelf.

Sink aerators and showers were generally specified to be as low flow at 8.33 L/min at 415 kPa (2.2 gal/min at 60 PSI). This rating complies with California Energy Commission requirements and the US Federal Energy Policy Act. Some lower water use fixtures are available but in limited makes and models.

A low-water use package of clothes washer and dishwasher was offered to the owners as an upgrade package. Horizontal axis clothes washers use 25% less water and 40% less energy. High efficiency dishwashers use about 25% less water. It is not known how many owners opted for these premium appliances.

1.3 Overview of Monitoring Program

The monitoring program evaluated five major subject areas:

- airtightness of building envelope
- heat, air, moisture and liquid water transport in the building envelope
- performance of the space and water heating systems
- effectiveness of the building ventilation systems
- overall energy and water consumption

Monitoring was performed using three testing protocols:

- detailed, computer-based monitoring
- one-time measurements and performance tests
- monthly manual readings of various utility meters

A comprehensive PC-based data acquisition system was installed in 2000. The system monitors several parameters:

- outdoor weather conditions
- indoor environmental conditions in three suites
- heat, air and moisture movement in four wall systems
- energy performance of two combination space/water heating systems
- energy performance of one hot air furnace heating system and independent water heater
- energy performance of the central boiler system that serves the common areas

The data acquisition system was commissioned in December 2000 and data collection began in January 2001. The sensors were continuously scanned and data was sent to the PC at 15-minute intervals. The data acquisition system was attached to a modem that allows data retrieval on a weekly basis. Continuous data retrieval and analysis helped to quickly identify any problems with instrumentation.

Several one-time tests to assess the indoor air quality (IAQ) and air movement within the building were conducted during the winter of 2000/2001—after the building was occupied. The objectives of the tests were to assess:

- the ability of the ventilation system to maintain good IAQ by providing the prescribed fresh air volume continuously and distributing the fresh air throughout the suite
- the effectiveness of the garage ventilation system in keeping automobile fumes from accumulating in the parking garage
- the ability of the building structure to provide compartmentalization, thereby impeding the movement of air contaminants between the different areas within the building, e.g., from the parking garage to the suites

The long-term trends in indoor air quality in suites and in corridors were assessed using the data acquisition system.

The monitoring program began in 1999 with assessments of the building envelope airtightness. Blower door tests on parts of the building envelope were made during construction to ensure that the walls were being properly constructed. A final whole-building blower test was performed when construction was complete. This testing is described in Section 2.

Appendix A provides a list of all sensors installed. The monitoring results for heat, air and moisture transport in the building envelope and the energy performance of the heating system are described in Sections 3 and 4.

A complete description of the indoor air quality testing, including procedures and results, is presented in Section 5.

Manual readings of the suite and building utility meters are taken monthly to track overall energy use. The results are described in Section 6.

2. BUILDING ENVELOPE AIRTIGHTNESS

2.1 Overview

The building design incorporated several strategies to reduce overall energy use and improve building durability. One of the most important of these strategies was the design of an airtight building shell. The design specified that exterior walls incorporate continuous air barrier and vapour retarder planes, that these elements be placed where they would be protected them from damage during construction and that they produce a verifiable level of airtightness.

A review of published literature on airtightness of buildings and building components was conducted [Kokko, 1998]. The following air leakage rates were established as design targets:

- an air leakage rate of 0.75 L/s/m² @75 Pa for individual building components
- an air leakage rate of 1.0 L/s/m² @75 Pa for the whole building

Building airtightness depends not only on adequate design but also on the commitment of stakeholders and building trades to constructing a building as designed. Four activities were initiated to encourage this commitment and to monitor the success of this innovative building design:

1. To ensure buy-in and a commitment from stakeholders (building owner/developer, the general contractor, the air-sealing contractors and utility representatives), an education session to communicate the value of air sealing was presented.
2. To ensure that the objectives and details were clearly understood by the contractor, a contractor training session was presented.
3. To ensure the integrity and quality of air sealing work and to facilitate any changes required to accommodate construction preferences, continuous construction inspections were instituted.
4. To verify that the expected airtightness objectives had been achieved, three sets of air-leakage tests were conducted during construction.

Stakeholder and Contractor Education

Early discussions with the owner/developer achieved acceptance for the principle of an airtight design for the building and for a construction crew-training program. It was agreed that all stakeholders would be asked to attend this training session. It was also agreed that accommodation would be made for verification and testing of air barrier and vapour retarder installation and details.

Early in construction, several changes in building design and construction management personnel took place resulting in delays and schedule setbacks. Air sealing crews were not on site when training had originally been planned. When the crews finally did arrive, the schedule had become very tight. The general contractor was not willing to have them set aside time for training fearing the consequences of further delays. He requested that training be given to himself and a representative of the air-sealing contractor. They would then pass the training information on to the crews as work progressed.

The training session was presented to the owner, the general contractor, the air-sealing contractor and the building science specialist. Discussion included air sealing details to be implemented and the level of quality to be maintained. A copy of the Power Point presentation made is included in Appendix B. Site visits to inspect the air barrier installation for adherence to the specifications and quality of workmanship were still performed on a regular basis by the engineer as installation progressed.

Air Leakage Testing

The fan depressurization tests were based on CGSB Standard 149.10 M86 Determination of the Airtightness of Building Envelopes by the Fan Depressurization Method [CAN/CGSB, 1986]. This standard is applicable to small, detached buildings but can be modified for the testing of other buildings. The standard describes the preparation of the building for testing, the equipment to be used and the calculation method necessary to determine a quantitative value from the test data. The standard was used to determine which intentional penetrations would be sealed and how the basic calculations would be made. Procedural modifications were made to adapt to the construction situation.[1]

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[1] A comparable standard (CAN/CGSB 149.15) exists for large buildings where a central building air distribution system can be used in testing rather than a separate fan. The condominium building does not have an air distribution system so this system could not be used.

Construction difficulties required the timing of the first two air tests be altered. Although tests were conducted later than originally envisioned, the tests provided significant benefit to the building project and valuable information for the research program.

The initial fan depressurization test was to have been of a single suite on the first-floor that was produced as a sample specifically for training, testing, and verification of workmanship. Instead, the test had to be performed on a third-floor suite after about one half of the air sealing was completed. Nevertheless, problems in air sealing were identified and corrections made. The general contractor witnessed the tests and reviewed the identified deficiencies with the air-sealing contractor for remediation.

2.2 Envelope Design

Original Envelope Design

The building employs two different exterior wall-finish systems. The air barrier and vapour retarder were designed to bridge transitions between the two wall-finish systems. The strategy for sealing the building included the installation of a continuous vapour retarder outboard of the steel stud walls that would cover the entire building surface. The brick-veneer wall system, illustrated in

Figure 2.1, consists of the following components (from inside to out):

- 13 mm interior gypsum wall board
- 89 mm steel studs @ 400 O/C filled with RSI 1.4 mineral wool insulation
- 13 mm exterior grade gypsum wall board, joints taped with 150 mm wide strips of Blueskin SA™ (air barrier)
- 60 mm spray applied polyurethane insulation
- 35 mm air space
- 100 mm face brick

The EIFS wall, illustrated in Figure 2.2

Figure 2.2, consists of (from inside to out):

- 13 mm interior gypsum wall board
- 89 mm steel studs @ 400 O/C filled with RSI 1.4 mineral wool insulation

- 13 mm Dens-Glass Gold® exterior wall board
- a continuous layer of Blueskin SA™
- 90 mm expanded polystyrene (EPS) insulation
- a stucco finish

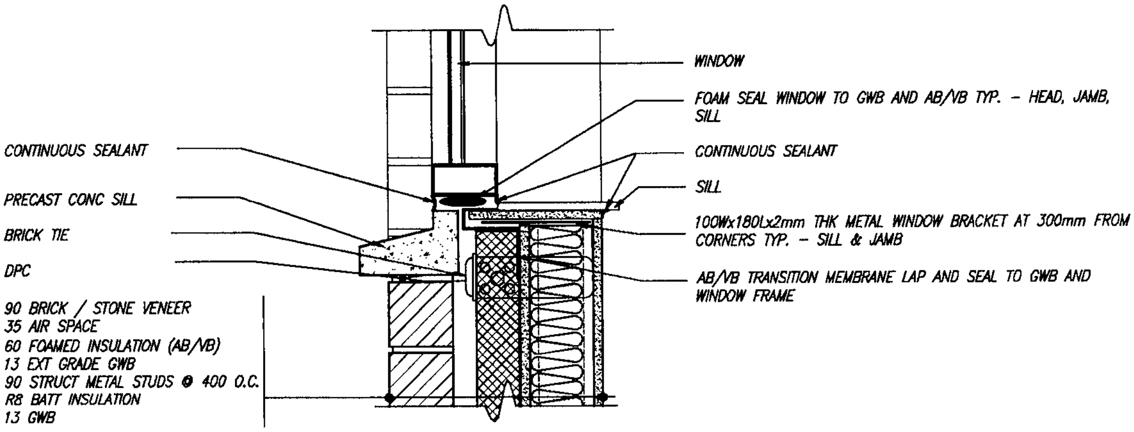


Figure 2.1: As-Designed Window Sealing Detail – Brick Veneer Wall

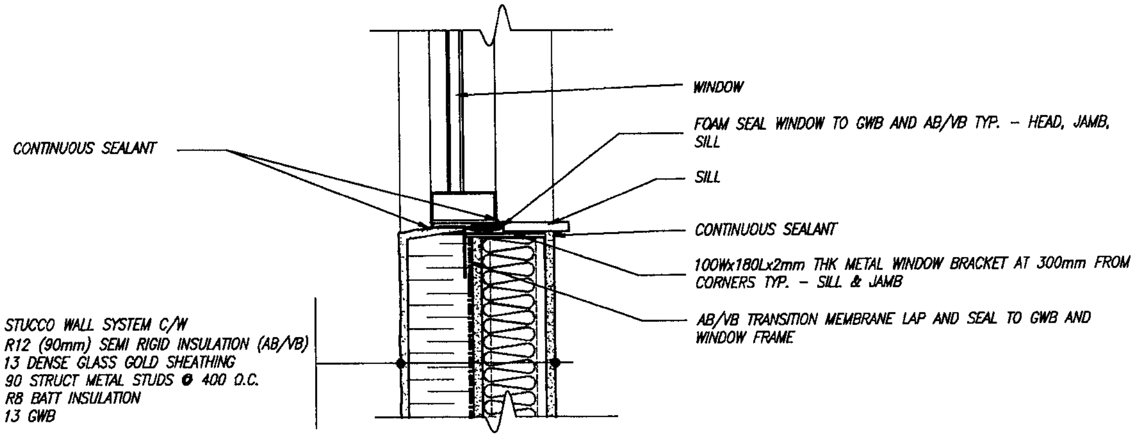


Figure 2.2: As-Designed Window Sealing Detail – EIFS Wall

In areas finished with brick, spray-on polyurethane was installed over the entire wall surface to form a vapour retarder. In areas with EIFS, a layer of self-adhesive modified bitumen membrane with polyethylene reinforcing (Blueskin SA™ from Mosey-Bakor) was installed on the warm side of the EPS over the exterior gypsum wall board as a vapour retarder.

In both wall systems, the exterior sheathing is the plane of the air barrier. Air barrier continuity at rough frame openings was achieved by sealing the window, door or mechanical frames to the exterior sheathing. The original design specified that in areas finished with brick, polyurethane was to be foamed into the rough openings, and then the foam to rough opening joint be caulked on both sides. The original design specified that in areas with an EIFS finish, strips of Blueskin SA™ were to be lapped from the air barrier to the window frame. Air barrier continuity at transitions from one wall-type to another (illustrated in Figure 2.3) was ensured by sealing gaps between the two layers of exterior sheathing with Blueskin SA™. Further details can be found in Appendix A.

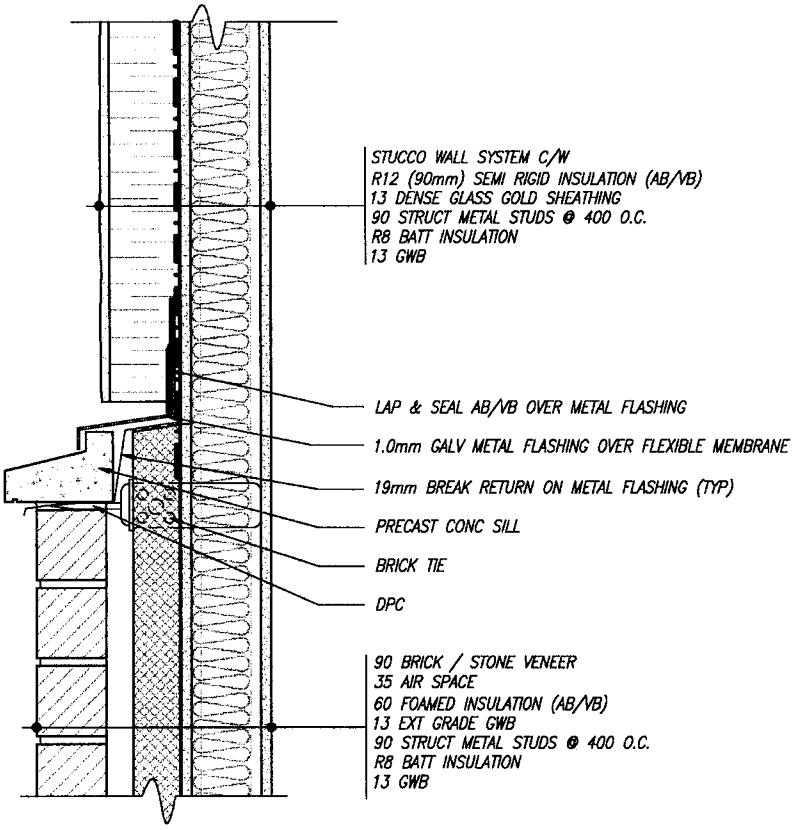


Figure 2.3: As-Designed Wall Intersection Detail – Brick Veneer and EIFS

Changes to the Original Design

Soon after the building structure and floors were completed and one-third of the wall framing had been installed, the local building inspector found that there were structural concerns that required remediation. The structural repairs took approximately eight months and put the project significantly behind schedule.

While the remedial work was in progress, two changes in the construction management team took place. First, the lead architect position changed from one firm to another. Second, on the advice of the New Home Warranty Program, the developer retained a building science consultant to review and comment on issues including building envelope sealing. The new architect changed the insulation details on EIFS walls removing the continuous Blueskin SA™ air barrier and vapour retarder, replacing it with a trowel-on sealer/adhesive called Dryflex™ over joints in the Dens-Glass Gold® exterior sheathing. This change was made to lower costs and because the architect was more comfortable with more conventional installation details. The building science specialist recommended that a sealed polyethylene sheet be added on the interior of the building to serve as a vapour retarder in place of the Blueskin SA™ sheet that had been removed.

When construction resumed after remediation, time pressures dictated that each job in the construction sequence was completed on the entire building at once, and not on a floor-by-floor basis, as was originally planned. This resulted in some difficulties. For example, as soon as the exterior sheathing was installed, the air barrier components, windows and exterior insulation were quickly installed, limiting the opportunity for detailed air barrier inspections.

Several site inspections conducted during exterior component installation permitted reasonable inspection of sealing details and identification of necessary modifications/corrections as work progressed. Air sealing details were reviewed with the architect, the contractor and the building owner during regular site meetings. Two issues needed to be dealt with as a result of construction anomalies.

Contrary to the specifications, the contractor tried to use Blueskin SA™ to seal the rough frame opening between the wall sheathing and the fiberglass window frames in brick clad areas. Early in the process, it was found that the Blueskin SA™ did not adhere to fibreglass. The new architect and the building science specialist redesigned the sealing of rough frame openings in both brick veneer and EIFS areas.

For brick veneer walls, the Blueskin SA™ was left in place and caulked to the window and door frames. Additionally, the rough frame openings were filled with polyurethane from the inside. The foam to frame joints were caulked at the plane of the interior finish as were all points where window trim met the surrounding walls.

On EIFS wall areas, Dryflex™ was sealed to the frames to form a continuous layer over the rough frame opening at the exterior. Dryflex™ was specified because it is the standard detail for Dryvit™ EIFS systems. The Dryflex™ to window and door frame joints were caulked. The rough frame opening between the window/door frame and the framing was filled with polyurethane from the interior. The foam to frame joints were caulked at the plane of the interior finish as were all points where trim met the wall. These changes are illustrated in Figure 2.4 and 2.5.

Remediation work included the installation of structural steel beams. The beam flanges penetrated what would have been the original vapour retarder. Polyurethane foam was used to seal around these beams. This approach provided a continuous vapour retarder at the beams bridging the original vapour retarder on either side.

The contractor instructed air-sealing crews on the implementation of this modification. This modification had been implemented prior to the first air test.

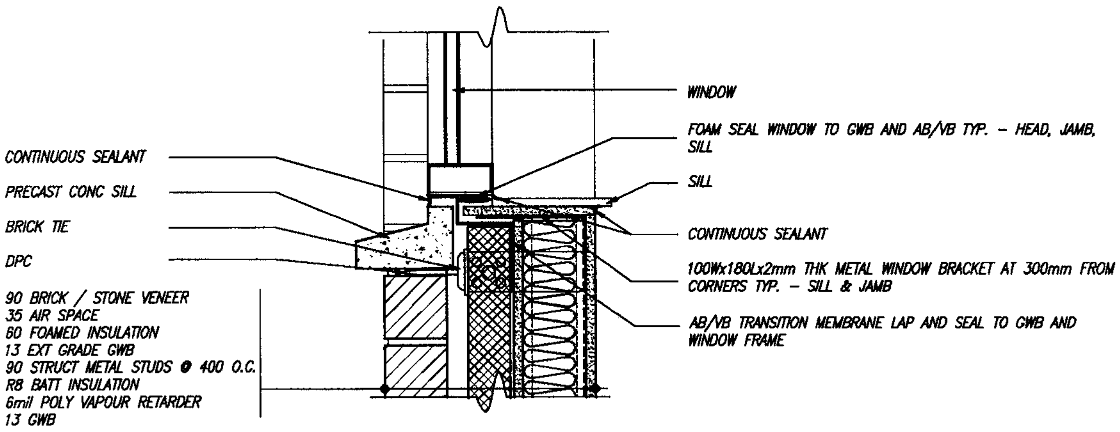


Figure 2.4: As-Built Window Sealing Detail – Brick Veneer Wall

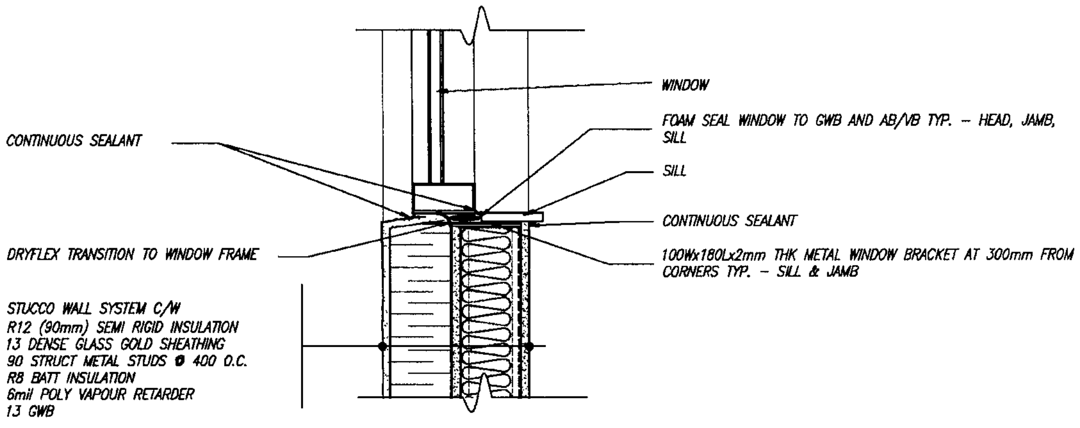


Figure 2.5: As-Built Window Sealing Detail – EIFS Wall

2.3 Representative Wall Air Leakage Test

Purpose

The representative wall test was performed after structural modifications were completed and the majority of the air barrier had been installed. The interior insulation had not been installed at the time of testing and the plane of the air barrier was still accessible for testing and, if necessary, repairs. The test was intended to be both quantitative (to determine if airtightness was near the target value) and qualitative (to determine if there were problems with the design and/or construction techniques). The testing was used to identify areas where air-sealing procedures needed improvement.

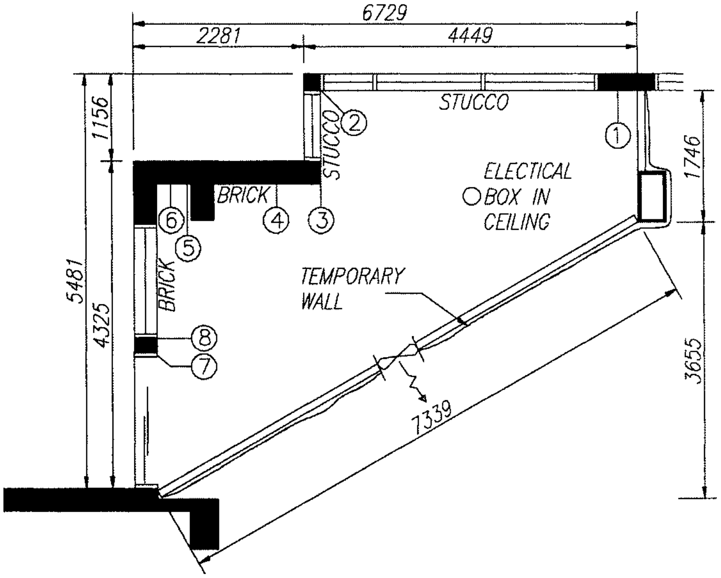
Test Procedure

The test procedure required building a temporary wall to isolate a portion of the building wall so that it could be placed under negative pressure and leakage locations identified. Figure 2.6 is a plan view of the wall section that was under test. Figure 2.7 is a photograph showing the temporary polyethylene wall with edges taped to the floor, ceiling, and exterior wall studs. As much as possible, the exterior wall was to be the only area that allowed airflow. The exterior wall can be seen below the window on the right-hand side of the photograph. The polyethylene covering the glass was intended to protect the window during installation of the EIFS cladding.

The two walls tested were located in the northwest corner of the third floor. The exterior wall on the north side of the suite is clad with an exterior insulated finish system and the exterior wall on the west side of the suite is clad with brick veneer. The area chosen for the test included as many different elements and discontinuities as possible (e.g. windows, doors, and corners).

The owner/developer, general contractor and building science consultant all participated in the test, which was conducted as follows:

1. A temporary interior partition wall was constructed of 2x4s and 6-mil poly. The poly was taped along all four edges and all joints to provide an airtight seal and eliminate these surfaces from the air-leakage area.
2. The blower door was installed in a doorway that was built into the temporary partition and discharged into the remainder of the empty floor. The exterior windows and doors were opened to ensure that the area outside of the temporary wall was at the same pressure as the exterior of the building.
3. The CGSB-M149.10 procedure was followed for sealing the remainder of the suite (i.e. all intentional openings were sealed and mechanical dampers closed).
4. The multipoint test procedure was performed and inside/outside pressure difference and fan pressure readings were recorded for each point.
5. The fan was set to maintain an inside to outside pressure difference of approximately 50 Pa while a smoke pencil was used to identify air leakage locations. Smoke testing was done to provide a qualitative analysis of the air leakage through the exterior wall. Leakage areas were identified and shortcomings in the design were brought to the attention of the architect, while deficiencies in construction were brought to the attention of the contractor. Methods of addressing the leakage locations were discussed and remedial actions agreed upon.



MAJOR LEAKAGE LOCATIONS:

① KING STUDS BESIDE WINDOW BETWEEN STUDS AND GYPSUM BOARD.

② CORNER POST LEAK BETWEEN FIBREBOARD.

③ AT TOP TRACK CHANNEL CORNER.

⑥ ⑤ ④ LOWER HOLE - FOR NON-EXIST.BRICK TIE.

⑦ WIRING PENETRATION @ 6'-0" HEIGHT.

⑧ JACK STUDS BESIDE WINDOW @ TIES FOR WINDOW SILL.

Figure 2.6: Leakage Locations Identified in Representative Wall

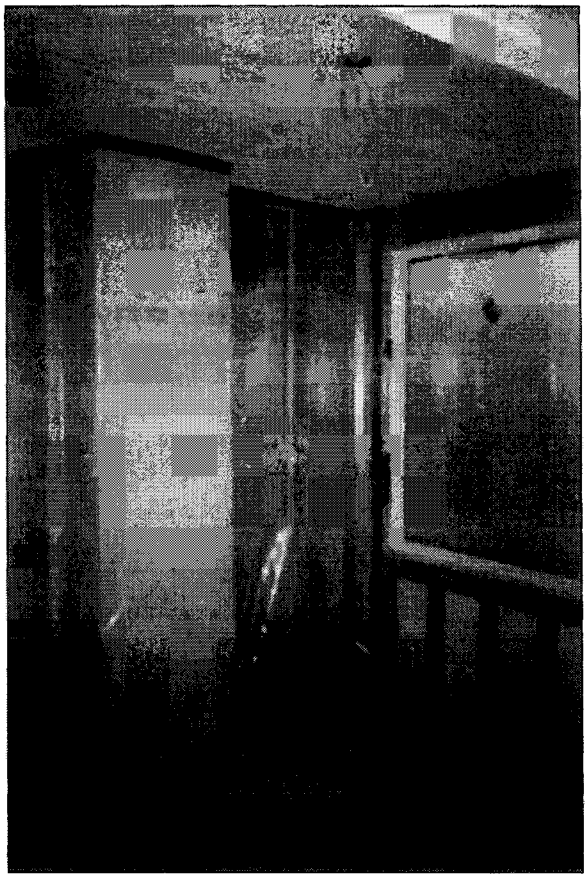


Figure 2.7: Temporary Polyethylene Wall with Perimeter Taped

Test Conditions

The test was performed on December 14th, 1999. It was a relatively windy day with an ambient temperature of 0°C and an indoor temperature of 2°C. The room volume was 69.7 m^3, the exterior wall surface area was 32.2 m^2, and the entire surface area of the enclosure was 113.7 m^2 (including the temporary polyethylene wall).

Analysis and Results

During testing, it was noted that there were leakage paths other than those through the exterior wall. Two that were positively identified were an electrical box in the ceiling and gaps between the wall studs and the exterior sheathing at each end of the temporary wall. This internal air leakage artificially inflated the exterior wall or raw air leakage index. The calculation procedure of CAN/CGSB-149.10 M86 was modified to remove the effects of these internal air leakage paths and provide an estimate of the true or adjusted leakage index.

The adjusted ELA_{50} was calculated as follows:

- only exterior wall surface area only was used to determine the raw index and raw ELA_{50}.
- ELA_{50}s for known internal air leakage paths (i.e. through the electrical box and past the wall studs) were estimated using values from ASHRAE Fundamentals [ASHRAE 1997].
- the adjusted ELA_{50} was calculated as the raw ELA_{50} minus the ELA_{50} for internal leakage paths.
- the fan flows were scaled until the adjusted ELA_{50} was reached using the CAN/CGSB 149.10 calculation method.

Table 2.1 provides both the raw values and the adjusted value of the test results.

Table 2.1: Air-Tightness Results for Representative Wall Test

	Test Volume (m^3)	Surface Area (m^2)	Building Pressure (Pa)	Flow Index ($L/s/m^2{}_{75}$)	C Flow Coeff.	n Flow Exponent	R	ELA_{50} (cm^2)
Measured	69.7	32.2	75	2.95	1.1367	1.025	0.97	48.35
Adjusted				1.07	0.413	1.025		17.55

The adjusted flow index for the representative suite is 1.07 $L/s/m^2{}_{75}$. This result was above the target value and indicated that there was more leakage area through the exterior wall than considered acceptable. Note, the flow exponent is just above the normal range of 0.5 to 1.0. This is likely because the correlation coefficient is below 0.99 indicting the fit of the experimental data is not perfect and there is an error band associated with the calculated values. The high value (close to 1.0) indicates leakage is through long, small diameter holes. This would be consistent with air having to find its way in through many small imperfections in a relatively airtight, thick building shell.

Leakage Locations

A smoke pencil puffer was used to visually identify leakage locations in the exterior wall. It was often difficult to see the exact location of the leak in the air barrier because the smoke could run vertically or horizontally behind other surfaces (e.g., the steel framing) for some distance before coming out through an opening. However, there were some very obvious penetrations through the exterior wall. Major air leakage locations in the exterior wall are located on Figure 2.6 and the following notes correspond to the numbering on the drawing.

1. Air leakage at the king studs to the right of the large picture window in the living room indicated a gap in the air barrier at the window frame. The king studs and other window framing can be seen in Figure 2.8.
2. Air leakage through the vertical joint in the framing between two corner windows indicated gaps in the air barrier around the window. The air was likely traveling behind the studs until it exited at the corner.
3. Air was exiting the channel that formed the top track at the interior corner. This leak may also be related to poor sealing around the window.
4. 5. & 6. Air leaked through holes left where brick ties had been removed. Brick ties, made of 100 mm wide sheet metal and attached to the wall studs, were installed through the exterior sheathing when the walls were first built. Spray-on polyurethane foam insulation was applied to embed the brick ties and sealing the hole in the sheathing. Where these ties had to be relocated, the masonry crews had not sealed the holes. Figure 2.9 shows the hole left from a brick tie that was removed.
5. Air leaked through a hole that had been drilled through the exterior sheathing to run a power cable to a light on the balcony. In this case, the hole had not been caulked after the cable was installed. In other cases, workers had damaged the caulking by moving the cable as they worked around it.
6. Air leaked around a jack stud at the base of the window. This is likely a due to a discontinuity in the air barrier where it attached to the window frame.

Figure 2.8: Air Leakage Found at King Studs

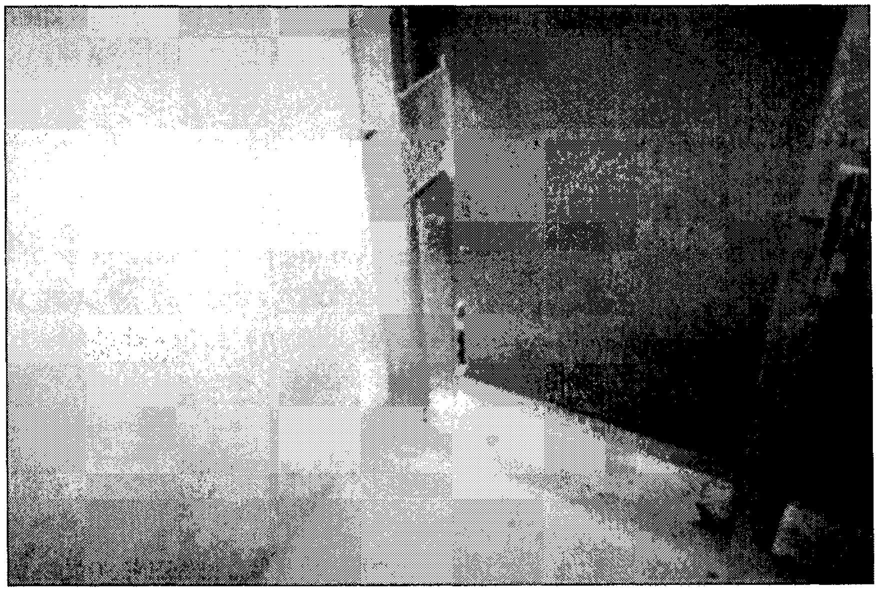


Figure 2.9: Hole Left Unsealed When Brick Tie Relocated

Air leakage problems fell into two categories: leakage around window frames and leakage through unsealed holes created after the air barrier had been completed.

The revised window sealing method discussed was implemented. On the EIFS walls, the Dryflex™ was not sealing adequately to the window frames. Discussions with the stakeholders at this point concluded with the decision to seal all rough frame openings with polyurethane foam and caulking. All windows and doors in both EIFS and brick veneer walls were consequently sealed with polyurethane foam and caulking.

To deal with leakage through unsealed holes, the general contractor agreed to inspect the back of the exterior sheathing (i.e. the air barrier) before the stud spaces were filled with batt insulation. Any holes created since the air barrier was installed (e.g. brick ties, wiring, etc.) would be caulked from the interior before the wall was closed in.

2.4 Individual Suite Test

Purpose

The individual suite test was performed to verify that quality control with respect to air sealing of the building was being maintained. All sealing work and the interior finishes had been installed. The test was intended to be both quantitative and qualitative—to determine if the air tightness was near the target value and to determine if there were any remaining problems with construction. The results were to be used to identify opportunities to correct any deficiencies before the building was completed.

Test Procedure

The test was performed on a third-floor suite (305) in the northwest corner of the building. This was the same location where the individual wall test had been performed. The main modification made to the procedure described in CAN/CGSB 149.10 was to depressurize adjacent suites to isolate the exterior walls of the test suite. The test suite and the adjacent suites (304 and 306) are shown in Figure 2.10. The suites above and below the test suite were also depressurized. Suites 205 and 405 have floor plans identical to the test suite.

The test suite was chosen to include wall areas with stucco and brick exterior wall finishes and as many different elements and discontinuities as possible (e.g. windows, doors and corners).

The test procedure was as follows:

1. Intentional openings in the test suite and adjacent suites were temporarily sealed as per CAN/CGSB-M149 sealing procedure.

2. A blower door was installed in the suite doorway and discharged into the corridor. Stairwell doors, exterior doors in the stairwell, other suite doors and other suite windows were opened to ensure that there was no restriction to airflow between the corridor and the exterior of the building.
3. Blower doors were installed in the doorways of the four adjacent suites (above, below, left and right) and discharged into the corridors. Stairwell doors and other suite windows and doors were opened to ensure that there was no restriction to airflow between the corridors and the exterior.
4. All suites were depressurized simultaneously to the same pressure as the test suite to isolate the exterior walls of the test suite as the location through which air was drawn during the blower door test. (Note: the corridor outside the suite was not depressurized therefore the suite-to-corridor partition was not pressure balanced.
5. A multi-point test was performed recording inside/outside pressure difference and fan pressure readings.
6. Visual testing with a smoke puffer while the indoor/outdoor pressure difference was set to 50 Pa was used to accurately locate air leakage locations. Photographs were used to document the leakage locations found.

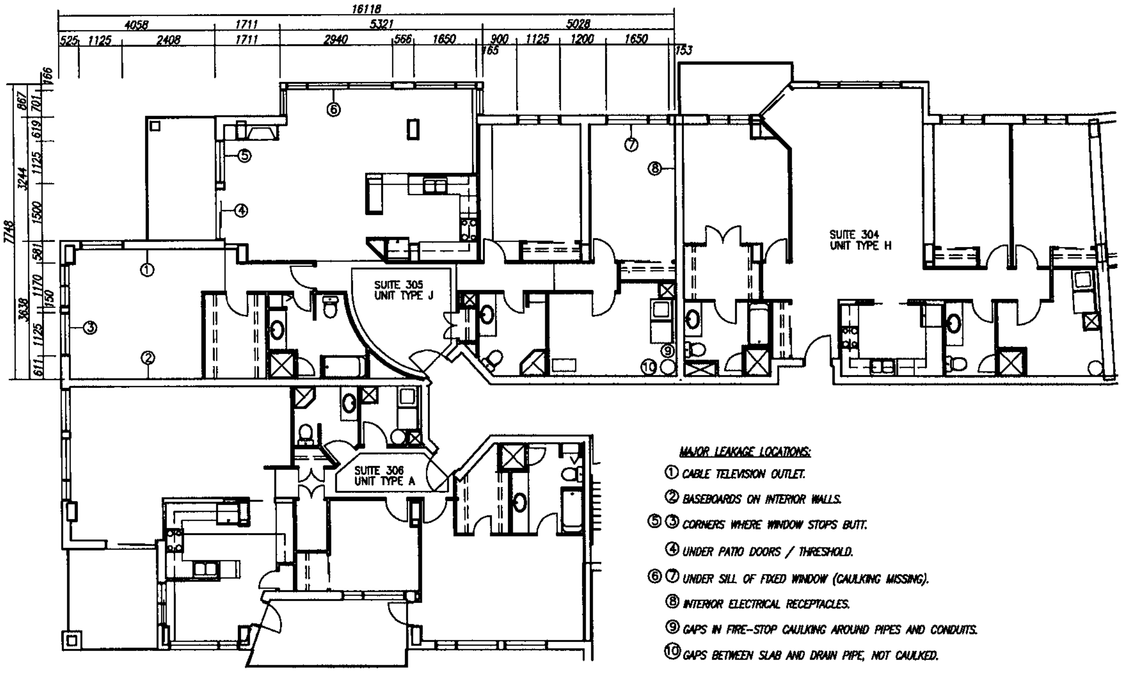


Figure 2.10: Leakage Location Identified in Representative Suite

Test Conditions

Testing was conducted on the afternoon of May 4th, 2000, a clear sunny day. Ambient and indoor temperatures were measured at 21.4°C and 20.0°C respectively. Local barometric pressure was slightly above standard pressure, or approximately 101.7 kPa. The winds were relatively high, estimated at about 11 km/h. The high winds did not appear to cause any instability in the measurements.

The finished floor area of the test suite was 192.6 m^2 and the suite had a volume of 539.4 m^3. The suite had stucco finish on the north face for a length of 9.4 m and a brick finish for a length of 23.8 m on the west and north sides. The stucco wall was 47% window area with a total window perimeter of 22.0 m; the brick wall was 30% window area with a total window perimeter of 36.9 m.

The percent window area in this suite is the same as the average for the entire building (35%). This is important because air leakage is usually proportional to the crack lengths of penetration through the building shell. Corners in the wall are also areas of discontinuity that can be difficult to seal. This suite has more corners than a typical suite.

Results and Analysis

The test procedure used was to isolate the suite exterior wall as the area from which air leakage could enter the suite. Any air leaking from other areas (e.g. interior partition walls) would be attributed to leakage from the exterior walls of the suite, inducing an error in the calculated results. Leakage locations other than those through the exterior wall were found throughout the suite. This shows that the pressure balancing of adjacent suites did not isolate the exterior wall. One significant issue was not depressurizing the corridor outside the suite. For others, see Possible Sources of Error below.

The raw leakage index based on the exterior wall area only was 3.53 $L/s/m^2{}_{75}$. The adjusted exterior wall index is estimated to be in the range of 0.81 to 1.6 $L/s/m^2$ (see Interpretation of Results below). This range is close to the target value of 0.75 $L/s/m^2{}_{75}$ for the individual suite wall. Raw test results are tabulated in Table 2.2 below. The adjusted index range and ELA_{50} are included for comparison.

Table 2.2: Air-Tightness Results for Representative Suite

	Test Volume (m^3)	Surface Area (m^2)	Building Pressure (Pa)	Index ($L/s/m^2{}_{75}$)	C Flow Coeff.	n Flow Exponent	R	ELA_{50} (cm^2)
Measured	539.4	96.1	75	3.29	34.6	0.51	0.987	444
Adjusted				0.81 – 1.6	8.5-17	0.51		111-222

Due to the economic and physical limitations of testing in multi-family buildings, it seems that individual suite tests may be most valuable for obtaining qualitative data for verifying the workmanship in air sealing and locating problem areas. The quantitative results are subject to a relatively large margin of error, which this test was not designed to quantify. Therefore, it may be best if an adjusted air leakage index were used only as a guide to whether air sealing is on target and that information from the visual inspection be used to identify deficiencies in construction.

Leakage through areas such as interior baseboards, electrical receptacle boxes and around conduit penetrations shows that the individual suites are not well compartmentalized. Though not a target of this building's design criteria, this finding shows that a significant amount of design and construction supervision would be required to obtain good compartmentalization. Major issues that are likely to drive compartmentalization in future projects are greater demands for smoke, odour and noise control.

Possible Sources of Error

There are several possible sources of leakage other than the exterior wall. Suites on four sides that shared common surfaces (partition walls, floor and ceiling) were depressurized concurrently with the test suite. There are four additional suites and two corridors where the corners (e.g. a partition wall-to-floor or ceiling intersection) are adjacent to the test suite. These suites have the capacity to communicate with the test suite via common vertical shafts that pass small pipes or wiring inside partition walls. None of these other suites were depressurized. Such an undertaking would have required at least 12 blower doors operating simultaneously with 12 operators, all in radio contact. The resources to perform such a complex test were not available. Even with 12 blower doors, the effect of the vertical shafts would not be eliminated.

Another possible source of error was the fact that the corridor outside the suite was not depressurized. Therefore, it was possible that air could leak from the corridor into the test suite. The corridor wall was not air-sealed and leakage would affect the test results. Depressurization of the corridor would have required a minimum of five blower doors and radio contact between all operators. Adding this complexity could not guarantee that other sources of leakage would not still be sources of error.

A third possible source of error is the common utility shaft that runs the entire height of the building and is open to the outdoors at the top. Services running through the shaft wall (such as dryer vents) were sealed. During the test it was found that the caulking around these penetrations did not always seal completely.

Conduits carrying electrical feeds, telephone, cable TV, and other services can allow air in from outside the suite. They may come from central utility closets or run several floors to a mechanical room.

Interpretation of Results

The magnitude of the error caused by interior air leaks can only be estimated based on experience in other building tests. In 1993, five independent field-investigation surveys conducted across Canada for CMHC were reviewed [Wardrop, 1993]. The intent of the investigation was to determine air leakage rates through the building envelope, inter-floor and inter-suite leakage rates. The building shell, inter-suite and inter-floor air leakage rates were measured by whole building, suite, and entire-floor fan depressurization tests.

Leakage rates per unit of exterior wall area were found to be in the range of 2.10 to 3.15 L/s/m^2 at 50 Pa during suite fan depressurization testing. When testing was conducted such that the corridor wall could not be isolated from leakage through the exterior wall, the range of air leakage rates increased to 4.56 to 8.33 L/s/m^2 at 50 Pa. Overall leakage rates per unit of exterior wall area found during full floor testing was 0.68 to 10.9 L/s/m^2 at 50 Pa.

These results indicate that if a corridor is not depressurized, then the leakage index can increase from two to four times. And if the test is done on a whole floor basis, the air leakage index can be significantly less than that found with a suite test.

Comparing the results of the suite test at the innovative condominium in Dundas with the results of this earlier study, it can be concluded that the raw suite test result is significantly higher than the actual exterior wall index. Assuming that the index for the tightest building without the corridor isolated is some three to five times higher than the actual exterior wall index, then the result at the innovative condominium in Dundas (3.29 L/s/m^2 $_{75}$) would suggest that the index for the exterior wall alone is in the range of 0.81 to 1.6 L/s/m^2 $_{75}$. Though the range is rather wide (a factor of 2) it does suggest that the air leakage index should be relatively close to the target range. At leakage rates this low, even a relatively large change in the index (e.g. 25%) will have a very small effect on the actual amount of infiltration occurring.

Air Leakage Location Identification

An investigation to identify air leakage locations was undertaken. The test suite alone was depressurized to 50 Pa and a smoke puffer was used to find leakage locations. The leakage locations were identified and are shown in

Figure 2.10. Leakage locations found during the test were discussed with the developer and the contractor. Steps were taken to correct these air-sealing deficiencies.

In general, the exterior wall components were found to be relatively airtight. For example, operable windows showed almost no leakage. Leaks were found at the corners where the glazing stops met on most fixed windows. This indicates that quality control at the factory could be improved. No quantitative measure was made of the window alone; thus, no comparison of actual air leakage with the air leakage rating for the window can be made.

In most cases, the rough frame openings under the windowsills showed some leakage. Other minor sources of air leakage in the exterior walls include a limited number of electrical outlets; the area beneath the threshold on the patio door; and one window where the caulking under the sill was missed altogether. This indicates that quality control on the job site was not always diligent. Common leakage areas such as the baseboards, most window frames at the rough opening, and seals on operable windows were all found to be airtight. This shows that it is possible to produce airtight exterior walls in commercial construction.

Interior partitions, on the other hand, were relatively leaky. Leakage locations include all boxes for electrical and other services such as cable and telephone, baseboards, and gaps in firestopping where the caulk did not go completely around conduits and piping. Figure 2.11 shows an electrical cable passing through a hole in a floor slab that had not been firestopped. Figure 2.12 shows an electrical box in a party wall that had been firestopped with drywall compound and a large section of the compound had fallen off, eliminating the airtight seal. During discussions with the building science specialist, it was suggested that imperfect firestopping is common in most construction projects. Thus firestopping reduces the movement of hot gasses and smoke but does not eliminate it. Odour and noise control would also be compromised when details such as firestopping are not completed to a reasonable level of quality.

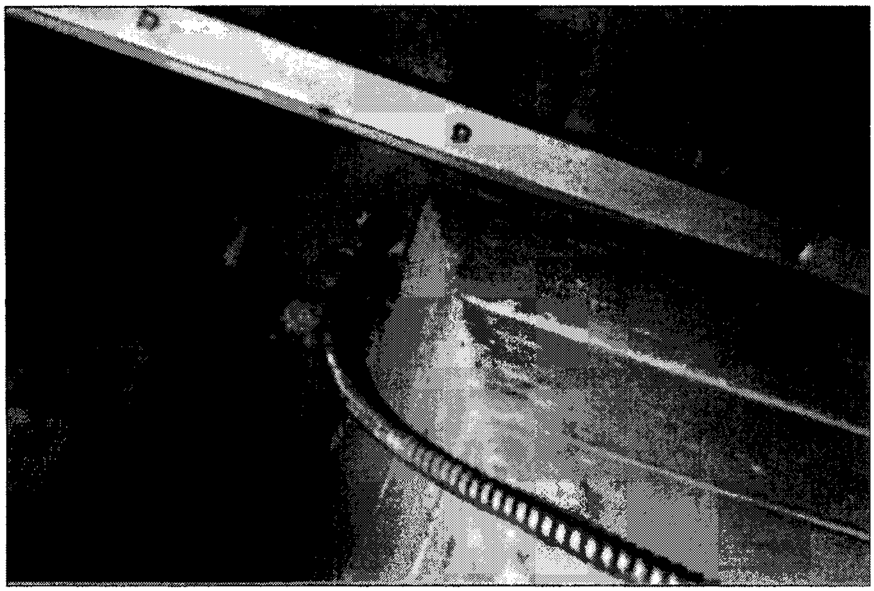


Figure 2.11: Wiring Passing Through Floor Slab Left Unsealed

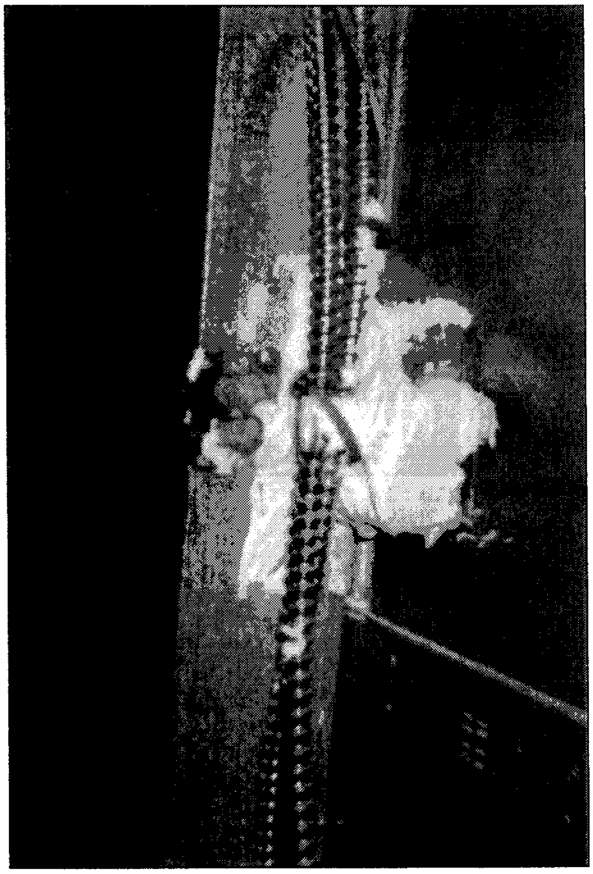


Figure 2.12: Drywall Compound for Smoke Control Falls Off Electrical Box

2.5 Whole Building Air Leakage Test

Purpose

The first two partial building tests were to measure how well the air sealing objectives were being met and to identify air leakage locations that could be sealed if problems were found. The whole building depressurization test generated the air leakage index for the entire building.

Test Procedure

It was intended that this test use a large, trailer-mounted, whole building fan owned and operated by the National Research Council of Canada (NRC) and built specifically for large building depressurize testing. This fan was not available when the test had to be done. It was then estimated that 4 or 5 residential blower doors operating in parallel could provide sufficient capacity to do a multi-point depressurization test on the building.

The test was conducted as follows:

1. All intentional openings to the outdoors including HRV ducts, combustion-air vents, range hood vents, dryer vents, water heater vents, floor drains etc. in each unit were sealed.
2. All suite doors and windows leading to the exterior of the building were closed and all doors within each suite and doors to the hallways were propped opened.
3. Two adjacent, first floor suites did not have window frames sealed or interior finishes completed and were therefore, insufficiently complete to include in the test. The suite doors were closed and sealed to exclude them from the test. A small error would have resulted from the leakage into the corridor and adjacent suites through the partition walls. Average partition wall leakage rates estimated from the suite test were used to adjust the raw leakage index for exclusion of these two suites.
4. Two combustion air vents located behind water heaters were unreachable and could not be sealed. The total free area of these two 150 mm ducts was used as the basis for calculating the adjusted air leakage index for the building.
5. Four blower doors were located on the main floor of the building; one at the bottom of each of the two stairwells, one in the main front door near the elevators and one near the garbage chute. All stairwell doors were open so that the fans could communicate with all floors. Figure 2.13 shows the layout of the first floor and location of each of the four blower doors.
6. A multi-point depressurization test was performed recording indoor/outdoor pressure difference and fan flow pressure readings. Fan flows were summed to obtain the total flow at any given indoor/outdoor pressure difference.

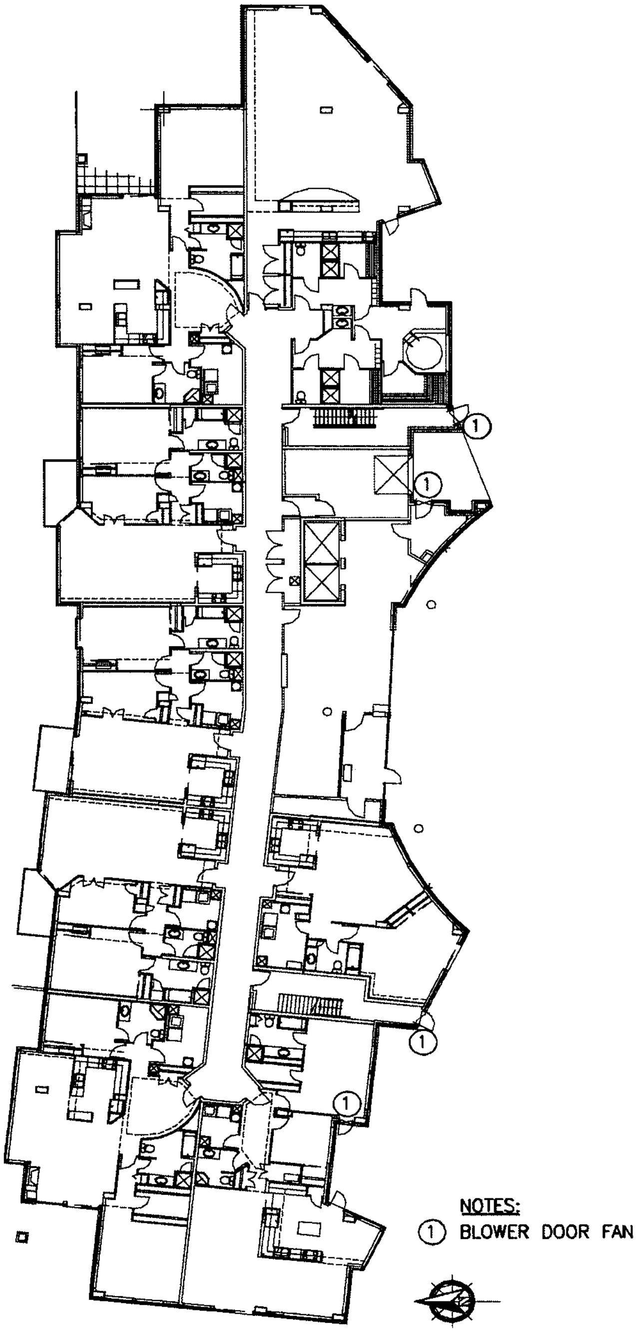


Figure 2.13: Blower Doors Locations for Whole Building Depressurization Testing

Test Conditions

The test was conducted May 10th, 2000. The ambient temperature was 14.8°C and the indoor temperature was 22°C. The winds were moderate at 6.1 km/h from the SE. The building had an envelope surface area of 6,826 m^2 and an internal volume of 24,320 m^3 (not including the two sealed-off suites).

Because the building is relatively low (six storeys) and the indoor-outdoor temperature difference is very small, stack effect did not have any significant effect on the test.

Analysis and Results

The target air leakage index for the building shell was 1.0 L/s/m^2 @ 75 Pa. There is limited information on the air leakage characteristics in commercial buildings. Two information sources were reviewed. ASHRAE Fundamentals [ASHRAE, 1997] references an American and a Canadian study. The American study examined eight buildings and reported a median leakage index of 3.2 L/s/m^2 @ 75 Pa. The Canadian study by CMHC looked at eight Canadian office buildings and suggested an average wall leakage of 1.5 L/s/m^2 @ 75Pa. The CMHC study [Wardrop, 1993] found a median of 7.5 L/s/m^2 in five apartment buildings. An NRCan study of 6 office buildings in the Ottawa area found an average of 3.4 L/s/m^2 @ 75 Pa. The average of the 4 studies is 3.9 L/s/m^2@ 75 Pa.

The depressurization test result showed a raw air leakage index of 1.26 L/s/m^2 @ 75 Pa and an adjusted index of 1.18 L/s/m^2@ 75 Pa. The target index of 1.0 L/s/m^2@ 75 Pa was expected to provide a reduction in air leakage of 75% compared to a typical building; the actual reduction was 70%. The final result was only 5 percentage points off the expected reduction.

Table 2.3: Test Results for Whole Building Depressurization Test

	Test Volume (m^3)	Surface Area (m^2)	Building Pressure (Pa)	Index (L/s/m^2 @ 75 Pa)	c Flow Coeff.	n Flow Exponent	R	ELA$_{50}$ (cm^2)
Measured	24,320	6,826	75	1.26	1,048	0.51	0.921	12,800
Adjusted				1.18	879.2	0.51		11,480

During the walk-through of the building, the following leakage locations were noted:

- Holes left by repositioning of brick ties and holes for electrical cables feeding outdoor circuits had been sealed. This was seen in a limited sample of suites where interior finishes were not yet installed. The site superintendent confirmed that this had been done on all other suites.
- All suites checked had window trim caulked and sealed as a result of the deficiencies found in the suite test. Again the site superintendent confirmed that this work had been done in all suites.

- Some suites had 2.44 m high sliding glass doors. Approximately half of the doors checked were relatively leaky and the other half of the doors were airtight.

Several air leakage locations were identified in the building's common spaces. These included the following, listed in order of significance:

- the main entry door
- the overhead door in the garbage room
- the elevator shaft, which has a concrete block top that protruded into the mechanical penthouse. This room is outside the building shell.
- the garbage chute, which has an explosion relief cap above the roofline
- the corridor HRV supply ducts; the dampers for these were located in the penthouse but did not seal well.

2.6 Conclusions

The building shell at the innovative condominium in Dundas was designed and constructed to be airtight. The building envelope commissioning included contractor training, site inspections and air leakage testing to ensure that an airtight envelope was produced. Three air tests were performed during construction.

Three design modifications were made to the air barrier/vapour retarder after it was designed. First, air barrier materials were changed from Blueskin SA™ to Dryflex™ and the plane of the vapour retarder was changed; polyethylene sheeting was installed behind the interior drywall. Second, during construction, structural modifications were needed and steel beams penetrated the original vapour retarder. Spray-applied polyurethane was used to seal these areas. Third, the Blueskin SA™ air barrier would not adhere to the fibreglass window frame so all rough frame openings were sealed with polyurethane foam and caulking. None of these changes was expected to affect the overall integrity of the air barrier or vapour retarder.

The first air leakage test was done on a section of wall after the air barrier had been installed but before the interior finishes were in place. This test provided good qualitative information on air leakage paths around window and door frames as well as unanticipated holes in the air barrier and vapour retarder requiring remedial action by the contractor. Air leakage into the test volume from indoors made it difficult to provide an accurate air leakage index for the exterior wall alone. The adjusted value of 1.07 $L/s/m^2$ @ 75 Pa showed that relatively airtight construction was achieved. The crews' haste resulted in significant leakage around windows and through unplanned openings. Such haste demonstrates additional supervision was needed.

The second test, on an entire suite, showed that leakage locations identified in the first test had been sealed, but a few places on the exterior wall (most notably window trim) still needed to be sealed. Considerable leakage was found around the interior partitions, which showed that pressure balancing with blower doors in adjacent suites was not achieving the desired results. The adjusted index ranged from 0.81 to 1.6 L/s/m^2 @ 75 Pa showing that good airtightness results were being maintained. The number of areas where leakage was occurring showed that additional supervision of sealing would be helpful.

Difficulties were encountered in sealing for the partial and pressure balancing for the suite tests. Until a definitive test procedure is developed, these tests will provide more qualitative results than quantitative. The value of these qualitative results should not be underestimated as they are the best way to show the contractor's construction deficiencies and the corrective work required.

The adjusted results for the three depressurization tests conducted are given in Table 2.4 below.

Table 2.4: Adjusted Air-Tightness Results for Three Tests

	C	N	ELA (cm^2)	Index (L/s/m^2 @ 75 Pa)
Representative Wall	0.413	1.025	17.55	1.07
Representative Suite	8.5-17	0.51	111-222	0.81-1.6
Whole Building	879.2	0.51	11,480	1.18

The final test was a whole building air leakage test. This test was successfully performed using multiple, residential type blower doors distributed around the building. The adjusted whole building air leakage index is 1.18 L/s/m^2 @ 75 Pa

The target index (1.0 L/s/m^2@ 75 Pa) is 75% below the average commercial building. The air tightness at the innovative condominium in Dundas is 70% below that average, or within five percentage points of the original goal.

3. HEAT, AIR AND MOISTURE TRANSPORT IN THE BUILDING ENVELOPE

3.1 Wall Systems

The building has two innovative exterior wall systems that provide higher levels of insulation and air-tightness than conventional construction. One wall system has a brick veneer while the other uses an exterior insulation finish system (EIFS). Both of the wall systems incorporate elements that perform specific functions:

- a continuous air barrier (AB) to control the movement of air
- insulating layers to control the movement of heat
- a vapour retarder (VR) to control the movement of water vapour
- a pressure moderating draining layer (for the brick veneer) to control liquid water penetration

Figure 3.1 and Figure 3.2 are cross-sections of the two wall systems showing construction details and monitoring instrumentation. The energy efficiency and durability of these wall systems is directly related to their ability to control the movement of heat, air, and moisture.

The original design placed a vapour retarder at the surface of the exterior gypsum board. As construction proceeded, major structural problems were identified (unrelated to the wall systems) and new personnel were hired to implement a structural remediation program. As a part of the structural changes, the new personnel installed a new VR. A 6-mil polyethylene sheet was placed behind the interior gypsum board to act as a vapour retarder. The sheet may also provide additional resistance to air movement. The original air barrier remained at the exterior gypsum board throughout the building.

The monitoring program was designed to assess the performance of these wall systems year-round by determining their effectiveness in controlling heat, air, and moisture transport. This knowledge will help infer the durability of wall systems and help the construction industry to understand and accept innovative practices.

Four wall sections were monitored:

- One east-facing section of brick wall on the fourth floor was instrumented as shown in Figure 3.1.

- One north-facing EIFS wall on the fourth floor was instrumented as shown in Figure 3.3.
- Two EIFS walls on the sixth floor (one facing south and the other facing west) were instrumented as shown in Figure 3.2.

Temperature and humidity for outdoor conditions were measured in two places. For the sixth floor south-facing EIFS wall, measurements were taken one metre away from the wall. For the other three walls, ambient conditions were measured at the weather station above the building roof.

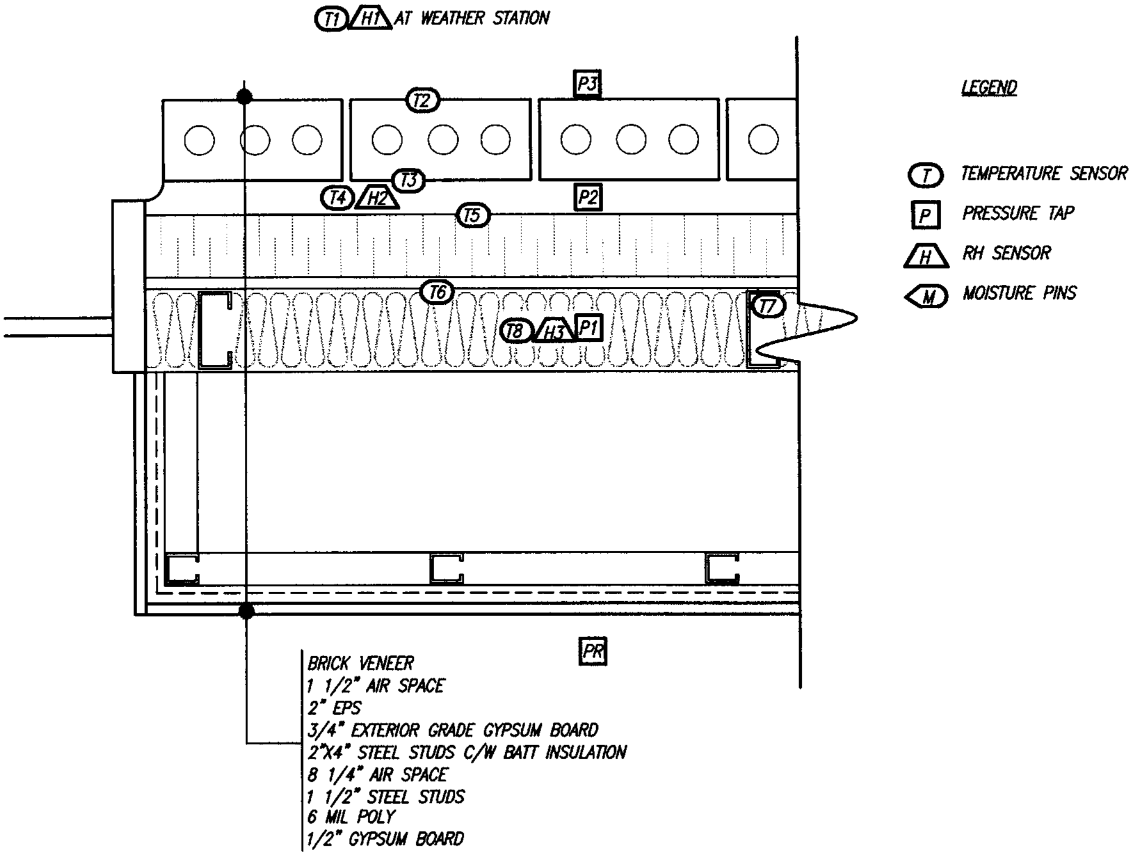


Figure 3.1: Instrument Locations In Brick Veneer Wall

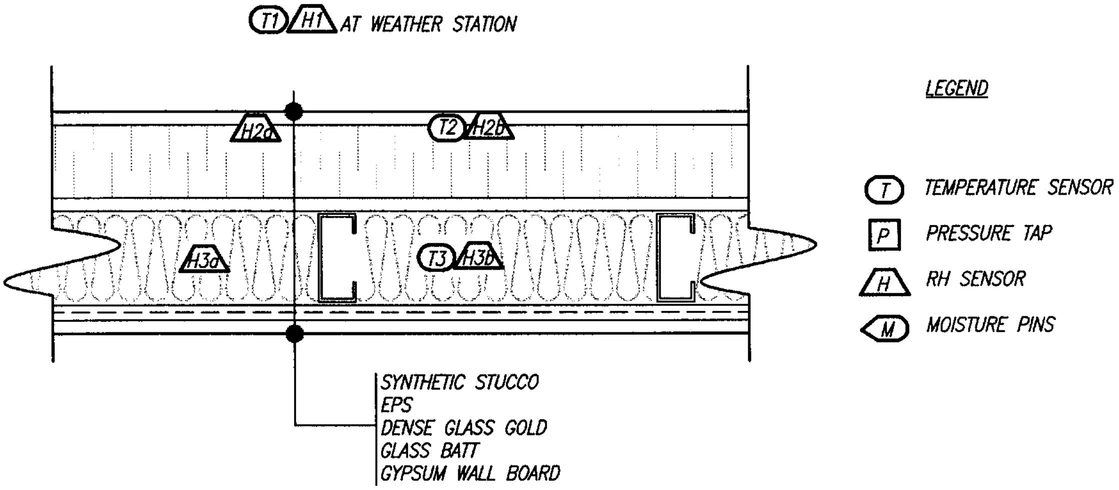


Figure 3.2: Instrumentation Locations for Sixth Floor EIFS Wall

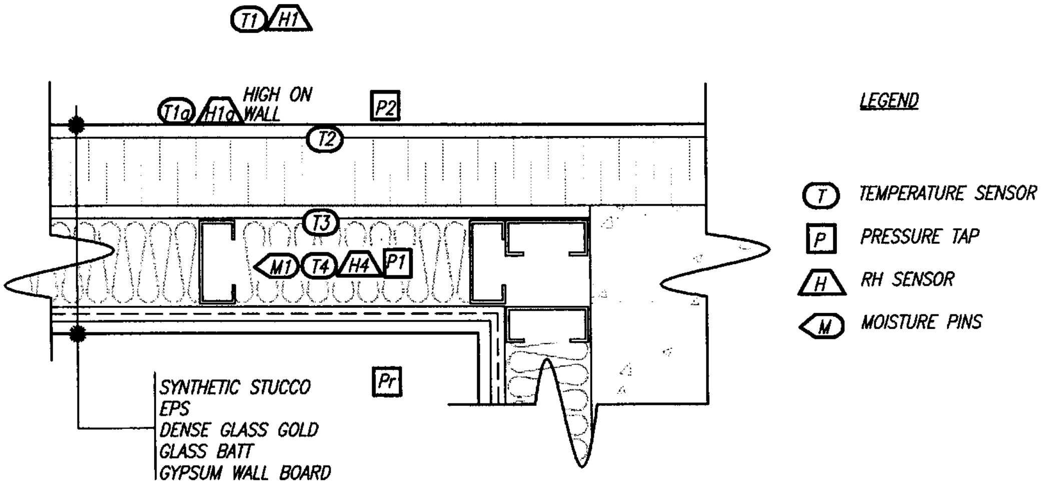


Figure 3.3: Instrument Locations for Fourth Floor EIFS Wall

3.2 Monitoring Approach

Instrumentation was installed in four walls: one brick veneer wall and three EIFS walls. Five parameters were measured:

- temperature
- relative humidity
- static pressure
- wind-driven rain
- moisture

These parameters were measured at specific locations throughout the wall system. The CMHC *Air Leakage Detection and Analysis Method* [CMHC, 1999b] was used as the basis of performance monitoring and analysis of the wall systems.

Monitoring of the Brick Veneer Wall

Sixteen points were measured in the brick wall system:

- temperature at seven points in the wall and at one point in the interior space
- relative humidity at two points in the wall and at one point in the interior space
- static air pressure at two points in the wall and at one point at the exterior surface (all relative to the static air pressure in the interior space)
- driving rain at one point on the wall
- moisture content of a white pine block in the steel stud framing's bottom track

The monitoring points for the brick veneer wall are illustrated in Figure 3.1.

Fifteen points were measured in the two EIFS walls on the sixth floor:

- temperature at six points in the wall and at one point in the interior space
- relative humidity at one point in the wall and at one point in the interior space
- static air pressure at one point in the wall and at one point at the exterior surface (both relative to the static air pressure in the interior space)
- driving rain at one point on an east-facing wall
- moisture content of a white pine block in the steel stud framing's bottom track

The monitoring points for the sixth floor EIFS walls are illustrated in Figure 3.2. In addition, temperature and humidity were measured behind the stucco and in the stud space of an EIFS wall on the fourth floor. The instrumentation described above was used to determine the dew point of the interior air. The dew point was compared to the surface temperature of the exterior gypsum board (i.e. the primary air barrier) because this is the most likely location for condensation.

Monitored Weather Conditions

Several parameters to characterize weather conditions were monitored:

- ambient air temperature
- outdoor relative humidity
- wind speed and direction
- rainfall on a horizontal surface
- solar radiation on a horizontal surface

These parameters are measured at a central weather station located 4 m above the highest point of the building.

3.3 Monitoring Results

Temperature Performance

Published insulating values of materials are indicative of their performance under ideal conditions. In actual installations, a wide variety of factors can reduce the performance of an insulated wall. The two most important factors are air movement and moisture buildup. Monitored wall temperatures and pressures can be used to determine if air movement and moisture buildup have been adequately controlled.

Figures 3.4 and 3.5 show four representative temperatures over a typical three-day period in the winter for the brick wall and EIFS systems respectively. From top to bottom, the temperatures are indoor space temperature, surface temperature on the AB (exterior gypsum), dew point temperature of the indoor air, and outdoor temperature. All temperatures were measured, with the exception of the dew point temperature, which was calculated based on the measured temperature and humidity for the air in the space (typically around 25%). In the brick wall system (Figure 3.4), the surface temperature at the plane of the AB is generally between 6 and 7°C warmer than the dew point temperature. Thus, there is little risk of condensation occurring on the plane of the AB.

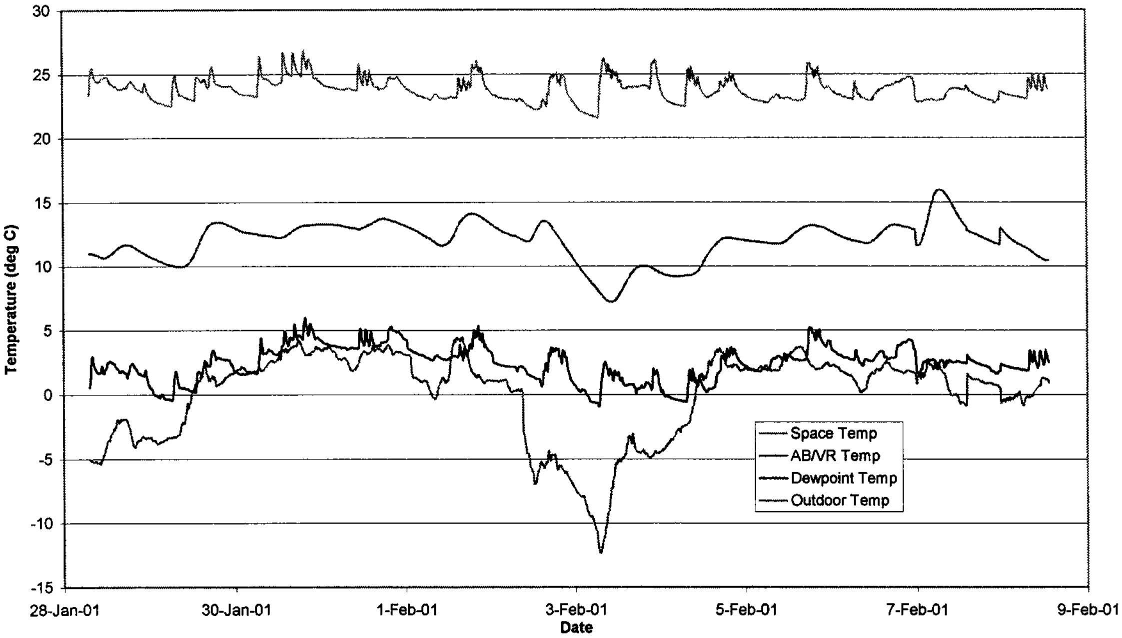


Figure 3.4: Temperatures Across Brick Wall on a Cold Day

Figure 3.5 shows the temperature measurements across the EIFS wall. Here the surface temperature at the plane of the AB is slightly closer to the dew point temperature than in the brick wall system. There are two reasons for this. First, the relative humidity in the suite is maintained significantly higher than in the suite with the brick wall section (35% vs. 25%). Second, the percentage of the total wall insulating value on the warm side of the exterior gypsum board is greater than for the brick wall. That is, the surface temperature at the AB is closer to the outside temperature because there is less insulation outboard with the EIFS system. Still, there is no real concern with condensation at the surface of the AB.

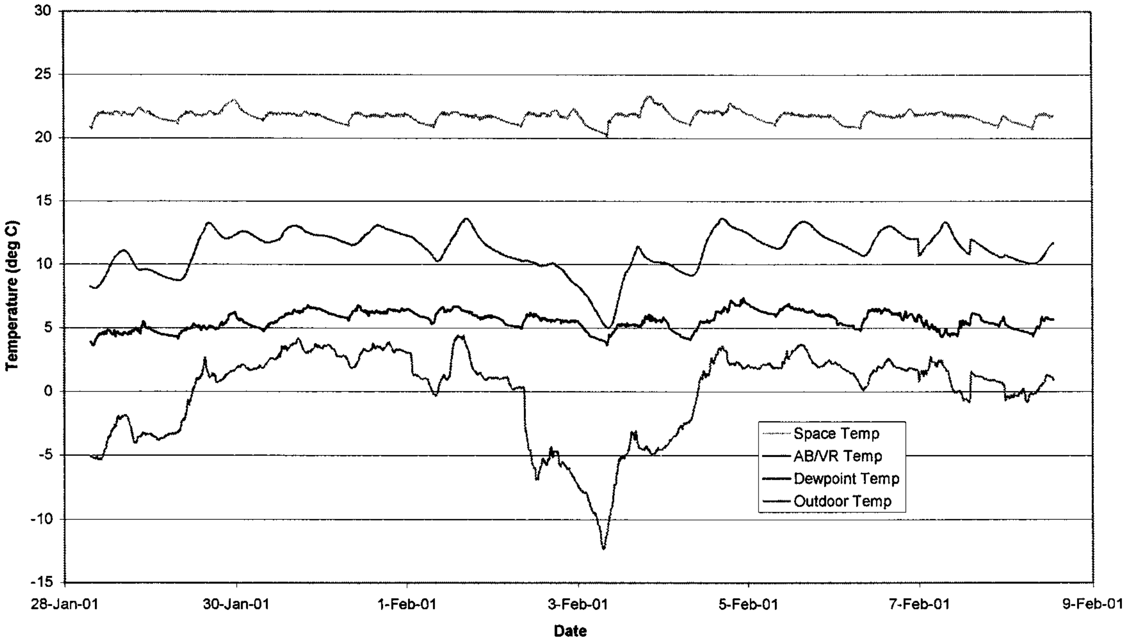


Figure 3.5: Temperatures Across an EIFS Wall on a Cold Day

Figures 3.6 and 3.7 show the theoretical temperature index (based on the theoretical wall R-values) and the corresponding temperature index from measured temperature data for each of the two walls. The temperature index is defined as the temperature difference between the indoor temperature and the temperature at the plane of the AB divided by the total temperature difference across the wall. In this case, it has been assumed that the exterior sheathing is that plane. The temperature index plot can identify potential air leakage problems in the wall.

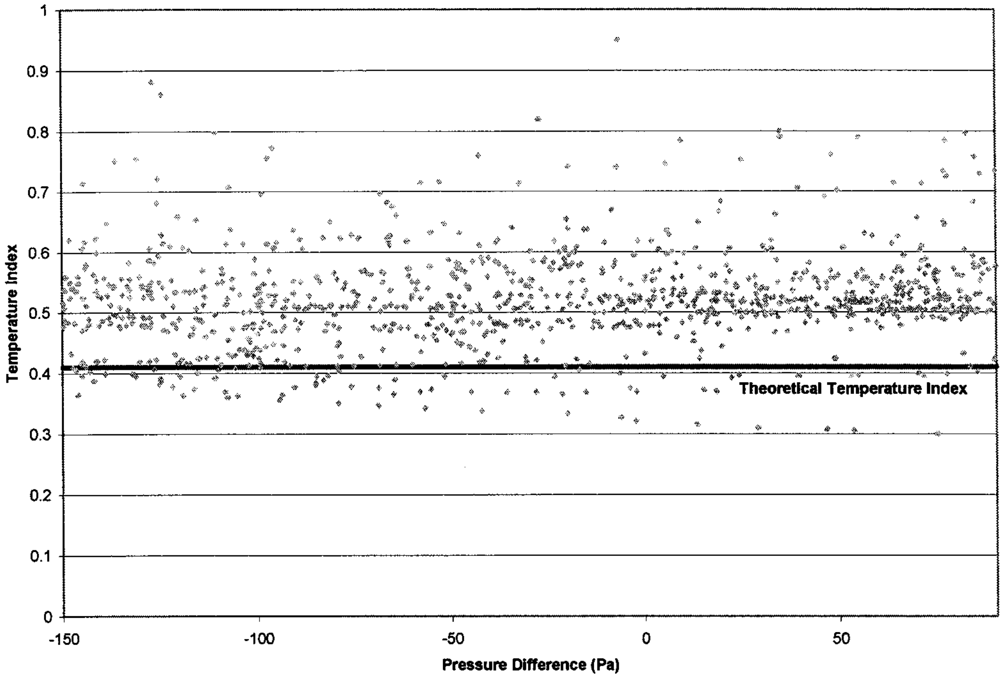


Figure 3.6: Theoretical and Monitored Temperature Index for a Brick-clad Wall

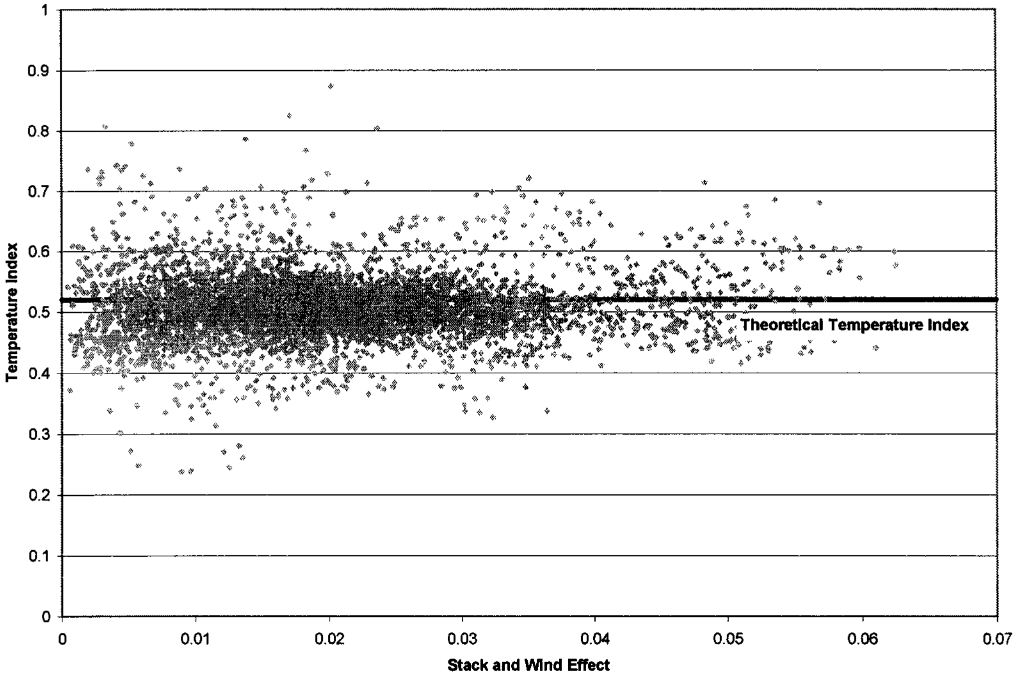


Figure 3.7: Theoretical And Monitored Temperature Index for an EIFS Wall

Mathematically the measured temperature index is $\left(\frac{(T_{indoor} - T_{AB/VR})}{(T_{indoor} - T_{exterior\_surface})}\right)$

In this study, the exterior surface temperature was used rather than the outdoor air temperature to reduce the effects of the transients as the sun heats the building surface.

The theoretical temperature index can be calculated as the ratio of resistances or expressed mathematically as $\frac{(R_1 + R_2 + R_3 + \ldots)}{R_{total}}$

Where: R_1, R_2, R_3, etc., are the thermal resistance of each layer between the indoor air and the . R_{total} is the resistance of the total wall assembly, excluding the outdoor air film.

The temperature index is plotted against the pressure difference across the wall. The theoretical line of 0.41 shows that under ideal, steady-state conditions the surface of the VR will be 41% of the way to the brick surface temperature. For example, if, on a design day it is 22°C indoors and -18°C at the brick surface, the temperature at the plane of the original VR should be 5.6°C. Index values above the theoretical line show that the VR is colder than ideal and measured values below the theoretical index show a temperature higher than theoretical.

If air leakage is present, then under negative pressure differences (i.e. indoor air pressure is higher than outdoor) the temperature index will drop, indicating that warm air is being drawn out through the wall. Under positive pressure differences the index will rise as cold air is pushed through from outside. Since there is no trend to the data, it can be concluded there is little if any air leakage.

The measured values for the brick wall are generally between 0.5 and 0.6. Almost all exceed the theoretical value of 0.41. This indicates that either the insulation installed on the exterior of the building may not be providing the insulation value expected, or that the pressure-equalized rain screen may allow air to circulate through the cavity behind the brick. This air circulation would eliminate the air cavity and the brick as an insulating layer. This alone, however, does not explain the large difference between the theoretical and the measured values.

The theoretical temperature index for the stucco wall is 0.52. In this case, the pressure transducer was giving erroneous readings and a substitute value for pressure difference was needed. Since it was not possible to replace the transducer, readings of temperature, wind speed, and wind direction were used in ASHRAE recommended calculations [ASHRAE, 1993] for stack and wind induced infiltration. The flow is proportional to pressure difference and allows the data to be sorted in a similar manner to what it might be were actual pressure readings available.

Figure 3.7 illustrates that the measured temperature index sometimes can exceed the theoretical index for the stucco wall. The variations do not follow any pattern with respect to pressure difference. This suggests that the air barrier is performing well and that there is practically no air movement through the air barrier. The scatter in the data is indicative of non steady-state conditions in the wall.

Moisture Accumulation in the Walls

Pine block moisture sensors were installed at floor level inside the steel stud cavity of three wall sections. Any changes in moisture content in the blocks over long periods would show either the accumulation of moisture or drying occurring in the wall over time. The major advantage of the moisture block is that it is in contact with a large area of wall in the vicinity of the sensor.

The moisture content of the block in the west-facing EIFS wall varied between 10.6 and 11.2% moisture content by weight. Using the wood sorption isotherm for white pine [Canadian Wood Council, 1990] this corresponds to an air relative humidity of 60 to 65%. In the other walls, moisture content was below the measurable range of the pine block, indicating moisture content of below 10%. This corresponds to a relative humidity of less than 55%. In all cases there was no net increase in the moisture content of any blocks, showing that there is no condensation accumulating in the wall sections being monitored.

4. HEATING SYSTEM PERFORMANCE

4.1 Description of Heating Systems

Two types of space and water heating systems were installed in the suites at the innovative condominium in Dundas:

- combination space and water heating systems (combo-systems)
- high-efficiency furnace and separate power-vented water heater

In addition, common areas are heated by a variety of baseboard radiators and fan coils from a mid-efficiency central boiler. Domestic hot water is supplied to the common areas by a separate storage-type power-vented, natural gas water heater.

Combo-Systems

Most suites have an in-suite combination space and water heating system. These combo-systems use a John Woods/GSW natural gas-fired, power-vented, 151 or 190 L storage water heater as the heating source and hot water supply. An Enerzone air-handler complete with hot water-to-air fan-coil and high-efficiency ECM fan motor, distributes space-heating air.

The combo-system offers several advantages over the use of separate appliances for space and water heating:

- reduced capital costs because only one fuel-burning appliance is purchased and installed
- reduced venting (only one appliance)
- increased high-value floor space near exterior walls from installation in an interior mechanical room
- increased thermal performance because of the increased loading on the combined appliance
- provided opportunity to install individual suite metering

There have, however, been concerns raised about the thermal and energy performance of combo-systems. One concern is that the system must be sized so that both water and space heating loads are met when required, especially with concurrent loads. Another concern is the inherent low efficiency of storage-type devices that operate with small and intermittent loads. Two combo-systems at the innovative condominium in Dundas were monitored to assess their thermal and energy performance.

Independent Furnace/Water Heating Systems

Two suites have a separate high-efficiency forced air furnace and a power-vented natural gas-fired water heater. One of these systems was monitored to provide reference data to compare with the performance of the combo-systems.

Central Common Area System

A cast-iron, mid-efficiency (84%), 150-kW hot water boiler serves the heating requirements of the common areas, using fan coils and baseboard radiation for heat delivery. The areas heated by this system include:

- meeting room
- exercise room
- guest room
- two stairwells
- lounge
- parking garage above the insulated ceiling
- lobby
- garbage room
- spa and shower areas
- multi-purpose room
- heating coil in spa HRV supply

The system has numerous parallel circuits with their own on-off flow controls. One circuit runs continuously to ensure flow through the boiler under no-load conditions during the heating season. Heating energy delivered and natural gas consumed by the boiler system were monitored to obtain long-term performance data.

4.2 Monitoring System

The purpose of the monitoring program is to evaluate the seasonal performance of the three types of heating systems. Parameters of interest include the following:

- space temperature
- delivered water temperature
- space heating energy delivered
- domestic hot water energy delivered
- standby losses
- seasonal efficiency
- electricity consumption
- cycling frequency and duration
- potential operating and maintenance difficulties

Computer-based monitoring was installed in three suites—two with combo-systems and one with a high-efficiency furnace and power-vented water heater. Figure 4.1 is a schematic of the monitoring system for the combo-system. The monitoring system consisted of the following instruments:

- two temperature sensors and one water flow meter to measure domestic hot water load
- two temperature sensors and one water flow meter to measure space heating load
- a gas meter to measure natural gas consumption
- a watt-hour meter to measure electric consumption of fans and controls (air-handler electricity was measured in heating mode only)

Measurements were taken every 30 seconds and averages or totals were stored every 15 minutes. Measurements from the above instruments provided the basic information required for the performance assessments. One-time measurements of steady-state efficiency were also made on all combustion equipment monitored. The measurements provide a check to ensure that the system, as installed, is operating acceptably. These measurements also provide the baseline combustion efficiency value for evaluating the long-term performance of the systems.

Calculated system parameters include the following:

- useful loads (heat delivered to the domestic hot water and to the space)

- primary and parasitic energy consumed (gas and electricity consumption respectively)
- heat delivered to the storage tank (combustion efficiency multiplied by the gas use)
- standby losses and cycling losses (heat delivered to the tank minus heat delivered to the useful loads)

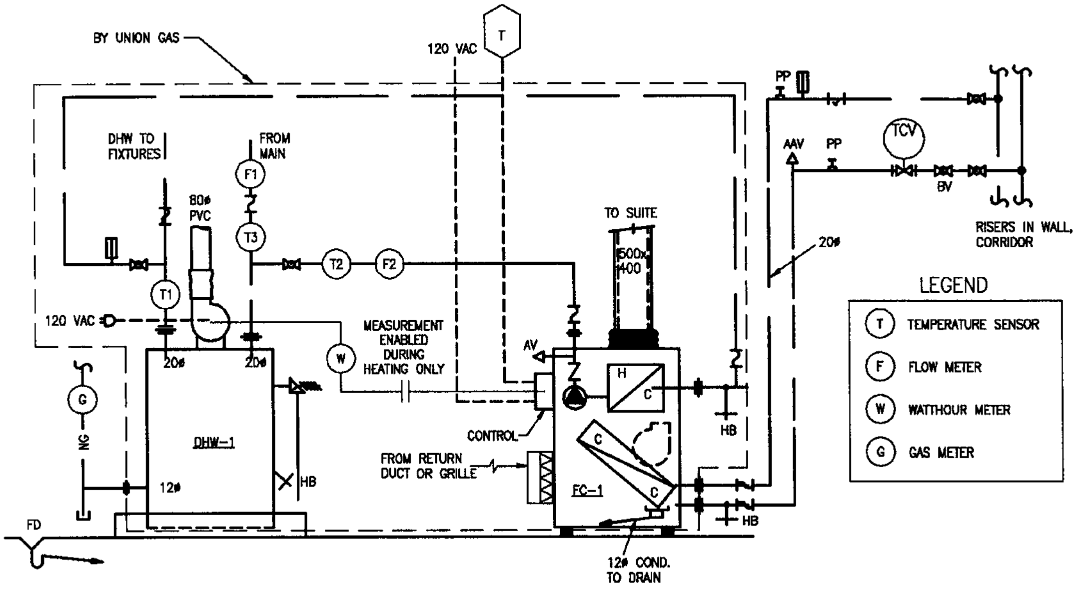


Figure 4.1: Combo-System Monitoring Schematic

4.3 Monitoring Results

Combustion Efficiency Results

One-time combustion efficiency measurements were performed on 3 conventional hot water heaters and the common area boiler. A high-accuracy Ecom A+ Combustion Analyzer was used. Sample readings were taken in the flue upstream of introduction of dilution air to ensure accurate results. The meter read:

- draft
- percent concentration of CO_2 in the flue gas

- stack temperature
- room temperature

and from those calculated the combustion efficiency. Table 4.1 shows two measurements for two of the three in-suite systems and for the common area boiler.

Table 4.1: Combustion Efficiency Test Results for Four Appliances

Suite	Heater Type	Test #	Net Temp (°C)	CO_2 (%)	Combustion Efficiency (%)
6	DHW	1	160	3.8	74.9
		2	187	4.5	74.8
4	DHW	1	156	3.1	71.8
		2	168	4.3	75.7
3	DHW	1	216	3.0	65.0
Common	Boiler	1	135	3.4	76.3
		2	129	3.0	74.5

Storage water heaters do not have a combustion efficiency rating because the water temperature is constantly changing and it would be difficult (and arbitrary) to obtain any steady state reading. Instead, water heaters have a recovery performance that rates the ability to produce a 55oC (100oF) increase in water temperature from a cold start. From this information, an "average" efficiency can be calculated for conditions when the tank is partially heated. For the combo-system water heaters, this average efficiency would be 76.7%.

The results generally show a relatively small range in combustion efficiency between the water heaters as installed. With the exception of Suite 3, the readings are between 71.8% and 75.7%. Suite 3 showed a lower efficiency at 65%. Operating efficiency for the boiler was also somewhat low, being well below the 84% rated efficiency.

There are two possible explanations for the variation in efficiency. First, efficiency will vary with water temperature. When the water temperature is low (e.g. due to a recent large water draw), combustion efficiency is high. As the water temperature increases, less heat is transferred to the water and thus the efficiency decreases.

Second, gas appliances have a gas valve adjustment and a combustion air shutter adjustment. If these adjustments are not set when the system is installed, combustion conditions could be less than optimum, thus reducing efficiency.

The high flue gas temperature for Suite 3 suggests that the water temperature may have been higher than for the other units. Another consideration is that installers do not routinely measure combustion efficiency nor do they often make adjustments at start-up to ensure optimum combustion efficiency. Standard practice in the industry is to install a gas appliance and then to check the appliance only to ensure that it fires (and possibly to check the colour of the flame). Therefore, it is not surprising that the combustion efficiency for two of the four units measured could be below the expected value. Low combustion efficiency will have a corresponding influence on the annual energy performance.

Heating Loads

The operating conditions in the suites are listed in Table 4.2. There were significant differences in the operation of the suites. Suite 3 was unoccupied for a significant portion of the winter with one of the two occupants returning occasionally for short periods. Two people occupied Suite 4 for the entire monitoring period. In Suite 6, the two occupants were away occasionally, only for short periods.

Although the owners of Suite 3 were away significant portions of the winter, they did leave the heat on in the apartment and maintained the indoor temperature at about 23°C, thus maintaining a high heating load. The owners of Suite 4 preferred a cooler living space. While the room temperature was about 22°C over the monitoring period, the heating system rarely came on because the thermostat was set to about 20°C. This was a relatively small west-facing suite. In Suite 6, the space temperature was maintained at a relatively constant 22°C

Ventilation air can add significantly to the suite's heating load. In Suite 3, the HRV was off the entire monitoring period leaving only a minimal ventilation load due to natural infiltration. In Suite 4, the HRV operated constantly. The air change rate was 0.25 to 0.4 ACH depending on the operating speed. In Suite 6, the HRV was operated manually an hour or so most mornings and evenings based on the homeowners' perception of indoor air quality. The HRV provides 50% to 60% heat recovery depending on airflow. Heat recovery significantly reduces the heating requirements associated with providing fresh ventilation air. Natural infiltration into the suites was low. IAQ testing showed that in was in the order of 0.04 to 0.09 air changes per hour (see Section 5.2).

With the owners of Suite 3 absent much of the monitoring period, little water was used. During the days when a single person occupied the suite, hot water use per day was 88 L/d at a delivered water temperature of 59.7°C. In Suite 4, the owners used 125 L/d of hot water at 51.1°C. Hot water use for Suite 6 was 74 L/d at a temperature of 49°C.

These loads are within the range suggested in ASHRAE [ASHRAE Handbook, 1995] for service water heating design calculations. Information on senior's apartments suggests hot water use is in the range of 53 L/person/day (or 106 L/d for an apartment occupied by two people) to 152 L/d for apartment buildings with 50 or less suites. These figures are for hot water use at 60°C.

Table 4.2: Monitored Operating Parameters for Three Suites

	Suite 3	Suite 4	Suite 6
Occupancy (% occupancy)	56	100	100
Space Temperature (°C)	22.8	21.9	21.8
Water Consumption (L/day when occupied)	88	125	74
Water Consumption (L/day overall)	48	125	74
Delivered Water Temp (°C)	59.7	51.1	49.2
HRV operation (% of time)	0	100	10

The overall effect of these differences was that Suite 3 had a typical space heating load and modest water heating load, while Suite 4 had a higher total water heating load but a very low space heating load.

Heating System Monitored Results

Three in-suite space heating/DHW systems and the common area boiler were monitored to determine seasonal efficiency based on useful heat delivered. The results for the monitoring period from February 2001 to February 2002 appear in Table 4.3.

Table 4.3: Monitored Performance Parameters for Five Appliances

	Suite 3 Combo	Suite 4 Combo	Suite 6 Furnace	Suite 6 Water Heater	Central Boiler
Space Heating Delivered (MJ)	7,612	126	7,773	--	169,131
Water Heating Delivered (MJ)	11,330	8'048	--	4,690	--
Total Energy Delivered (MJ)	18,942	8,174	7,773	4,690	169,131
Natural Gas Consumed (m^3)	1,121	497	263	356	7,031
Seasonal Efficiency (%)	44.5%	43.3%	77.8%	34.7%	63.3%
Combustion Efficiency (%)	65.0%	73.8%	--	74.9%	75.4%
Seasonal Rating (EF / AFUE)	0.58	0.58	96.6%	0.58	83%

The calculated efficiencies in the table above take into account the electricity consumed by fan coil/furnace blower and water heater exhaust fan. In all cases, the electrical input was approximately 1% of the natural gas input during the heating season.

Combo-Systems

The seasonal efficiency of a storage water heater is proportional to the load. That is, efficiency decreases as the load decreases. This occurs because energy is required to overcome standby losses and maintain the storage set-point temperature whether or not any hot water is used. The magnitude of those losses is relatively constant regardless of load. As the water-heating load falls, useful heating as a fraction of the total gas consumed also falls.

As expected, Figure 4.2 shows that generally the seasonal efficiency fell as the water-heating load fell for the three water heaters monitored. As well, the monthly combustion efficiency is well below the measured combustion efficiency (Table 4.1) and the rated energy factor.

Water heaters do not have a combustion efficiency rating, rather they have a recovery rating (i.e. how quickly does the tank recover after being depleted of hot water). This is because water heaters do not operate at steady state. Rather, the stored water temperature is constantly changing while the appliance is firing. The recovery efficiency can be calculated by dividing the recovery rate by the gas consumption. For the water heaters used this calculation gives a value of 76%. The calculated recovery efficiency is 0.6 to 11 percentage points above the measured combustion efficiencies.

A water heater's annual performance is rated in terms of energy factor. This is a laboratory measurement of performance based on an intermittent water draw totaling 246 L over one day. The energy factor for the water heaters used at the innovative condominium is 0.58 (i.e. 58%). It is less than the recovery efficiency because the energy factor includes a calculation for standby losses.

The monitored results show some correlation between DHW load and efficiency. Figure 4.2 below shows the correlation between monthly DHW and/or space heating load vs. calculated monthly efficiency. Each data point represents total load and efficiency for one month between February and August 2001. The rated energy factor of .58 (based on a load of 15 kWh/day or 1674 MJ/month) is also shown. A trend line drawn through the monitored points shows two effects, a linear relationship between load and efficiency, and the seasonal efficiency at the rating point below the energy factor. The limited number of data points (24) is insufficient for drawing definitive quantitative conclusions but the trends are valid.

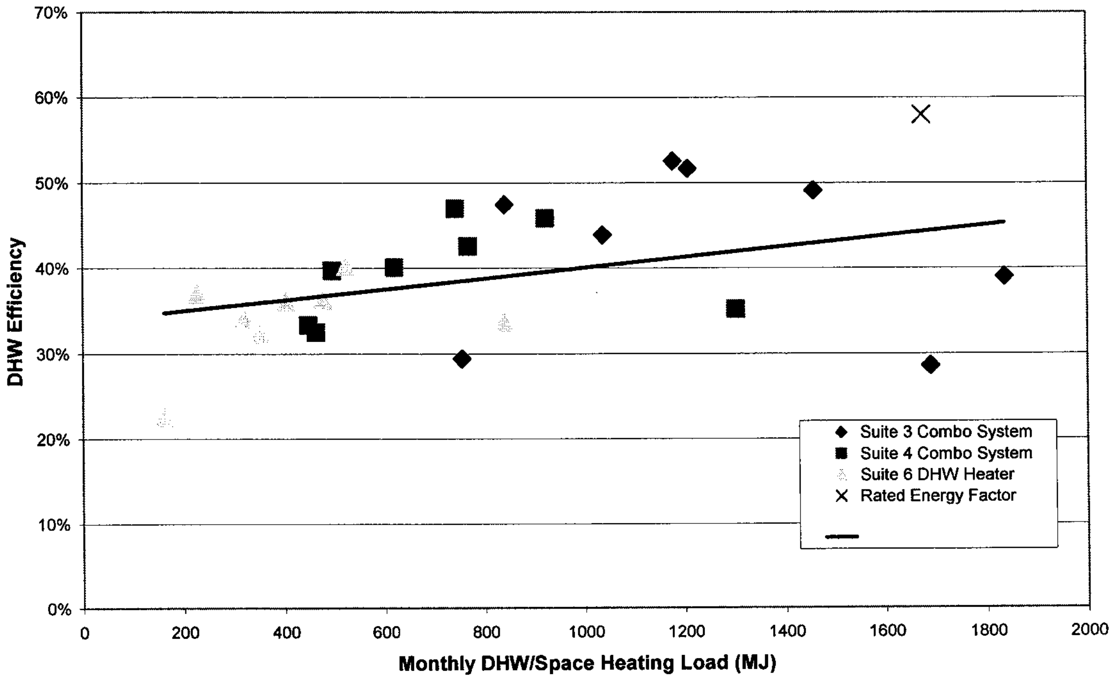


Figure 4.2: Monitored Efficiency for Three Water Heaters

If it is assumed that the rated recovery efficiency (76%) is the combustion efficiency (excludes standby losses), then the standby losses calculated from the monitored data were 175 to 210 W. A significant amount of the standby loss is from a constant natural convection loss up the central flue. Electric water heaters (with no central flue) have typical standby losses of 85 to 150 watts, about half that of gas water heaters. Further, the energy factor for electric water heaters is about 0.7 to 0.9. For natural gas water heaters, the energy factor is about 0.5 to 0.6. Therefore, the monitored standby losses appear reasonable.

Ontario Hydro testing of electric water heaters in the mid-1980s showed that beyond tank skin losses, one of the major locations for standby loss is at the tank fittings. These include the cold and hot water connections, the temperature and pressure relief valve, and anode fittings. Research has also shown that there is significant thermosyphoning of heat up the hot and cold water pipes attached to the tank. This was confirmed by monitoring at the innovative condominium, which showed a rise in temperature to near the tank set-point in both the hot and cold water pipes during periods of no water flow.

The occupants did not run short of either domestic hot water or space heating capacity. Thus, it appears that the combo-systems are capable of providing the thermal performance demanded. Unfortunately, the standby losses to accomplish those tasks were relatively high. The combo-system worked slightly better than a storage water heater would work under normal operating conditions in a conventional house. That is, for the combo-systems (Suites 3 and 4) the seasonal efficiency was over 40%, compared with the operation of the stand-alone water heater installed in Suite 6 at 35%.

A major opportunity for improving the energy performance of combo-systems is through reducing standby losses. This requires attention to several areas:

- increased levels of jacket insulation on the tank
- reduced losses from tank fittings
- installation of heat traps (or other means of stopping convection in the pipes rising out of the tank)
- reduced convective heat loss through the flue

By setting the tank temperature lower, standby heat loss would be reduced. This however, is not advisable. First, a larger fan coil to deliver space heating would be required. Second, hot water for high-temperature domestic applications such as dishwashers is lost. Finally, temperatures of 60°C or higher are recommended to reduce the risk of Legionella pneumophila.

Boiler and Furnace

It is argued that standby losses from heating appliances provide useful space conditioning, reducing the output space heating systems would otherwise have to deliver (e.g., AFUE calculations). There are three limitations to this argument. First, if the heat is concentrated in the mechanical room and is not distributed to the rest of the suite, then the suite does not receive the full value of that heat. Second, the fraction of space heating the standby losses offsets is only of value in the winter. Third, flue losses (the major loss for gas-fired storage water heaters) are not delivered to the space.

Results show that the monitored seasonal efficiencies based on heat delivered for the boiler and forced air furnace are 19.7 and 18.8 percentage points below the Annual Fuel Utilization Efficiency (AFUE) ratings respectively. The difference can be attributed to several factors. First, the combustion efficiency on the boiler is below the rated efficiency. This could be due to a lack of burner adjustment on initial set-up. Second, the AFUE calculation counts losses from the boiler casing into the boiler room as useful heat, while monitoring counted only the heat delivered by the water to the building as useful. Third, AFUE does not account for convective flue losses carrying away heat from the continuously circulating boiler water. Again, monitoring would have shown these to be losses.

Monitoring shows that the heat delivered to the load by the boiler water is less than is suggested by the AFUE. There seems to be a similar trend with the high efficiency furnace. Therefore, it would be best to use AFUE as a relative measure to compare heating appliances rather than an absolute value for calculating annual energy consumption.

Comparison of Separate Furnace and Water Heater to Combo-System

Combo-systems were monitored in two suites and separate appliances in one. There are differences in load due to the size of the suites served and homeowner interaction. To eliminate these differences from the comparison it is best to compare system efficiencies.

For the two combo-systems monitored, the load varied by about a factor of two, but the efficiency varied by only one percentage point (see Table 4.3). Therefore, the combo-systems are considered to have operated at an average efficiency of 44%. Using separate appliances in Suite 6, space heating was 62% of the combined total load and the water heater was 38%. When the total energy delivered is compared to the total natural gas consumed, the average efficiency for the separate appliances is 53% (see Table 4.4).

Table 4.4: Performance Comparison: Combo-System to Separate Appliances

	Combo-system Average (for 2)	Suite 6 –Furnace and Water Heater Combined
Energy Delivered (MJ)	13,558	12,463
Natural Gas Consumed (m^3)	809	619
Seasonal Efficiency (%)	44	53

The combo-system did draw less electric power than the individual appliances. The furnace had a PSC motor while the combo-system's air handler had an ECM. The average draw for the separate appliances was 150 W, or two and one-half times higher than the 60W draw for the combo-system. This was interesting because the combo-system fan was operated continuously and the electrical energy used over the heating season was five times that used by the furnace and water heater system.

The combo-system did raise the average efficiency of the water heater. The combo-systems in Suites 3 and 4 showed a 10 percentage-point efficiency advantage compared to the water heater alone in Suite 6. Adding the space-heating load to the water heater would have reduced standby losses and reduced the average tank temperature over the year. However, the efficiency increase was not sufficient to overcome the energy advantage of using a high efficiency furnace for the space-heating component (usually the larger component) of the load. Using separate appliances proved to be the more energy efficient option in this case. A high-efficiency (AFUE greater than 90%) water heater in a combo-system instead of a power vent water heater should outperform separate appliances.

5. VENTILATION AND INDOOR AIR QUALITY

5.1 Ventilation Design for IAQ

Individual Suites

In-suite ventilation systems were designed in accordance with Standard CAN/CSA-F326-M91 Residential Mechanical Ventilation Systems [CSA, 1991]. Building codes for high-rise residential construction do not mandate mechanical ventilation to individual suites and F326 does not specifically apply to high-rise residential buildings. Nevertheless, it was deemed prudent to apply this standard to ensure good IAQ, considering the airtight construction of the building shell and the failure of conventional apartment building ventilation strategies to maintain good IAQ in a cost-effective manner.

Fresh air flows continuously and independently to each suite using heat recovery ventilators (HRVs). Distribution throughout the suite was accomplished by using the space conditioning supply ducting. Figure 5.1 shows the general arrangement of the suite system.

The HRVs operate continuously on low speed (approximately 30L/s) to provide approximately 0.35 air changes per hour (ACH) of fresh air. The units have a high-speed capacity of about 60 L/s to provide higher ventilation rates when a buildup of humidity or other contaminants warrants. Manual switches and a humidity-activated automatic switch initiate high speed. Fresh air supply is balanced with an equal amount of stale air exhaust during both low and high-speed operation. Exhaust air is drawn through dedicated ductwork from the bathroom and kitchen. Only heat is recovered from the stale air—there is no re-circulation of exhaust air within the suite. An air-balancing contractor was employed to test, adjust and balance the airflows of all HRVs.

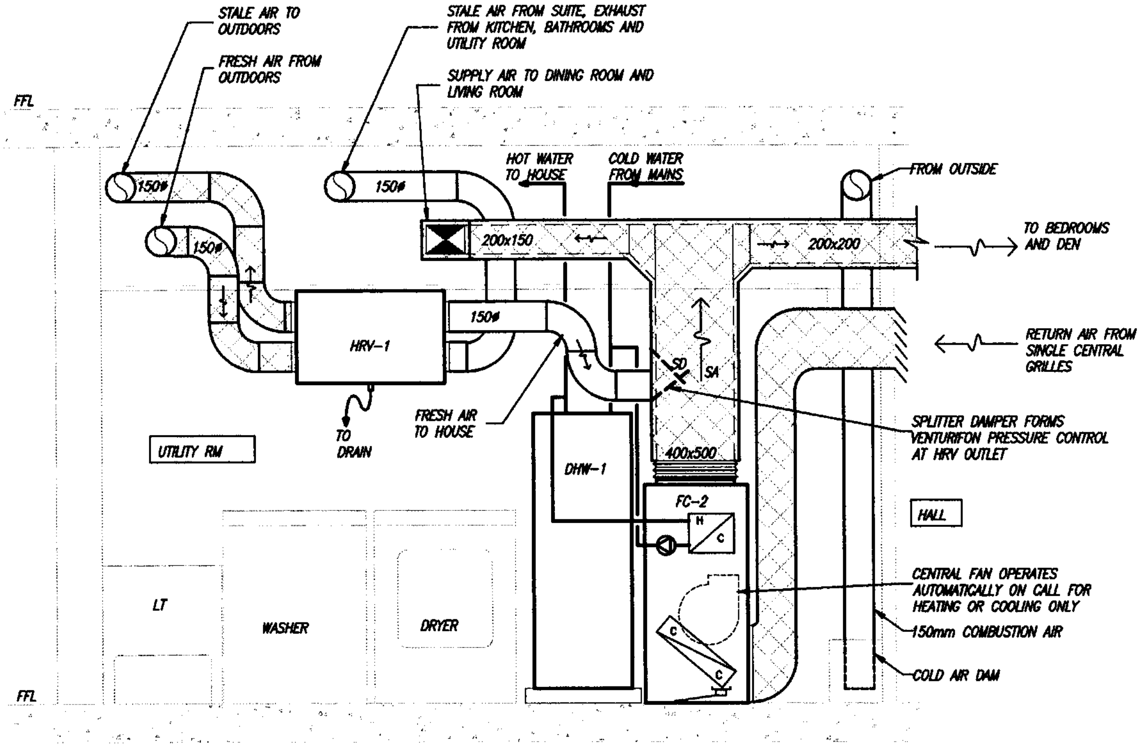


Figure 5.1: Typical Suite Ventilation System Schematic

Balanced ventilation and a 150 mm combustion air supply vent were installed to prevent depressurization and protect against the potential for combustion gas spillage. The combustion air duct was sized (design produced in accordance with the Ontario Gas Utilization Code) to provide relief air for the water heater, natural gas clothes dryer, natural gas range and vented range hood. Each suite has balanced ventilation with heat recovery. The overall building shell is also relatively airtight. Both factors reduce pressure gradients throughout the building helping to ensure proper functioning of a combustion air duct in all suites.

The range hood, rated 47 L/s, exhausts combustion products from the natural gas stove directly outdoors and was installed in accordance with F326. No evidence of stack effect, inducing reverse flow through the combustion air duct, was noted on the top floor.

Corridor Ventilation

In most high-rise residential buildings, outdoor air is provided by a corridor make-up air system. Traditionally, the corridors are pressurized to force air from the hall into the suites to provide odour control. By default, this also provides some suite ventilation. At the innovative condominium, suite ventilation is provided by an in-suite system; therefore, corridor air is not needed for suite ventilation.

A small amount of ventilation air is provided to maintain fresh air in the corridor. The larger concern was preventing garbage odours from migrating into the hallways. To address both issues, the exhaust side of a commercial sized HRV was attached to the top of the garbage chute. Depressurizing the chute, and consequently the garbage rooms, prevents odours from migrating into the building. This also pulls some exhaust through the chute door on each floor and induces some corridor ventilation.

The supply side of the HRV delivers fresh, tempered air to the corridor on each floor. The supply grilles are located near the ceiling, just down the hall from the garbage rooms. Corridor and garbage chute flow rates were based on good engineering practice since no code deals specifically with this situation. A total exhaust flow of 330 L/s was chosen to maintain the chute under a constant negative pressure. The equivalent supply provides approximately 50 L/s to each of the six corridors and 30 L/s to the parking level elevator lobby area. ASHRAE suggests a ventilation rate of 2.0 ACH in corridors and the system provides 1.6 ACH.

Common Area Ventilation

Common areas, especially the whirlpool spa, required ventilation to prevent excessive humidity buildup. A separate 330 L/s HRV was installed with a heating coil and cooling coil in the supply duct. These coils provide space heating and cooling to the common spaces in conjunction with the ventilation air supply and eliminate the need for separate space conditioning systems.

Garage Ventilation

The garage, located in the partially-sunken basement, is a large, unheated, enclosed space. The walls are not open; therefore the Ontario Building Code requires mechanical ventilation to protect against a buildup of carbon monoxide and other contaminants. Cross-ventilation was provided at six air changes an hour. A through-the-wall propeller fan exhausts 8,000 L/s from the east end of the building and an interlocked motorized damper supplies fresh air from the west end. A CO controller activates the system whenever CO levels rise above 15 ppm, thus saving electrical energy for fan operation in the garage.

5.2 Indoor Air Quality Testing

A testing program was designed to assess the effectiveness of the building ventilation systems in maintaining adequate indoor air quality. The program consisted of six components:

- week-long tracer gas tests to assess the effectiveness of the garage ventilation system in keeping automobile fumes from accumulating in the parking garage
- week-long tracer gas tests to evaluate the compartmentalization of the building structure (the ability to impede the movement of air contaminants from suite to suite and from common areas to suites)
- short-term tracer gas decay testing (using SF_6) in an unoccupied suite to measure the natural infiltration rate with no fans operating as well as the mechanical ventilation rate with the HRV operating and with and without air-handler operation
- week-long tracer gas tests to evaluate air distribution throughout a single suite
- week-long measurements of formaldehyde, total volatile organic compounds (VOCs) and respirable particulates to assess suite indoor air quality
- long-term measurements of carbon dioxide (CO_2) levels in suites and corridors to assess apparent ventilation performance over a full year

All testing was conducted after the building was complete and air balancing had been done on all systems including all suite HRV's by a qualified air balance contractor. All testing, except the SF_6 tests, were conducted with the building occupied to capture typical usage and occupancy patterns. Testing was conducted during the winter so that the impacts of stack effect and wind-induced infiltration/exfiltration were included. Windows were kept closed so that internal air movement patterns were typical for winter conditions.

Parking Garage Ventilation and Building Compartmentalization Testing

The parking garage ventilation and compartmentalization tests were conducted simultaneously using perfluorocarbon tracer (PFT) gas emitters and capillary adsorption tube samplers (CATS) Figure 5.2 shows the locations of the PFTs (black circles labeled Sx) and the CATS (rectangles labeled CATS). The testing was performed during the week of March 19 to 26, 2001. For the test period, the HRV in each suite was set on low-speed and allowed to operate on high as required to ensure the building was operated as designed.

Seven PFT sources of the same composition (labeled S1) were distributed throughout the garage to provide adequate coverage by the tracer gas. Two CAT samplers were used to measure the average PFT concentrations within the garage. The average ventilation rate was calculated from these measurements. The test was run over seven days.

Additional CATS were placed in 12 locations throughout the building to monitor the effectiveness of garage sealing from the building interior and the amount of air moving from the garage into the suites and corridors. The concentration of PFT from S1 found in each of the 12 CATS was indicative of the airflow from the garage to each of those locations.

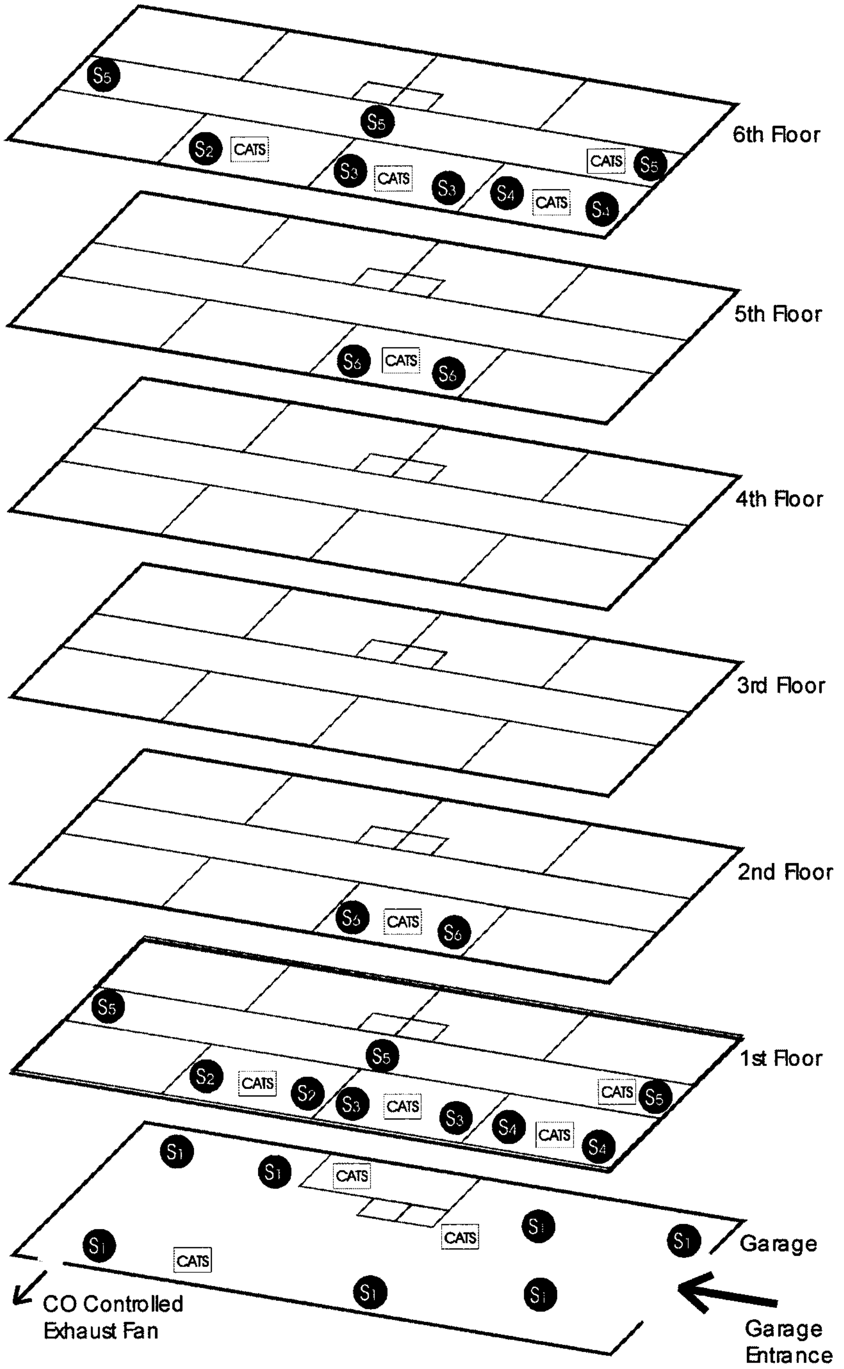


Figure 5.2: PFT Equipment Layout for Whole Building Testing

Another series of PFT sensors (labeled S2 to S6) were distributed throughout the building to assess building compartmentalization. Representative suites on the first and sixth floors were selected and the PFTs and CATS samplers set-up to characterize the air movement to and from those suites. As shown in Figure 5.2, the representative suites contained PFTs labeled S3. PFTs in the corridor, the suites on either side and the suite above/below are used to complete the characterization of the representative suites. The locations were chosen as worst-case scenarios (those having the largest driving forces for air movement). Diffusion force and direct air leakage are highest between adjacent suites, such as the two side-by-side on the first floor. The suites on the first and sixth floors have the highest potential pressure difference due to stack effect carrying air through common shafts. The suites between the first and sixth floors were expected to have leakage values lower than these extremes because of reduced driving forces.

The PFT arrangement also provided information on air movement between the garage and the suites. As with the suites, there are two mechanisms of air movement from the garage into the building: diffusion and induced circulation. Diffusion, which occurs by virtue of large concentration differences, was expected to be highest between the basement and first floor suites and corridor. Induced circulation occurs because of pressure differences moving air through connecting passageways.

The PFTs on the lower floors are near the outer walls because it is assumed that infiltrating air will carry the tracer gas across the rooms to the hallway return air grille. On the upper floors, the source locations are closer to the unit's entrance door and the bedroom door because more air tends to exfiltrate from upper suites, being replaced by air from the central corridor and other adjacent spaces.

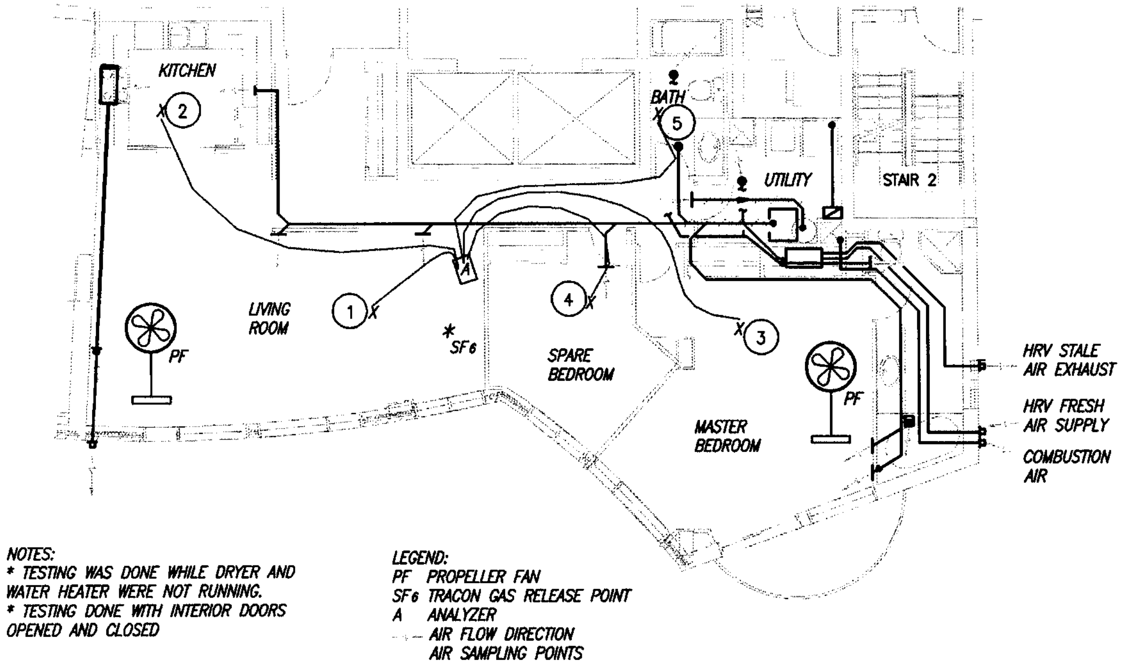
This testing provides a time-averaged air exchange rate for the locations that have PFT/CATS. Specifically, the PFT and CAT testing was used to calculate the average air transfer rates for five interconnections:

- suite to suite
- outdoors to suite
- corridor to suite
- garage to outdoors
- garage to suite

Ventilation Effectiveness in a Single Suite

Tracer gas decay testing using SF_6 was performed in an unoccupied south-facing suite on the fifth floor to assess the ability of the ventilation system to deliver outdoor air to the various rooms. The tests were performed over the afternoon of November 23, 2000. The weather for the test period was sunny with an outdoor temperature of about -5°C and the winds light at about 1.8 m/s.

A Foxboro MIRAN SapphIRe-100E IR portable ambient air analyzer was used to measure and record the concentrations of SF_6. A multi-port sampling station was used to draw air samples from each of five locations throughout the suite on a rotating basis. The sampling tubes were located 1.22 meters from the floor. Figure 5.3 shows the suite test locations.



NOTES:
* TESTING WAS DONE WHILE DRYER AND WATER HEATER WERE NOT RUNNING.
* TESTING DONE WITH INTERIOR DOORS OPENED AND CLOSED

LEGEND:
PF PROPELLER FAN
SF6 TRACON GAS RELEASE POINT
A ANALYZER
– – AIR FLOW DIRECTION
AIR SAMPLING POINTS

Figure 5.3: Equipment Layout for SF_6 Testing

SF_6 was released from a canister in the living room. The central air handler and two pedestal fans were used to mix the air thoroughly in the suite with all interior doors open. Once each of the sampling locations showed a similar concentration of 1200 ppm or higher, the space was assumed to be well mixed. The pedestal fans were then shut off, the HRV and air handler adjusted to the appropriate setting, and interior doors opened or closed as required for each particular test.

The concentrations of SF_6 were measured at 15-second intervals, continuously rotating through the sampling points. Therefore, each point was measured every 75 seconds. The air change rate for any space is approximately equal to the negative slope of the concentration-time curve plotted on a semi-log graph.

Three different tests were conducted:

- Test 1: Measured the ability of the HRV alone to deliver outdoor air to rooms with the interior doors closed. For this test, the HRV was set on low speed and the air handler was off.
- Test 2: Measured the ability of the HRV/air handler combination to deliver outdoor air to all rooms with interior doors closed. For this test, the HRV was set on low speed and the air handler was on.
- Test 3: Measured the ability of natural infiltration (air leakage through the building shell) to provide ventilation. For this test, all interior doors were open and the HRV and air handler were off.

Air Distribution Within Suites

The air distribution within the suites was assessed over one week. This test was similar to the PFT/CATS testing performed for garage and building compartmentalization testing except that the sources and samplers were all located in only one suite (see Figure 5.4).

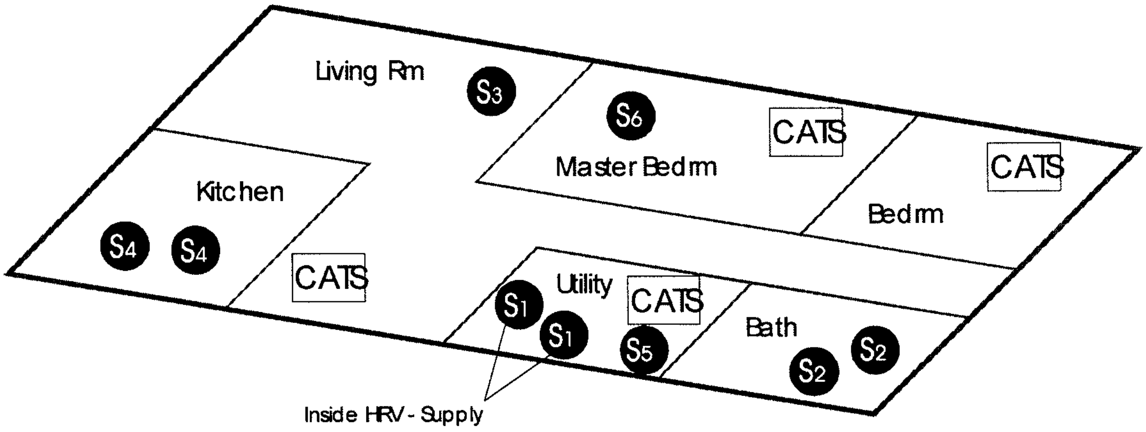


Figure 5.4: PFT Equipment Layout for In-Suite Testing

The sources marked S1 were located in the outdoor air supply duct of the HRV and functioned as a direct indicator for outdoor air entering the suite. The four CATS were used to determine a good average concentration for the entire suite as well as concentrations in specific areas. Another five PFT sources were distributed between the different rooms provided unique markers for sources originating in those rooms. The testing was done during March 2001.

Short-Term Indoor Air Quality Testing

Short-term measurements were made of the indoor air quality in the building. The short-term testing consisted of measuring the concentration of common indoor pollutants in one suite over one week. The following pollutants were measured:

- respirable particulates
- formaldehyde
- volatile organic compounds (VOC)

For each of these pollutants, a sampler was placed in a representative location in the suite (see Figure 5.5) and retrieved one week later. The samplers were sent to a laboratory for analysis.

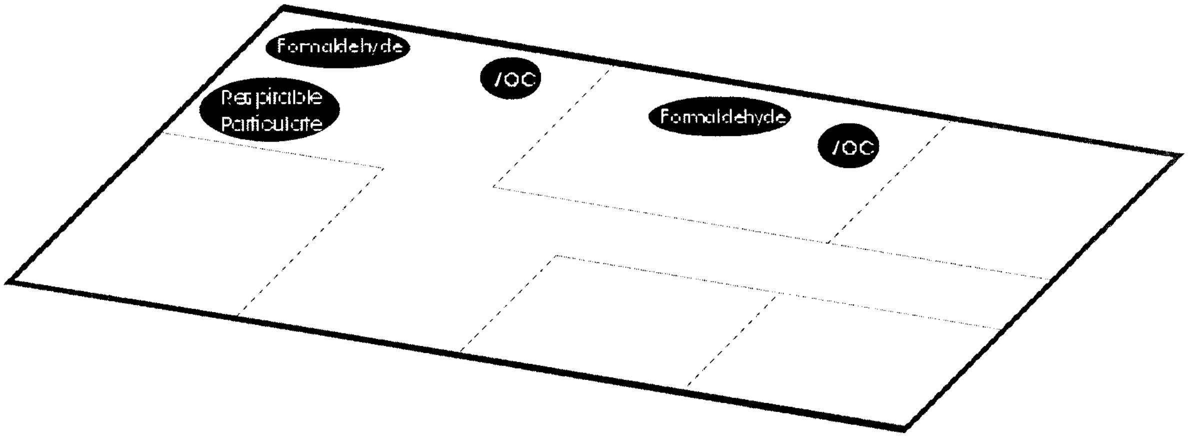


Figure 5.5: Equipment Layout for Suite IAQ Testing

Long-Term Indoor Air Quality Testing

Long-term air quality measurements were conducted with sensors connected to the computer-based data acquisition system. Sensors measuring temperature, relative humidity and CO_2 were located in four suites and in the sixth floor corridor (common area).

5.3 Ventilation Testing Results

Parking Garage and Building Compartmentalization Testing

Figure 5.6 shows the air exchange between the garage, the building and outdoors (values shown in m^3/hr). The largest air exchange is between the garage and the outdoors; an average of 217 L/s (782 m^3/h or 0.16 ACH). The garage ventilation system operated 20.7 hours over the 7-day monitoring period, or an average of 3 hours per day. The low operating hours indicate that the CO levels in the garage rarely reached 15 ppm, the set-point for activating the garage ventilation system. At 8,000 L/s for 3 hours per day, the ventilation fan provided an equivalent average of 986 L/s (or 0.71 ACH) over the 7-day period.

The two different measurements should not be compared directly. The 0.16 ACH average tracer gas air change rates refer to an effective rate of removal for contaminants emitted at a constant rate. The 0.71 ACH is the average ventilation rate when the fan is operated an average of 3 hours per day to remove CO produced at a highly variable rate. The tracer gas result shows that there is a background level of continuous ventilation. The mathematical average shows that there is a reasonable expectation that the garage is flushed regularly.

There is some air movement from the garage into the corridors—109 m^3/h for the first floor and 99 m^3/h for the sixth floor (average of 28 L/s per floor). These exchange rates are approximately half the ventilation rate provided by the corridor HRV. Because of the complexity of air leakage paths throughout the building, it is impossible to determine exactly what route the air is taking from the garage to the corridors. Stairwells, common pipe shafts, and the elevator shaft are the most likely routes. All of these shafts have multiple entry points from the garage. Corridor ventilation was installed to dilute and exhaust contaminants, rather than push contaminated corridor air into the suites as traditional systems do.

The air movement from the garage to the suites was very low at 12 m^3/h (3 L/s) for the first floor suites and almost negligible for the sixth floor suites. The amount of garage air entering Suite 103 is about 5.5% of the total air entering the suite from all sides. The garage air moving to the sixth floor suites was an average of only 2 m^3/h for the three suites. These results indicated that garage air moving into the suites was negligible. Separate corridor ventilation and individual suite ventilation systems seem to help keep vehicular contamination from entering the suites.

There was a small amount of air flowing from the sixth floor suites and corridor to the garage. At first glance this seems odd. On reflection there are three points that should be considered. First, the readings are so small as to be insignificant. Second, in each case, the standard deviation on the number for is approximately half the reading value. The large standard deviation suggests that there could be periods of no counter flow and periods of some counter flow. Finally, having any counter flow value is indicative of a tight building shell and possibly some mechanically induced airflow. For example, the garage fan could create a negative pressure in the building during the time that the inlet damper at the other end of the garage is opening.

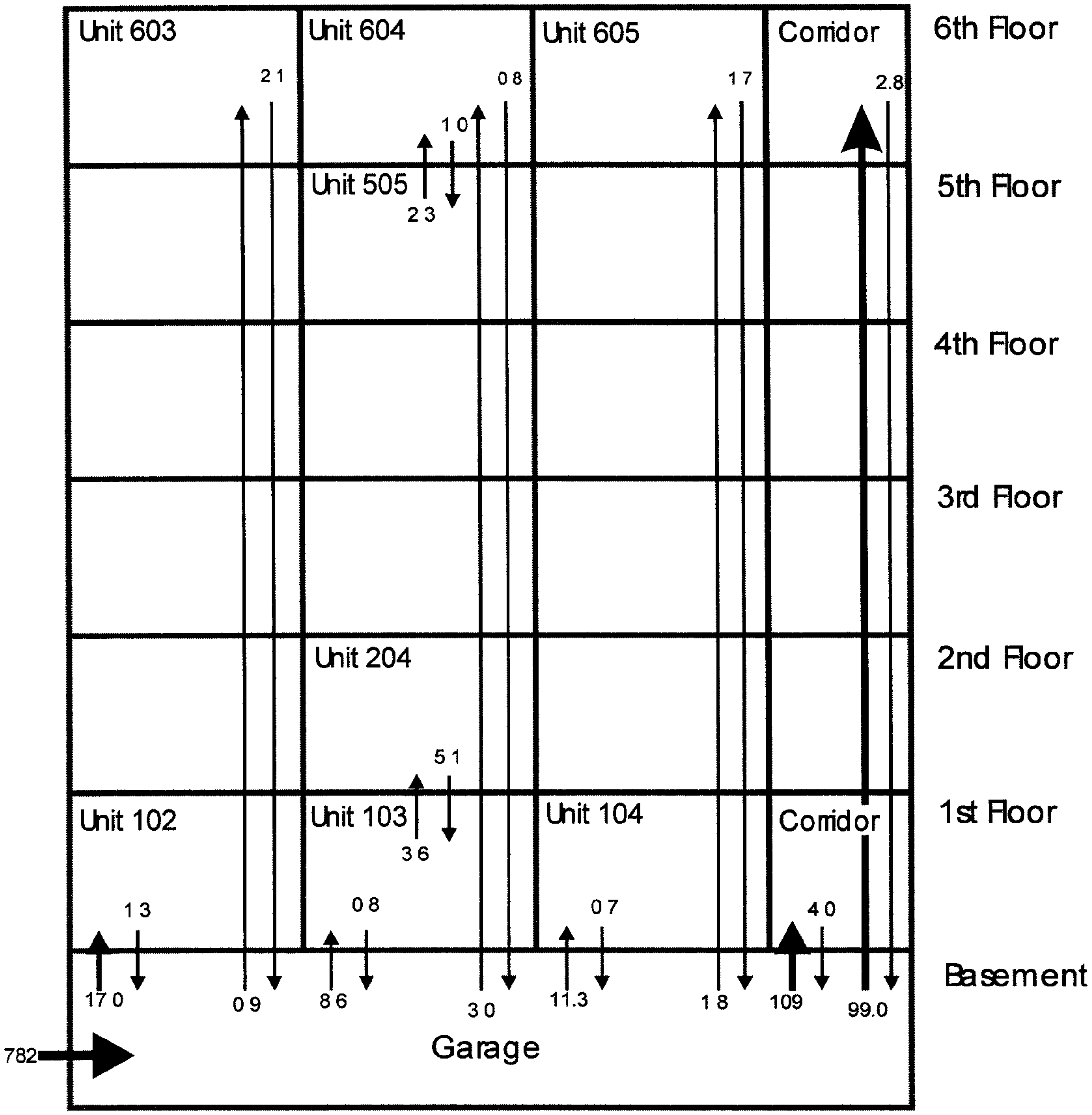


Figure 5.6: PFT Test Results for Vertical Air Movement Within Building.

Figure 5.7 and Figure 5.8 show the measured suite-to-suite and corridor-to-suite air (i.e. horizontal) air movement rates for the first and sixth floors, respectively (all values shown in m^3/hr). The building exhibited air movement patterns typical of tall buildings where fresh air is drawn into the building at the lower floors and moving out of the building near the top.

The phenomenon of infiltration near ground level and exfiltration on upper floors was seen in two places. First, Figure 5.7 shows that more air was drawn into Suite 103 than was exhausted to the outdoors (125.9 m^3/h in versus 100.9 m^3/h out). Figure 5.8 shows the opposite trend for Suite 604, with the air moving to the outdoors exceeding the airflow inward (103.2 m^3/h out versus 50.4 m^3/h in). Second, Figure 5.6 suggests a net airflow moving down from the second floor (Suite 204) to the first floor (Suite 103). This may be because of a pressure difference (i.e. kitchen range hood running in the first floor suite) or it may be that, due to the standard deviation on the measurements, the flow is actually close to the same (Note: flow direction reverses after one standard deviation). At the upper levels, the net airflow is upward with more flow from the fifth floor (Suite 505) to the sixth floor (Suite 604). Here, the flow direction does not reverse until after two standard deviations.

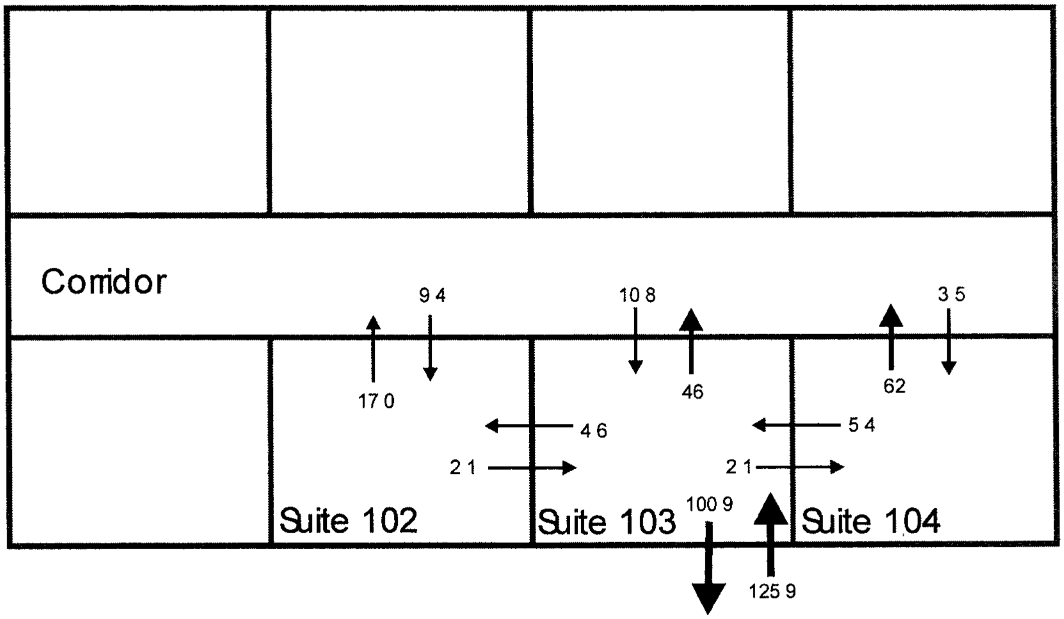


Figure 5.7: PFT Test Results for Horizontal Air Movement on First Floor

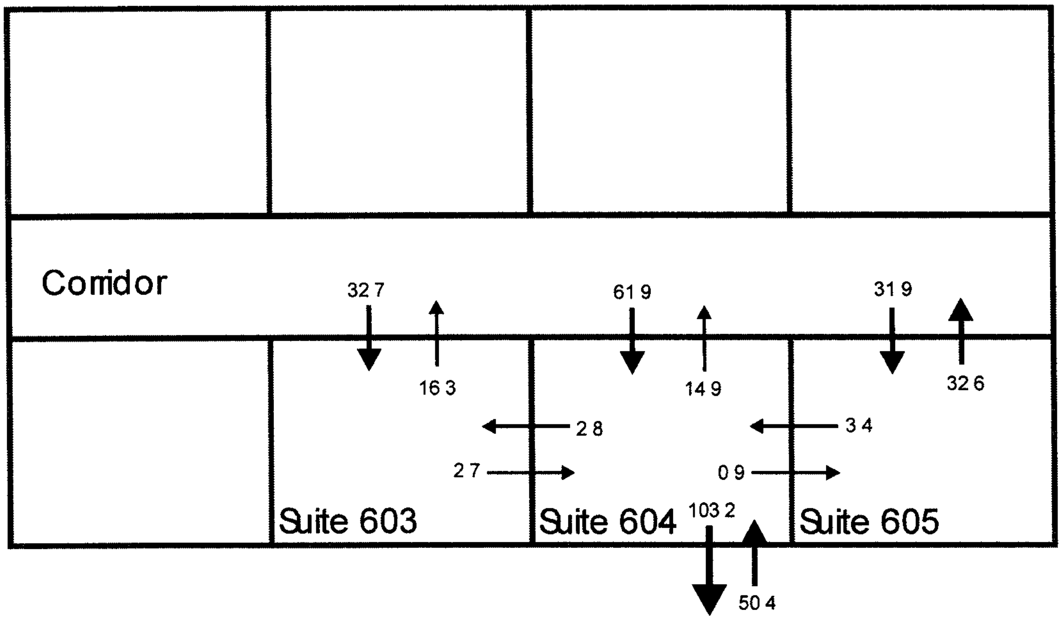


Figure 5.8: PFT Test Results for Horizontal Air Movement on First Floor

One consequence of these air movement patterns is the amount of corridor air infiltrating the suites. Figure 5.7 shows that the movement of corridor air into the first floor suites is quite small—8 m^3/h (0.02 ACH average). On the sixth floor, the rates are higher—42 m^3/h (0.16 ACH average). Nevertheless, even with the larger flow of corridor air into the sixth floor suites, little garage air makes its way into these suites. This appears to be because there is a very large fresh air exchange with the outdoors providing good dilution of any garage pollutants that do reach the sixth floor. The sixth floor corridor has an infiltration/exfiltration rate of approximately 440 m^3/h (122 L/s) from a combination of the corridor HRV 200 m^3/h (approx 55L/s) and natural ventilation.

Brookhaven National Laboratory has developed an index to assess the air communication between zones. The index is based on the tracer gas concentrations in each zone to calculate 'zonal condition numbers'. Zonal condition numbers near unity indicate those zones do not communicate to a great extent one with another. Zonal condition numbers of 5 or more indicate much air communication. In this study, the corridors, garage and suites were treated as separate zones. The analysis gave zonal condition numbers close to unity (range 1.007 to 1.290) for all zones indicating that zones flow relatively independent of each other, inferring that airflow is predominantly due to infiltration and exfiltration rather than interzonal. This, in turn, implies that the mechanical ventilation system strategy is working well.

Table 5.1 provides a summary of air movement in the building.

Table 5.1: Results Summary for Building Air Movement

Direction of Air Movement	7 Day Average Air Movement (L/s)	
	1st Floor	6th Floor
Fresh Air to Suites	32.4	21.6
Fresh Air to Corridor	69.6	119.4
Corridor to Suite	2.8	10.3
Suite to Suite	0.7	0.5
Garage to Corridor	30.4	27.5
Garage to Suite	3.6	1.1
Fresh Air to Garage	217.2	

From Table 5.1 it can be seen that fresh air to the suites, corridors and garage are all large values relative to other sources to those areas. That is, mechanical ventilation combined with infiltration provides the majority of air movement into the various building areas. On the negative side, there is significant communication between the garage and the corridors; yet this air does not make it into the suites. There are three possible explanations for this. First, corridor air is well diluted, and second, the balanced ventilation supplied by the HRVs reduces the driving force into the suites. Thirdly, the airflow regimes established by the corridor air-garbage chute ventilation system would also serve to limit corridor to suite airflow. Weatherstripping on suite doors may also have helped limit garage pollutants from entering the suites.

Ventilation Effectiveness in a Single Suite

The test results for the SF_6 tracer gas tests are given in Table 5.2. The values are the average outdoor air ventilation rate for each room. The overall average ventilation rates were 0.40 ACH with the air handler and HRV on, and 0.28 with only the HRV on. The small standard deviation shows that there is good distribution of fresh air throughout the suite.

Table 5.2: Results Summary for SF_6 Tracer Gas Testing

	Air Change Rate (Air Changes / Hour)						
	Zone 1 Living Room	Zone 2 Kitch	Zone 3 Master Bdrm	Zone 4 Spare Bdrm	Zone 5 Bathrm	Avg.	Stnd. Dev.
Test 1 – HRV ON / Fan Coil OFF – doors closed	0.26	0.25	0.30	0.27	0.32	0.28	0.03
Test 2 – HRV ON / Fan Coil ON – doors closed	0.44	0.42	0.33	0.40	0.39	0.40	0.04
Test 3 – HRV OFF / Fan Coil OFF – doors open	0.04	0.05	0.09	0.04	0.08	0.06	0.02

The ventilation rate was slightly higher than design with both the fan coil and HRV operating, and slightly lower than design with just the HRV operating. These results suggest good overall ventilation and good distribution to each room regardless of fan-operating strategy. It would appear that, with proper ducting design, the HRV can distribute ventilation air throughout the suite (without continuously operating the central air handler). During the testing, the combustion air duct was not sealed, but the water heater and the range hood were not operated. It is unknown if any of the measured ventilation air was provided by the combustion air duct. Nevertheless, it would have been operating normally during the test period.

A backdraft damper was considered for this project but was not installed. The damper would have been installed in the furnace return duct. This would keep fresh air from short-circuiting back through the fan and out the return air grilles. It would appear that the system operated well without it in this case.

Natural infiltration was very low, with an ACH of only about 0.06, indicating an airtight envelope. The higher value in the master bedroom and bathroom compared with other rooms indicated that natural infiltration does not distribute fresh air through the suite very well. The low value in all rooms indicated that airtight construction requires the mechanical ventilation to ensure adequate ventilation air.

Long Term Air Distribution Within the Suite

The PFT/CATS individual suite testing results for one sixth floor suite showed an average infiltration rate of 0.18 ACH over one week. This is very close to the 0.16 average found for all sixth floor suites during building compartmentalization testing (Note: that particular suite measured 0.17 ACH). Fresh air infiltration to all rooms, except the utility room, was the same value.

There was essentially infinite air communication from room to room. That is, for example, the concentration of outdoor air or air originating in the master bedroom was the same in the other three rooms measured. These results were consistent with the SF_6 testing described in the previous section.

Quality of Indoor Air

The results of three, one-week indoor air quality tests are shown in Table 5.3. All the measured concentrations of indoor contaminants were below Health Canada recommended guidelines. Respirable particulate matter, measured at 2.5 $\mu g/m^3$, was well below both recommended Health Canada Guideline values. The acceptable long-term exposure rate (ALTER) is 40 $\mu g/m^3$ and the acceptable short-term exposure rate (ASTER) is 100 $\mu g/m^3$ [Health Canada, 1989]. The formaldehyde concentrations at less than 0.03 ppm were below both the Health Canadian of action level of 0.1 ppm and target level of 0.05 ppm [Health Canada, 1989]. The TVOC concentrations were below the detection limit of the equipment. Heath Canada does not currently publish a recommended target or action level for TVOC. ASHRAE does recommend that concentrations should be no higher than 1.0 mg/m^3 in offices and suggests that people should expect no irritation or discomfort at concentrations below 0.2 mg/m^3 [ASHRAE, 1996].

It must be recognized that IAQ testing was for one suite only. Results cannot be used to definitively comment on the entire building. The test suite was expected to be a "typical" suite, but the IAQ in other suites will depend on the furnishings and finishes used. Different materials have different pollutant source strengths. Individual suite ventilation will help ensure pollutants have minimal opportunity to buildup.

Table 5.3: Results Summary for Indoor Air Quality Testing

Location	Respirable Particulate (micro-gm/m^3)	Formaldehyde (ppm)	VOC (ppm)
Living Room	2.5	0.016	<0.05
Master Bedroom	N/A	0.029	<0.05

5.4 Long-Term Testing Results

Temperature

The results of long-term monitoring for indoor temperature are presented in Table 5.4. It can be seen that the average suite temperatures are all quite consistent and right in line with the values used by the MNECB for energy calculations (i.e., 22°C in winter and 24°C in summer). The maximum temperatures are high and more than two standard deviations above the average. This would indicate that such high temperatures were seldom reached, probably resulting from thermostats being set-up when no one is home. The corridors in the building are not air-conditioned and this can be seen in the high average temperature and the maximum being within two standard deviations of the average.

Table 5.4: Monitored Indoor Temperatures for Five Locations

Suite	Average (°C)	Std. Dev. (°C)	Minimum (°C)	Maximum (°C)
6	23.2	1.9	20.1	29.6
Common	27.3	1	24.9	29.5
4	23.4	1	18.6	28.1
4b	23.5	1.6	19.5	27.6
3	23.8	1	21.4	26.8

The jagged line in Figure 5.9 shows the monitored temperature in Suite 6. The temperature was generally maintained between 21°C and 23°C in the winter and between 23°C and 26°C in the summer. The other two suites had very similar temperature fluctuations.

The solid lines show the trend lines for all three suites. The average temperature was generally around 22°C in winter and 24°C or slightly above in summer. The comfort levels appear to have been well maintained in the suites.

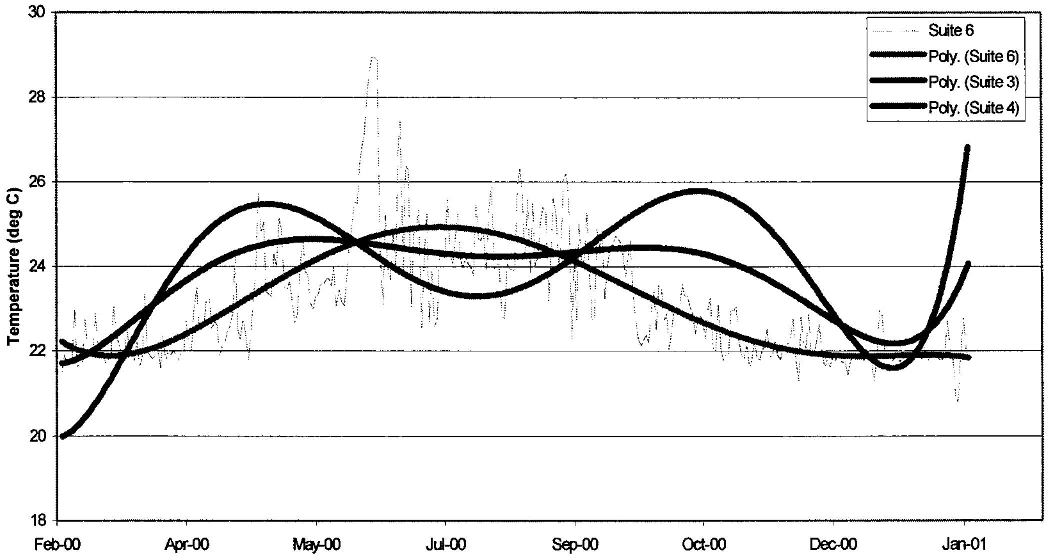


Figure 5.9: Monitored Temperatures in Three Suites

Relative Humidity

The results of long term monitoring of relative humidity are given in Table 5.5. The monitored data shows that the suites were maintained at reasonable comfort condition. Relative humidity in the winter seems to have been slightly below the minimum ASHRAE comfort condition of 25% at 23°C. This is due to providing fresh air continuously through mechanical ventilation. Maximum humidity levels for all suites were recorded during summer months (July and August). As well, it was observed that RH levels are held at levels not conducive to exterior wall surface condensation.

Table 5.5: Monitored Relative Humidity for Five Locations

Suite	Average (%)	Std. Dev. (%)	Minimum (%)	Maximum (%)
6	42.6	10	21.7	70.4
Common	34.9	10.6	15.5	59.2
4	42.6	11.6	17.4	67.8
4b	39.5	11.9	17.7	64.3
3	43.9	12.3	19.2	72.3

The jagged line in Figure 5.10 shows the fluctuations in relative humidity in Suite 6. Fluctuations in the winter generally fall between 25% and 40%, and in summer they generally fall between 40% and 60%. These values are very close to ASHRAE comfort conditions, which for summer peak at 26°C and 60% RH. Winter comfort conditions are a minimum of 21°C and 30% RH [ASHRAE, 2001].

The solid lines are trends for three suites. All three have similar tends. Winter 2000 saw low average RH in two suites. Winter 2001 saw slightly higher humidity in those two suites. Summertime RH was about 55% in all suites. The building was able to maintain reasonable RH levels without mechanical humidification or dehumidification.

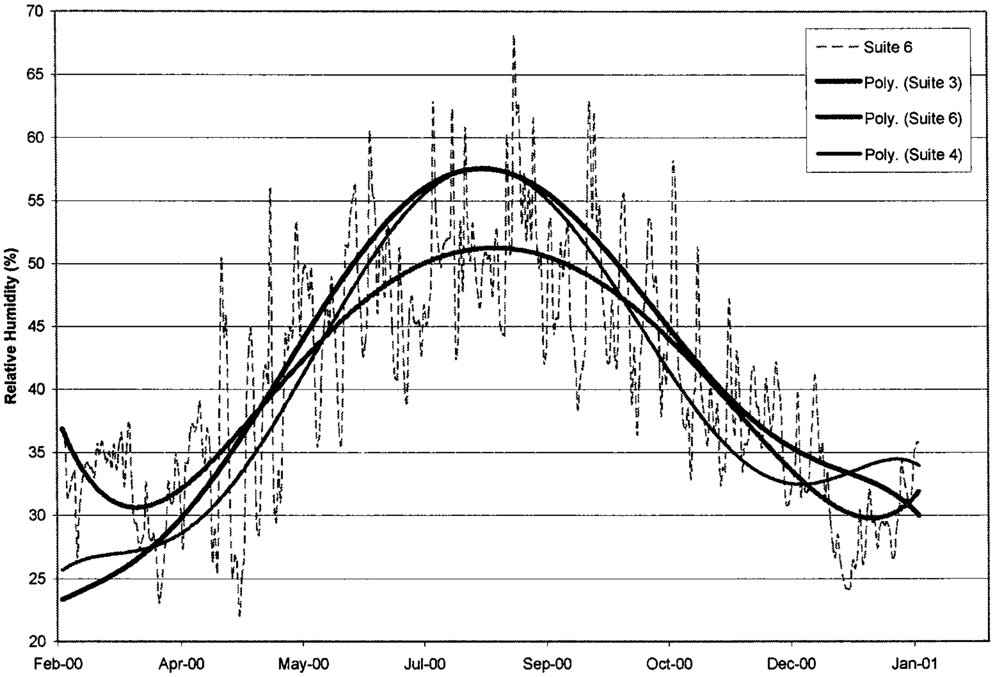


Figure 5.10: Monitored Relative Humidity in Three Suites

Carbon Dioxide (CO_2)

The results of long term monitoring of CO_2 are given in Table 5.6.The results a show that concentrations are generally below ASHRAE recommendation of 1,000 ppm. Maintaining levels below 1,000 ppm is indicative of the ventilation system's ability to maintain an adequate air exchange rate for dilution of typical indoor contaminants. In-suites 6 and 3, CO_2 levels would rise above 1,000 ppm. This is because the owners would regularly turn off the HRV.

Table 5.6: Monitored CO_2 Levels for Four Locations

Location	Average (ppm)	Std. Dev. (ppm)	Minimum (ppm)	Maximum (ppm)
6	827	382	400	2,021
common	516	200	240	972
4	564	189	305	1,778
3	777	266	365	2,019

6. ANNUAL ENERGY CONSUMPTION

6.1 Overview

Superior energy performance in any building arises from the synergy between a highly insulated and airtight building shell, high-performance windows, heat recovery ventilation, and energy-efficient lights and appliances. The details of technologies used in this innovative condominium are all described in earlier chapters of this report. Computer simulations predicted total energy consumption would be 35% below that of a similar building built to meet the requirements of the Model National Energy Code for Buildings (MNECB). Total energy consumption in the simulations included all natural gas and electricity use except outdoor and parking garage lighting, the sauna and a few small miscellaneous items. The total predicted energy use was 125 kWh_e/m^2 of floor area. The computer program automatically simulates a reference building that matches the proposed building in size and shape but uses envelope construction and mechanical systems that match the requirements of the MNECB. The MNECB building was predicted to use 195 kWh_e/m^2, with the same exclusions. Even the MNECB building would use less than existing apartment buildings that typically use 140 to over 500 kWh_e/m^2 per year [CMHC,1999a]

Another feature intended to encourage energy conservation was individual suite metering for both gas and electricity. Anecdotal evidence, at least, points to changes in consumer habits that reduce energy consumption when individual metering is installed. In this building, the meters are installed in meter closets outside the suites and can be easily read without disturbing the owners. Monitoring overall building energy use was achieved by manually reading all suite and building meters. The sum of the all suite use plus common area consumption added up to the total building energy use. Individual readings allow comparisons between tenants.

Natural gas, electricity and water consumption for all tenant and common area use was manually recorded each month over the 2001 calendar year. Electricity and natural gas energy were converted to a common unit so that they could be added together. A single utility meter measures all water used in the building. This meter was also read manually once a month. The 2001 monitoring period was used because the building was fully occupied. A full year's energy and water consumption figures are presented.

6.2 Energy Consumption

Electricity

Average electricity use per suite (excluding the central chiller for air conditioning) was 11.8 kWh per day. Individual suite averages ranged from 4.9 kWh/day to 26.0 kWh/day. It is important to note that the above figures do not include cooling energy production because a central chiller provides suite cooling. Fan coil power required to distribute cool air throughout the suites, however, is included in the suite electrical consumption. For a discussion on air handler fan electricity use see "*Comparison of Separate Furnace and Water Heater to Combo-System*". Average suite electricity use varied with the seasons. The lowest use occurred in the spring (between 11.2 and 11.6 kWh/d February through June). On several visits it was found that some people turned off HRVs once warmer weather arrived preferring to open windows in the mild weather. During the summer, electricity use rose, likely due to an increase in the use of the air handler for air-conditioning. Electricity consumption continued to rise through the fall. This is probably because people would again turn on HRV's for ventilation through the winter. Electricity use was highest in the winter (as high as 13.2 kWh/d in December) because both the HRV and the air-handler operated during the heating season.

A central chiller and cooling tower provide air-conditioning. Cold water is pumped to the suites where the central circulating fan is turned on when air conditioning is needed. Electricity to operate the chiller, cooling tower and associated pumps was monitored as part of the common area electricity use. From the non-cooling season data it was estimated that there was a base electrical load of 675 kWh/d. During the months when cooling was operating, the base load was subtracted from the monthly consumption values to estimate the cooling energy use. The total cooling energy use is estimated at 61,610 kWh, excluding the in-suite electricity to operate the fan and pump in the air handler. Dividing chiller electricity by 53 spreads the cooling energy consumption over the 48 suites plus the equivalent of 5 suites in common area cooling (note: corridors are not cooled). Total daily per suite electricity consumption on an annual basis then rises by 3.2 kWh/d. Average annual in-suite electricity use then rises to 15.0 kWh/d. Electricity consumption at this level is generally regarded as being quite low for residential occupancy.

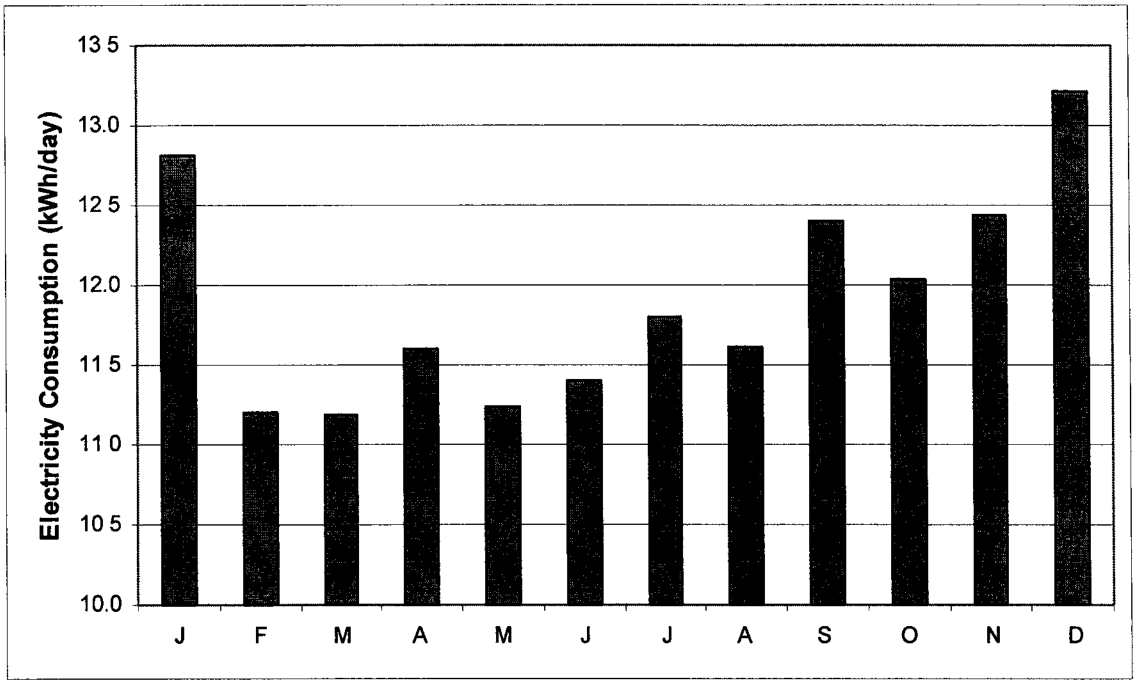


Figure 6.1: Daily Average Suite Electricity Consumption

Figure 6.2 shows suite-to-suite variation in electricity use throughout the building. Six bins, in 5 kWh/d steps, ranging from 0 to >25 kWh/d were established for the comparison. The number of suites falling into each bin was then determined.

Only one suite used 5 kWh/d or less. It is assumed that the people in this suite were absent much of the year and had heating on minimum and all other electricity using devices (e.g., the HRV) turned off. Owners in this condominium building are mostly retirees and several are known to take extended vacations away from home, especially during the winter.

Six suites (12.5%) used over 15 kWh/d and only 2 used over 20 kWh/day. Here, it is assumed that comfort conditions are maintained warmer in winter and cooler in summer than average. As well, it is assumed that several appliances were operated 24 hours/day. For example, HRVs, big screen TVs and computers could have been left on continuously.

Over half of the suites in the building had daily average electrical consumption in the 10-15 kWh per day range; and about one-third more used 5-10 kWh/d. Again, these numbers do not include air-conditioning energy associated with chiller operation, which would raise all values by about 3.2 kWh/d.

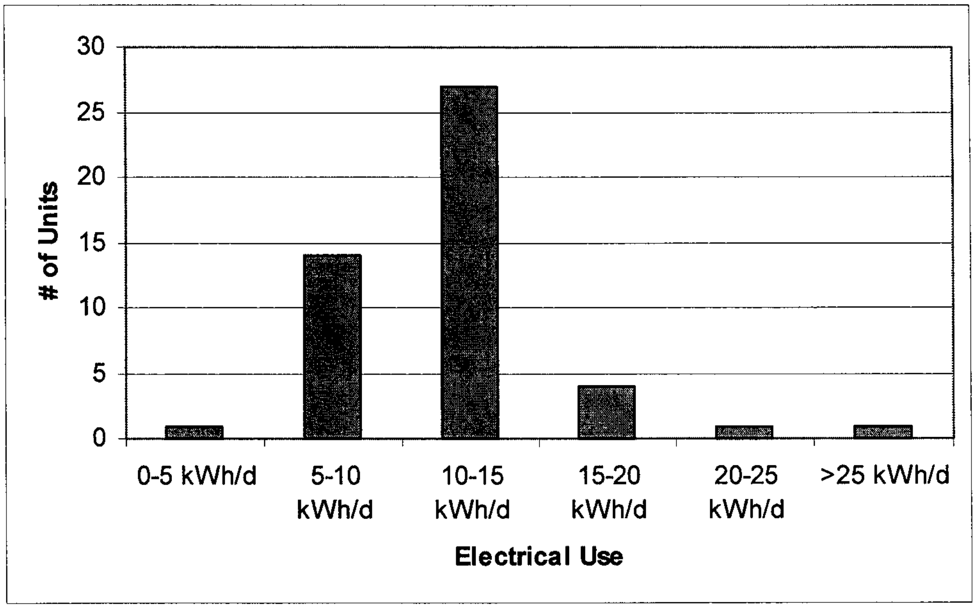


Figure 6.2: Variation in Suite Electricity Consumption

Electricity use for common areas is not included in the suite electricity figures above. A central common area electrical meter monitors electricity use for the following:

- common area lights (corridors, stairwells, vestibules, garbage room, underground parking, building exterior, hospitality suite and maintenance office, etc.)
- two common area HRVs, underground garage fan, rooftop fans for gas appliance exhaust
- elevators
- central chiller, cooling tower and associated pumps and fans
- sauna
- miscellaneous common-area receptacles

Gross common-area electricity use was an average of 833 kWh/day over the entire year.

There was a seasonal trend to electricity use. Electricity consumption was higher in the summer than in the winter. For example, 1,272 kWh/day was used in August in contrast to only 563 kWh/day used in December. The central cooling system increases common area electricity use in the cooling season. A graph of daily average electricity consumption for common area use, by month, is shown in Figure 6.3 below.

The central chiller and associated components use a total of approximately 61,610 kW over the entire cooling season, or 169 kWh/d distributed over the entire year. This leaves 664 kWh/d for electricity use over the entire year when cooling is removed.

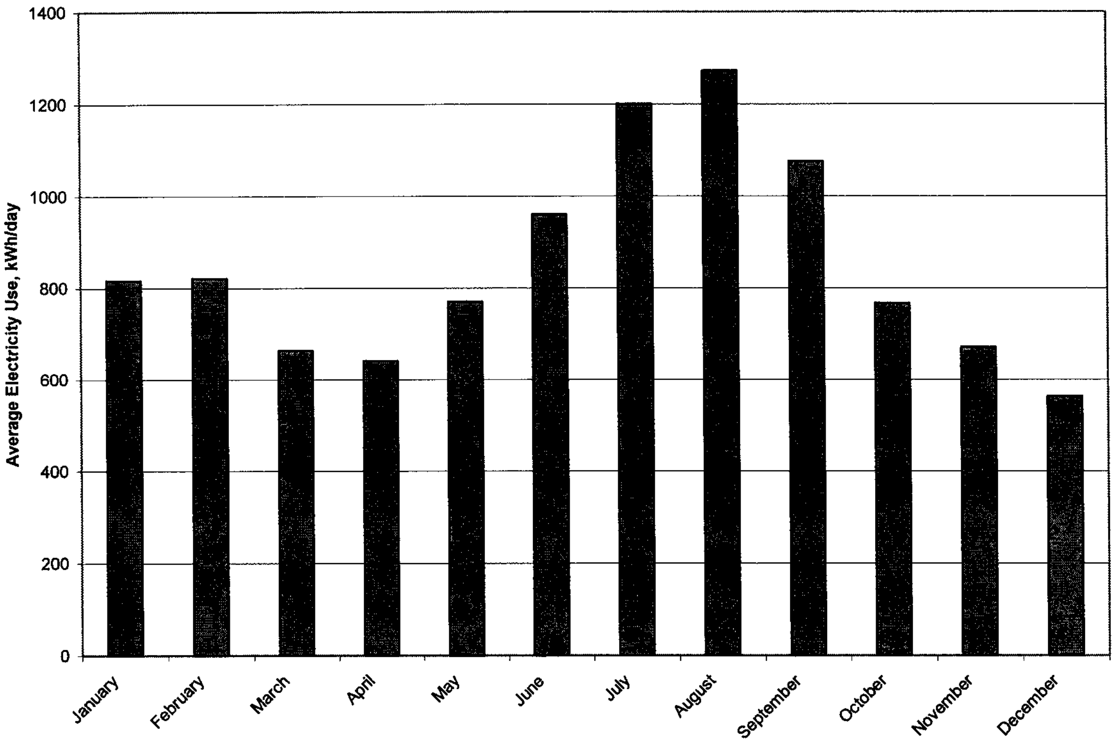


Figure 6.3: Common Area Daily Average Electricity Consumption

Natural Gas

Average natural gas use per suite over the year was 2.6 m^3/day. There was a significant decrease in suite gas use over the summer months when space heating was not required; however, gas was still required for domestic hot water. Natural gas is also used for cooking and clothes drying in some suites. The figures below indicate average daily suite natural gas consumption by month, and distribution of average daily consumption by suite.

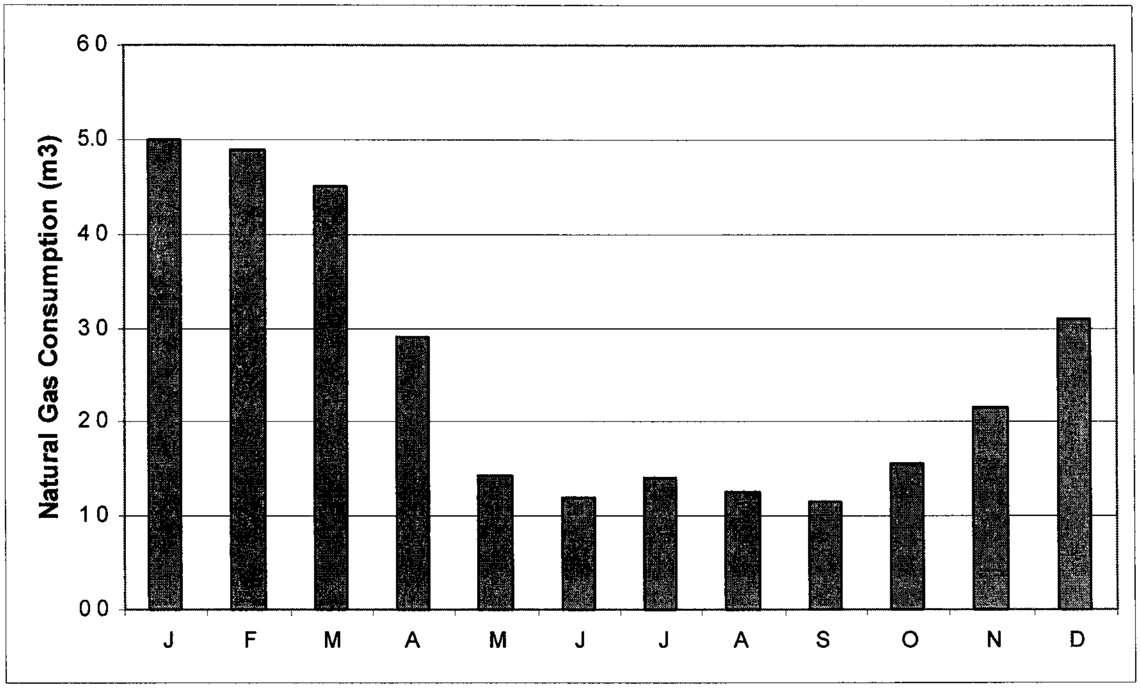


Figure 6.4: Daily Average Suite Natural Gas Consumption

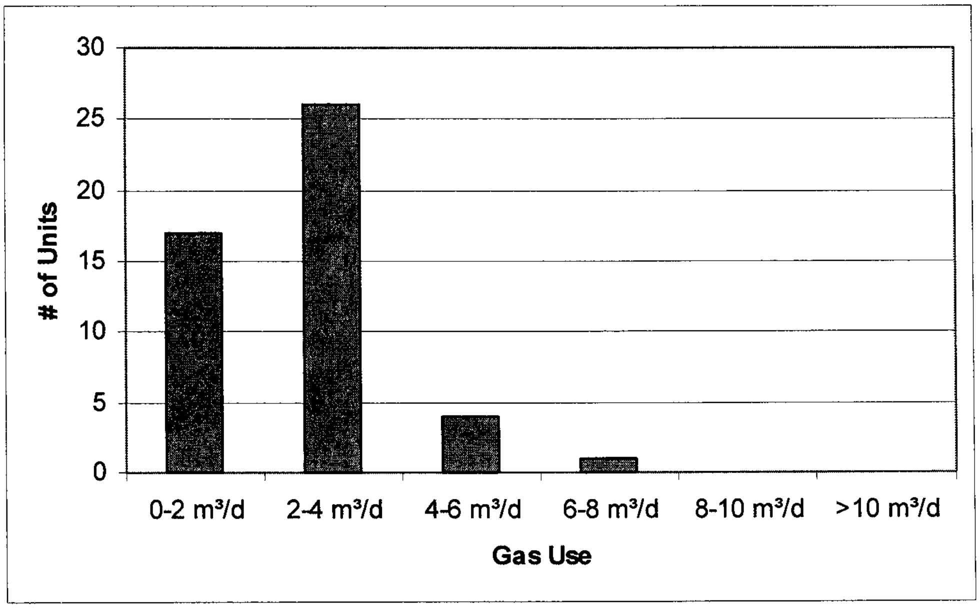


Figure 6.5: Variation in Daily Average Natural Gas Consumption

A central boiler is used for conditioning the common spaces (the areas heated are outlined in *"Central Common Area System"*. In 2001, the boiler used an average of 23.7 m^3/day of natural gas based on a full calendar year. The boiler was actually shut off for the summer, from the end of April to the end of September. That is, it was operated for about 6 months during the winter season.

The use per unit area (excluding the heating in the garage ceiling space) was approximately the same as for all gas use in the average suite. This is understandable because the common areas had higher loads associated with glass areas and ventilation loads.

Total Building Energy Consumption

To put these numbers into perspective, the energy use in $kWh_{equivalent}/m^2/yr$ was calculated. This calculation normalizes total building energy consumption by floor area and allows electricity and natural gas consumption to be summed. The normalized parameters are summarized in Table 6.1 below.

Table 6.1: Monitored Building Energy Consumption

Usage Parameters	Consumption
Suite electricity use (48 suites)	212,987 kWh
Common area electricity use	304,080 kWh
Total building electricity use	**517,067 kWh**
Suite natural gas use (48 suites)	46,285 m^3
Common area natural gas use	8,657 m^3
Total building natural gas use	**54,942 m^3**
Natural gas energy equivalent	**579,089 kWh_e**
Total building energy consumption	**1,096,156 kWh_e**
Suite floor area	6,747 m^2
Common area floor area	1,229 m^2
Total building floor area	**7,976 m^2**
Total normalized energy consumption	**137 $kWh_e/m^2/yr$**

The EE4 program [NRCan, 1999] was used to compare the innovative condominium to the Model National Energy Code (MNECB) reference building. The EE4 program uses the DOE2.1 calculation engine and is used for verification of building energy performance for the Commercial Building Incentive Program (CBIP).

The simulation results showed that the reference building would use 195kWhe/m2/yr compared to the as-built building (the innovative condominium) at 125 kWhe/m2/yr. The as-built building was expected to provide a 35% reduction in energy consumption over the MNECB reference building.

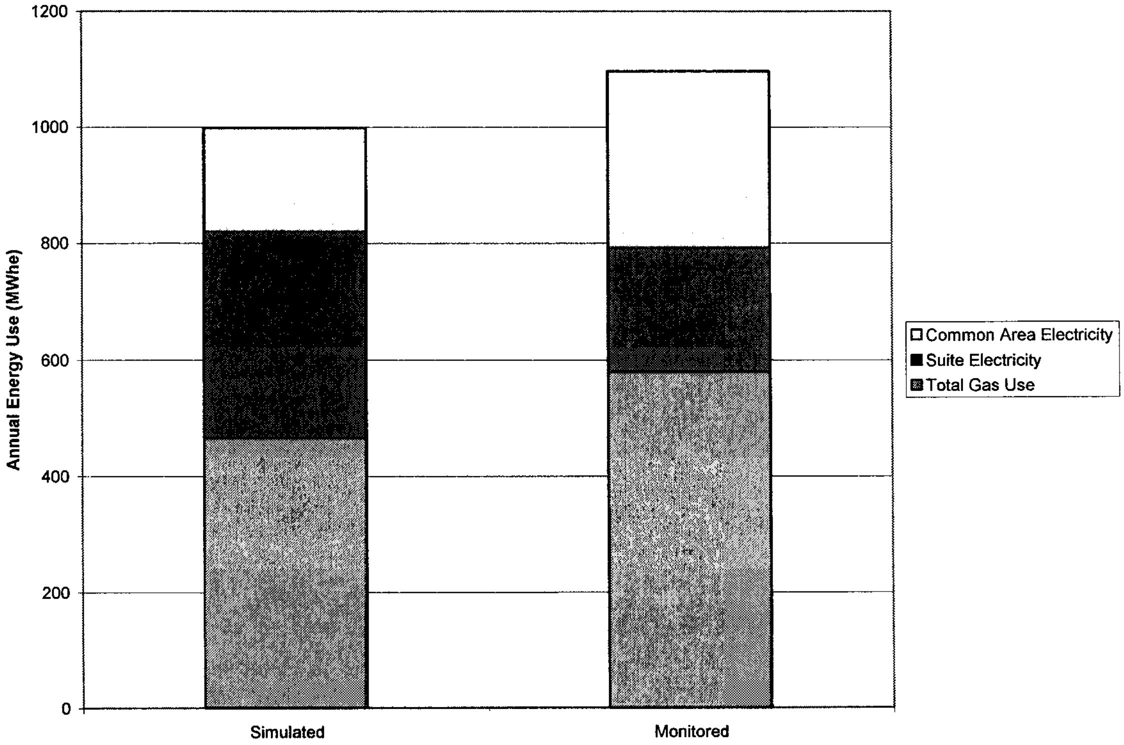


Figure 6.6: Comparison of Monitored and Simulated Energy Consumption

Monitored results of 137 $kWh_e/m^2/yr$ should not be compared directly to the simulated results. The simulations do not include some energy-using devices such as outdoor lighting, parking garage lighting, sauna and other miscellaneous items. If these items were added to the simulation, it is expected that as-built energy use would rise 10% or more. Simulated building energy use would then be 137 $kWh_e/m^2/yr$ or more. Therefore, the building is performing as well as, if not better than the simulation predicted. The performance is good despite less than perfect performance from the in-suite combo heaters.

There could be a number of reasons for the discrepancy between measured combo heating system performance and the good overall building performance. Many reasons are likely to be related to occupant behavior such as:

- extended vacations with the suite basically shut down
- operating the suite at temperatures other than the assumed set-point
- turning off the HRV for significant periods

Good building shell performance (low heat loss and little infiltration) is also likely to be responsible for good overall building performance. At least one owner interviewed during the course of monitoring stated they never turned their heating on and were always quite comfortable.

The energy breakdown by end-use, as predicted by the EE4 computer model, appears in Figure 6.7. It is interesting to note that space heating is a relatively small portion of entire use. It is generally accepted that space heating is the largest single component in energy use. In this case, water heating is predicted to be the largest energy consumer followed by space heating. The low space-heating requirement attests to the high performance of the building shell both in reducing conduction losses and in reducing infiltration.

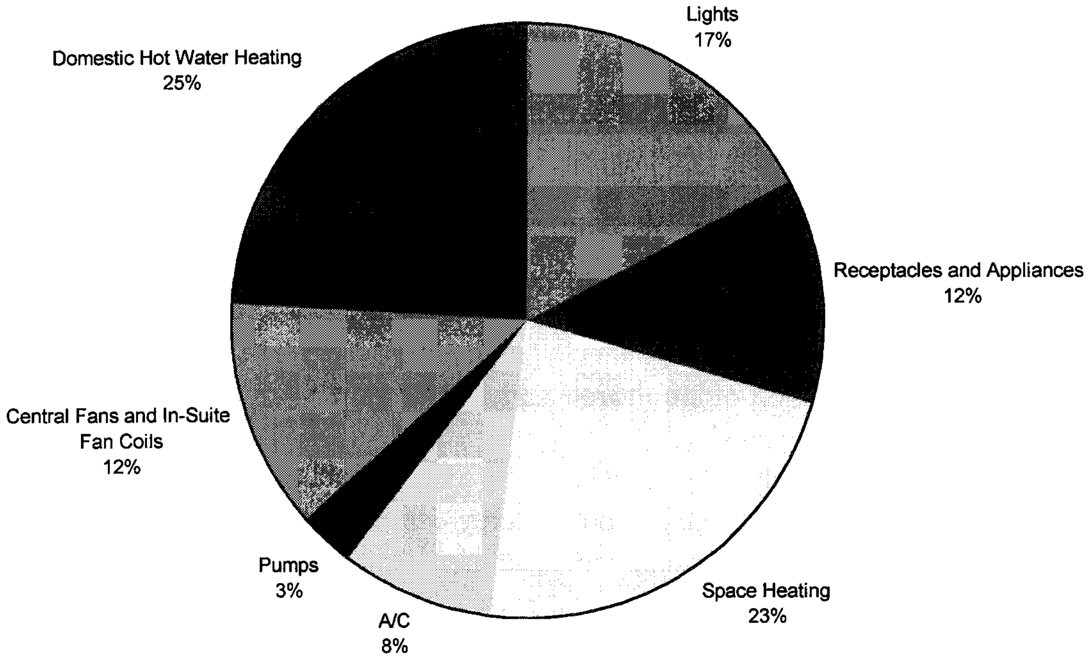


Figure 6.7: Building Energy End-Use Breakdown from EE4 Model

6.3 Water Consumption

A single utility meter measures water use for the entire building, including suites, common areas and outdoor irrigation. Meter readings show the water consumption was 4,085 m^3 over the one-year monitoring period. This translates to a normalized annual water consumption index (WCI) of 0.50 m^3/m^2/year. This is very low compared to the Ontario Housing Corporation average WCI of 1.91 m^3/m^2/year [CMHC, 2002b], and the 40-building HiSTAR average WCI of 2.24 m^3/m^2/year [CMHC, 2001a]. The 75% reduction in water consumption is attributed to a combination of low water-use appliances and fixtures, and the fact the residents are primarily seniors. Seniors tend to use less water and may be away on vacation more.

7. CONCLUSIONS

The innovative condominium was designed around four worthy goals of the IDEAS Challenge and C-2000 programs:

- envelope durability
- energy efficiency
- indoor air quality and mechanical ventilation
- environmental and resource conservation

Based on the results of the multi-faceted research program undertaken, a number of significant and interesting conclusions can be drawn.

Building Air Tightness

The overall building airtightness was measured at 1.18 $L/s/m^2{}_{75}$. This is within 5 percentage points of the target 75% reduction in envelope air leakage when compared with conventional, modern, commercial buildings. Design details are the foundation for a well-sealed building envelope. Actually achieving the results envisioned requires a quality assurance program be undertaken during construction. Four important components of such a program are:

- inspection
- testing
- feedback
- re-testing

The results show that air leakage can be significantly reduced in multi-unit residential buildings without overly onerous requirements or high costs.

Heat, Air and Moisture Transport in Walls

The wall construction details used appear to be functioning as designed in retarding the transport of heat, air and moisture. As predicted, temperatures at the plane of the vapour retarder are generally above the dew point for the indoor air. Maintaining low dew point temperatures was aided by reduced indoor humidity during the winter as the consequence of good mechanical ventilation.

The temperature index indicated there was practically no air movement through the wall under any indoor/outdoor pressure conditions. Controlling air movement controls the largest potential source of moisture movement into the wall. Moisture monitoring gave no indication of any moisture buildup or condensation in the walls. These factors combined to indicate that long-term durability of the wall system, with proper maintenance, is expected to be excellent.

Heating System Performance

One-time measurements of combustion efficiency of the three monitored water heaters ranged from 65 to 76%. This variation could be due to a lack of in-field adjustments of the fuel-to-air mixture when the units were installed. The seasonal efficiency of the storage tank water heaters ranged from 35 to 45%, well below the water heater energy factor of 0.58.

The high and low space and water heating loads of the three monitored suites differed by a factor of three. This difference was due to variations in HRV operation, thermostat set-point, occupancy patterns and heating equipment efficiency. At lower loads the standby losses were a more significant issue and the seasonal efficiency was reduced.

The in-situ seasonal performance of the high-efficiency furnace and common area boiler were also found to be 77% and 65% respectively. Both values are below the AFUE ratings of 96.6% and 83%. There are two significant reasons that help explain the discrepancy. First, the boiler's measured combustion efficiency was below the manufacturer's rating, which may have been due to inadequate set-up on installation. Second, AFUE assumes that most of the standby losses provide useful space heating which the monitoring did not do. Monitoring measured only the heat delivered by the heated air or heated water by the furnace and the boiler respectively.

Ventilation and Indoor Air Quality

PFT measurements indicated that little air from the garage managed to make its way into the suites. Some garage air did enter the corridors, but high air change rates diluted and/or remove those contaminants rather than allowing them into suites. A combination of garage ventilation, corridor ventilation, individual suite ventilation and some air sealing combined to effectively prevent garage pollutants from entering the suites.

Tracer gas testing in a single suite indicated good average ventilation at 0.28 ACH with only the HRV operating, and 0.40 ACH with both the HRV and the central air handler operating. A low standard deviation in air change between rooms indicated good distribution is achieved with ducted supplies to each room. A natural infiltration rate of 0.06 ACH was a good indication that an airtight envelope was achieved.

Indoor air quality measurements in one apartment found that formaldehyde, respirable particulates and VOCs are all well below Canadian guideline values. Acceptable findings in one suite is no guarantee other suites would be the same. It does, however, suggest that the design, construction and materials selection details are capable of providing acceptable IAQ.

Annual Energy Consumption

Energy consumption for the innovative condominium is 35% less than for the same building built to the requirements of the MNECB. Table 7.1 shows the monitored electricity and gas use over one full year. The normalized consumption of 137 kWh_e/m^2/yr is the same as, or lower than the predicted value after the components not in the model are added in. The MNECB building would have used 195 kWh_e/m^2/yr.

Table 7.1: Total Building Energy Consumption Summary

Usage Parameters	Consumption
Total building electricity use	517,067 kWh
Natural gas energy equivalent	579,089 kWh_e
Total building energy consumption	1,096,156 kWh_e
Total normalized energy consumption	**137 kWh_e/m^2/yr**

In conclusion, despite low operating efficiency for heating equipment, the building has met environmental and energy design goals. The building energy consumption is approximately 35% less than that of a comparable building constructed to MNECB guidelines. Water consumption is 75% less than typical apartment buildings. Indoor air quality is excellent. The concepts of an airtight, well-insulated envelope, individual in-suite ventilation systems and some air sealing within the building are working to maintain ample levels of fresh air in the suites.

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Appendix A. List of Sensors

First Draft			
15-Nov-99			
Weather Station			
Parameter Measured	**Location**	**Objective**	**Units**
Horiz. Solar Radiation	Rooftop Weather Station	Input for Weather File	W/m^2
Outdoor Temp.	Rooftop Weather Station	Input for Weather File	°C
Outdoor R.H.	Rooftop Weather Station	Input for Weather File	% R.H.
Wind Direction	Rooftop Weather Station	Input for Weather File	deg.
Wind Speed	Rooftop Weather Station	Input for Weather File	m/s
Total Rain on Horiz. Surface	Rooftop Weather Station	Input for Weather File	mm
Driving Rain	R1 - Outside sufrace of brick veneer	Wall moisture profile	mm
Combo Systems (3 suites & 1 common area)			
Parameter Measured	**Location**	**Objective**	**Units**
Total Gas Consumed	Gas line to DHW Htr	Gas Demand	m^3
Total Electricity Consumed	Power to DHW Htr & Fan Coil Unit	Elec. Demand (Htg. Only	Wh
Mains Water Temp	Inlet to DHW Htr	Energy Balance	°C
Total Domestic Water Flow	Inlet to DHW Htr	Water Demand	m^3
Domestic Water Temp.	DHW Htr Outlet to Fixtures	Energy Balance	°C
Total Space Heating Flow	DHW Htr Outlet to Fan Coil Unit	Space Heat Demand	m^3
Booster Pump			
Space Heating Water Temp.	DHW Htr Outlet to Fan Coil Unit	Space Heat Demand	°C
Fan Coil Unit Htg. On/Off	Fan Coil Unit	Heating On/Off	
Ventilation Effectiveness			
Parameter Measured	**Location**	**Objective**	**Units**
Corridor Temp	Central in Corridor	Ventillation	°C
Corridor R.H.	Central in Corridor	Ventillation	% R.H.
Corridor CO2 Concentration	Central in Corridor	Ventillation	ppm
Corridor CO Concentration	Central in Corridor	Ventillation	ppm
Corridor HRV Fan On/Off	HRV at top of Garbage Chute	HRV Fan On/Off	
Total Corridor HRV Fan Runtime	HRV at top of Garbage Chute	HRV Fan Runtime	min.
Total Corridor HRV Electricity	Power to HRV top of Garbage Chute	Elec. Demand	Wh

Indoor Air Quality (3 suites)

Parameter Measured	**Location**	**Objective**	**Units**
Suite Temp	Central in Suite	Occupant Comfort	°C
Suite R.H.	Central in Suite	Occupant Comfort	% R.H.
Suite CO2 Concentration	Central in Suite	Occupant Comfort	ppm
Suite HRV Fan On/Off	*HRV in Suite*	*HRV Fan On/Off*	
Total Suite HRV Fan Runtime	*HRV in Suite*	*HRV Fan Runtime*	*min.*
Suite Fan Coil Unit On/Off	*Fan Coil Unit in Suite*	*Fan Coil Unit On/Off*	
Total Suite Fan Coil Unit Runtime	*Fan Coil Unit in Suite*	*Fan Coil Unit Runtime*	*min.*

Heat, Air & Moisture Transport in Brick Wall (1)

Parameter Measured	**Location**	**Objective**	**Units**
Suite Temp	T9 - Central in suite	Reference	°C
Stud Space Temp.	T8 - Center of insul in stud space	Wall temp. profile	°C
Ext. Sheathing Temp. @ Stud	T7 - Inside of exterior sheathing	Wall temp. profile	°C
Ext. Sheathing Temp. @ Stud space	T6 - Inside of exterior sheathing	Wall temp. profile	°C
Exterior Insulation Surface Temp.	T5 - Outside surface of Ext. Insul.	Wall temp. profile	°C
Airspace Temp.	T4 - Center of air space	Wall temp. profile	°C
Interior Surface Temp. of Brick	T3 - Inside surface of brick veneer	Wall temp. profile	°C
Exterior Surface Temp. of Brick	T2 - Outside sufrace of brick veneer	Wall temp. profile	°C
Outside Air Temp.	T1 - Weather station	Reference	°C
Studspace Moisture	W - Pine block in bottom track	Wall moisture profile	% M.C. (wt)
Suite R.H.	RH4 - Central in suite	Reference	% R.H.
Studspace R.H.	RH3 - Center of insul in stud space	Wall moisture profile	% R.H.
Airspace R.H.	RH2 - Center of air space	Wall moisture profile	% R.H.
Outside Air R.H.	RH1 - Weather station	Reference	% R.H.
Driving Rain	R1 - Outside sufrace of brick veneer	Wall moisture profile	mm
Interior to Exterior delta P	P3 - Outside surface of brick veneer	Wall pressure profile	Pa
Interior to Airspace delta P	P2 - Centre of air space	Wall pressure profile	Pa
Interior to Studspace delta P	P1 - Centre of insul in stud space	Wall pressure profile	Pa

Heat, Air & Moisture Transport in EIFS Walls (2)

Parameter Measured	**Location**	**Objective**	**Units**
Suite Temp	T5 - Central in suite	Reference	°C
Stud Space Temp.	T4 - Center of insul in stud space	Wall temp. profile	°C
Ext. Sheathing Temp. @ Stud space	T3 - Inside of exterior sheathing	Wall temp. profile	°C
Exterior Surface Temp. of EIFS	T2 - Outside sufrace of EIFS	Wall temp. profile	°C
Outside Air Temp.	T1 - Weather station	Reference	°C
Studspace Moisture	W - Pine block in bottom track	Wall moisture profile	% M.C. (wt)
Suite R.H.	RH3 - Central in suite	Reference	% R.H.
Studspace R.H.	RH2 - Center of insul in stud space	Wall moisture profile	% R.H.
Outside Air R.H.	RH1 - Weather station	Reference	% R.H.
Driving Rain	R1 - Outside sufrace of brick veneer	Wall moisture profile	mm
Interior to Exterior delta P	P2 - Outside surface of brick veneer	Wall pressure profile	Pa
Interior to Studspace delta P	P1 - Centre of insul in stud space	Wall pressure profile	Pa

Appendix B. Air Sealing Objectives and Strategies Presentation

Air Sealing Objectives and Strategies

The Innovative Condominium in
Dundas, Ontario

Enermodal Engineering Ltd.

Air Sealing

- “Natural air infiltration is the uncontrolled flow of air through penetrations in the building envelope caused by the action of wind and temperature difference.”
- “Air infiltration has a profound influence on both the internal environment and on the energy needs of buildings.”

Goals of Air Sealing a Building

- Energy Savings
- Increased Durability
- Improved Thermal Comfort
- Improved Indoor Air Quality (IAQ)

Air Leakage Facts

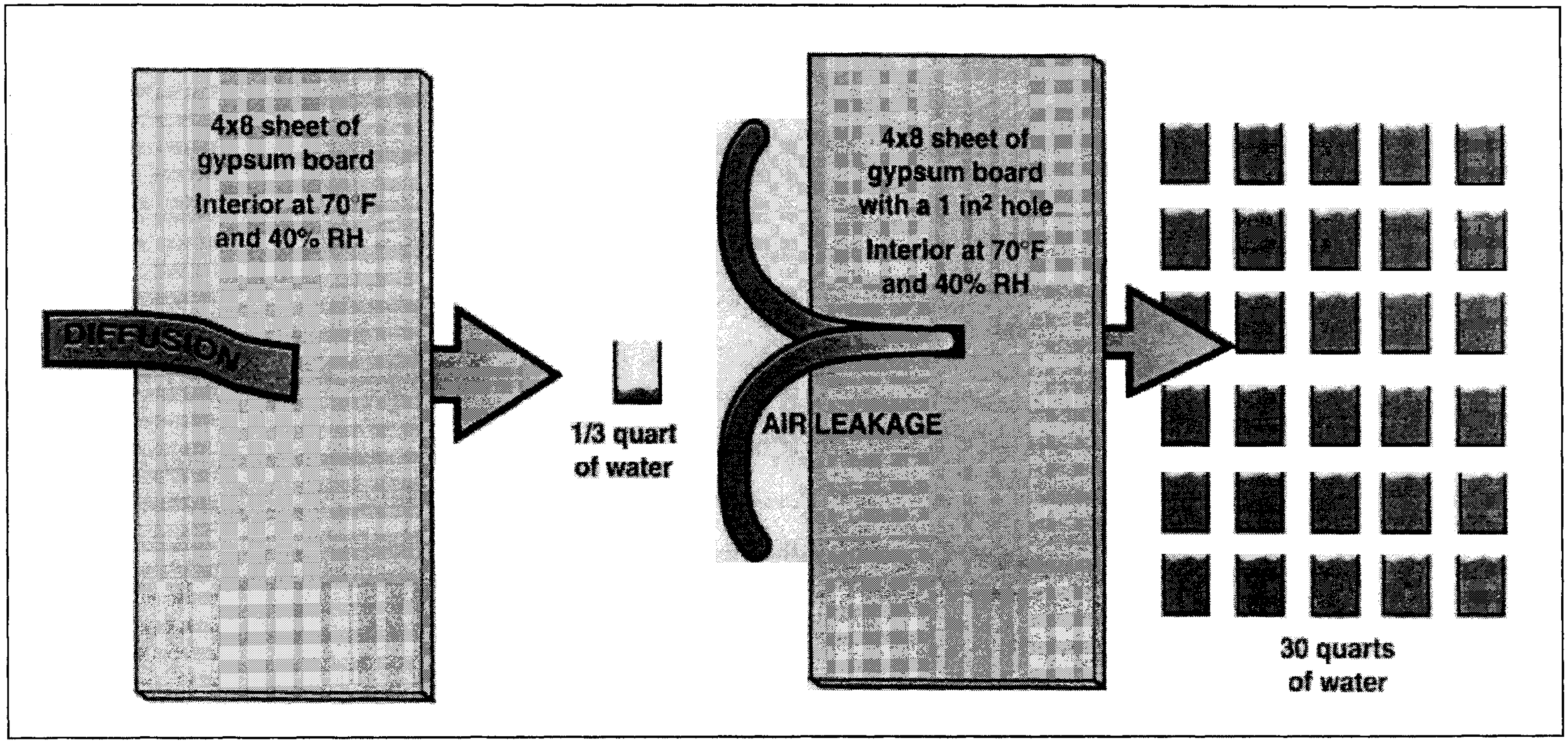
- Energy Savings
  - During peak winter conditions, air infiltration contributes 25 to 40% of peak heating demand, or 12 to 25 W/m^2 of floor space

Air Leakage Facts

- Increased Durability
  - Moisture is deposited at cool surfaces or within assemblies, resulting in damage such as:
    - rotting
    - degraded insulation
  - More moisture is deposited by air leakage than by vapour diffusion

Air Leakage Facts

- Diffusion vs. Air Leakage



Air Leakage Facts

- Thermal Comfort
  - Movement of air (drafts) cause discomfort
  - Cool surfaces give sensation of draft even if air movement is not detected
  - Temperature and RH distribution is not uniform

Air Leakage Facts

- Indoor Air Quality
  - Air and odours are transported from other suites
  - Mould growth occurs due to moisture deposits
  - Car fumes from attached garages can be transported into the building

Air Sealing Concepts

- Forces that drive Air Leakage
  - Wind pressures
  - Stack effect
- Properties of an Air Barrier
  - Continuous
  - Air impermeable
  - Supported to resist wind loads

Air Sealing Techniques

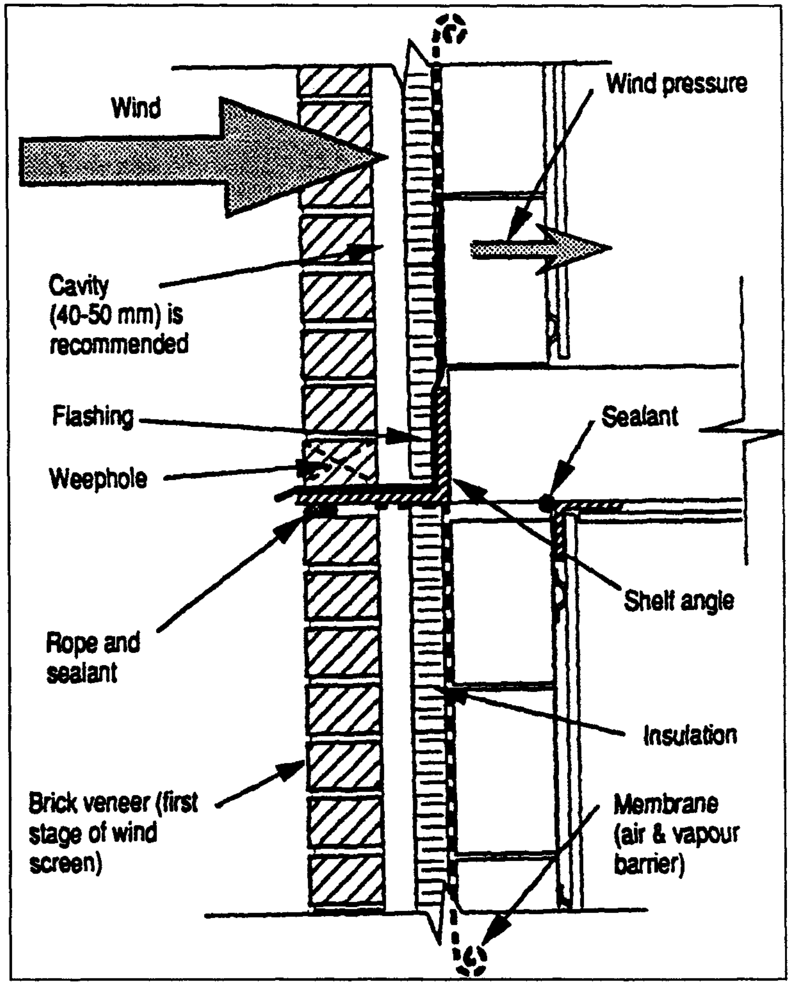
- Traditional (none)
- ADA - Airtight Drywall Approach
- Sealed Poly - Sealing the Vapour Barrier
- EASE - Exterior Air System Element

Governors Road Condo Strategy

- Exterior sheathing forms air barrier
  - Stucco – continuous Blueskin membrane over dense glass gold sheathing
  - Brick – joints taped with Blueskin over exterior grade gypsum
- Openings sealed with Blueskin and spray-in-place polyurethane.
- Partial compartmentalization (garage, shafts, stairwells, penthouse etc.)

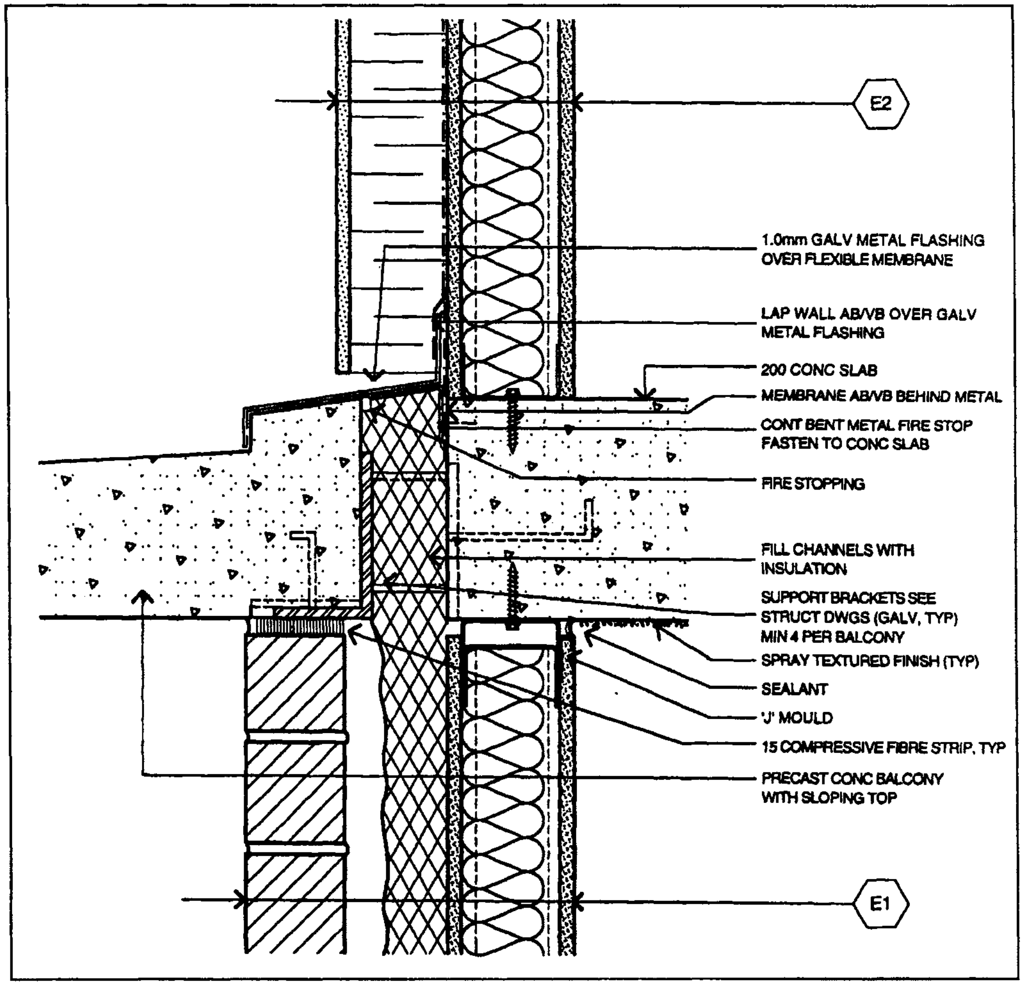
Air Sealing Details

- Typical Continuity at Shelf Angles



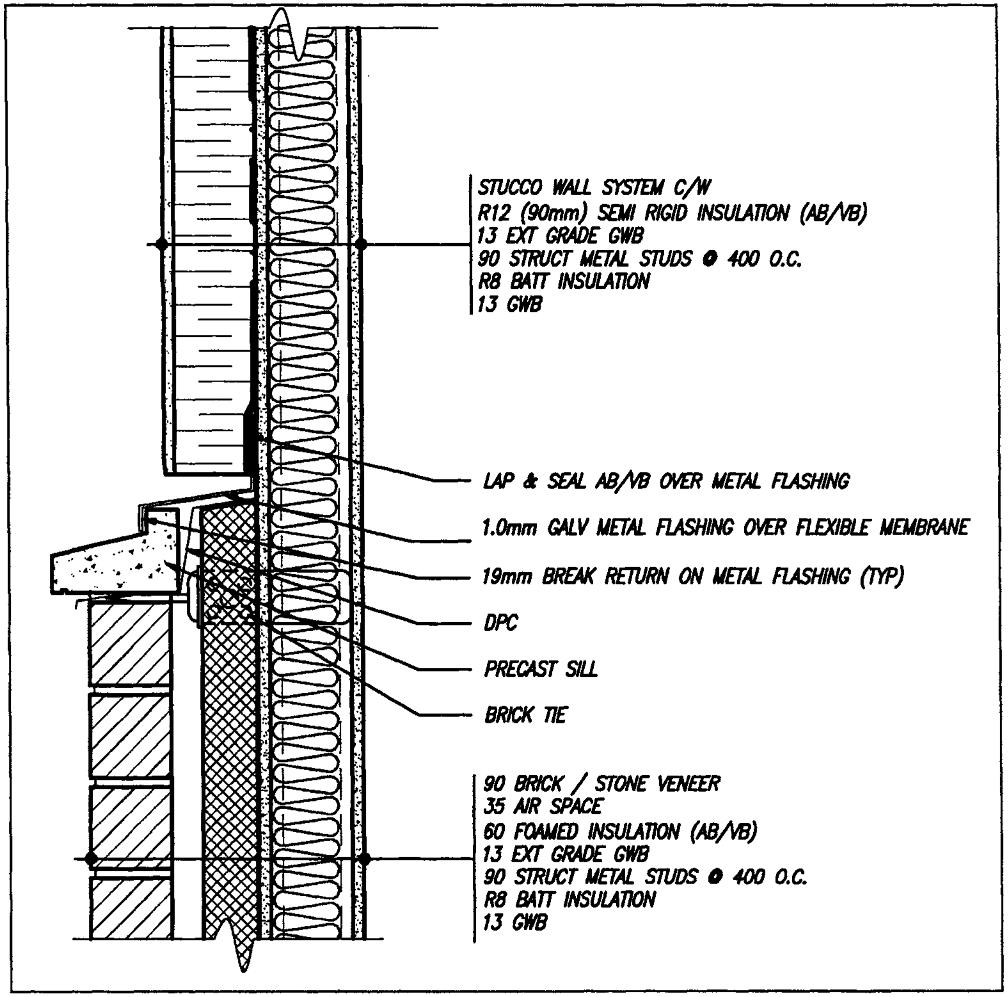
Air Sealing Details

- Continuity at Floors



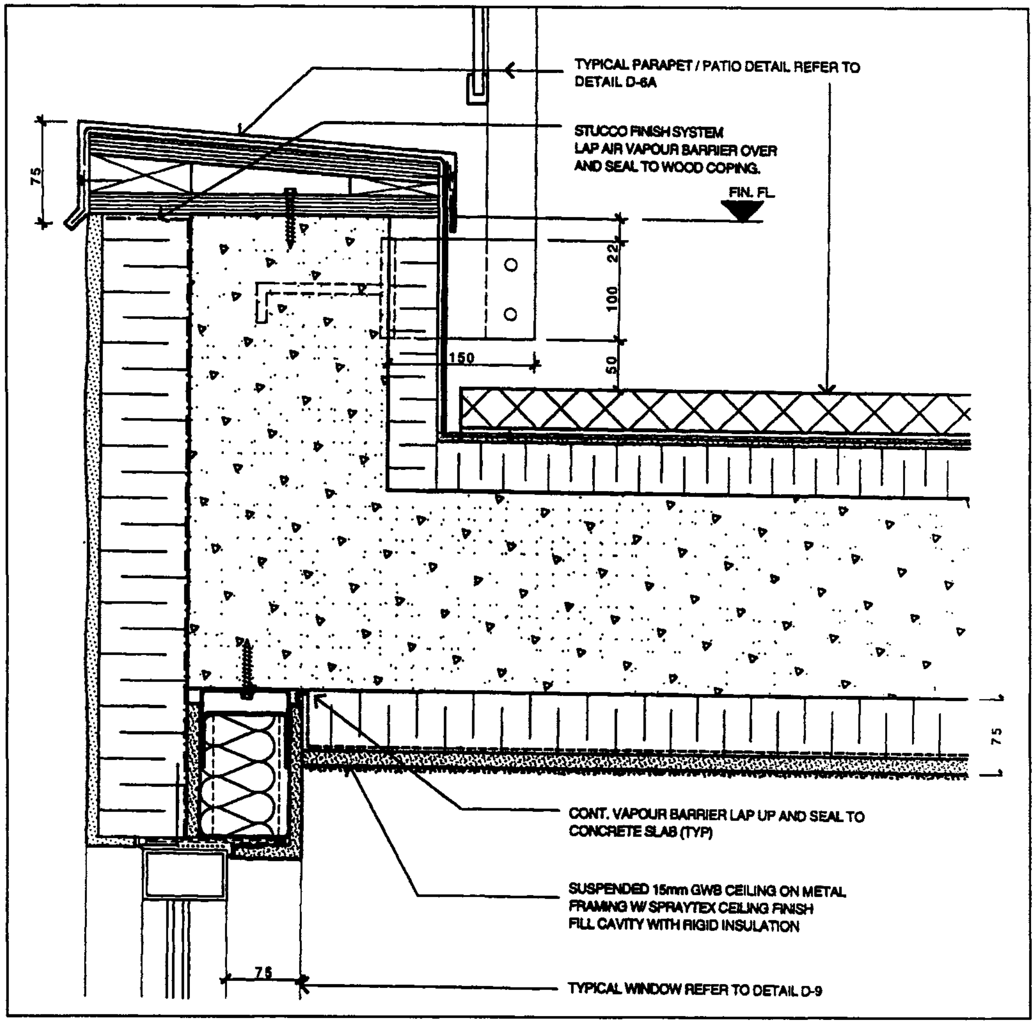
Air Sealing Details

- Continuity at Brick / Stucco Transitions



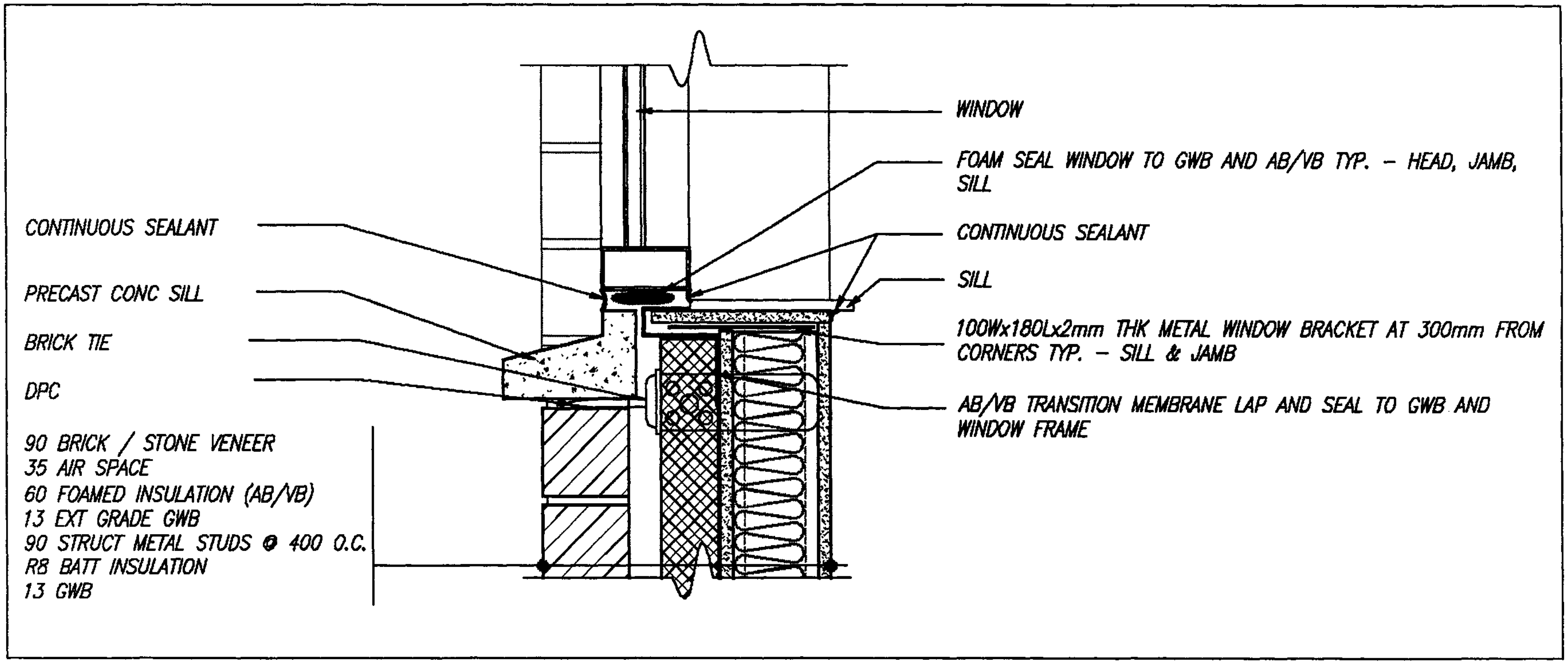
Air Sealing Details

- Roof and Parapet Detail



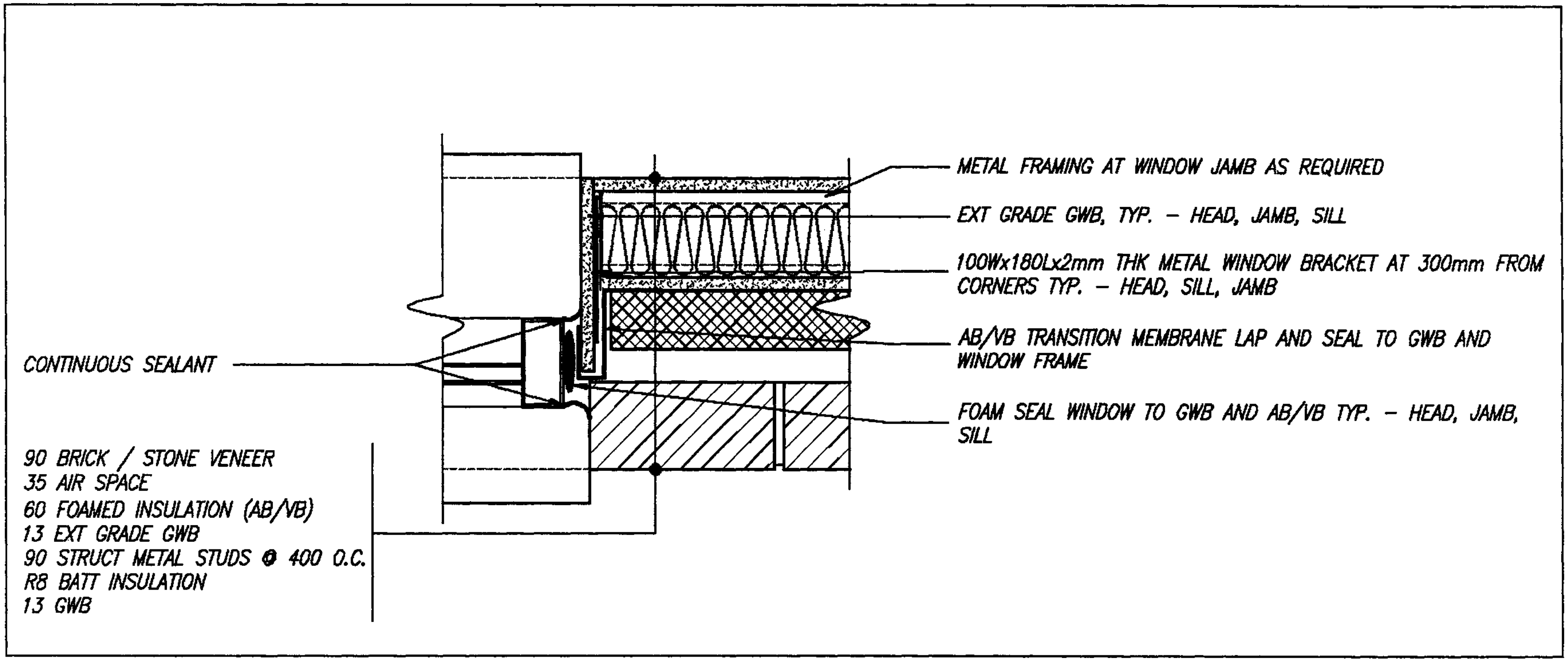
Air Sealing Details

- Brick Veneer at window sill



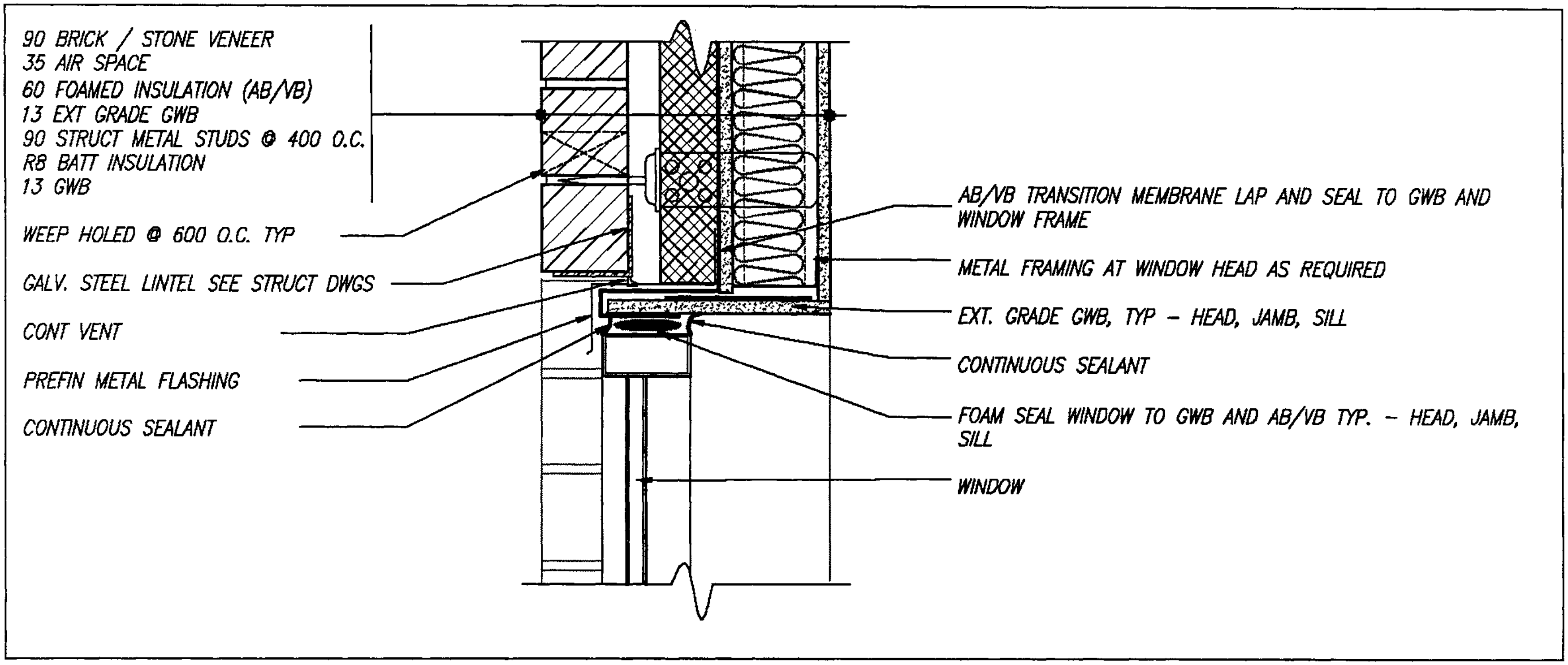
Air Sealing Details

- Brick Veneer at window jamb



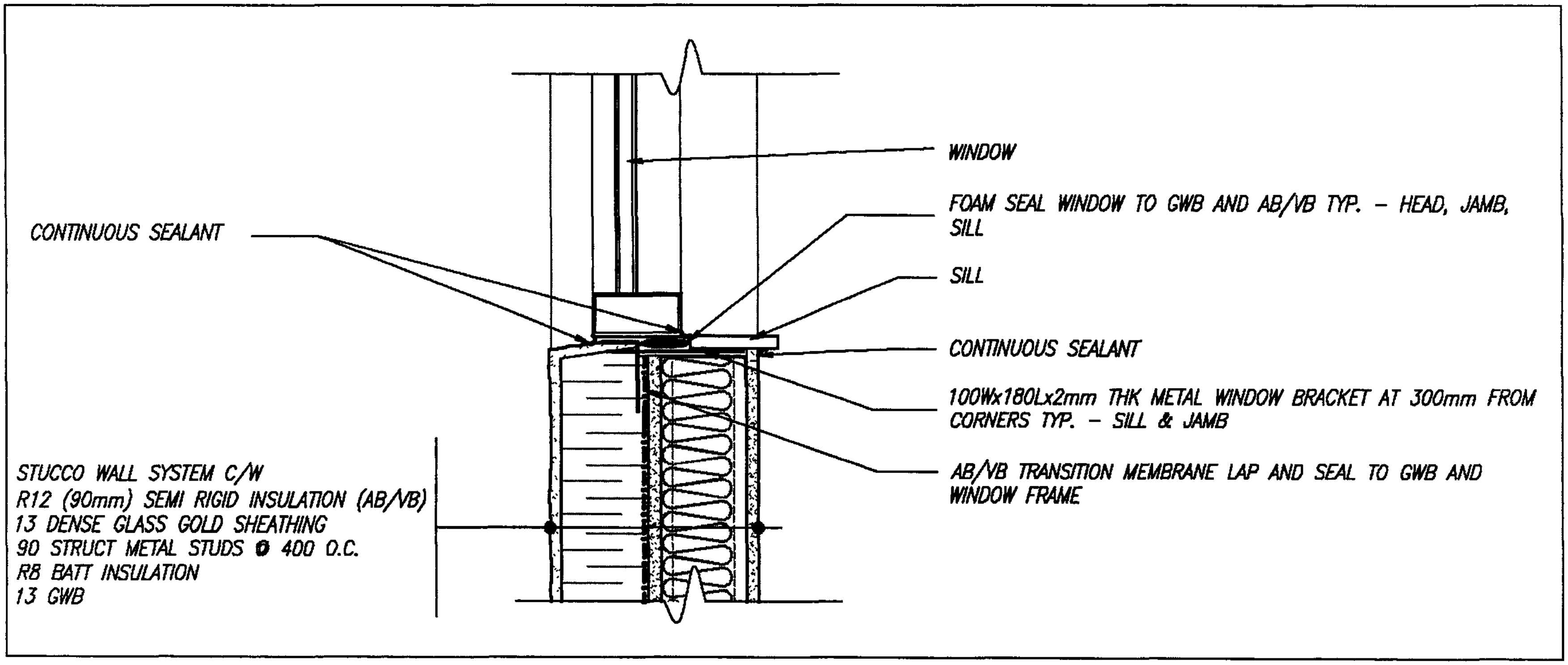
Air Sealing Details

- Brick Veneer at window head



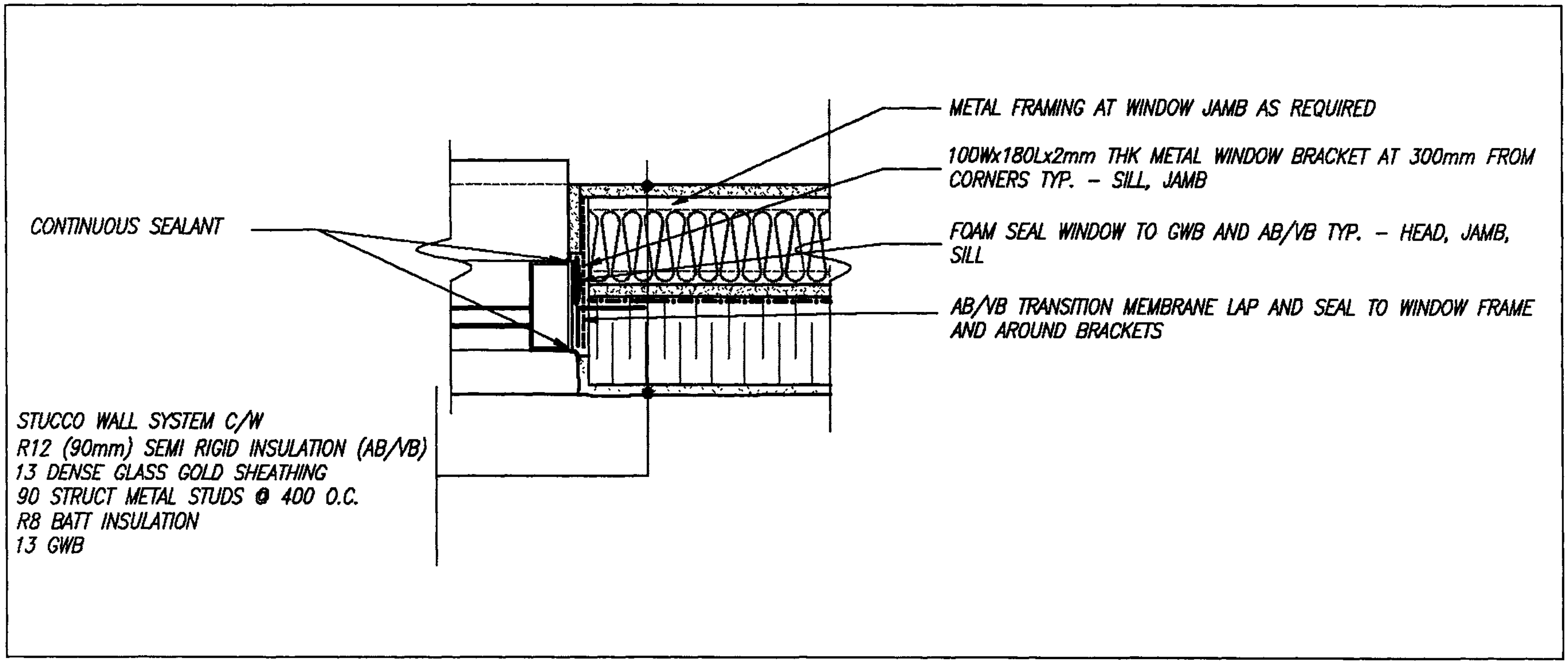
Air Sealing Details

- EIFS at window sill



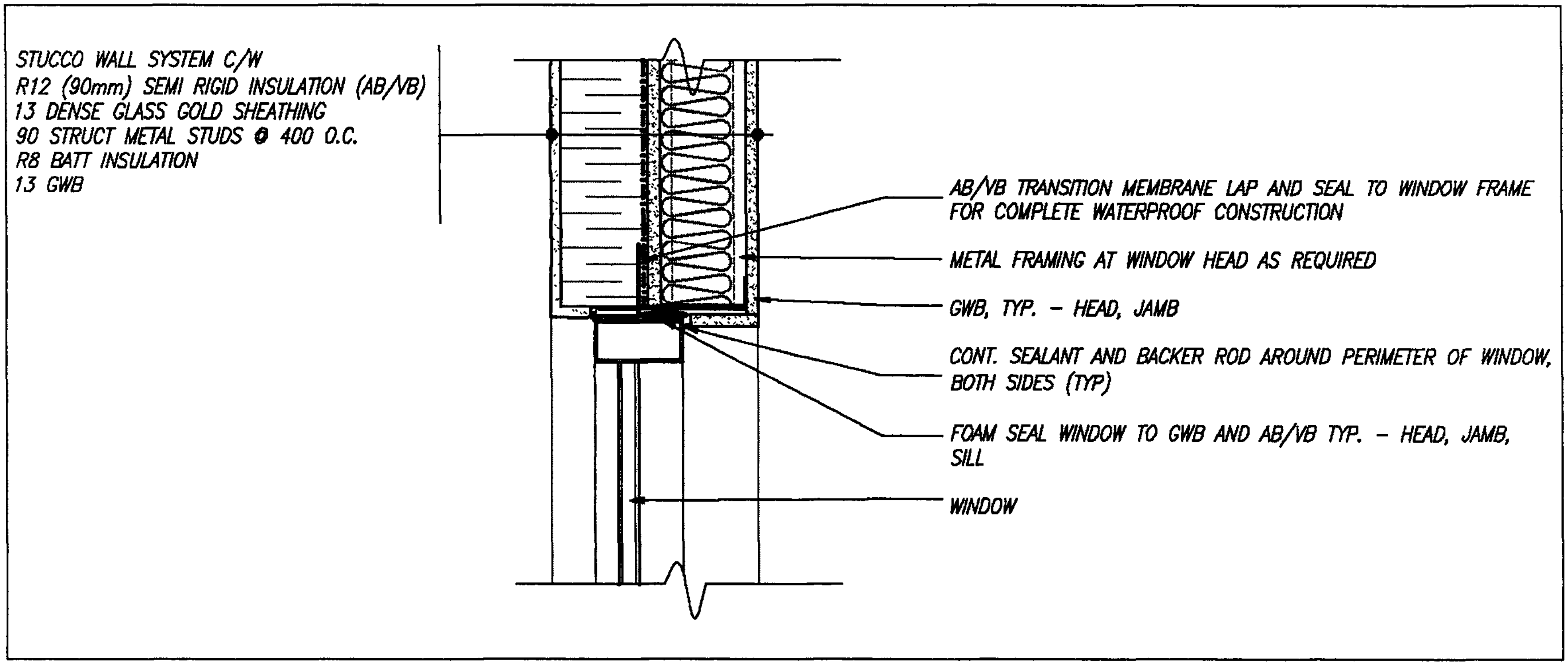
Air Sealing Details

- EIFS at window jamb



Air Sealing Details

- EIFS at window head



Air Sealing Details

- Typical Mechanical/ Electrical Room and Shafts

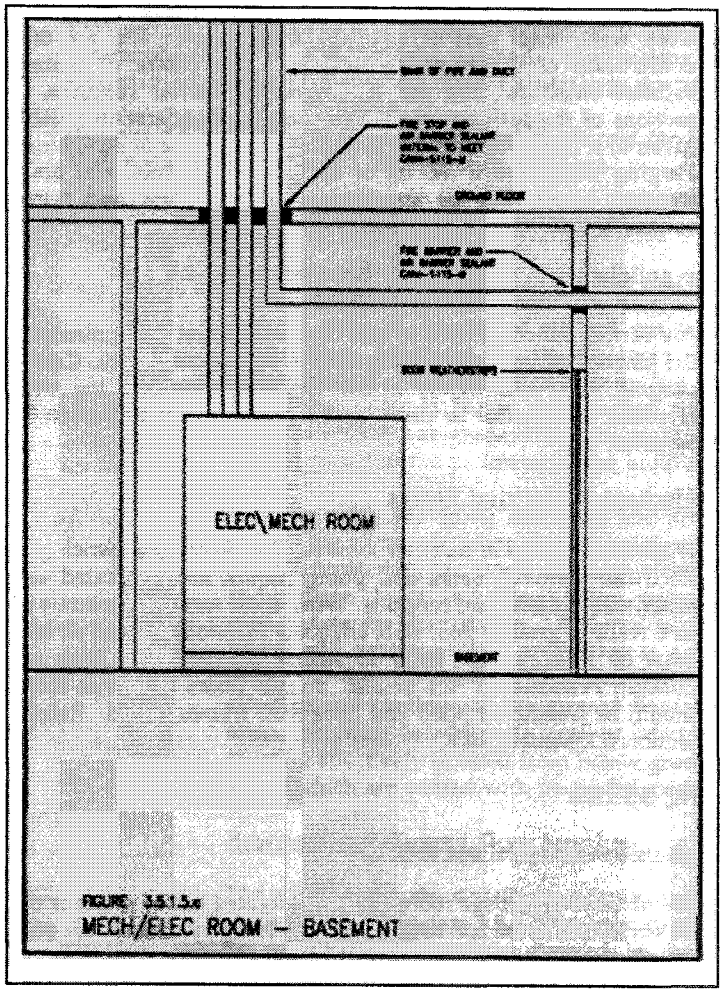


FIGURE 3.5.1.5.a
MECH/ELEC ROOM – BASEMENT

Governors Road Condo

- Pay particular attention to:
  - Exterior Walls
  - Continuity at slabs/floors
  - Continuity at windows and exterior doors
  - Service penetrations through exterior walls and service shafts
  - Walls between suites and service shafts
  - Walls between suites and stairwells
  - Doors between corridors and stairwells