CONDENSATION AND INDOOR AIR QUALITY PROBLEMS AS A RESULT OF HIGH PERFORMANCE BUILDING ENCLOSURES - THE NEED FOR INTEGRATED DESIGN AND A NEW INVESTIGATION PROTOCOL

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ABSTRACT

Multi-family buildings in the Lower Mainland of British Columbia and the U.S. Pacific Northwest have come under increasing scrutiny due to the high incidence of water ingress and resulting deterioration of exterior wall assemblies. The fact that the majority of these moisture problems have been related to water ingress has overshadowed other moisture related building enclosure issues. With the recent widespread adoption of rainscreen technology, improved detailing and better quality control, water ingress issues have been reduced significantly, raising the profile of other moisture issues such as condensation control.

Current trends in architectural and HVAC design, in combination with changes in building enclosure design to improve water penetration control and energy efficiency often result in increased potential for condensation related moisture problems. This paper examines these changes through a series of case studies showcasing typical problems that can occur. Innovative monitoring and modeling techniques are also presented that shed new light on the multi-disciplinary cause of the problem.

Recommendations for integrated Architectural and HVAC design to accommodate the more airtight and insulated wall and window assemblies used on buildings today, as well as guidance to occupants and building managers to minimize risk of condensation related moisture problems in exterior wall assemblies is provided. A new test methodology for the investigation and monitoring of condensation problems is also presented.

INTRODUCTION

The potential for condensation to occur on the interior surfaces of walls and windows in simple terms is related to several factors:

- Exterior environmental conditions
- Thermal resistance of layers within the wall assembly
- Thermal characteristics of the window assembly
- Position of the window within the wall assembly as well as details of the installation
- Location and distribution of heat within the suite
- Interior source generation of moisture
- Ventilation of interior air to manage interior humidity conditions

These basic influences on condensation potential have been understood for many years. However, recent trends within multi-unit residential construction have created a combination of factors that can lead to increased potential for condensation and accumulation of moisture. Moisture accumulation can in turn result in damaged materials and mould growth on surfaces.

For example, the current housing boom and corresponding increase in housing prices has created a market for very small living spaces. For architects this results in a challenge to design usable living spaces while minimizing footprint area. Often with limited floor space the only available location to place large furniture such as beds and couches is adjacent to exterior walls. In addition, the trend towards maximizing the amount of glazing area and ceiling height discourages the use of drop ceilings to enclose perimeter mechanical ductwork and adds to the need for opaque window coverings for privacy. These two factors reduce the amount of interior heat getting to the perimeter and increase the potential for condensation.

The trend towards rainscreen walls, windows (and window-wall), especially those with exterior insulation over a waterproof air/vapour/moisture barrier membrane, results in much higher effective air tightness compared to traditional wall and window assemblies. This change in air tightness level needs to be considered when designing the HVAC system.

A trend towards exposed concrete walls incorporating eyebrows and concrete curbs increases the risk of condensation on colder surfaces created by thermal bridging of the concrete from the interior to the exterior. Attachment to these exposed concrete elements at connections, in particular at the window to wall interface also increase the risk of condensation.

In an effort to reduce costs or in some cases increase LEED points, some designers are moving away from traditional electric or steam based perimeter heating systems and moving to more centralized heating forms such as gas fireplaces, radiant flooring and core based radiant or forced air systems. This can result in a reduction in perimeter heating and thus colder surfaces leading to increased risk of condensation and associated moisture problems.

Measured Relative Humidity levels within suites has been found to be higher in newer buildings than is traditionally assumed in HVAC and building envelope design. Our design assumptions and consequentially our designs, need to be re-evaluated.

It is also clear that the way occupants use their suites and maintain HVAC equipment can have a profound impact on condensation performance. In particular, the typical occupant's lack of basic knowledge regarding the factors influencing condensation potential can result in increased condensation problems.

Clearly it is a fairly complicated interaction of architectural design, HVAC design and maintenance/occupant use that together determine success of an exterior wall assembly with respect to condensation control. It is not simply a matter of making assumptions regarding internal and external environmental conditions and undertaking a basic vapour diffusion analysis of the wall assembly.

FIELD CASE STUDIES

Case Study 1: Field Survey of Performance of HVAC Systems

A survey of buildings was undertaken as part of the development of an HVAC guideline for multi-unit residential buildings in the U.S. Pacific North-West (Portland and Seattle areas) [1]. The purpose of this survey was to examine the actual in-service performance of HVAC systems a few years after construction. Information was gathered through visual observations, measurements of pressure differentials and air flow, as well as through discussions with on-site maintenance personnel and occupants. A summary of performance issues and observations follows. Fieldwork was performed only on calm days in May 2004 to minimize wind effects and stack effect respectively.

Heating

- In some suites the electric heating systems are not used by the occupants, as they are perceived to be expensive. Occupants also complain that the cadet heaters (electric fan coils) are noisy. At some buildings, plug in style oil filled radiators are used in lieu of the electric baseboard or cadet heaters. See Figure 2.
- In many instances, the electric cadets are located towards the unit interior rather than at or near an exterior wall. Also, interior located heat sources are often situated directly beneath thermostats. In some suites the occupants reported feeling cold even when the heaters were used. Since heat was not being provided at the exterior walls, the relatively cold walls reduce

occupant thermal comfort and increase the likelihood of condensation related issues at the exterior walls and windows. See Figure 1.

- In several instances furniture was located in front of cadet heaters, lowering their effectiveness and/or creating a fire risk. See Figure 1.

Ventilation

- The air flow at many bath fans were measured qualitatively (business card or toilet paper test) and quantitatively with a flow meter. Some exhaust fans (continuous) do not operate properly (not maintained, not commissioned, other design issue affecting performance such as gap at door sill suffocating fan).
- In corridor buildings, many suites were positively pressurized relative to the corridor. Of the units that were negatively pressurized, most were 1 to 5 Pa negative relative to the corridor. One suite was 25 Pa negative relative to the corridor.
- Also in corridor buildings, the supply air flow rate varied between floors of the same building. Supply air seemed insufficient in some cases to balance the sum of the continuous exhaust of the suites at that particular floor.
- In many suites with continuous exhaust fans, significant lint has built up.

Make- up Air

- Little to no gap beneath hallway doors to allow make-up air to flow to units (supply from corridor). Little gap at base of bathroom door, suffocates continuous bath fan (suite layout, such that bathroom door remains closed the majority of the time).
- Closures are installed at base of hallway doors to stop draft and odors from under the door and hence cut off “fresh” air supply. See Figure 3.
- Trickle vents in windows are closed.
- In some corridor buildings, stairwell doors are propped open raising the question of building pressures, mechanical system balancing, Continuous exhaust – where is make up really being drawn from in corridor buildings. See Figure 4.
- Draft under door in corridor buildings
- Complaints of odors from suite occupants in many buildings

Point Source Odor and Moisture Control

- Manual operating point source exhaust fans are not used in kitchens and baths.
- Fans are disconnected if they are noisy, or alternately when they become noisy rather than replacing or maintaining them.
- Exhaust grills fitted with covers by occupants to shut-off flow do to perception of heat loss from exhaust system. See Figure 5.
- Exhaust ducts terminated within attic spaces ‘close’ to the exterior. See Figure 6.

Figure 1
Electric cadet wall heater located behind couch, away from exterior wall and directly below thermostat leading to poor temperature control within the room.

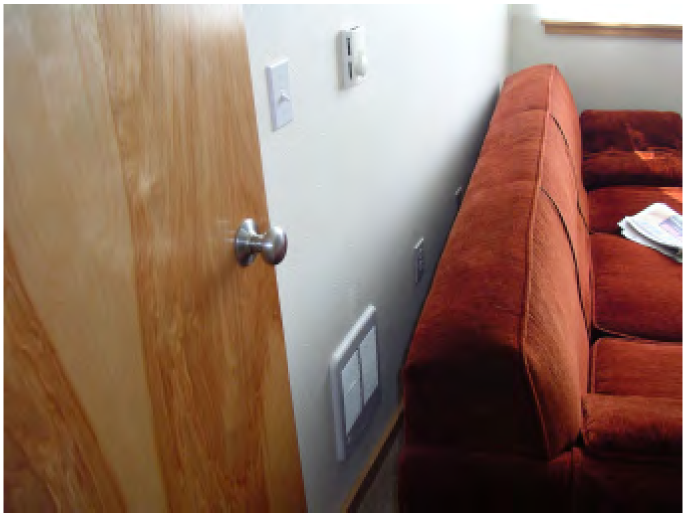


Figure 2
Use of oil filled radiators in same room as shown in Figure 1.

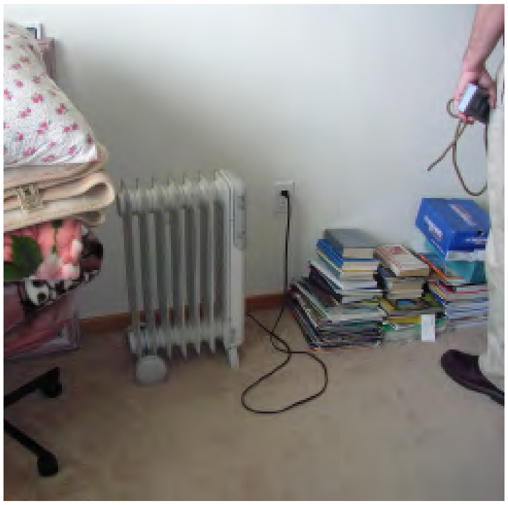


Figure 3
Undercut door intentionally blocked to resist drafts and control odors from hallway into suite.

Figure 4
Stairwell doors propped open frustrating attempts to control air flow within building.

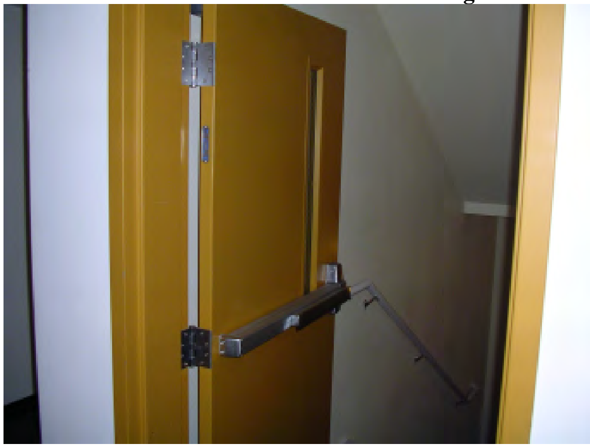


Figure 5
Cover to close exhaust grill.

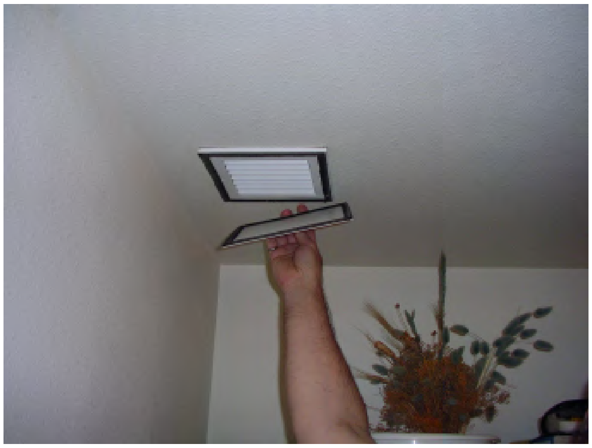


Figure 6
Exhaust duct terminated in attic space.

Figure 7
Curtains prevent air from circulating at exterior wall and window-wall. Conditioned air is being directed to the outside walls from an interior location almost 7m away.

The field survey clearly illustrated that a combination of architectural, HVAC and occupant factors can conspire to cause HVAC systems to not function as intended. The case studies that follow illustrate some examples in more detail where this dysfunction has led to condensation and moisture related damage.

Case Study 2: Forensic Investigation of Moisture Troubled Building

Significant levels of mould and deterioration were observed within a vinyl clad townhouse complex in Washington State [2]. The damage occurred along the base of the walls both at the exterior sheathing and on the interior surface of the interior gypsum sheathing. The investigation of the cause of the moisture problems identified issues related to exterior water penetration as the cause of deterioration of the sheathing. However, the high levels of mould and deterioration on the interior gypsum board (Figure 8) could not be explained by exterior moisture sources alone. In many cases all of the visible mould was located on the interior of the polyethylene vapour retarder while insulation and framing to the exterior of the polyethylene was observed to be in good condition (Figure 9).

Figure 8
Mould on Interior Surface of Exterior Wall in Bedroom

Figure 9
Insulation and Studs in Good Condition on Exterior of Vapour Barrier

The investigation revealed the following issues:

- Electric cadet heaters and thermostat controls were located a significant distance from the exterior walls and were often not directed at the exterior walls (Figure 10).

- The interior space layout dictated that many of the obvious locations for large furniture such as beds and couches are adjacent to exterior walls. The location of large furniture in these areas had the dual effect of adding insulation to the interior of the wall and blocking heat flow from the cadet heaters (Figures 8 and 10).
- Units were constructed over an unheated parkade and the interior floor consisted of a structural concrete slab covered with polystyrene insulation, gypcrete and carpet. The detail at the base of the exterior walls incorporated a perimeter concrete curb that was attached to the suspended structural slab, creating a thermal bridge through the insulation in the sandwich slab (Figure 11).
- Humidity in many of the units was higher than expected, and clothing and other personal affects were found piled up against the exterior walls in a number of units.

Figure 10
Location/Orientation of Cadet Heater, Furniture and Resultant Mould

A simulation of the base of wall detail was performed using Therm 5.2 [3] to better understand the contribution of the thermal bridging to the condensation and mold problem. The model utilized an exterior temperature of 0^{o}C and an interior temperature of 20^{o}C. At this temperature and an interior relative humidity of 50% the dew point of the air is 9^{o}C. The simulation in Figure 12 models the wall interface without interior furniture. The coldest interior temperature is 12.5^{o}C indicating that the risk of condensation would be quite low under the modeled conditions. When the same detail was modeled with a sofa on the interior of the wall in Figure 13, the results show surface temperatures of 6.7 ^{o}C, which is significantly below the dew point of the modeled conditions. The temperature region between 6.7^{o}C and 9^{o}C (dewpoint), shown on Figure 12 is approximately the same location where interior mould was observed on the walls during the investigation.

Figure 11
Detail at Base of Perimeter Wall

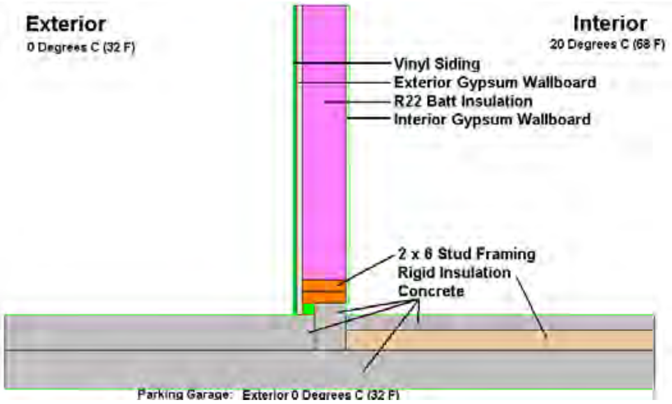


Figure 12
Temperature Isotherm At Base of Wall

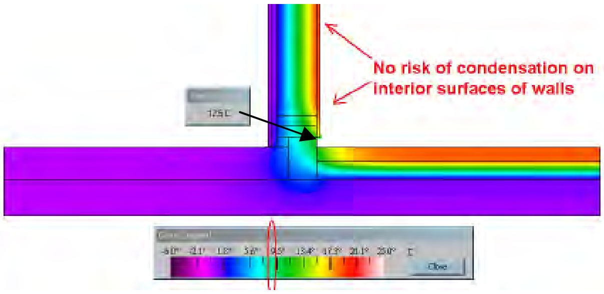
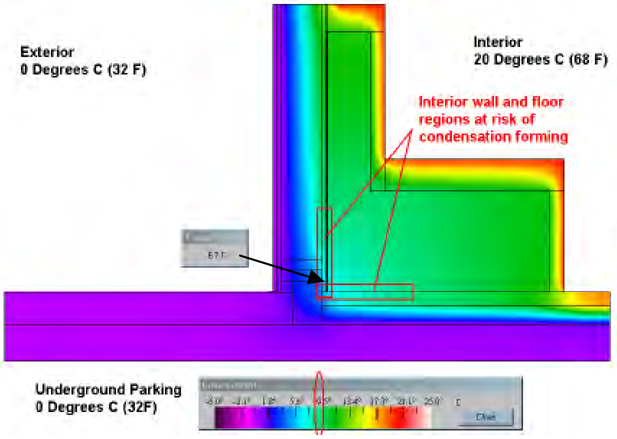


Figure 13
Temperature Isotherm At Base of Wall With Sofa Adjacent to Interior Surface



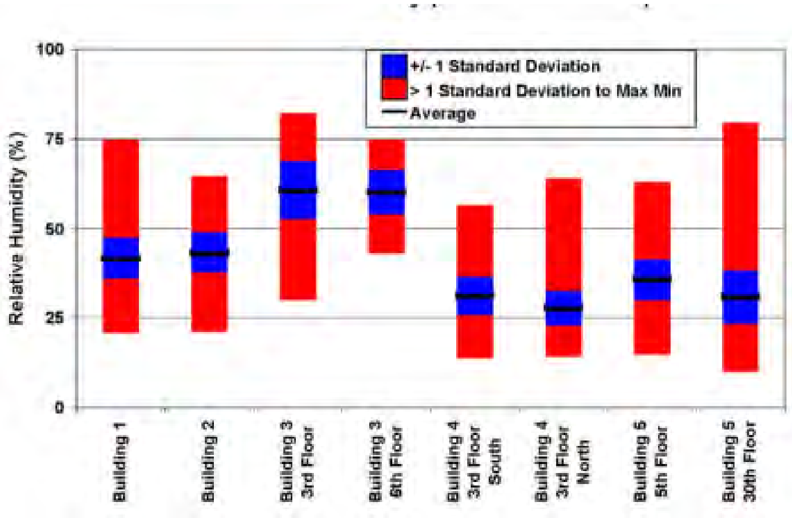
The results of the investigation indicate that the interior condensation and mould sources on this building were a result of a combination of HVAC design, interior space planning, architectural detailing and occupant lifestyle.

Case Study 3: Building Performance Monitoring –Interior Winter RH Levels

The Building Envelope Performance Monitoring Project [4] is being undertaken to monitor the performance of five rainscreen buildings in Vancouver, BC. The project has been underway since 2001 and includes three multi-unit wood frame residential projects that utilize a strapped cavity rainscreen water penetration control strategy with several different cladding types (Buildings 1,2,4), a concrete frame mid-rise residential rehabilitation project that has converted a face seal stucco clad wall assembly to a dual insulation (exterior/interior) rainscreen assembly (Building 3), and a new residential high-rise project with an exterior insulation rainscreen wall assembly (Building 5). To date, no abnormally high moisture contents or humidity levels have been measured that can be correlated with precipitation or exterior moisture sources.

As part of the building monitoring protocol the interior relative humidity was measured within suites of each building. On Buildings 3, 4 and 5 the interior relative humidity was measured in two suites located in different areas of the building.

Figure 14
Interior relative humidity (winter 2003/2004)



** Each distribution represents readings for one suite in the given building. Measurements were taken every 15 minutes over the winter of 2003/2004.*

Figure 14 shows the interior RH values for all five monitored buildings during the winter of 2003/2004. The interior relative humidity in all five buildings exceeds 50% for some period of time during winter months. Readings on Buildings 4 and 5 are indicative of common assumptions with regards to interior relative humidity with an average winter RH of 32% and a standard deviation of 6%. Buildings 1 and 2 have elevated RH levels with the average being 43% and a standard deviation of 6%, meaning that it would not be unusual to experience interior RH values exceeding the commonly used design RH of 50% during the winter months. The interior RH measured for Building 3 is much higher than traditional expectations for winter RH. With an average RH of 61% and a standard deviation of 7% it would not be uncommon to find RH levels exceeding 68%. The consistency of the results between different units in the same buildings may also indicate that RH is impacted more by the interaction of the building envelope and HVAC system than the occupancy of the suite.

The highest RH levels were observed in Building 3. Building 3 is a mid-rise building that was originally clad with a face seal stucco wall assembly and aluminium window assemblies. Building 3 had been experiencing water infiltration problems and high humidity levels since construction. Traditionally these wall and window assemblies have allowed relatively high levels of air leakage both through and around the assemblies. As a result, mechanical designers were able to assume that a significant portion of the overall ventilation requirement would be taken up by air leakage thorough the wall and window assemblies. When the building was rehabilitated to reduce water infiltration and repair damage to underlying wall components, the conventional sheathing paper was replaced with a continuous self-adhesive modified bituminous air and moisture barrier membrane. In addition, the existing windows were replaced with higher performance windows. The resulting exterior building envelope was much more watertight and airtight than the original construction. The expected result of the recladding would be that the reduction in water infiltration would result in lower moisture levels and in turn humidity levels in the building after the work was completed. The continued high humidity levels observed post remediation are at least partially a result of the increased air tightness of the wall assembly invalidating the original mechanical assumptions regarding air leakage through the exterior walls. Occupant lifestyle and building HVAC systems are also likely playing a significant role in the abnormally high interior RH levels observed after the rehabilitation.

This case study supports the need for understanding the interaction between the existing HVAC system design, the original assumptions regarding natural ventilation through the building enclosure, as well as occupant lifestyle issues, prior to upgrading building enclosure elements to reduce water infiltration or renew components.

Case Study 4: Air Leakage Testing

As part of the quality assurance testing of new building envelope assemblies, ASTM E783 air leakage testing was performed on a number of installed rainscreen high-rise residential wall and glazing assemblies

[5]. The major envelope assemblies consisted of sliding balcony doors, floor to ceiling window-wall and exterior insulated rainscreen metal panels. The results of this air leakage testing revealed that overall air leakage rates across the building envelope assembly were in the order of 0.09 L/(s m^2) @75 Pa which is within the recommended level outlined by the building code [6] (Max 0.10 L/(s m^2) @75 Pa).

Since most of the buildings utilized hallway pressurization as a component of the supply air to the suites it was decided to assess whether the measured air leakage rates across the building envelope were consistent with the expectations commonly used in HVAC design. The measured air leakage rate @75 Pa was converted to an equivalent leakage area (ELA_{75}) using $Q=CA[(2/p)\Delta P]^{1/2}$ with the following assumptions - C=0.6, p=1.29, suite wall area=80m^2. Based on these assumptions the ELA_{75} was found to be 11.4 cm^2.

While 75 Pa is a standard test pressure used to determine leakage through exterior walls, it has been our experience that this pressure is not representative of the typical pressure differences measured across building enclosures. During field-testing we have typically found that for high-rise residential buildings, less than 4 Pa of depressurization is created when all exhaust fans are operated simultaneously. In addition, the mean pressure across the building envelope was found to be 0.5 Pa (exfiltrating) with a standard deviation of 8.1 Pa in the Building Performance Monitoring project. This indicates that the exhaust fans had a negligible overall impact on suite pressurization. Using ½ of the standard deviation as a reasonable representation of pressure profile range created by wind for air leakage ventilation purposes also suggests that 4 Pa is reasonable. Therefore utilizing ELA_{75} and a ΔP of 4 Pa the equivalent air leakage rate would be 1.7 L/s for the entire exterior wall area of the unit tested.

Table 5 of the ASHRAE Fundamentals Handbook [7] suggests that a two occupant unit should have a total ventilation rate greater than 16 L/s. In the past it was not uncommon for mechanical engineers to assume that up to one third to one half of the total air exchange is provided by uncontrolled ventilation through the exterior building envelope. Based on the testing and calculations presented above it is clear that this assumption is invalid for the newer more airtight wall and glazing assemblies used on high exposure buildings.

This case study suggests that air leakage through modern building envelope enclosures should not be relied upon to provide a significant portion of the required ventilation for the unit.

RECOMMENDATIONS

The following sections provide recommendations for architectural design, HVAC design and instructions that need to be communicated to the building occupants and/or managers to help them better understand the factors that influence condensation control. It is important to note that any one of these items is not likely to be critical on its own. There generally needs to be several factors contributing to create a condensation problem. As a result, each of these recommendations must be viewed in the overall building context. Concessions can be made without necessarily compromising condensation control.

Architectural Design Recommendations

There are a variety of architecturally related items that can influence condensation potential:

- The suites should be compartmentalized with an air-tight perimeter maintained between the suite and the corridor and between adjacent suites. This recommendation addresses many of the air flow control issues that were identified in the field survey.
- Space layout should be designed to encourage locating large pieces of furniture away from exterior walls and windows.
- Poorly ventilated spaces such as closets should not be located on outside walls.
- Windows should be located towards the interior portion of wall assemblies to encourage ‘washing’ of the window with interior heated air. This maintains warmer temperatures at the surface of the window assembly. This window placement is also better from a water penetration control perspective since the windows are somewhat protected when recessed.

- Walls should be designed and constructed with a continuous insulating layer located somewhere within the assembly to minimize thermal bridging and maintain warmer interior surface temperatures.
- Details should be designed and constructed to avoid thermal bridging such as continuous metal sill pans or anchors.

HVAC Design Recommendations

The majority of multi-unit residential buildings utilize heating systems that do not require ducts. Although they have higher initial costs, ducted systems do have some advantages since they permit a wider variety of fuel sources, easier addition of cooling, and often better delivery of fresh air and conditioned air throughout the suite. We have assumed that non-ducted systems are used. The recommendations for both heating and ventilation reflect this assumption.

A primary goal of ventilation is to provide good indoor air quality, which includes comfortable interior humidity levels. However, what constitutes good indoor air quality is not well defined, nor do we customarily measure it. It is assumed that by providing sufficient ventilation, good indoor air quality will be maintained. The recommendations for ventilation also reflect ASHRAE Standard 62.2 [8] Low-Rise Residential Ventilation that requires whole-house ventilation, local exhaust and source control.

Note that some of the recommendations are directly related to factors that may impact the intended function and thus condensation potential, while other recommendations are directed at managing owner / occupant impact or intervention.

Heating

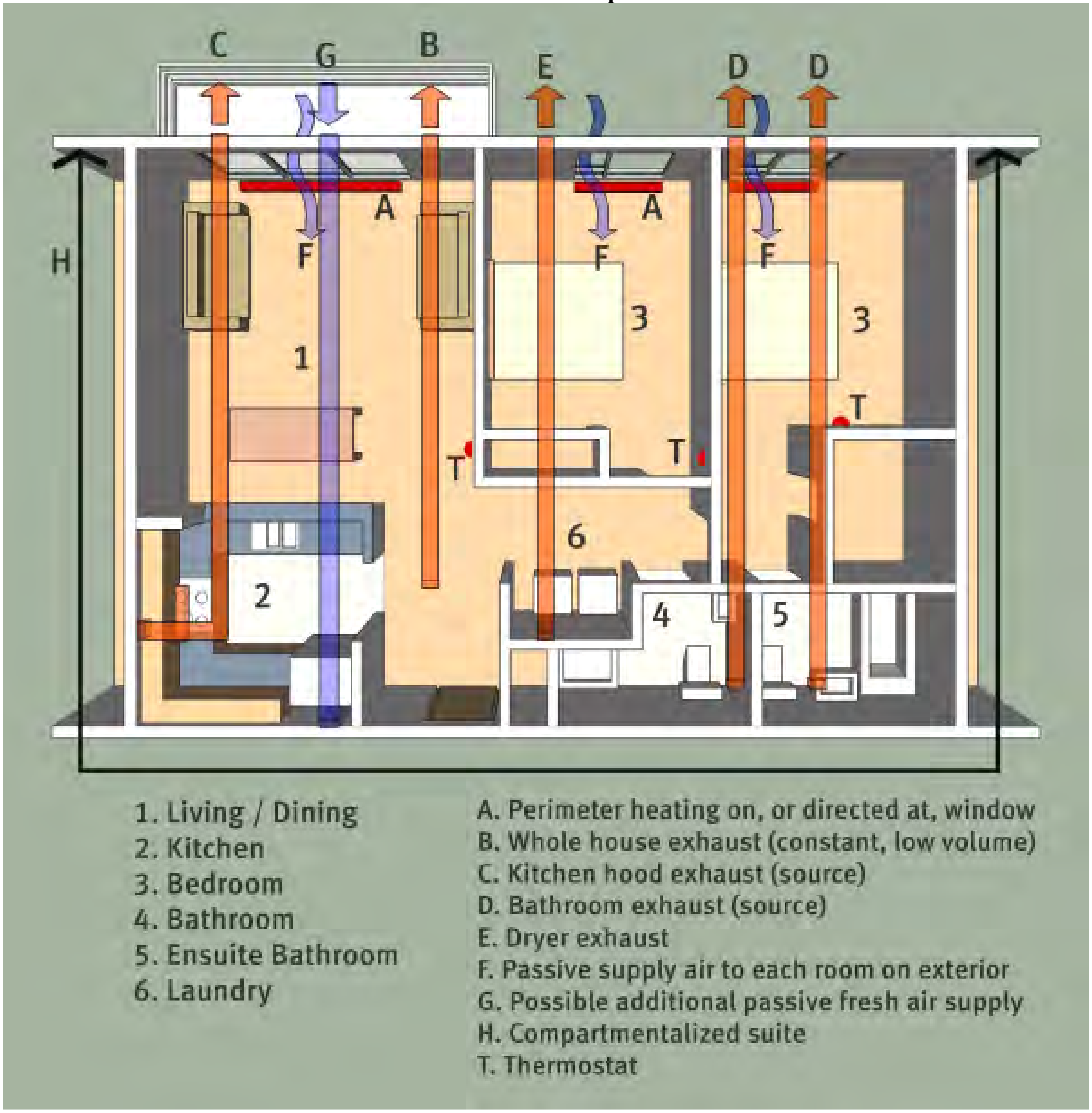
- **Locate heating either at the exterior walls** or so that heat is directed to and reaches the exterior walls. Baseboard heating is preferable to cadet heaters for this purpose. This is particularly important when designing small living spaces since wall space for shelving and storage is at a premium. Heaters that are located on opaque wall areas will reduce this space and will likely be modified or covered over by some occupants in order to meet their space needs.
- **Locate thermal controls on zoned basis** (usually in each room located at the building perimeter) and away from the exterior walls and heaters.
- **Use quiet systems** to discourage occupants from disabling. Baseboards may be preferable to cadets for this reason.
- **Use systems that require minimal maintenance** since occupants are not likely to do the maintenance nor notify the owner/manager.
- Provide the owner/manager with comprehensive **maintenance and renewal recommendations** for the heating components.

Ventilation

- **Meet ventilation requirements on an individual suite basis.** This effectively means that each suite is treated as an independent dwelling unit from an HVAC perspective.
- **Use low noise source exhaust fans** (<1.5 sonnes) to encourage proper use and discourage occupant tampering.
- **Utilize constant low volume whole house fans** to provide basic air exchange for suites
- **Provide fresh air to each suite at the suite perimeter**. Locate/detail inlets so that they are not readily blocked by occupants
- Provide the owner/manager with comprehensive **maintenance and renewal recommendations** for the heating components.
- **Take steps to minimize occupant control over source fans**. (utilize humidistat controls, connect to light switch so that fan is operational whenever light is on, or set to run automatically for periods of time each day)

Figure 15 provides a conceptual illustration of the recommendations for an arbitrary suite in a multi-unit residential building.

Figure 15
Conceptual HVAC strategy for multi-unit residential building that facilitates effective control of interior environmental conditions as well as temperatures at exterior walls.



Occupants / Building Manager

Given the limited understanding that occupants can be expected to have regarding the interaction of factors to create condensation problems, there is need to reinforce good operational procedures on an annual basis through education initiatives (flyers delivered to each suite, short presentations at owner meetings, etc.). In addition, there is a need for building managers to follow the maintenance and renewals recommendations provided by the design team, and to visit each suite, particularly during the winter months to confirm acceptable condensation performance.

The following provides a checklist of operational items that owners and building managers will need to address from time to time.

- Locate furniture so heating sources are not blocked
- Open drapes/blinds daily to allow warmer air to reach perimeter walls and windows
- Clean exhaust grilles on source fans (kitchen and bathroom) and dryers
- Use kitchen exhaust fan when cooking
- Use bathroom exhaust fan when using bathroom
- Notify manager of problems with fans, controls, or condensation

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