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Stack-Driven Moisture Problems in a Multi-Family Residential Building

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ABSTRACT

Wintertime window condensation problems were reported on the top two floors of a five-story, multi-unit residential building in central New York (7200, base 65°F heating degree-days). Initially built as a five-story brick hotel at the turn of the century, the building was rehabbed into low-income apartments in the early 1990s. Ventilation in each unit consisted of operable windows and a single bath exhaust. Condensation on windows was severe enough to support fungal contamination in the first winter of occupancy. During the renovation, vinyl-clad aluminum sash, double-hung, double-pane windows were installed to replace the original wood sash round-tops. Initial efforts to solve the problem included improving sealing and insulation details around the retrofitted windows on the fourth and fifth floors. The amount and duration of condensation was reduced, but condensation and new fungal growth occurred during the next winter. A more detailed investigation of the problems was then made. It was determined that the neutral pressure plane was in the center of the third floor of the building. A large fraction of the ventilation air for the upper three floors came from the floors below. This resulted in progressively higher relative humidity as air ascended through the building. Tested bath fans were moving less than 10 cfm (5 L/s). Surface temperature maps were made of windows and sheetrock. Poor ventilation, deep window returns, and windows with insulating details inappropriate for this climate resulted in condensation and fungal growth. Pressurization tests were conducted on a design day to determine how much exhaust it would take to raise the neutral pressure plane above the roof of the building.

INTRODUCTION

Chronic condensation and mold problems were reported in a five-story, multi-family building in Gloversville, New York. Gloversville is a small city located at the southern edge of the Adirondack region of central New York. Gloversville has a winter design dry-bulb (99%) of –8°F (–22°C) and around 7200 HDD per year. The building is an 80-year-old, five-story brick structure. There are nine apartments on each floor except the first floor, which has large common areas and only a few apartments. All apartments are heated with baseboard electric resistance units. The common areas are heated with gas-fired boilers and fin-tube hydronic heaters. Intentional ventilation in the units is limited to bathroom exhaust fans. Kitchen ranges have recirculating hoods. The windows are double-sealed glass units with air fill. The sash and frame are thermally broken aluminum with PVC interior cladding.

Complaints of moisture and mold were received from occupants on the top two floors the first year of occupation. Some complaints were received from the third floor. There is no swimming pool or laundry in the building. There are no rain leaks, and the basement is dry, with no signs of water damage. The major sources of moisture are the occupants and their activities. The contractor responded by removing the contaminated materials and additional material around the windows on the top two floors and replacing them with new materials. Insulation detailing was changed around the windows to reduce the chance of condensation. This effort reduced the duration of the condensation problem, but did not eliminate it. In December 1995 the contractor invited the authors to investigate the problems. The authors visited the building in December 1995 and January 1996.

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PURPOSE OF VISIT

The purpose of the visits was to collect information and to develop and test hypotheses for causes of the problem. The tests, measurements, and inspections performed were:

- Inspection of window installation details by disassembling portions of sheetrock returns and insulation system.
- Measurement of temperature profile on window and sheet rock return surfaces to determine thermal properties of window and wall assemblies.
- Measurement of bath exhaust fan flows.
- Measurements of temperatures, relative humidities, and pressure differences across the building shell on each floor.
- Fan door test to determine the amount of exhaust air needed to depressurize the top floors on a cold day.
- Depressurization test of an apartment using a low-wattage (20 Wt), ultra-quiet exhaust ventilator to determine whether a bathroom exhaust fan could depressurize an apartment.

PROCEDURES AND RESULTS

The windows are replacement windows installed in a masonry building that had been insulated on the inside during renovation. The window wells were about 14 inches deep. During both visits, condensation and fungal growth were observed on the windows of the top three floors. The results of the window inspection and measurements are shown in Figures 1, 2, and 3.

Temperature Profiles of the Window and Returns

The surface temperatures of the window and sheetrock returns were measured in an unoccupied apartment. The windows faced north and west. The measurements were made using a surface temperature probe. During the visit, condensation, frost, and fungal growth were observed on portions of the window and sheetrock. Condensation occurred at the window within a few inches of the lower edge of the upper and lower lites. Condensation was also observed on the inner face of the PVC-coated sash. Frost was observed on a piece of aluminum extrusion that frames the interior perimeter of the window jambs and inside the track portion of the jamb that holds the window in place. Fungal growth was observed at the bottom of each lite and in the corners where the frosted aluminum extrusion and sheetrock returns meet. The locations of condensation, frost, and fungal growth are shown in Figure 1.

The temperatures measured during the visit are shown in Figures 2 and 3. A north-facing window was selected because it did not receive any direct sunshine, which changes the temperature profile of the window elements. The room air was 66°F (19°C) and 33% relative humidity. Under these conditions, it is expected that dew point will occur at around 36°F (2°C). A measurement of the surface temperature of the window glass at the edge of the condensation (2 in. from the edge of the glass unit) was 40°F (4°C), close to what was expected. All surfaces with condensation were cooler than

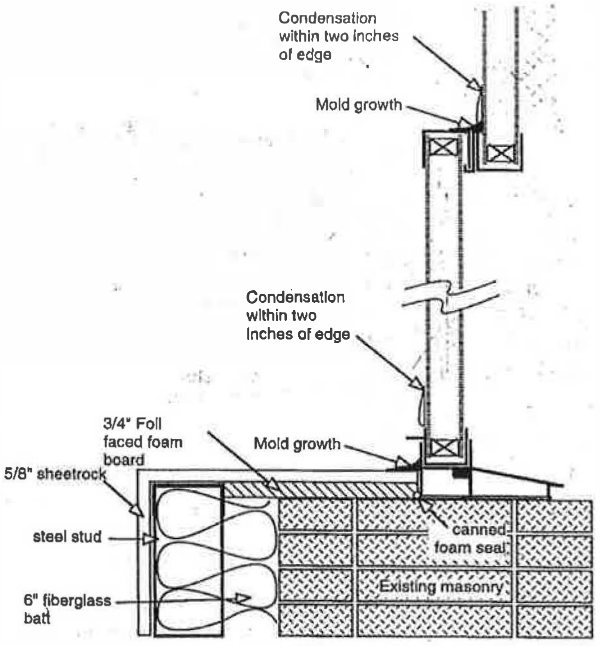

Figure 1 Section through window installation showing location of condensation and fungal growth.

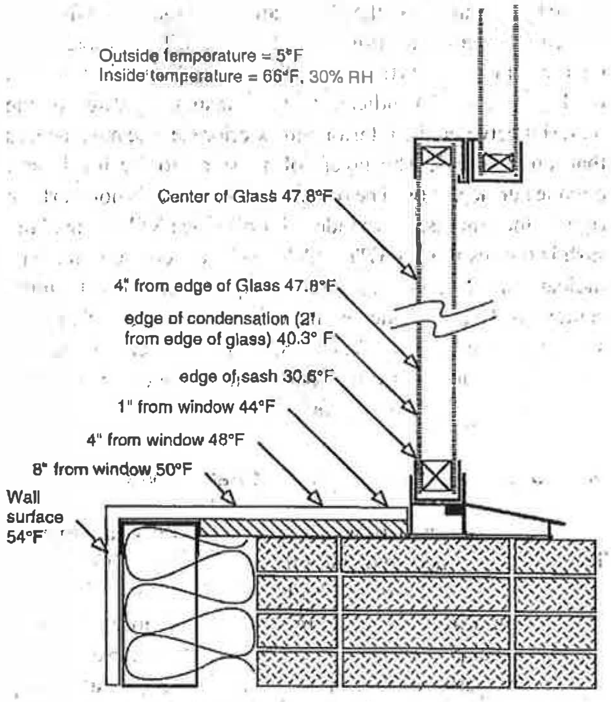

Figure 2 Surface temperatures of window components and surrounding sheetrock.

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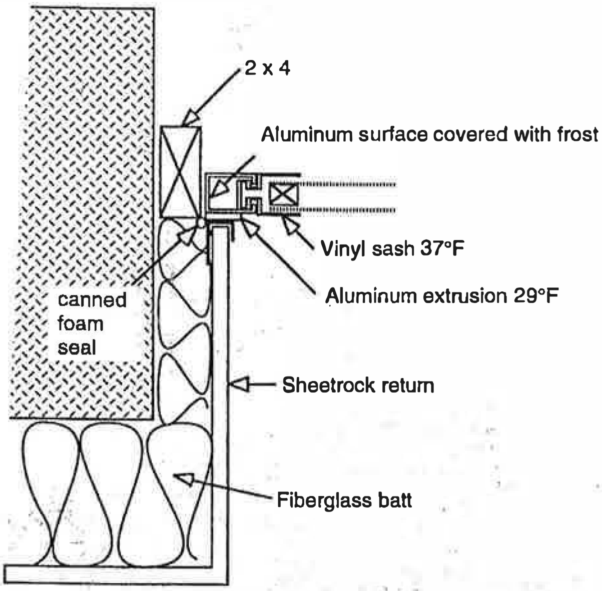

Figure 3 *Surface temperature of window sash and aluminum extrusion.*

this. All surfaces with frost were below 32°F (0°C). The window performs as expected except for the cold temperatures of the frosted areas on the aluminum extrusion and in the sash track and the condensation on the PVC sash. The temperatures on the aluminum extrusion (29°F, −1.7°C) and in the sash track (26°F, −3°C) indicate that the insulating value of the material between the interior and exterior surface must be less than an R of 1.5. The layers of air stuck to the inside and outside surfaces would be over R-1. Something is not working right in these areas. The condensation on the PVC facing of the sash is the result of a 37°F (2.8°C) surface temperature. This indicates an R-value less than 1.7, significantly less than the center-of-glass R-value of the window (R-2.15) where the surface temperature is 47.8°F (8.8°C). The thermal analysis program Window 4.0 was used to calculate a center-of-glass R-value of 2.0 for this window.

Measurement of Bath Exhaust Fan Flows

Bathroom fan airflows were tested in three apartments. The fans are connected to ducts that ran through a false ceiling to the exterior walls of the building. A flow grid with four upstream and four downstream pressure taps located in a 4-inch-diameter pipe was used to measure airflow. An electronic micromanometer was used to measure the pressure drop across the grid. The airflows on all three fans were below the lower limit of detection of the device (12 cfm, 6L/s). Smoke pencils showed a tiny amount of exhaust flow. *ANSI/ASHRAE Standard 62-1989* (ASHRAE 1989) recommends bathroom exhaust ventilation of 50 cfm (25 L/s) intermittent or 20 cfm (10 L/s) continuous.

Temperature, Relative Humidity, and Pressure Difference Measurements

Temperature and relative humidity measurements were made in the hallways of each floor and also outdoors, using a digital thermohygrometer. The instrument was checked against a laboratory thermometer and dew-point test.

Indoor-to-outdoor pressure difference measurements were made using a digital micromanometer. The measurements were made by gaining access to an apartment on each floor.

The measurements were made between 10 and 11 a.m. The results show that the temperature on each floor was nearly the same. This was expected because the temperature is controlled thermostatically. The outdoor weather conditions were: 5°F to 10°F (−15°C to −12°C), < 20% RH, and no detectable breeze.

The relative humidity was lowest on the first floor (24%) and progressively increased on each successive floor, peaking on the top floor at 35%. This was expected because the makeup air for the bottom two floors was cold outdoor air at a low relative humidity. As this cold, dry outdoor air was warmed up after entering the building, it could then hold considerably more moisture than could the cold air; therefore, it "picked up" moisture generated by the building occupants. This increased the relative humidity in the air. As it rose to the upper floors, the air picked up more moisture, and the relative humidity continued to increase, until it reached the top floor and the highest relative humidity. The significance of this becomes apparent when the indoor-to-outdoor air pressures are also considered. The first and second floors are below the neutral pressure plane; therefore, the outdoor air enters the building and essentially dries out the air on those two floors. The neutral pressure plane is located on the third floor. The fourth and fifth floors are above the neutral pressure plane, making it impossible for outdoor air to enter through envelope leaks. Figure 4 illustrates the results of the measurements as well as the dynamics involved.

Fan Door Test

A fan door test was made in the roof access door located at the top of the stairwell. The fan was used to depressurize the building. With the fan door set up, but not running, the fifth floor air was 10 to 13 pascals positive relative to outdoor air. Indoor air was flowing out through the cracks and holes in the windows and building shell. The purpose of the fan door test was to measure how much exhaust air it would take to depressurize the top floors so that makeup air would be drawn in from outdoors on all floors, drying out the upper floors and reducing the risk of condensation on cool surfaces. It took 2200 to 2700 cfm (1100 to 1350 L/s) of exhaust air to move the neutral pressure plane to the roof of the building.

Exhaust Fan Test on Apartment 408

A low-wattage, high-efficiency exhaust fan was temporarily set up in the window of Apartment 408. The purpose of

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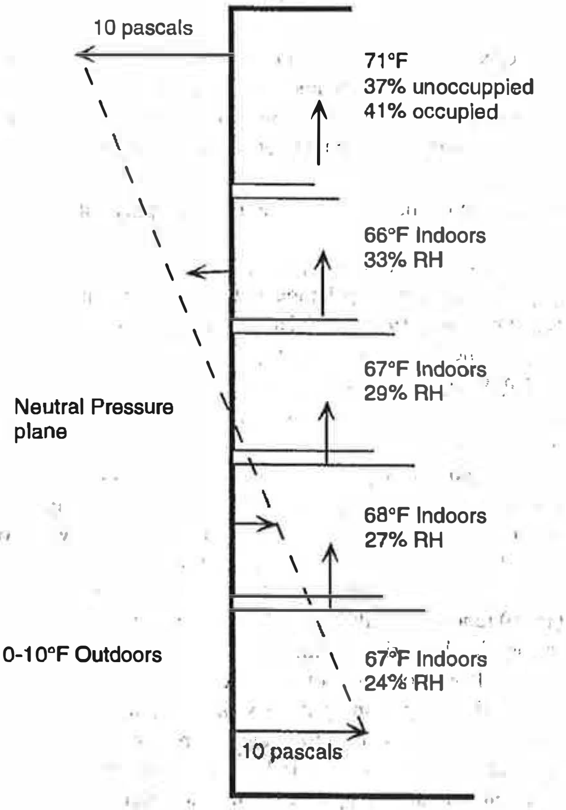

Figure 4 *Temperature, relative humidity, and pressure differences.*

this test was to determine whether or not a low-wattage, ultra-quiet bathroom exhaust could depressurize an apartment on the fourth floor. Before the fan was turned on, the pressure difference across the building shell was about 1 pascal positive. With the exhaust fan running, it was about 3 to 5 pascals negative, depressurizing the apartment. As measured by a flow-monitoring station, the fan was moving about 122 cfm (61 L/s).

DISCUSSION

Several factors combine to result in condensation on windows in this building. Wintertime stack-driven airflows transport moisture to the upper floors and prevent outdoor air from drying the upper floors. Bathroom fans in the apartments are ineffective at overpowering the stack forces. Occupied rooms on the top floor have wintertime relative humidity levels in the range of 40%. Cool window surfaces provide a condensation plane for the moderately elevated humidity. The cool window surfaces result from a combination of low thermal resistance of some of the window elements, deep window wells that interfere with room air circulation, and short on-time of the baseboard electric resistance heating units (many upper floor heating units have been turned off by the occupants, the apartments being heated by the transfer air from below).

There are two ASHRAE guidance documents that apply to this situation. *ANSI/ASHRAE Standard 62-1989, Ventilation for Acceptable Indoor Air Quality* (ASHRAE. 1989) applies to the ventilation of the spaces and *ANSI/ASHRAE Standard 55-1992, Thermal Environmental Conditions for Human Occupancy* (ASHRAE. 1992) applies to the indoor relative humidity levels.

For residential living areas, Standard 62 recommends outdoor air ventilation rates of 0.35 ACH but not less than 15 cfm (7 L/s) per person. For the apartments in question, it would be 15 cfm (7 L/s) per person. All units are one- and three-bedroom units, so that would be 30, 45, or 60 cfm (15, 23, 30 L/s) of exhaust, respectively. Unless Standard 62 implicitly allows the ventilation requirements to be met with transfer air from the apartments below, apartments on the top three floors of this building frequently do not meet the ventilation guidelines. Standard 62 does allow for makeup air for exhaust devices to be transferred from other parts of the building. Crude stack calculations for this building indicate that the ventilation rate during the heating season would go from under 1000 cfm to 2400 cfm (500 to 1200 L/s) if enough exhaust is added to the top floors to raise the neutral pressure plane out of the building. This will increase heating costs by several thousand dollars in electrical consumption plus another 500 dollars in electrical consumption by the fan motors.

ASHRAE guidance for indoor relative humidity levels is contained in Standard 55. Figure 3 of that document shows a portion of the psychrometric chart with a comfort zone blocked out. The lower humidity level recommended is found at a dew-point temperature of around 36°F (2°C). This is a relative humidity level of between 25% and 30% for operative temperatures in the range of 68°F (20°C) to 75°F (24°C). Increasing the ventilation rate should lower the relative humidity levels in the building. If the relative humidity levels were lowered to 30% on the top floor, the outdoor temperature would have to go substantially lower to cause condensation on the windows. Table 1 shows the outdoor temperatures that

TABLE 1
Outdoor Temperatures Below Which Condensation Occurs on Components of the Window for 30% and 40% Indoor Relative Humidity

Location	30% RH	40% RH
Aluminum extrusion around edge	18°F (−7.8°C)	28°F (−2.2°C)
Lower edge of glass	15° F (−9.4°C)	26°F (−3.3°C)
PVC sash on lower side of window	3°F (−16.1°C)	17°F (−8.3°C)
Center of glass	−20°F (−28.9°C)	−5°F (−20.6°C)

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would cause condensation on different components of the windows for 30% and 40% relative humidity.

Lowering the relative humidity from 40% to 30% on the top floor would eliminate condensation on the center of the glass and almost eliminate condensation on the lower sash. However, there are a fair number of days when there would be condensation on the lower edge of the glass and on the aluminum extrusion around the edge of the window. The manufacturer of the windows in the building was adamant that there was no problem with the windows. The problem, they said, was due to high relative humidity. The 35% to 40% relative humidity range found in the apartments on the top three floors is at the lower end of the ASHRAE guidance for 72°F (22°C) air. Older and more recent guidance from cooperative extension services (Rowley 1941; Huelman. 1996) is written in terms of controlling the room air relative humidity to avoid condensation on windows or window components. The ASHRAE guidance is written in terms of keeping room air relative humidity in a range that would be comfortable and healthy for the occupants. Section 5.1.3 of Standard 55 says that "temperatures of building surfaces and materials (e.g., windows, ductwork) must be controlled to avoid condensation." This seems to mean that window components must maintain an interior surface temperature of 36°F (2.2°C) or greater when outdoor temperatures are at a design value. Is the ASHRAE dew point of 36°F (2.2°C) a good lower limit for indoor humidity? Should windows be constructed so that interior surface temperatures will be higher than this on the design day? Or should room relative humidities be allowed to go as low as needed to prevent condensation on windows? This issue needs more clarification by ASHRAE.

Recommendations were made with the following three goals in mind:

- to provide outdoor air ventilation for the occupants of the upper floors,
- to lower the wintertime relative humidity in the upper floors,
- to raise the interior surface temperatures of the window elements that were condensing enough water to support fungal growth.

To accomplish these goals, the following recommendations were made to the contractor:

1. Raise the neutral pressure plane to ventilate and dry the upper floors.

- Install either a central exhaust system or individual bath exhaust fans to depressurize the affected floors (The third floor should be included as part of the affected area).

2. Raise the surface temperatures of the window components.

- Cover the aluminum extrusion around the interior of the windows that was covered with frost with an insulating material and a material to prevent contact with room air water vapor.
- Clean all hard-surfaced materials (aluminum, PVC) that have fungal growth and replace all soft materials (sheetrock, foam) that have fungal growth with new materials. The materials may be treated as nonhazardous construction waste.
- In the event that problems persist, apply interior storm windows.

The contractor implemented the above recommendations in the winter of 1996/1997. No follow-up inspection had been made at the time this paper was completed (December 1996). Storm windows were not applied.

Two recommendations that were not included in the report were discussed with the contractor at the site. The first was to find and seal penetrations between floors to reduce stack-induced pressure differences across the building shell. If sealing between the floors could be done effectively, it would have the advantage of increasing upper-floor outdoor air ventilation and reducing energy use. Blasnik and Fitzgerald (1996) report difficulty in sealing between floors in Canadian residential high-rise buildings well enough to prevent air transfer from floor to floor. The second recommendation was to retrofit the building with gas-fired hot water boilers and baseboard hydronic heat to reduce energy costs. The contractor was concerned that finding and sealing the airleaks between floors would be difficult and might not solve the problem. The contractor was not interested in the second option because they did not own the building.

During the review process of this paper, one reviewer made a suggestion that did not occur to the investigators but makes a great deal of sense. The suggestion is to seal the wall and doors between the corridors and the apartments. This divides the building into two stacks, one composed of the layered apartments and the other composed of the elevator shaft, the fire escape stairwell shaft, and the corridors. Under stack-dominated conditions, air should flow through the apartments into the corridors on the bottom floors and from the corridors through the apartments to outside on the upper floors. There are both horizontal and vertical series leakage paths. Sealing the wall between the corridors should increase the pressure difference between the corridors and apartments and decrease the pressure difference between the apartments and outdoors. This has the advantage of reducing stack-driven airflows and increasing the ease with which the upper floors can be ventilated with outdoor air. The effects of sealing leaks in this way can be estimated using methods developed by Hutcheon (1995) and Blasnik (1992).

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