Monitoring of the building envelope of a heritage house - a case study

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Monitoring of the Building Envelope of a Heritage House - A Case Study[1]

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Abstract

The paper describes the long-term monitoring of the hygrothermal performance of the building envelope of a heritage house located in Ottawa. The house, once the residence of two of Canada's Prime Ministers, now serves as a museum. To preserve the historical artifacts within the building, the specified temperature and relative humidity for the indoor air are 21°C and 35% to 50% respectively. As the house must also be preserved, there was concern about the effect of the high indoor relative humidity (moisture) on the durability of the building structure. The main objective of the monitoring was to assess the effect of the conditioned air on the building envelope.

Selected wall sections and a window were continuously monitored from March 1995 to August 1996. The monitoring included indoor and outdoor conditions and the attic environment. Temperature, relative humidity, surface wetting-drying cycles (from precipitation or condensation), and air pressure differential were monitored. This paper describes the monitoring approach and results.

The results indicated that the brick walls are unlikely to experience internal condensation problems as long as they are subjected to a negative air pressure difference. However, because the building is quite leaky, the negative pressure introduced too much cold dry air from the exterior. It caused localized cold spots with condensation and ice formation on interior of walls and ceiling. Negative air pressure differences are not a solution unless the leakage paths are reduced.
Keywords: thermal, moisture, building envelope, monitoring, heritage house, masonry

Résumé

Ce document décrit la surveillance à long terme de la performance hygrothermique de l'enveloppe d'une maison patrimoniale située à Ottawa. Cette maison, qui a été la résidence de deux premiers ministres du Canada, sert maintenant de musée. Pour préserver les artefacts patrimoniaux de l'édifice, l'air intérieur y est maintenu à 21°C et à une humidité relative allant de 35 à 50 %. Comme la maison doit aussi être préservée, les responsables s'inquiètent des effets de cette humidité élevée sur la durabilité de la structure. Le principal objectif de la surveillance était d'évaluer l'effet de l'air conditionné sur l'enveloppe du bâtiment.

Des sections choisies des murs et une fenêtre ont été surveillées de façon continue de mars 1995 jusqu'à août 1996. La surveillance portait sur les conditions intérieures et extérieures et sur l'environnement dans les combles. La température, l'humidité relative, les cycles mouillage-séchage des

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surfaces (précipitations ou condensation) et la pression différentielle étaient surveillés. Ce document expose la méthode et les résultats de la surveillance.

Les résultats indiquent que les murs de briques sont peu sujets à des problèmes de condensation interne tant que l'intérieur du bâtiment est maintenu sous une dépression. Toutefois, comme le bâtiment est assez peu étanche, cette dépression aspire à l'intérieur trop d'air froid et sec de l'extérieur. Ce phénomène produit des points froids s'accompagnant de condensation et de formation de glace sur la face intérieure des murs et des plafonds. Le maintien d'une dépression à l'intérieur n'est pas une solution à moins que les parcours d'infiltration soient réduits.

Introduction

Rehabilitation of buildings accounts for an increasing proportion of design and construction activities. Old schools are transformed into condominiums, factories become offices and old houses are used as museums. One of the challenges is the control of heat, air and moisture flow through the building envelope. The buildings usually experience a change in indoor climate, because higher standards of comfort are required (higher humidities and better temperature control). Changes should not adversely affect the long-term durability of the building envelope [1, 2, 3]. The Institute for Research in Construction has an ongoing collaborative research program to develop guidelines for the retrofitting of masonry walls. Installing sensors in buildings is an effective method of obtaining information on building performance [4, 5].

This paper describes the long-term monitoring of the hygrothermal performance of the building envelope of a heritage house (Laurier House) located in Ottawa. The house, once the residence of Prime Ministers Laurier and King, now serves as a museum (Fig. 1). To preserve the historical artifacts within the building, the indoor air conditions specified are a temperature of 21°C, and a relative humidity (RH) of 35% (dew-point 5°C) in the winter and 50% (dew-point 10°C) in the summer. It is also desirable that short-term (daily) variations in RH are no greater than 5%. High humidity can compromise the life of the building envelope and artifacts.

Figure 1 Laurier House

A preliminary study of selected windows and walls indicated that both the single pane windows and windows with storm windows can have significant condensation at outdoor temperatures below -10°C when interior conditions are maintained at 21°C and 35% RH [5]. The study recommended additional long-term monitoring which would include walls. Before the HVAC system was upgraded in 1993, hygrothermograph readings over the period January-February 1991 indicated a range of 5% to 10% RH and approximately 24°C indoor conditions (dew-point -19°C to -10°C). In the February-March 1993 preliminary monitoring, indoor conditions were 20% to 30% RH and 23°C (dew-point -1°C to 4.5°C). A long-term monitoring investigation from March 1995 to August 1996 was initiated to assess the effect of the addition of conditioned air on the building envelope. The investigation also included a thermographic survey of the exterior of the building and an air leakage test of the entire building. This paper describes the instrumentation used in the monitoring program and examples of results.

Building Description

The house, built in 1878, is a three storey building with an uninsulated full basement. A two storey wing at the rear was added later. Major renovations were carried out in 1922. The total floor area is about 650 m^2 (not including the basement). The first and second storey exterior walls are load bearing solid brick walls (330 mm thick), the third storey is enclosed by a wood frame mansard roof with the sides covered with slate tiles. The roof is insulated to approximately RSI-4.4 (R-25). All walls are finished with lath and plaster on the interior. Windows are either single-glazed, double hung wood frame windows with single-glazed wood frame storm windows on the exterior; or leaded, single-glazed metal casement windows with single-glazed wood frame storm windows on the interior.

The HVAC system consists of two air-cooled indoor air-conditioning units (20 ton refrigeration total capacity), an electric reheat coil (21 kW capacity), and four electrode steam humidifiers (42 kg/h total capacity). The humidifiers are controlled by a duct humidistat. One system serves the ground floor and the southern parts of the second and third floors. The other serves the northern parts of the second and third floors. In winter, the HVAC system provides ventilation but heating is provided by existing perimeter hot water radiators with individual thermostats.

Instrumentation

Four wall sections, the attic, two foyers, a window, and an outdoor location on the site were chosen to be instrumented. Figure 2 shows cross-sections of the walls monitored and the location of the instrumentation. The window selected was a leaded single-glazed metal frame casement window (glass 6 mm thick; the storm window was absent during the monitoring because of maintenance). The window is located in the east wall of the dining room on the first floor. The preliminary study showed severe condensation was possible on the same window. The wall sections instrumented were the east wall in the drawing room on the first floor, the north wall in the dining room on the first floor, the west wall in "Mr. King's" bedroom on the second floor, and the north knee-wall on the third floor. Figure 3 shows the locations monitored on the first and second floors.

The monitoring sites were chosen from openings for previous inspection. The openings in the walls were reconstructed after the instrumentation. One exception was the north wall in the dining room, which was instrumented through an existing electric outlet. The north-facing section of the attic (over mechanical room), the first floor foyer, and the second floor foyer were also instrumented. The parameters monitored were temperature, relative humidity, wetting-drying cycles on wall surfaces, and air pressure differential across the wall. The exterior air temperature and relative humidity were also monitored about 5 m to the east of the building at 2 m height.

Temperature: Temperature was measured using type T thermocouples (calibrated to ±0.1°C). The thermocouple wire was shielded to reduce any electrical noise caused by extensive alarm systems. For surface temperatures, the thermocouples were bonded with epoxy to the surface and covered with cloth construction tape. The thermocouple measuring exterior air temperature was protected from solar radiation by a radiation shield.

Relative humidity: Polymer relative humidity (RH) sensors were used (specified accuracy ±1% and ±2%). The calibration of the RH sensors were confirmed using saturated salt solutions in a small temperature-controlled environmental chamber.

Air pressure: Pressure transducers with two ranges were used: ±250 Pa for wall cavity-to-indoor air pressure differential and ±625 Pa for outdoor-to-indoor air pressure differential. The specified accuracy of the transducers is ±0.14% of full scale. The transducers were calibrated using a forced-balance calibrator to better than 1 Pa.

To avoid drilling through the window frames, a 3.2 mm copper tube (1.5 mm I.D.) was installed between the shutter and the window frame. Nylon tubing (6 mm I.D.) connected the copper tube to the pressure transducer placed indoors.

Moisture: Wetting-drying cycles were measured using two resistance-type moisture sensors: small ceramic blocks and conductive pins. Ceramic sensors were constructed of two wires fastened with conductive epoxy to opposite sides of a 5 mm thick block cut from a clay brick (size approximately 19 x 10 x 5 mm). They were attached with epoxy to the surface of the lath or the brick wall. When the sensor absorbs moisture, its electrical resistance drops. Results are presented in terms of conductance and are referred to as wetness (wetness = 800 / R, where R is sensor output in MΩ). The scale is arbitrary; it is only intended to show wetting and drying cycles.

The pin sensors consist of two insulated commercial moisture pins (2.4 mm diameter, 53.4 mm long). The pins were driven 10 mm deep, 25 mm apart, into the wood sheathing. The electric resistance between the 4 mm uninsulated tips of the two pins gives an indication of the moisture content. Moisture pins can determine the moisture content of wood to within 2% if corrected for wood species and temperature.

Data acquisition system: The sensors were connected to a data acquisition system. The system automatically sampled and stored the output from every sensor once a minute. In addition, the data were averaged and saved every 10 minutes and every hour. In-house software was written to provide the output data. No pre-screening of the data was done prior to averaging.

Measurement Results

Air leakage

The equivalent leakage area of the building was determined[4] to be 1.34 m^2 at 10 Pa (approximately 14 cm^2/m^2 normalized leakage area, i.e. 0.14% of envelope area). Indoor air temperature at the time of the test (Oct. 17, 1994) was 23°C. Outdoor air temperature was 16°C. Weather records showed the average hourly wind speed was 0 to 7 km/h. The building has a normalized leakage area at least twice that of pre-1945 houses surveyed in Saskatoon [see p 34 ref. 6].

A thermographic survey indicated that most of the leakage occurred at the top of the mansard roof (attic space and dormer); no other large leaks were observed. The thermographic survey of the building was conducted in the evening following the air leakage test; the building could only be pressurized to 6 Pa above the outdoor air pressure due to the leakiness of the building.

Air pressure

The indoor air pressures (hourly averages) were below the outdoor air pressure at the locations monitored (for example, during December 1995, the outdoor pressures were 7.7 Pa & 2.5 Pa higher for the first and second floors respectively, Fig. 4). The air pressure in the wall cavity was also higher than indoor air pressure (during December 1995, the mean cavity pressures were 2 Pa & 0.6 Pa higher for the first & second floors respectively). The negative indoor air pressures essentially eliminated the

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4 Standard CAN/CGSB-149.10-M86, *Determination of the airtightness of building envelopes by the fan depressurization method.*

leakage of the humid indoor air into the wall cavities and thus eliminated the potential for condensation on colder cavity surfaces. On the other hand, cold exterior air travelled through wall spaces, ceiling spaces and openings in the interior surfaces. This caused localized cold spots and ice formation on interior surfaces in several areas including walls and ceilings that have connection to the outdoors. This led to condensation and crack development. The latter was probably caused by dimensional changes due to changes in moisture content and temperature of the wall and ceiling materials.

The small diameter copper tubing of the pressure sensor leading to the outside was sometimes blocked by water during wet periods or by dew. This led to inconclusive high pressure readings between indoors and outdoors. False data was discarded. In future, a large diameter fitting should be attached to the end of the tube to stop capillary action and shed water.

Thermal performance

Indoor temperatures: During the summer, indoor air temperatures varied between 13°C and 22°C. Figure 5 shows that indoor air temperatures frequently dropped to 13°C during the night and rose to over 20°C the following morning. The figure also shows that indoor air temperatures tend to follow the diurnal variations in outdoor air temperature with a lag of about 12 h. This suggests that the HVAC system, which operated continuously, had limited control of indoor air temperatures especially during the summer. During the winter the variation was small (typically 20 to 23°C; Fig. 6) because the radiators had individual thermostats.

Wall-cavity: The variation in the surface temperatures of the brick and the lath within the wall cavities (air spaces in the walls) generally followed the daily average of the outdoor air temperature partly due to the damping effect of the thermal mass of the masonry wall (Figs. 5 & 6). The variations of surface temperatures in the east wall-cavity were less than those for the west wall-cavity surfaces. This is because the east wall is shaded by a neighbouring highrise building and a large tree. In addition, a west wall normally receives more sun than an east wall.

Attic space: Figure 7 shows the variation of temperature in the attic space above the third floor mechanical room during winter and summer. Solar heat caused a large increase in the roof sheathing and attic air temperature in the summer. In winter the roof sheathing and air temperature were more stable and were usually much higher than the outdoor air temperature (15-20°C higher; the temperature only approached the exterior temperature on windy days). This indicates a large heat loss into the attic space with the major part probably caused by air leakage. This also explains the ice-damming which is a problem on this building.

Moisture performance

Indoor air: The RH of the indoor air varied from room to room and also from month to month (Table 1). It far exceeded specified indoor conditions. The variation in RH during August was partially due to the large variation in indoor air temperatures. Figure 8 shows that variation in indoor air dew-point during August had a diurnal variation similar to the outdoor air dew-point (the dew-point is representative of the moisture in the air). Measured RH during the summer shows that the HVAC system did not adequately control the relative humidity. Possible causes may include improper operation, location, or type of the humidistat; faulty controller operation; or insufficient dehumidification capacity of the HVAC system.

Table 1 Variation in Relative Humidity

	Dining Room		Foyer		Bedroom	
	Min	Max	Min	Max	Min	Max
August '95	42	76	39	73	38	80
November '95	34	50	27	51	28	43
January '96	21	50	19	49	22	44

Wall cavity: The RH in the wall-cavity exceeded 60%. Figure 8 shows little variation in the cavity air dew-point during the summer while in winter it followed the variation in outdoor air dew-point. The results also indicate that, during summer, the brick is drying into the cavity air which led to higher dew-point in the cavity than in the indoor air.

Attic space: The variation of the RH in the attic followed the diurnal variation of the outdoor air with a time lag in both winter and summer. It reached up to 89%. The dew-point of attic air was 0 to 8°C higher than outdoor air.

Windows: Extensive condensation and ice buildup was observed on the single-glazed window during the winter months. The surface temperature of the single-glazed window in the dining room dropped below the dew-point for several days during November and for most of January (Fig. 9). Water stains and wood swelling were evident on the sill of the dining room window.

Wetting-drying cycles

Exterior surface: The data from ceramic moisture sensors mounted on the exterior surfaces showed periods of wetting during precipitation (Figs. 10 and 11). They dried out within 6 to 36 hours from the onset of precipitation.

Wall cavity and attic space: No condensation was detected within the air spaces of the walls at the locations monitored. The surface temperature of the brick and the lath within the wall-cavities was always higher than the dew-point of the cavity air. The ceramic and moisture pin sensors within the wall cavity indicated that no wetting occurred on the masonry interior surface or the lath (Figs. 10 and 11).

The temperature of the wood sheathing of the attic roof was usually higher than the dew-point of the attic air. However, on one occasion, in January 1996, the ceramic moisture sensor indicated surface wetting of the roof sheathing because of condensation. The temperature of the roof sheathing in the attic dropped about 1°C below the dew-point at about 6 a.m. The ceramic sensor dried out about 11 hours later. The moisture pins, inserted in the sheathing, indicated that moisture from the condensation was insufficient to affect the sensor at a depth greater than 6 mm.

The RH sensor in the cavity of the north knee-wall indicated excessive humidity, about 100% RH, within the wall-cavity on January 30, 1996. Examination of the knee-wall cavity indicated ice damming on the roof had caused water to leak through a crack in the roof slate, through torn roofing paper and a cutaway in the roof sheathing. As a result, monitoring of this wall section was terminated part-way through the monitoring program pending repair of the roof defect. This indicates the usefulness of sensors in critical areas to detect hidden problems before serious damage can occur.

Conclusions

The first two floors of the house, under low wind conditions, were operating most of the time under a negative air pressure with respect to the outdoor air pressure. As a result, cold-air infiltration through wall partitions and ceiling spaces caused localized cold spots and ice forming on the interior of walls and ceiling.

The results also indicated that the brick walls are unlikely to experience internal condensation problems as long as the walls are subjected to a negative air pressure. However, because the building is quite leaky, the negative pressure created other surface condensation problems. Negative pressures are not a solution unless the size of the leakage paths are reduced (between the roof, ceiling spaces and walls). Air leakage at roof and dormer levels must be addressed.

The windows require immediate attention. The high indoor humidity has caused excessive condensation on the windows. To reduce the adverse effect of condensation on the durability of the windows, the thermal performance and air tightness of the windows should be improved. Thermal performance could be improved by using double glazed storm windows. In this way the historic value of the windows would be least affected. The original storm windows can be kept in storage.

The relative humidity of the indoor air varied considerably from room to room and also from month to month. It reached up to 80%. This large variation in humidity is not desirable for the preservation of the historical artifacts. A complete review of the HVAC system is required. Factors to consider include the location of the RH control sensor, ensuring it controls the dew-point, and checking its calibration and operation. Also check the de-humidification capacity of the HVAC system. After the HVAC is modified and air leakage at roof and dormers is addressed, it will be necessary to monitor the building envelope again. The HVAC system should also be monitored.

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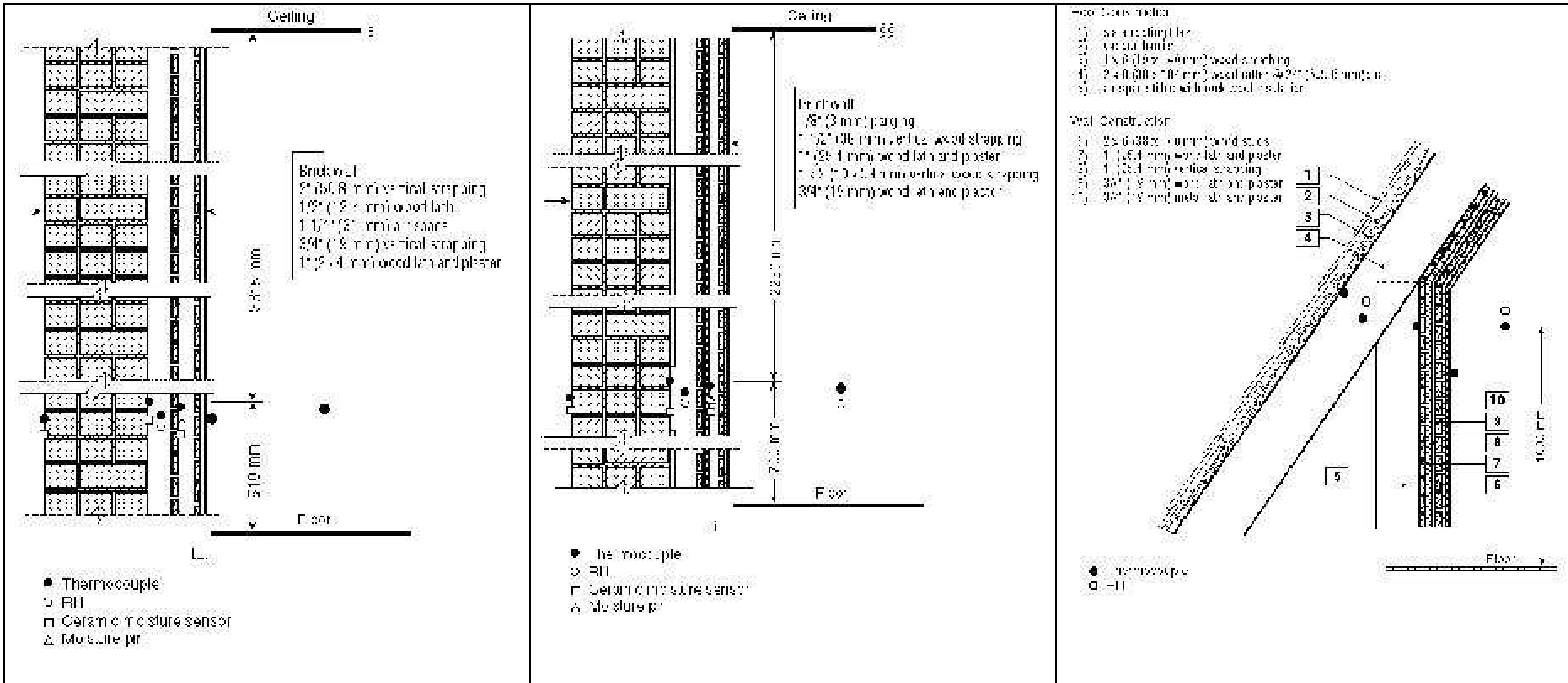


a) East wall (Drawing room), 1st floor

b) West wall (Mr. King's Bedroom), 2nd floor

c) North knee-wall/mansard roof, 3rd floor

(RH : relative humidity)

Figure 2. Sections through monitored walls on 1st, 2nd and 3rd floors showing instrumentation

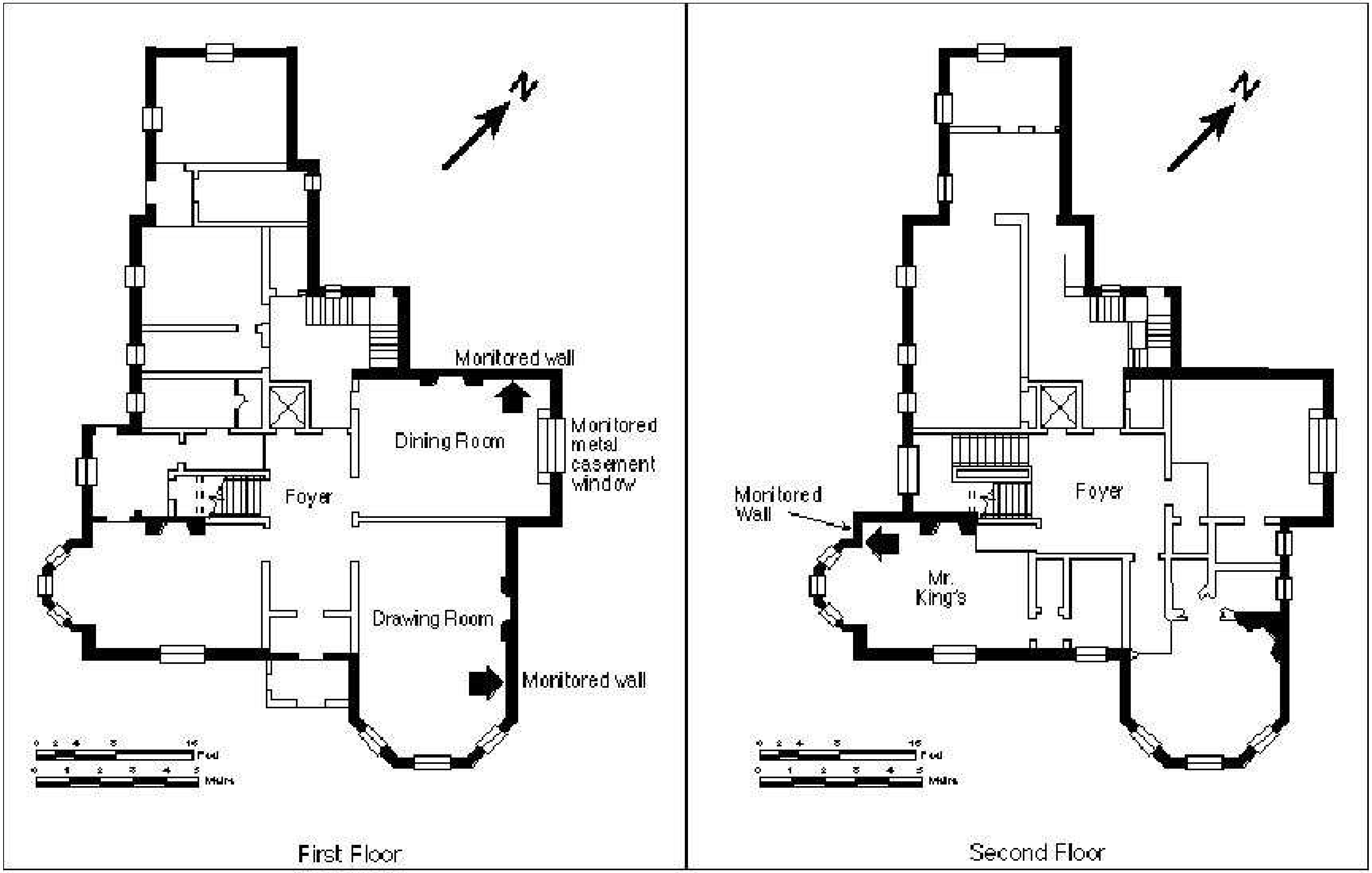
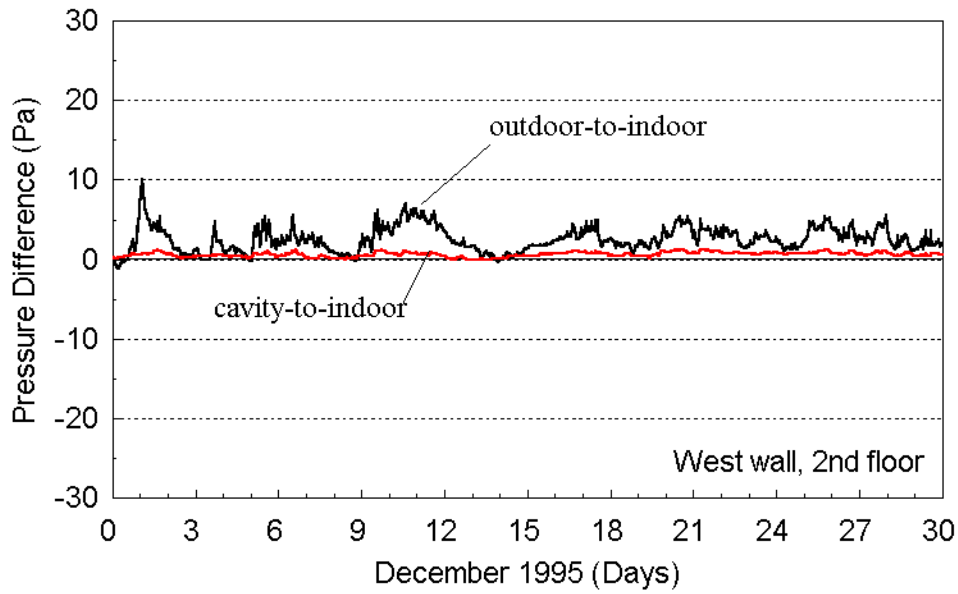
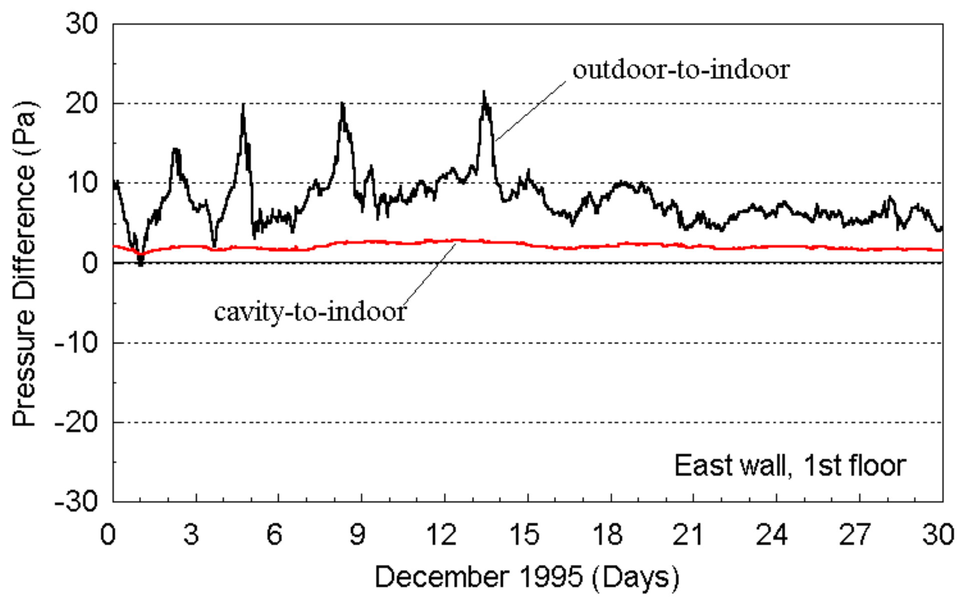


Figure 3. Plan of first and second floors of monitored house showing the location of monitoring sites

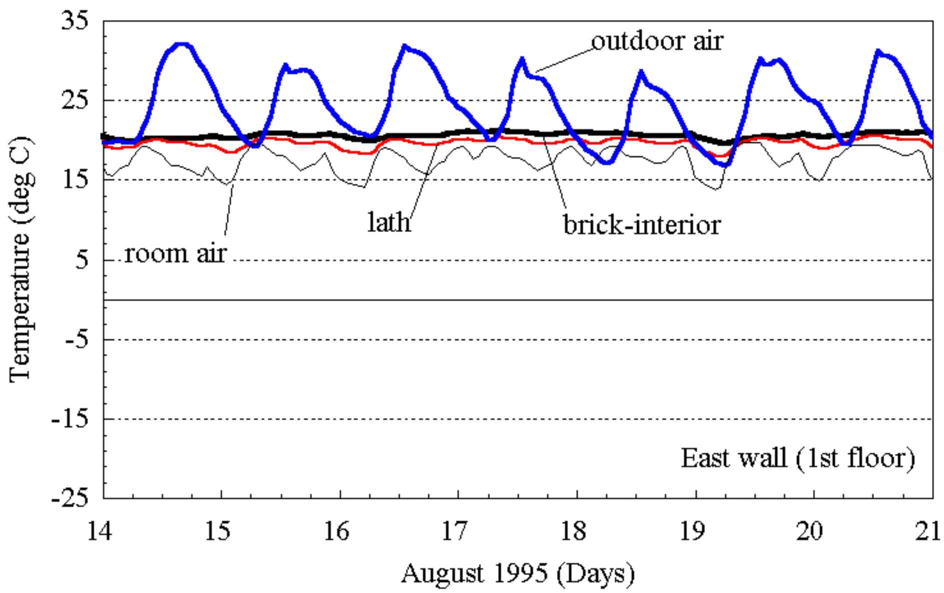


West wall, 2nd floor (Mr. King's Bedroom)

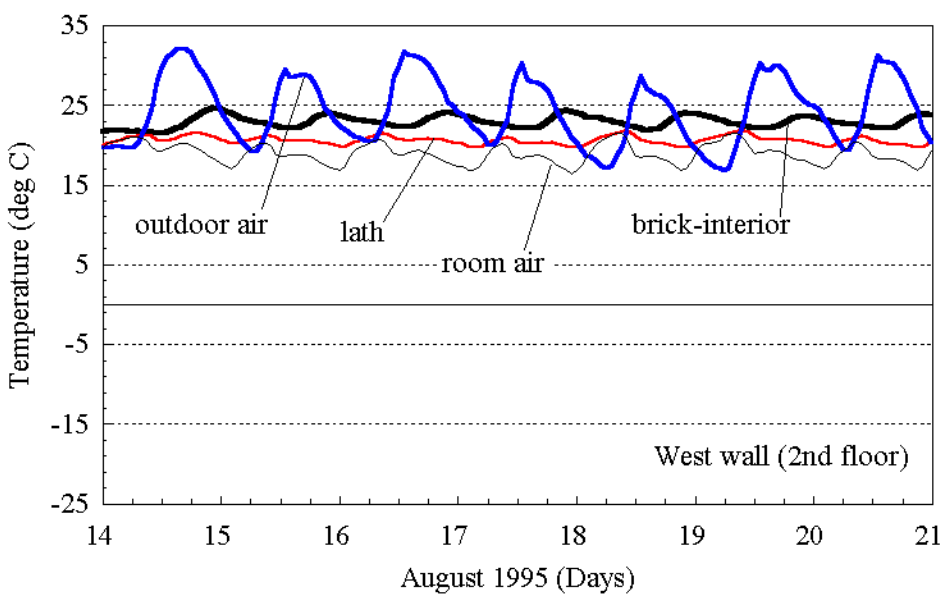


East wall, 1st floor (Drawing room)

Figure 4. Pressure differential, outdoor-to-indoor and wall cavity-to-indoor, December 1995.

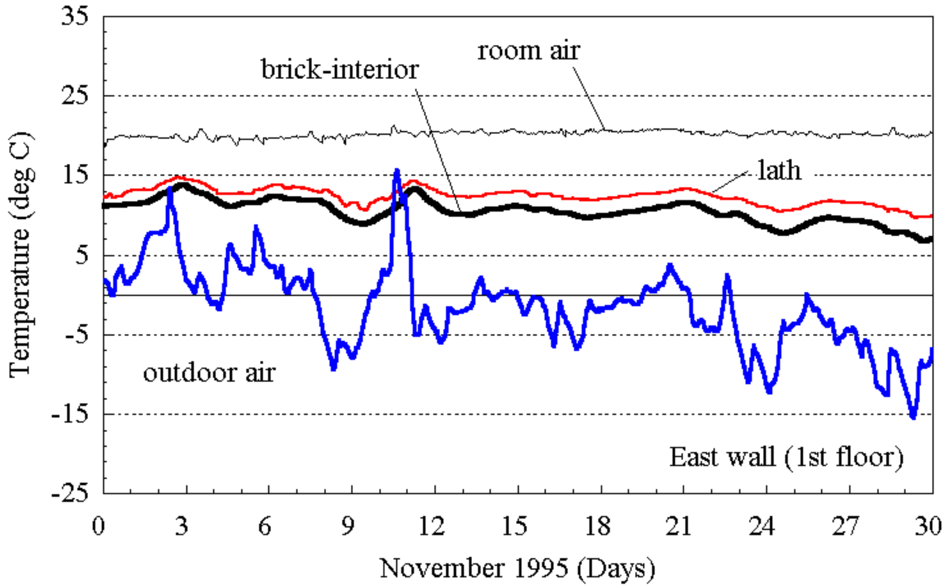


East wall, 1st floor (Drawing room)

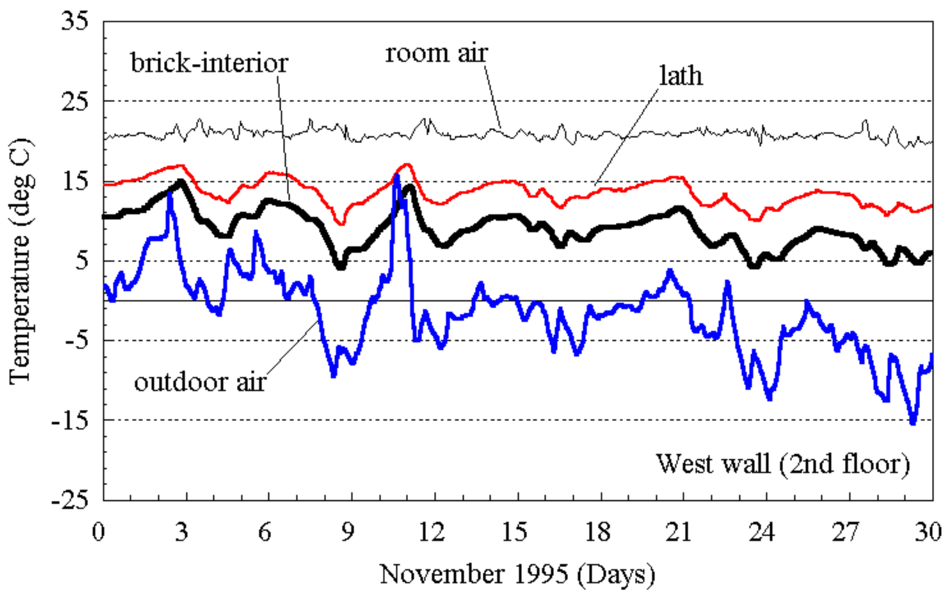


West wall, 2nd floor (Mr. King's Bedroom)

Figure 5. Temperatures of brick interior surface and intermediate lath within wall cavities and indoor and outdoor air, for selected periods in August 1995.

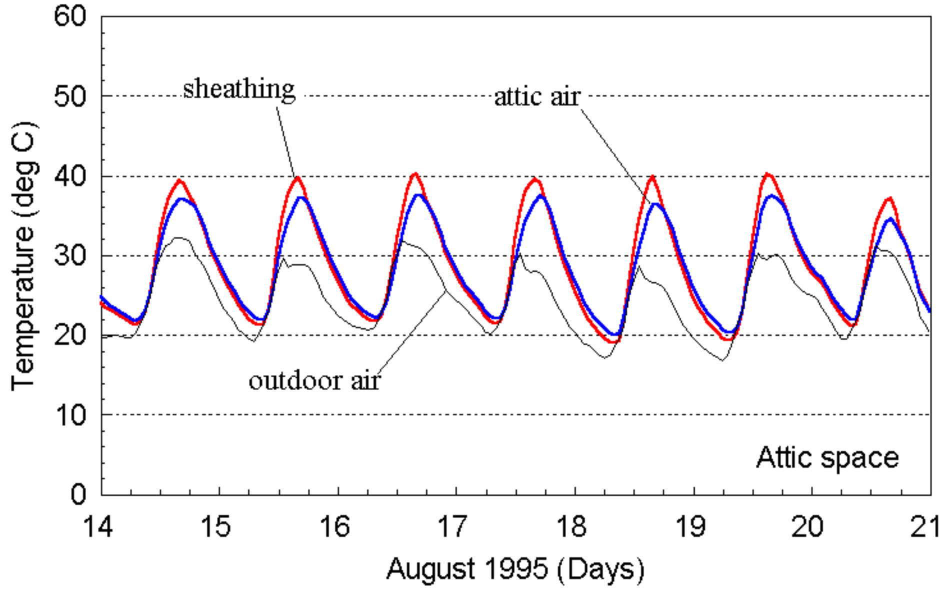


East wall, 1st floor (Drawing room)



West wall, 2nd floor (Mr. King's Bedroom)

Figure 6. Temperatures of brick interior surface and intermediate lath within wall cavities and indoor and outdoor air, November 1995.



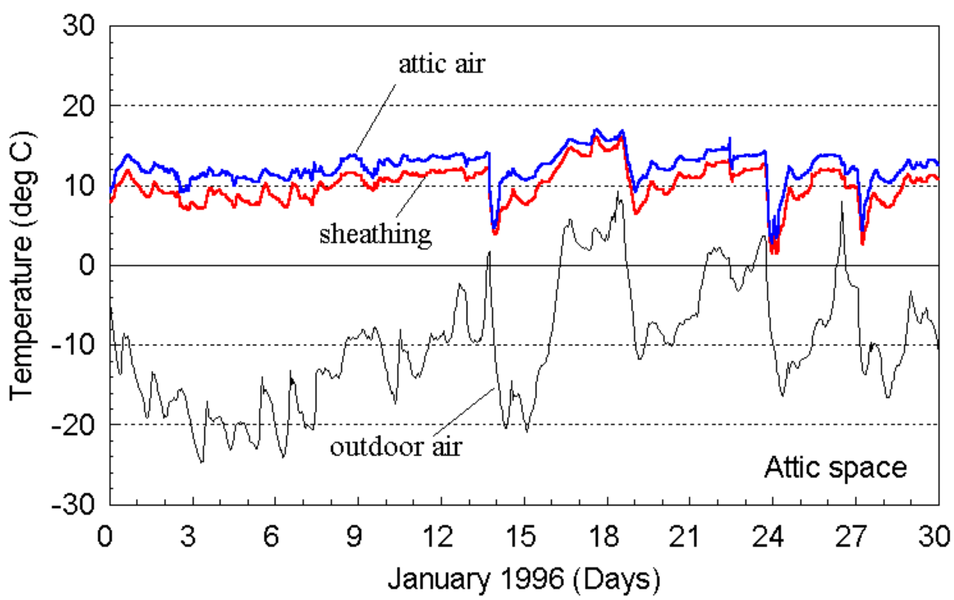
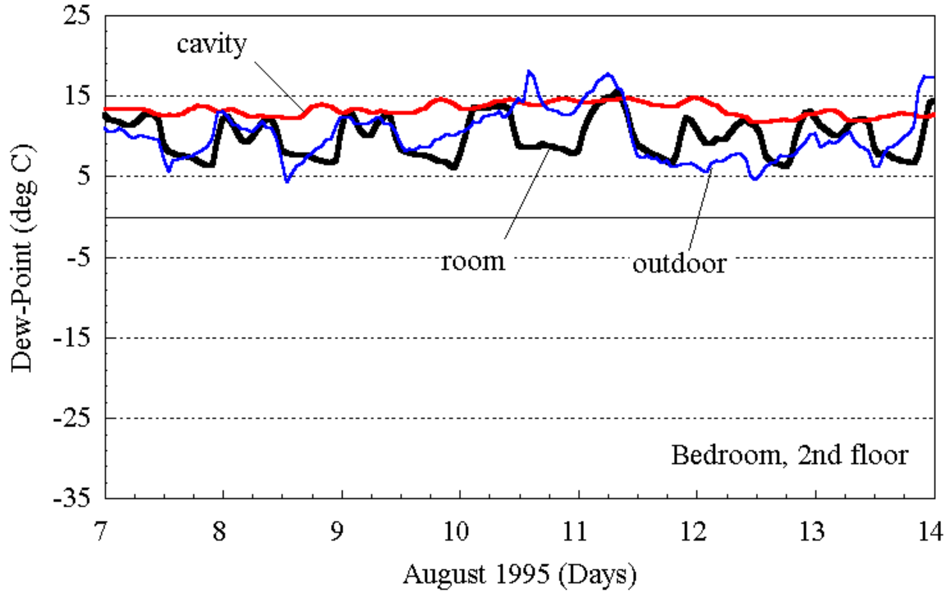


Figure 7. Temperatures of roof sheathing, attic air and outdoor air, for selected periods in August 1995 and in January 1996.


25
15
5
-5
-15
-25
-35
Dew-Point (deg C)
cavity
room
outdoor
Bedroom, 2nd floor
7
8
9
10
11
12
13
14
August 1995 (Days)

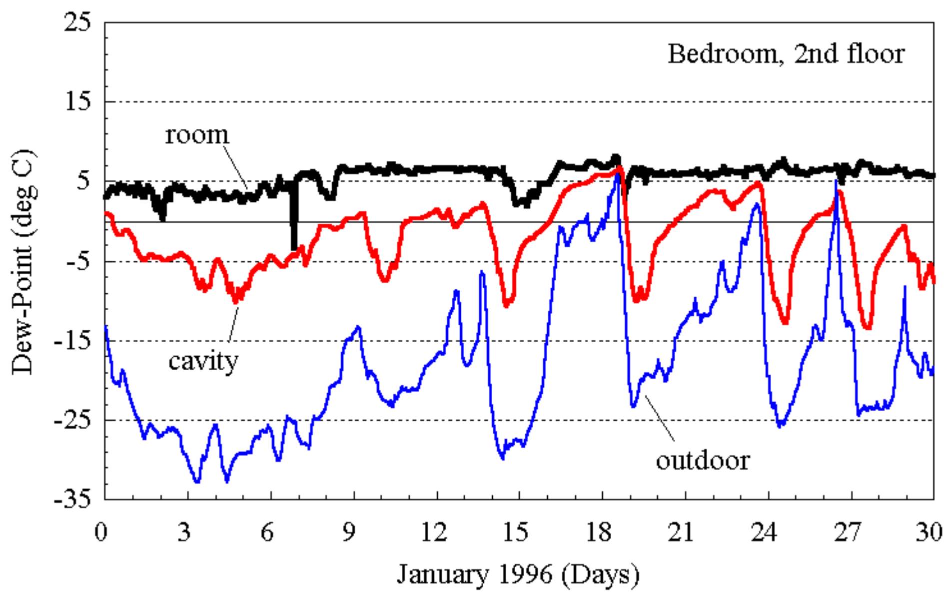
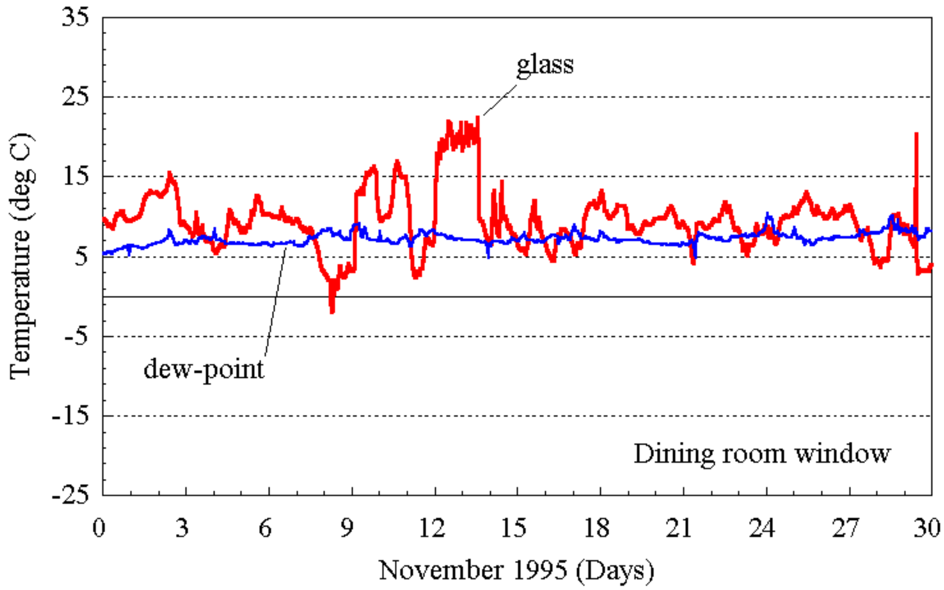

25
15
5
-5
-15
-25
-35
Dew-Point (deg C)
Bedroom, 2nd floor
room
cavity
outdoor
0
3
6
9
12
15
18
21
24
27
30
January 1996 (Days)

Figure 8. Dew-point of room air, wall cavity air and outdoor air, Mr. King's Bedroom (west wall, 2nd floor), for selected periods in August 1995 and in January 1996.



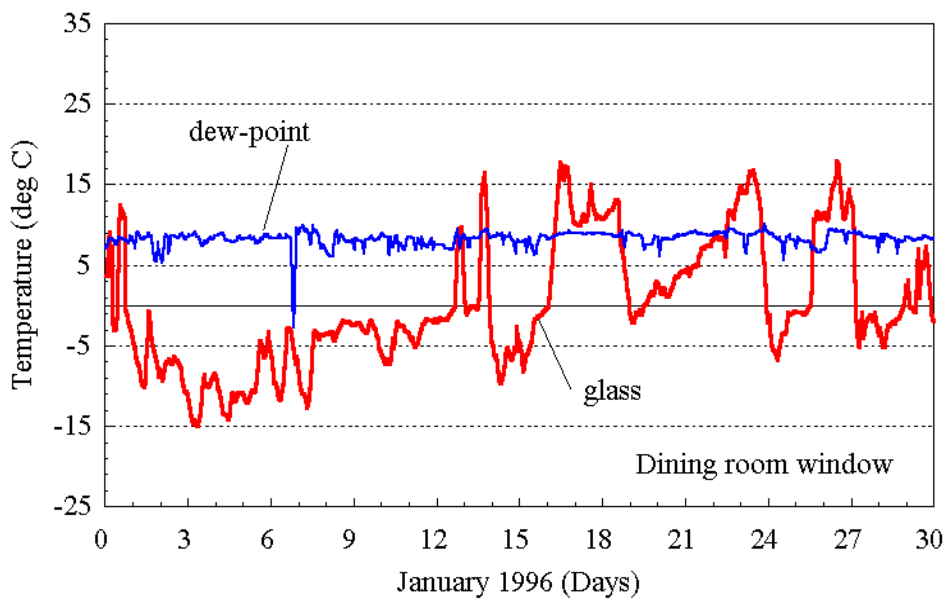


Figure 9. Temperatures of dining room window glass (single-glazed) and dew-point of indoor air, November 1995 and January 1996.

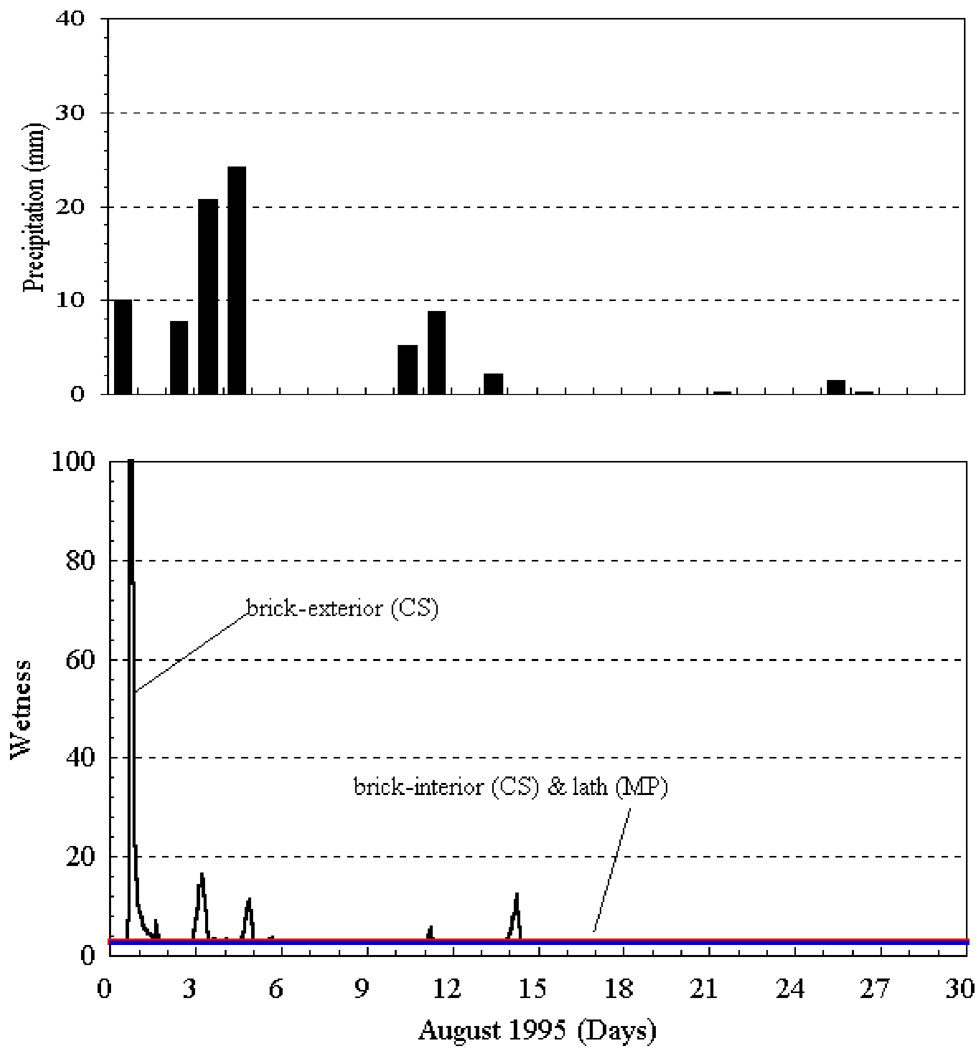


Figure 10 Wetting-drying cycles during August 1995 on the west wall of Mr. King's bedroom, 2nd floor. Wetness detected on exterior only. The scale for wetness is arbitrary. The top graph shows precipitation measured at Ottawa airport (source: Environment Canada). CS = ceramic sensor; MP = moisture pins.

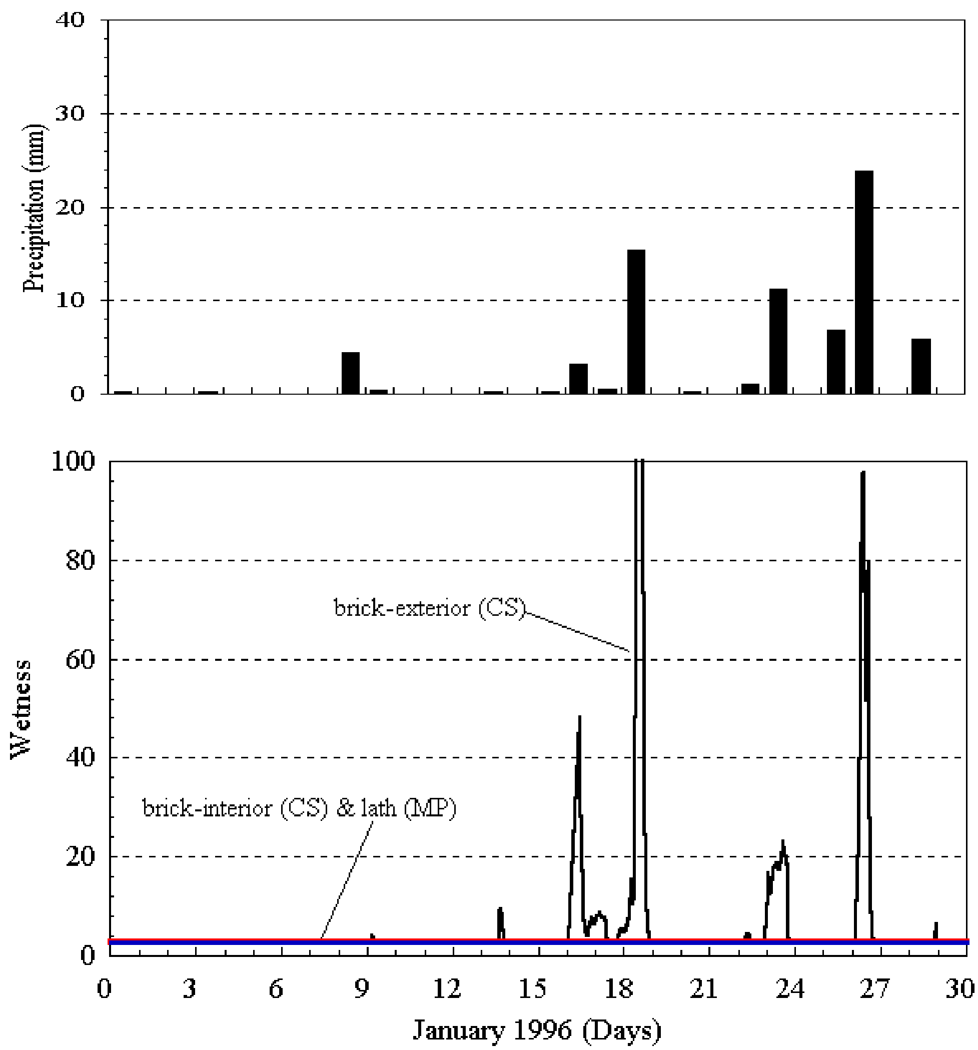


Figure 11 Wetting-drying cycles during January 1996 on the west wall of Mr. King's bedroom, 2nd floor. Wetness detected on the exterior only. The scale for wetness is arbitrary. The top graph shows precipitation measured at Ottawa airport (source: Environment Canada). CS = ceramic sensor; MP = moisture pins.