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Forensic Engineering Analysis of an Apartment Freezing Sequence Using Heat Flow Equations

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Abstract

Four students had staggered departures from their electrically heated third-floor shared residence apartment to travel home for the winter holiday break. Two pipe bursts and two frozen toilets were discovered a week after the last resident had left. The property management group gathered scene evidence and analyzed the cause of the water escape. The investigation revealed that some electric heaters had been turned off, and some bedroom and living room windows were open. A forensic engineering analysis was conducted to qualitatively determine the effects of heater disengagement and open window positions on the apartment temperature drop and to estimate the likely start date of sub-zero Celsius conditions. Heat flow and balance equations for different sets of factors were used to quantitatively assess the instantaneous heat flow trends as the basis for understanding whether certain students carried more burden of liability. The analysis revealed that the open windows were the dominant factor for the freeze-up condition development that led to the bursts.

Keywords

Heat balance, instantaneous heat flux, electrical heating, pipe freeze time, pipe burst, toilet freeze time, open window heat convection, room heat loss, forensic engineering

Introduction

A water supply pipe burst in the kitchen of an upper-floor apartment suite of a student residence (**Figure 1**) of a university in southeastern Ontario on or about December 30, 2009, resulting in subsequent significant water damage.

Investigation

The author was engaged to evaluate the circumstances and time sequence of the pipe freeze-up incident. The site had long since been repaired at the time of engagement such that there was no opportunity to inspect and confirm the original conditions. A series of photographic prints taken on December 30, 2009 at the site (as well as reports with opinions formulated by other engineers) was provided for review by the author. All company names and resident names have been obscured to respect conditions of confidentiality.

Suite Configuration

The plan view of Suite 36 showed a living room, dining room, four bedrooms, two washrooms (one with a shower/tub), central kitchen, and storage room. It was configured with a connecting wall to another suite on the longer living room wall and dining room side adjacent to the door. The relative dimensions of the rooms are laid out approximately in **Figure 2**. The living room and dining room had large windows, and every bedroom had a moderately sized window. The bathrooms each had a small window.

The rooms were heated with baseboards powered by electricity. The details of heating methods and the names

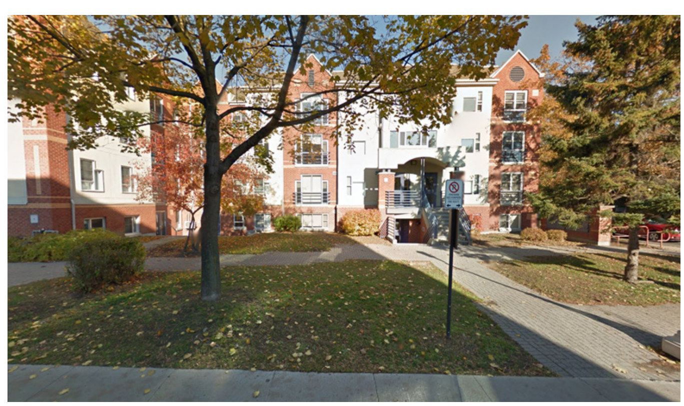

Figure 1
South elevation of University residence apartment block.

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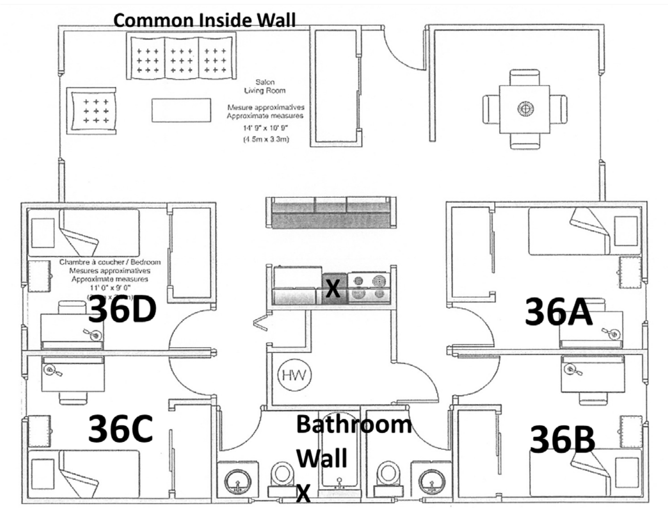

Figure 2
Suite plan showing where the pipes split (marked as X).

of their occupants were (counting clockwise from above left in the suite plan):

- Dining room — 1,750 watts (W) (6,000 BTU/h) electric baseboard, with a thermostat;
- Living room — 1,500W (5,100 BTU/h) baseboard, controlled by the dining room thermostat;
- Bedroom 36A (Allan) — 1,000W (3,400 BTU/h) baseboard, with a thermostat;
- Bedroom 36B (Bob) — 1,250W (4,260 BTU/h) baseboard, with a thermostat;
- Bathroom 1 — 300W (1,000 BTU/h) baseboard with a thermostat;
- Bathroom 2 with shower/tub — 300W (1,000 BTU/h) baseboard with a thermostat.
- Bedroom 36C (Charlie) — 1,250W (4,260 BTU/h) baseboard, with a thermostat; and
- Bedroom 36D (Dave) — 1,000W (3,400 BTU/h) baseboard, with a thermostat.

The total available heating power in Suite 36 was 8,350W (28,500 BTU/h).

Origins of the Water Escape

Based on the site photographs, one origin of the water escape was on the upstream side of the yellow-handled shut-off valve in the hot water copper supply line below the kitchen sink. **Figure 3** depicts a longitudinal split in the pipe adjacent to the soldered joint with the valve as well as a second short piece of pipe with a similar longitudinal split taken from behind the drywall in the exterior wall cavity behind a toilet. The short piece was assumed to be the second origin.

The water in the toilet tank and the bowl of both bathrooms had frozen with one tank shown in **Figure 4**. The float was immobilized in ice and the overflow pipe displaced. The interior wall of this tank was insulated with white closed-cell polystyrene with a smooth skin surface.

Door, Window, and Thermostat Positions

The status of the windows and heating devices on December 30, 2009 was generally confirmed during the examinations for discovery, in which principal parties to litigation were questioned under oath.

- The windows of the dining room and living room

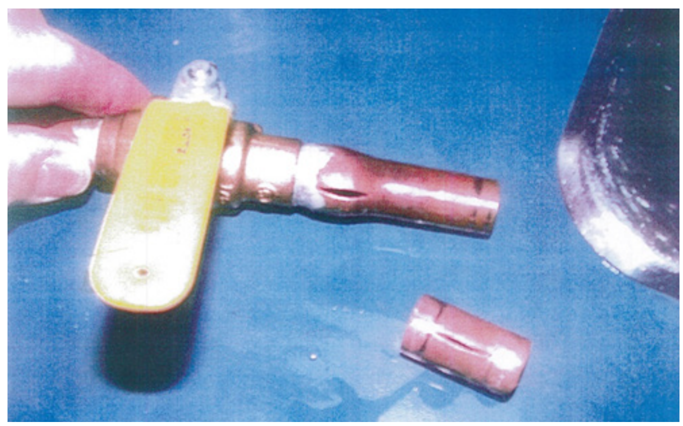

Figure 3
The two longitudinal splits in water supply pipes.

Figure 4
One of two toilet tanks with ice formation.

were open;

- Room 36C had its thermostat turned off and the window in open position with the door closed;

- Room 36D had its thermostat turned off and the window in open position with the door closed;

- The positions of doors, windows, and thermostats elsewhere were not remarked in the security or emergency response records; and

- No suite temperature measurements were taken by university security personnel at the time of the water escape.

Time line

From the examinations for discovery transcripts, the following sequence was established:

- Charlie had left the apartment on December 19, closed his door, left the thermostat in the off position, and opened the window in Room 36C;

- Allan had left the apartment on December 20. There was no evidence that he left the thermostat off or the window open in Room 36A;

- Bob left the apartment on December 23 at 10 or 11 a.m., and there was no evidence that he left the thermostat off or the window open in Room 36B;

- Dave and Bob opened the windows in the living room and dining room on the morning of December 23, prior to Bob's departure;

- Bob stated that he had closed these windows prior to leaving;

- Dave was the last to leave (at 3 a.m. on December 24), and had closed his door/left the thermostat in the off position and the window open in Room 36D;

- Dave claims not to have looked to see if the windows in the living room and dining room were open or closed when he left.

Considerations & Assumptions

The following factors and assumptions were made, in part due to the limited site access:

1. For construction, the exterior walls of the unit had typical drywall and brick construction dimensions, the interior walls of the suite were made with typical wood stud and drywall techniques, the ceiling was formed of drywall backed by insulation leading to an unheated attic, and one full interior wall (along the living room and dining room by the suite's entrance door) was not exposed to the exterior;

2. The rooms had 2.5-meter-high (8-foot-high) ceilings and dimensions shown in **Figures 5a** and **5b**. The windows of the suite were about 9 meters (29.5 feet) above grade;

3. The minimum internal temperature of a room with a window open was the exterior temperature. Once a room equilibrated with the exterior temperature, the room tracked the exterior efficiently

Room	Outside Wall Height (m)	Outside Wall Width (m)	Outside Wall Area (m^2)	Glazed Area (m^2)	Actual Wall Area (m^2)	Ceiling Area (m^2)
Living	2.5	3.5	8.75	3.24	5.51	15.75
Dining	2.5	3.5	8.75	3.24	5.51	19.25
36A	2.5	2.8	7.00	1.35	5.65	9.18
36B	2.5	6.2	15.5	1.35	14.15	9.18
36C	2.5	6.2	15.5	1.35	14.15	9.18
36D	2.5	2.8	7.00	1.35	5.65	9.18
Bath 1	2.5	1.6	4.00	0.4	3.60	6.6
Bath 2	2.5	3.2	8.00	0.4	7.60	3.2

Figure 5a
Estimated wall, glazed and ceiling areas for the rooms (metric).

Room	Outside Wall Height (ft)	Outside Wall Width (ft)	Outside Wall Area (sq ft)	Glazed Area (sq ft)	Actual Wall Area (sq ft)	Ceiling Area (sq ft)
Living	8.2	11.5	94	34.9	59.3	169.5
Dining	8.2	11.5	94	34.9	59.3	207.2
36A	8.2	9.2	75.3	14.5	60.8	98.8
36B	8.2	20.3	166.8	14.5	152.3	98.8
36C	8.2	20.3	166.8	14.5	152.3	98.8
36D	8.2	9.2	75.3	14.5	60.8	98.8
Bath 1	8.2	5.3	43	4.3	38.7	71
Bath 2	8.2	10.5	86	4.3	81.8	34.4

Figure 5b
Estimated wall, glazed and ceiling areas for the rooms (U.S. customary).

with only a minor lag when the exterior temperature changed;

4. Air will flow underneath closed bedroom doors, and this air will be at exterior temperatures once the room has equilibrated;

5. The interior wall of a room with an open window acted as an unheated exterior wall for the remainder of the suite;

6. All kitchen ventilation fans and bathroom fans were off;

7. The baseboard heaters were either fully on or fully off based on typical models. When the non-programmable thermostats were set to “off” in the narrative, that meant the units were unpowered rather than set to a minimum heating value such as 5°C (41°F);

8. Electrical power was available at all times to Suite 36;

9. Toilet tanks were porcelain ceramic with a polystyrene liner, which insulated against heat loss such that water in the tank took much longer to freeze than water in exposed copper pipes;

10. At least 25 mm (1 inch) of ice had formed on the top of the toilet tank, and the same thickness had formed within the bowl;

11. External conditions were represented by Heating-Degree-Day values obtained from International Airport and the Experimental Farm records for December 2009, and the daily outside mean temperature profile for the period[1] was that in **Figure 6**.

Analysis

Nature of the Pipe Bursts

Two sections of copper pipe with longitudinal splits within bulged areas were found at the scene. The splits were caused by localized pipe freeze-up events under the sink in the kitchen in the center of the apartment and in the exterior wall behind one of the bathrooms.

Both were created when locally formed ice fronts within the pipes trapped pockets of water. The mechanism of failure has to do with the water rather than the ice. The trapped water is incompressible, such that as the available volume shrinks, the pressure in the pocket increases past the yield point stress of the copper tube, initiating the permanent bulge deformation pattern and finally causing the longitudinal split. Recent experiments have shown that

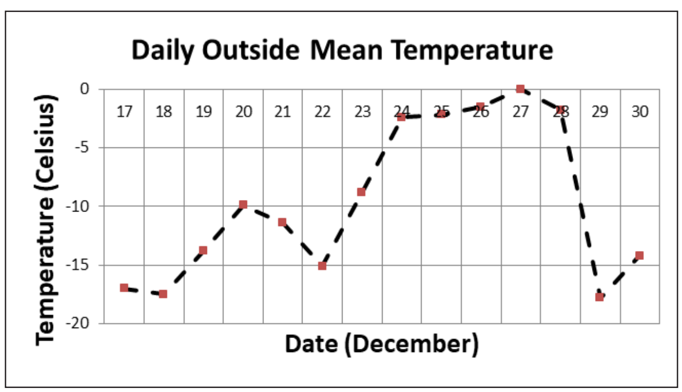

Figure 6
Daily outside mean temperature from Environment Canada, December 2009.

pressures in excess of 7,500 p.s.i. are needed to burst 12 mm (½-inch) diameter copper tubes[2]. Such pressures are not found in a domestic water supply in regular operation.

Consideration of the Requirements to Freeze the Toilet Tank

The time required to create 25 mm (1 inch) of ice on the top of the toilet tank in the bathroom was estimated from first principles. A standard toilet tank, measuring 200 by 300 by 500 mm (7.9 by11.8 by 19.7 inch), would have an approximate volume of 0.03 cubic meters (30 liters) (1835 cubic inches) and a ceramic surface area of 0.52 square meters (5.6 sq.ft).

The well-known steady state heat flow formula,

$$q / A = U \; x \; ((t(i) - t(o)) \qquad \text{EQ. 1}$$

derives q/A, in which q is the heat in Watts and A is the square area in metres across which the heat flows (from hot to cold), according to thermodynamic laws. The other side of the equation involves U, the overall coefficient of heat transmission, multiplied the difference between two temperatures, t(i) inside and t(o) outside, which drives the flow. U is calculated with the sum of the reciprocals of the conductance values, C:

where C_1, C_2, C_3 = conductance values for materials 1, 2, and 3 in a given wall

$$U = 1/C_1 + 1/C_2 + 1/C_3 + \ldots \qquad \text{EQ. 2}$$

Employing equation (1), with 1000 W/m^2-K (176 BTU/h-ft^2-°F) for porcelain and 1.8 W/m^2-K (0.317 BTU/h-ft^2-°F) for styrofoam, the author determined a value of q of 11.5W (39 BTU/h).

For a temperature decrease from 5°C to -1°C (41°F to 30°F), and a 2.5 liter volume (0.66 US gallon) of ice weighing 2.5 kg (5.5 lb), 825 kiloJoules (778 BTU) are required to cool the water to 0°C (32°F) and 1,588 kiloJoules (1,498 BTU) to crystallize it under typical freezing conditions. In the context of the very slow cooling of the insulated tank, the calculated time to freeze a 25-mm (1 inch) thick top layer was 138,800 seconds, equivalent to 38 hours or about one and a half days. Supercooling and nucleation effects were ignored for this estimate

If this process started with 10°C (50°F) water, this time would increase to approximately 60 hours or two and a half days. The range for the freezing completion means that the initiation occurred from two and a half days to one and a half days prior to the tank inspection on December 30.

Suite 36 Heat Flow Snapshot Analysis Model — Case Descriptions

A system heat flow model of the suite was created to give a snapshot of conditions at a particular instant, based on assumptions about the construction of the exterior walls and windows. Sequential snapshots at the daily mean temperature gave insight into the heat flow trends, and were a proxy for the temperature trend of the suite — because no direct temperature measurements had been made at the time of the incident. The goal was to establish if the suite was cooling or not at the time of the snapshot.

The sources of heat gain within Unit 36 were the baseboard heaters set in the individual rooms, the common living room and dining room, and bathrooms. Heat gain from residents was not included. Heat loss would be through the external walls and upward through the ceiling, with some counteractive gain from the common wall with another apartment but very little from the concrete floor slab of the suite. Convection through windows was factored in. At any given time, the instantaneous heat balance could be estimated for a given HDD value. For single side wind impact on a building window, the airflow[3,4] is calculated by:

$$F = 3.6 \; x \; 500 \; x \; Aow \; x \; V^{1/2} \qquad \text{EQ. 3}$$

in which the following variables were applied:

$$V = C_t + C_w \; x \; V_{met}^2 + C_{st} \; x \; H_{window} \; x \; abs(T_i - T_e)$$

F (m^3/h): air flow

Aow (m^2): window opening area

C_t = 0.01: wind turbulence factor

C_w = 0.001: wind speed factor

C_{st} = 0.0035: stack effect factor

H_{window} (m): free area height

V_{met} (m/s): meteorological wind speed at 10 m height

T_i : room air temperature, °C

T_e: outdoor air temperature, °C

An estimate of the sensible heat required to bring outdoor winter air to room temperature given by the Energy Cost Formula[5]. Once the air flow is calculated for the snapshot conditions, the F value is substituted as follows:

$$H_s = F \; x \; \rho \; x \; C_p \; (T_i - T_o) \qquad \text{EQ. 4}$$

When further simplified for ρ of 1.20 kg/m3 and Cp of 1.005 kJ/kg, the equation becomes

$$H_s = 1.21 \times F\ (T_i - T_o) \qquad \text{EQ. 5}$$

in which F is the flow rate in L/s converted from equation (2) above.

Heat transmission coefficient values for different materials[5], were used to determine a blended number for the exterior and interior walls of the suite. For example, a U-value of 1.41 W/m^2-K (0.248 BTU/h-ft^2-°F) was derived for an exterior wall with a proportion of glazing, and a U-value of 1.04 W/m^2-K (0.183 BTU/h-ft^2-°F) was calculated for the ceilings.

Nine cases, encompassing possible configurations of the heat gain and loss for the system were set. The most extreme condition, an interior temperature of 18°C (64.4°F) and an exterior temperature of -21°C (-6°F), equivalent to a heating-degree-day (HDD) value of 39, was used to evaluate the regular case. The heat losses for the suite walls were 4,090W (14,000 BTU/h) and for the suite ceiling were 4,149W (14,150 BTU/h). For the listed heating capacity of the room as 8,350W (28,500 BTU/h), there would be a slight positive remainder of 111W (378 BTU/h), indicating that the suite would hold the 18°C (64.4°F) temperature. This confirmed that the assumptions were reasonable for a first principles assessment, with an acceptable range of error.

As the starting point for each case, the extreme condition heat balance was calculated, and then extended over the range of HDD values for the time period starting on December 17. In Cases 1 and 2 (see **Figure 7**), the baseboard heaters in Room 36D and Room 36C were turned off, to determine how this would change the heat flow patterns. Case 3 examined the consequences to heat flow of turning both heaters (36D and 36C) off.

To include the effects of opening windows, equations, including such factors as the height of the window above grade (assumed to be 9 meters, 29.5 feet), wind turbulence, stack effects, area of window opening and air flow volume, were used to calculate the heat flow through such an opening. The process was driven by the difference between room air temperature and outdoor air temperature.

For Cases 4 and 5, the effects of opening the window to 10% and 20% for Rooms 36C and 36D, respectively, were modeled, for a series of days beginning on December 17, using the HDD value. The number of air changes per hour for the rooms was estimated and compared with the flow of air to known devices, such as kitchen and bathroom fans, as a reference point to better understand these effects.

In Case 6, the window opening model was deployed with both the dining room and living room windows open, at either 10% or 20%, beginning on December 24, with the heating elements engaged in Rooms 36C and 36D, with those windows closed. Case 7 was similar, but turned off the heating elements in Rooms 36C and 36D from December 17 to December 30, again with those windows closed.

Case 8 put the known positions of the windows and heating elements in the sequence given by the narrative,

Case	Living Room Window	Dining Room Window	Room 36A Heater	Room 36A Window	Room 36B Heater	Room 36B Window	Room 36C Heater	Room 36C Window	Room 36D Heater	Room 36D Window
1	Closed	Closed	On	Closed	On	Closed	On	Closed	Off	Closed
2	Closed	Closed	On	Closed	On	Closed	Off	Closed	On	Closed
3	Closed	Closed	On	Closed	On	Closed	Off	Closed	Off	Closed
4	Closed	Closed	On	Closed	On	Closed	Off	Open	On	Closed
5	Closed	Closed	On	Closed	On	Closed	On	Closed	Off	Open
6	Open	Open	On	Closed	On	Closed	On	Closed	On	Closed
7	Open	Open	On	Closed	On	Closed	Off	Closed	Off	Closed
8	Open	Open	On	Closed	On	Closed	Off	Open	Off	Open
9	Open	Open	On	Closed	On	Closed	On	Closed	Off	Open

Figure 7
Case conditions for the heat flow model.

that is with the window open and the element off in Room 36C beginning December 19, with the window open and the element off in Room 36 D beginning December 24, and the dining room and living room windows open after the latter date. All windows were set simultaneously open at either 10% or 20% in the model.

Finally, Case 9 was created to assess the question about the status of the 36C heater, and whether its operation might have prevented the freeze up.

Model Calculation Results

In Case 1, (room schematic shown in **Figure 8**) for an extreme day with an HDD of 39 (-21°C outside, 18°C inside), the wall area is 74.5 m^2 (798 sq.ft) with U value of 1.41 W/m^2-K, such that q/A is 54.9, while the ceiling area is 102.28 m^2 (1100 sq.ft) with U value of 1.04 W/m^2-K such that q/A is 40.6. For the walls, q calculates as 4,089W (14,000 BTU/h), while for the ceilings, q is 4,148 W (14,150 BTU/h). The estimated total heat loss will be 8,239W (28,100 BTU/h), following Equation (1) above.

When the 1,000W (3,400 BTU/h) heating source was removed, the main room loses 1,195W (4,100 BTU/h) to the space of Room 36D, while Room 36C will transfer 713W (2,430 BTU/h) to the space through the three interior walls which have 53% more conductance. However, losses to the ceiling of Room 36D (normally about 372W (1,270 BTU/h)) will stop, such that the net additional outflow with these settings is 1,908 less 372, or 1,536W (5,240 BTU/h).

The new main room outflow becomes 8,239 plus 1,536, or 9,775W (33,300 BTU/h), which is much higher than the 7,350W (25,000 BTU/h) available from the remaining baseboard heaters. In particular, Room 36C now loses 1,936W (6,600 BTU/h), much more than its 1,250W (4,260 BTU/h) source. The effect of having more wall area of higher conductance becomes apparent.

> *Case 1 Summary:* The main room begins to cool as soon as the heat source in Room 36D is interrupted, in a 39 HDD situation, with a 2,425W (8,270 BTU/h) deficit. The corner Room 36C begins to cool as soon as the heat source in Room 36D is interrupted.

For Case 2, the results follow the format of Case 1, except that the position of the non-functional baseboard heater changed to the corner room (see **Figure 9**), Room 36C, taking out 1,250W (4,260 BTU/h).

> *Case 2 Summary*: The main room begins to cool as soon as the heat source in Room 36C is interrupted, in a 39 HDD situation. The deficit of 821W (2,800 BTU/h) is less significant than that of Case 1, in part because there would be a smaller area of higher conductance wall involved.

Whenever a room would lose its source of heat gain, the exterior wall to that room would move toward equilibrating with the outside temperature. This process made that exterior wall become "invisible," such that the interior walls of the room became the new exterior walls of the main room. By switching walls constructed to meet the demands of exterior walls (U = 1.41 W/m^2-K) for drywall and stud constructed interior walls with higher coefficient

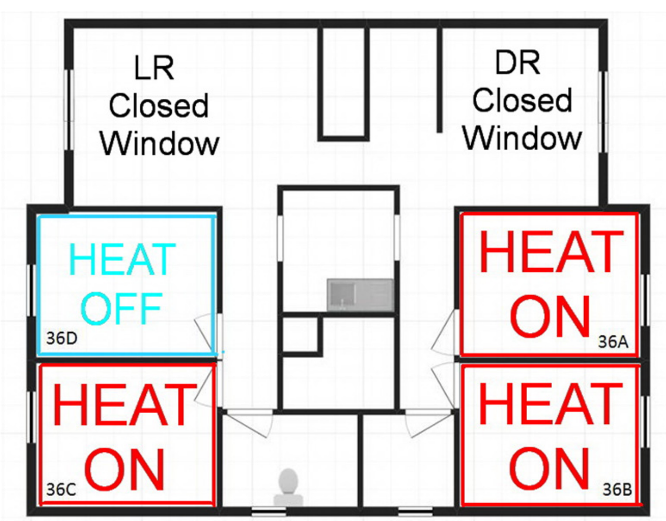

Figure 8
Case 1 suite diagram – heat source off in 36D.

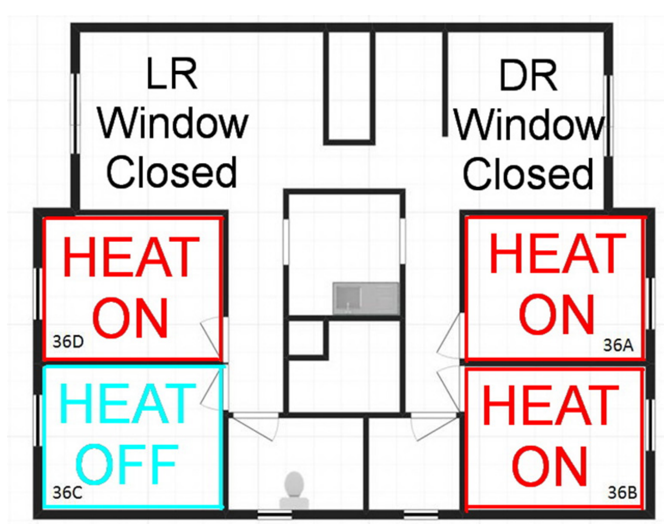

Figure 9
Case 2 suite diagram – heat source off in 36C.

of heat transfer (U = 2.15 W/m^2-K), the dynamics for the heat transfer of the main room changed significantly.

Case 3 combines Cases 1 and 2, such that the corner of the suite loses its heat sources, as shown in **Figure 10**. The principle applies once again — the interior wall now acting as an exterior wall copes poorly with the situation, such that the net outflow falls slightly to 8,204W (28,000 BTU/h) compared to 8,238W (28,100 BTU/h). However, only 6,100W (20,800 BTU/h) are available to heat the suite, resulting in a deficit of 2,104W (7,200 BTU/h).

> *Case 3 Summary*: The main room begins to cool as soon as the heat sources in Rooms 36C and 36D are interrupted in a 39 HDD situation. The deficit of 2,104W (7,200 BTU/h) is smaller than that of Case 1, but larger than that of Case 2, due to the different areas of higher conductance wall in the calculations.

The corner Room 36C allegedly had its window open and baseboard heater off (**Figure 11**) from December 19 through December 30, and this was examined in Case 4. For example, using equation (5) assuming 10% window opening with a velocity 1.14 m/s (3.74 ft/s), with a volume of 72 L/s (152 cubic feet per minute) calculates a convection loss of 3,210W (11,000 BTU/h) for an HDD of 35.8 on December 29th. When combined with the through-wall heat loss of 1,175W (4,000 BTU/h), the net heat loss value for the suite was 4,294W (14,600 BTU/h). The equivalent air changes per hour for Room 36C was 11.3 on that date.

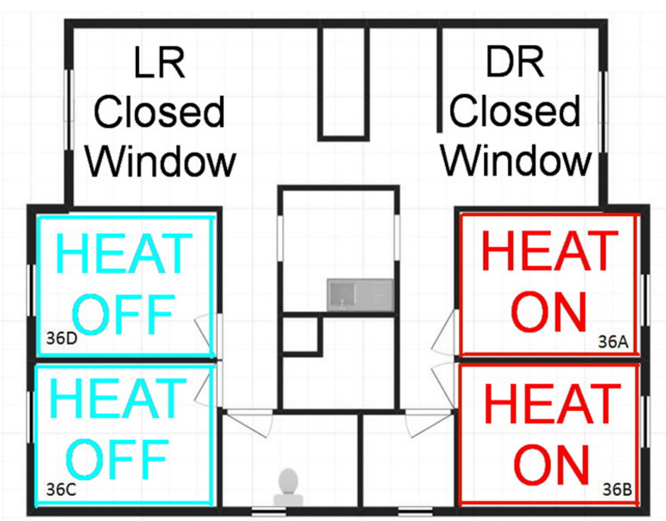

Figure 10
Case 3 suite diagram — heat sources off in both 36C and 36D.

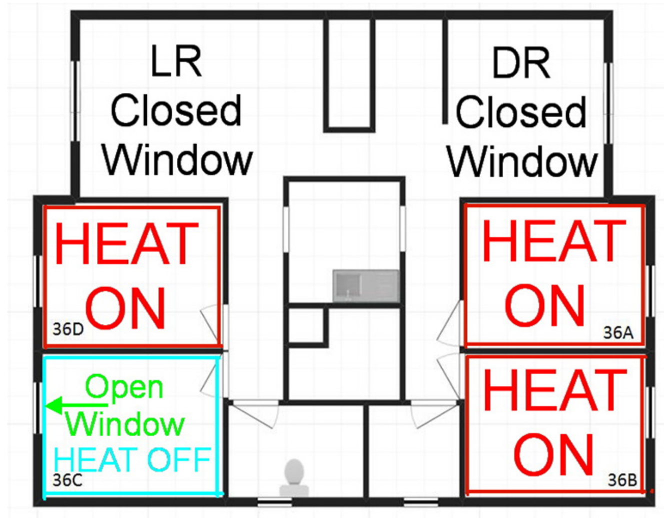

Figure 11
Case 4 suite diagram — window open and heat source off in 36C.

> *Case 4 Summary*: Room 36C begins to cool as soon as the heat source is interrupted and the window is opened, as calculated on a daily basis beginning on December 19, and shown in **Figure 12**. The additional heat loss is about three and a half times larger, and the situation would lead to a disruption of the suite heating dynamics — since between 1,700 and 4,300W (5,800 to 14,600 BTU/h) are required to keep the room at 18°C (64.4°F). This deficit means that the room will cool quickly to the exterior temperature and then track this with a lag. The effect of the percentage opening (10% or 20%) is seen in the cooling trend magnitude.

For Case 5, an adjustment of the wall area from 14.15 square meters (152 sq. ft.) to 22.75 square metres (244 sq. ft.) occurs when the interruption happens, to account

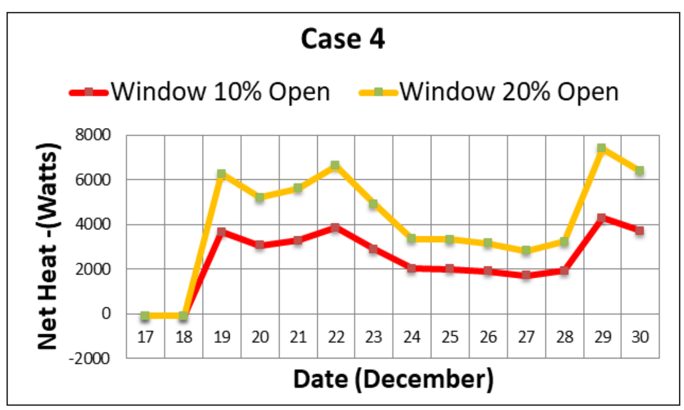

Figure 12
Net heat loss trend by date for Case 4 conditions: window open and heat source off in 36C.

for the equilibration process that begins on three sides: – two walls adjoining the main room and the third adjoining Room 36C (**Figure 13**). The baseboard heater copes well up to and including December 23.

> *Case 5 Summary*: Room 36D begins to cool, behaving in a manner similar to Room 36C in Case 4, as soon as the heat source is interrupted and the window is opened, as calculated on a daily basis beginning on December 24. The additional heat loss is about twice the expected value for a given HDD value, and the situation would lead to a disruption of the dynamics throughout the suite, since between 2,000 and 4,900W (6,820 to 16,700 BTU/h) are required to keep the room at 18°C (64.4°F). This deficit means that the room will cool quickly to the exterior temperature and then track this with a lag, as shown in **Figure 14**.

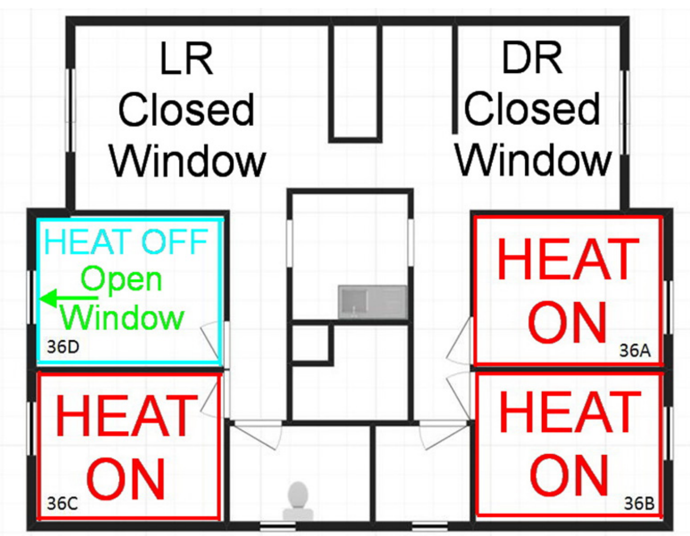

Figure 13
Case 5 suite diagram — window open and heat source off in 36D.

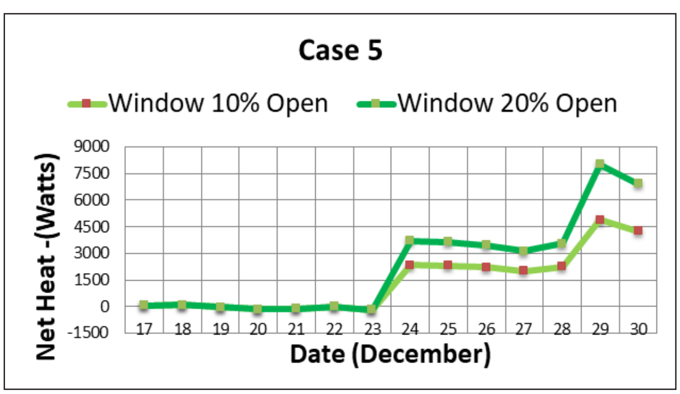

Figure 14
Net heat loss trend by date for Case 5 conditions:
window open and heat off in 36D beginning December 24.

Case 6 mimics having two large windows open while the occupants continue to heat the premises, beginning December 24 (**Figure 15**). Of course, the immediate effect is that the two baseboard thermostatically controlled heaters in these rooms move to 'ON' setting and remain there.

Case 6 Summary: The living and dining rooms begin to cool as soon as the windows are opened, as calculated on a daily basis beginning on December 24. With between 2,300 and 14,000W (7,840 and 47,700 BTU/h) required to keep the room at 18°C (64.4°F), the cooling trend is affected by the large variance as it responds to the exterior temperature changes. This deficit means that the room will cool most quickly to the exterior temperature on December 29 and 30, when compared to preceding days.

Case 7 follows the set-up of Case 6 except that the elements in Rooms 36C and 36D are turned off, but their windows are kept closed (**Figure 16**). Only when the windows are opened does the heat deficit go well beyond the suite's heating system 6,100W (20,800 BTU/h) heating capability with about four air changes per hour. A comparison of these cases is shown in **Figure 17**.

> *Case 7 Summary*: Removing the heating elements makes the situation dramatically worse in the first few days. The results are similar to Case 6 with a large heat deficit as soon as the windows are opened on December 24. Between 3,000 and 16,200W (10,200 and 55,250

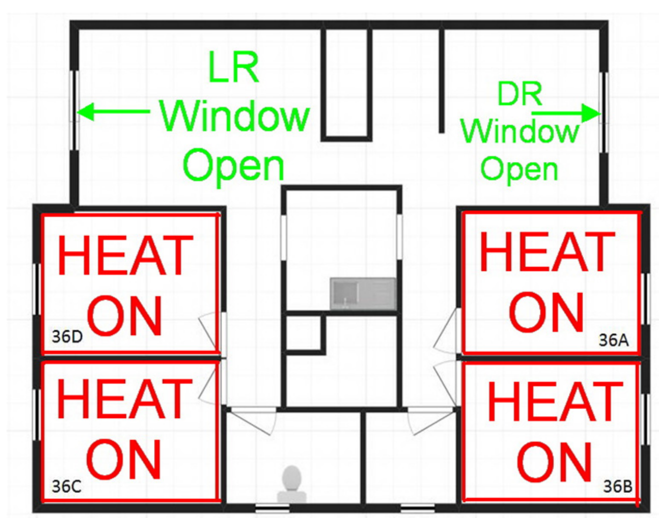

Figure 15
Case 6 suite diagram — windows open
in living room and dining room.

BTU/h) are required to keep the room at 18°C (64.4°F), due to the response to the exterior temperature changes. The room will cool most quickly to the exterior temperature on December 29 and 30.

The known conditions from the sequence described in the summary of the examination for discovery evidence narrative were the basis for Case 8. The heater interruption only causes the heat flow deficit of 1,475W (5,000 BTU/h) to occur on December 29, with a deficit of 711W (2,420 BTU/h) the next day. In sharp contrast, the open window of Room 36C (**Figure 18**) brings the net heat value to a deficit of 2,300W (7,840 BTU/h) on the first day the windows were open in that room.

The heat deficit stays below 3,000W (10,230 BTU/h)

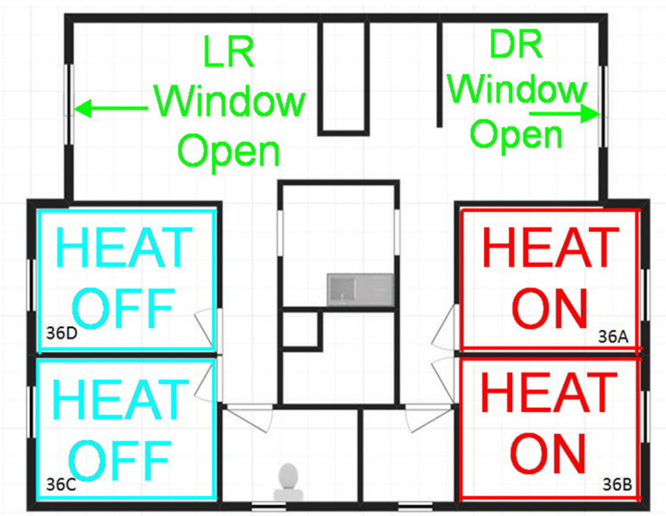

Figure 16
Case 7 suite diagram — heat source off in both 36C and 36D, windows open in living room and dining room.

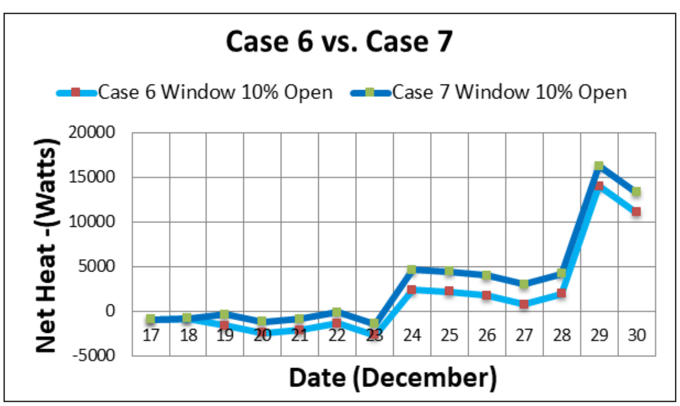

Figure 17
Comparison of net heat loss trends by date for Cases 6 and 7, living room and dining room windows 10% open.

until December 24, when three more sets of windows are opened in the suite (Room 36D, living room and dining room), and the deficit falls to 7,300W (24,900 BTU/h). It changes to 5,200W (17,700 BTU/h) on the warm day of December 27 and then drops dramatically to 22,500W (76,700 BTU/h) on December 29, and remains at 19,000W (64,800 BTU/h) the next day when the water escape was discovered.

Case 8 Summary: The suite began to cool as soon as Charlie opened his window and turned off the heat in Room 36C on December 19 (see **Figure 18**), instilling a heating deficit range of 700 to 2,300W (2,400 to 7,840 BTU/h) for the whole suite, depending on the HDD value. The heating deficit was exacerbated on December 24 by the opening of the windows in 36D by Dave and the living room and dining room by Dave and Bob as well as the interruption of the baseboard heater in Dave's room. The suite temperature then equilibrated with the outside after December 24, rendering the suite pipes susceptible to freezing on December 28 (when the temperature dropped to -21°C or -6°F) because the water in the pipes started from a cold temperature other than 18°C (64.4°F), as would be expected in a heated suite.

DISCUSSION

Heat Flow Model Trends

The model's cases break out the separate effects of the heating source interruption and the exchange of outdoor air through open window(s). The minor relative importance of the baseboard heaters being turned off was shown in contrast to the drastic impact of the opening of

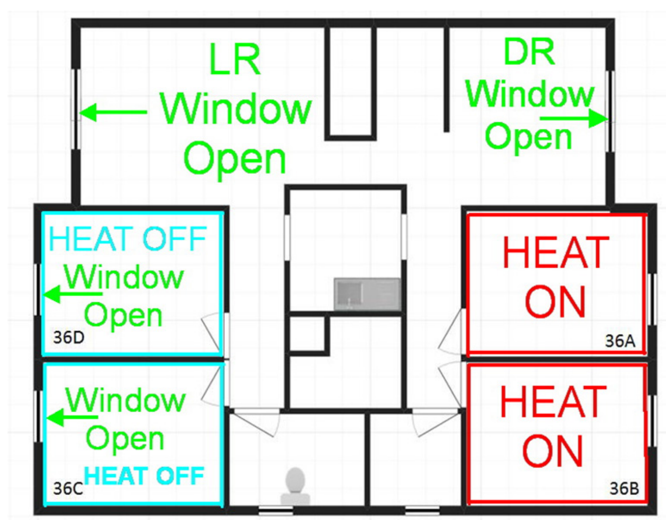

Figure 18
Case 8 unit diagram — heat source off in both 36C and 36C, windows open in 36D, 36C, living room and dining room.

four sets of windows to 10% positions on December 24. The chart in **Figure 19** reveals that the suite was in a heating deficit condition from the first day, December 19, that the window of Room 36C was opened 10%, its baseboard heater turned off, and the volume of air in the suite was changing about once per hour.

The alleged actions of Charlie of opening the window in Room 36C and turning off the baseboard heater in that room created the precursor conditions of a heat deficit that developed in the suite. The now unavailable 1,250W (4,260 BTU/h) may have prevented the cooling of the main portion of the suite to below freezing, and there would have been no convective cooling losses associated with the air changes in that room. Opening these windows and closing and locking the room door initiated the freeze-up process by lowering the average temperature of the suite in the days coming up to December 24.

The immediate effect of Dave opening the window to his room, and to Dave and Bob leaving the living room and dining room window open was a threefold increase in the heating deficit to 7,300W (24,900 BTU/h) and a quintupling of the air change cycle to five main room volumes per hour. The temperature of the suite cannot do anything except decrease to match the exterior low temperatures, which ranged from -7°C (19.4°F) on December 24 to -21°C (-6°F) on December 30.

The effect of having the corner room act as part of the exterior world would have made for cold spots on that side of the suite. For example, the adjacent inside of the exterior wall would cool down, and the air space behind the washrooms would cool laterally, providing the impetus for one of the pipe bursts if the ice front was moving from 36D toward the toilet of one of the bathrooms.

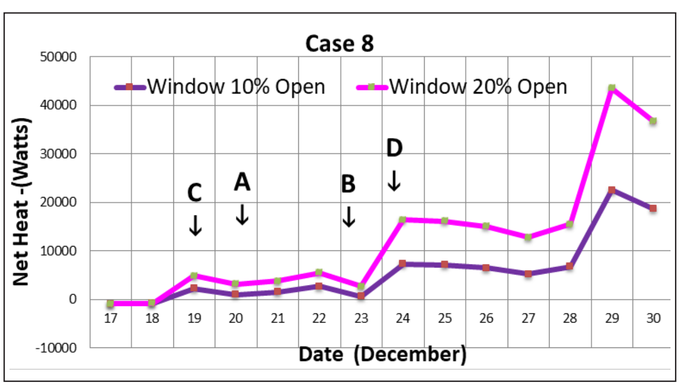

Figure 19
Graph of Case 8 showing the net heat flow by date with heat off in Room 36C and 36D; windows at 10% or 20% open in living room, dining room, Room 36D and Room 36C. Departure dates are labelled by resident initial and arrow.

The model dynamics suggested that the suite began its cooling on December 19 and experienced a steady average decrease in temperature until the night of December 29, when the deficit was too much for system. In other words, the starting point temperature was low enough on December 28 that the equilibration with the exterior on December 29 could create an effective freeze-up of the pipes within the kitchen and the exterior bathroom wall.

The relative effect of shutting down baseboard heaters was demonstrated to be less than that of opening windows, and to the layman, this makes sense and speaks to everyday experience. The attempt to heat the downtown of a Canadian city in winter with two baseboard heaters was futile.

Limitations of the Heat Flow Model

The calculations are limited to being a best estimate of the site conditions in the absence of evidence from inspection by other parties on the construction techniques in existence at the time of the incident. A quantitative viewpoint provided the baseline for a qualitative assessment of the trend of whether the suite was cooling or staying put. The analysis is sensitive to the factors used — in particular, the calculated area of exterior walls and glazing and the blended coefficients of heat transmission for the exterior and interior walls. Decreasing the area of the walls or the ceiling will lower the value of q, while an increase of the coefficient will increase the heat loss of the suite. The heat flow calculations are susceptible to compounding errors from the underlying assumptions. The assessment was restricted by budgetary constraints, so employing a commercially available heat flow software package was not practical.

Pipe Burst Circumstances

There are many reported instances of pipes that froze but did not burst. It is not a "sure thing" that pipes will burst under freezing conditions. A special subset of circumstance may be required to initiate the bursting process, which is an extreme reaction of the water supply system to a severe drop in temperature.

Generally, a large-volume insulated vessel will take longer to freeze than a small-volume bare copper pipe. Given the dynamics of heat flow in the suite from the model, it is more likely that the toilet freeze-up occurred approximately two days prior to its discovery on the night of December 30. In other words, the toilet tank had to begin to freeze on or before December 28, but the exposed copper pipes would have begun to freeze prior to that date.

One of two pipe bursts occurred within an exterior wall. It is well-known that air spaces act as insulators. Since the air gap within is acting as one of the heat-resistive layers in the wall cross-section, it has a role in keeping a pipe within the space above the freezing point. The Ontario Building Code specifically states that pipes that are installed in areas that can freeze must be protected against freezing. It was assumed that in the original design of the building, this area was not one that was anticipated to fall below freezing. On the other hand, insulation along the exterior behind the pipe would have kept some of the heat in the suite rather than letting it escape.

The main source of the water escape was in the kitchen underneath the sink within a cabinet. This hot water pipe was within that air space which would have not been subjected to direct contact with outdoor air, given the distance from the kitchen to either the dining room or living room windows. The cabinet would act to delay onset of freezing from air contact until the adjacent room had significantly dropped in temperature. Therefore, a lag would be expected between the minimum temperature occurrence and the development of freezing conditions under the sink.

Case 9 — Model of Heat Flux with Room 36D Window Shut and Heating Element On

The freezing of the pipes would have begun within 12 hours of the last tenants' departure from the suite at 3 a.m. on December 24, that is, about 3 p.m. on December 25, taken with the evidence of the frozen toilet tank, which required a minimum of 38 hours to a maximum of 60 hours to freeze.

Putting some context to the incident, an unheated sealed detached home beginning at 18°C (64.4°F) will cool to -6°C (21F) in 24 hours (about 1°C per hour) depending on the methods of construction, based on Arcon's measurements during winter power failures in Toronto.

The fact that the windows were open was more relevant to the development of the incident, since this provided uncontrolled exchange of outdoor air, while the absence of baseboard heaters in the rooms meant that the whole suite would have a larger heating deficit. Case 3 demonstrated that the absence of these heaters in Rooms 36C and 36D will cause the main room to be more sensitive to the exterior temperature, and that it will cool down. By adding the open windows, however, the modeled process of cooling was accelerated considerably.

Figure 19 reveals that the suite was in a heating deficit condition from the first day (December 19) that the window of Room 36C (Charlie's) was opened 10%, and its baseboard heater turned off. Case 8 represents the reported configuration discovered with the water escape.

The alleged actions of Charlie set in place the precursor conditions of heat deficit to develop in the suite, by lowering the average temperature of the suite in the days coming up to December 24, when the actions by others precipitated the process. Closing the room door, which was included in the author's analysis as part of the wall of Room 36C, did not retard the cooling process.

The author was asked to consider, "Whether having the window shut and the heating element on in the room would have prevented or lessened the water damage from the frozen pipes that was ultimately discovered on December 30, 2009."

In response, another engineer opined that, based on the total baseboard capacity in the living room, dining room and bathrooms of 3,850W (13,100 BTU/h), that 'the 1250W heater in Charlie's bedroom would have been incapable at preventing or lessening the large drop in indoor temperature in the common open space. Having the bedroom door closed would have prevented any movement of warm bedroom air to the adjoining corridor.'

Case 9 of the model was created to assess this statement, and the configuration is shown in **Figure 20**. With just the heating element added on, the net heat deficit for the suite occurs on December 29, and had a value of 665W (2,270 BTU/h) loss, not typically enough to freeze the pipes in a day. The closing of the window shifts the first net heat loss value to 5,000W on December 24 (**Figure 21**), considerably less than the 7,300W (24,900 BTU/h) seen in our Case 8. The maximum heat deficit becomes 18,500W (63,000 BTU/h) on December 29, compared to 22,500W (76,700 BTU/h) in Case 8.

The effects of Charlie's actions were not inconsequential to the overall circumstances. Rather, they interfered with the dynamics of the heat flow within the suite, and caused the base conditions of the main suite to alter to a lower temperature such that it was more susceptible

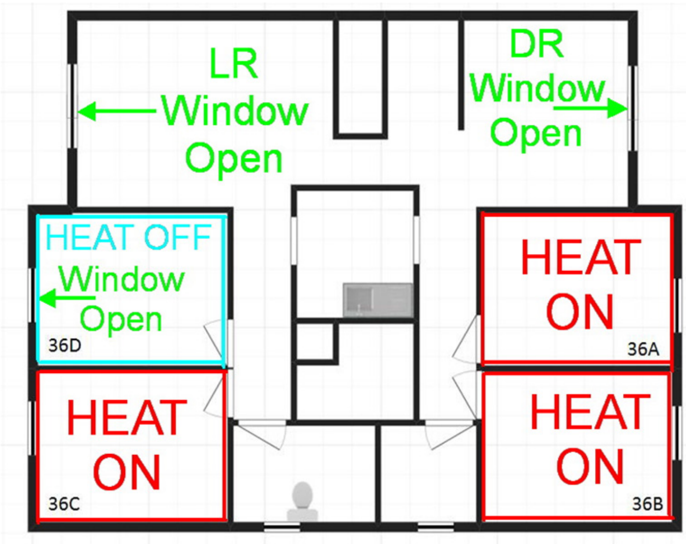

Figure 20
Case 9 suite diagram — heat source off in 36D, windows open in 36D, living room and dining room.

to the freeze-up.

Had Charlie not opened his window, he might have prevented the main suite from cooling as quickly during the post-December 24 period, but it remained unclear whether it would have prevented localized freeze-up damage.

The problems in the bathroom are possibly associated with Charlie's corner room not having adequate heat after December 19, rather than due to the bathroom door being opened. The wall behind the bathroom connects to Room 36C, and would have been subject to the heat losses seen in Room 36C.

Opening the doors to Rooms 36C and 36D provides a path for air to circulate, which would increase the ability

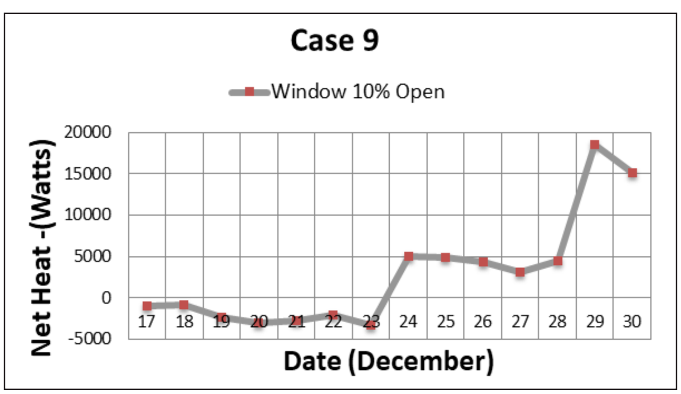

Figure 21
Net heat trend by date with Case 9 conditions: Heat off in Room 36D; Room 36D, living room and dining room with windows 10% open.

of air change cycles to occur and increase the heat flow. Rooms 36C and 36D had about eight to 10 room volume changes of air per hour occurring even with the door closed and their windows at 10% open position (see Cases 4 and 5). Open doors would quicken the air circulation process and let equilibrium conditions develop faster, such that air in the main room would circulate more than seen in our Case 8, and reach the outdoor temperature sooner. Having doors open for Rooms 36C and 36D would correspondingly hurry along the freeze-up of the water pipes.

Conclusions

A thermodynamic heat flow snapshot model was developed from first principles to assess the status of gain or loss trend at any time, as a proxy for the temperature in the suite. The model revealed that a combination of factors led to the water escape circumstances. The most significant factor was that the living room and dining room windows were left open on December 24, 2009, with a strong contribution from the cessation of heating and the open windows of Rooms 36D and 36C.

A contributing factor for the development of the precursor conditions was the activity of Charlie in Room 36C, who left the window open and the baseboard heater turned off on December 19. The actions of Charlie were not inconsequential because the model showed they set the stage for the freeze-up incident by lowering the temperature within the suite.

After December 24, based on the HDD records, the model indicated that the suite had a large heating deficit that left it unprepared for the cold snap to -21°C (-6°F) on December 28. The insulated toilet tank freeze-up provided an independent source of information on the timing, and put the tank freeze-up event at two to three days before December 30, that is December 27 to December 28. The bare copper pipes would freeze before the toilet tank so they must have frozen before December 27.

The thermodynamic heat flow model supported an inference that the pipes most likely began to freeze about 3 p.m. on December 25, that is approximately 12 hours after the last tenant, Dave, exited at 3 a.m. on December 24.

The bathroom supply pipe froze from the inside out, rather than from the outside exposure, in a space that was not insulated, but these "no-heat" conditions may not have been anticipated at the time of the building design and construction.

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Appendix A: Calculations of Constants Used in the Analysis and Charts of Heat Loss

Thermal Resistance Values, K-m^2/W

$$16.6 \rightarrow \textit{for drywall/plasterboard}$$
$$8.3 \rightarrow \textit{vertical surface in still air}$$
$$6.1 \rightarrow \textit{horizontal surface in still air}$$
$$6.1 \rightarrow \textit{air space in a wall}$$

$$k = 2.15 \rightarrow \textit{for inside wall of wood stud and plasterboard (two layers)}$$

$$\textit{To calculate U value, Thermal Transmittance, } \frac{W}{(m2\cdot K)}$$

Where C_1, C_2, C_3 = resistance values for materials 1, 2, and 3 in a given wall

$U = 1/C_1 + 1/C_2 + 1/C_3 + \ldots$

U values calculated for the suite:

$$1.41 \rightarrow \textit{combined for the exterior walls and windows}$$
$$3.2 \rightarrow \textit{for windows in the suite, storm type}$$
$$1.04 \rightarrow \textit{for stud walls}$$

To convert from W/m^2-K to BTU/hr-ft^2-°F, divide by 5.678:

$$0.248 \rightarrow \textit{combined for the exterior walls and windows}$$
$$0.563 \rightarrow \textit{for windows in the suite, storm type}$$
$$0.183 \rightarrow \textit{for stud walls}$$