Testing of Flat Roofs Insulated with Cellulose Fiber

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ABSTRACT

A series of laboratory tests using a large-scale environmental chamber has been carried out on two flat roof models fully insulated with cellulose fiber. These two models represent typical flat roofs of urban houses, built in Montreal between 1930 and 1970. The insulating strategy consists of packing cellulose fiber to a density of approximately 4 lb/ft^3 (67 kg/m^3) in a single cavity roof between the roof planking and the ceiling plaster. The goal of the test program was to determine the performance of the assembly in terms of the risk of moisture accumulation in the roof assembly.

The physical setup is a full-scale mock-up of the most common shallow flat roofs found in the Montreal area. The selection of the physical characteristics of the two test huts was based on the characteristics of 500 residential buildings. The two roof assemblies had different thicknesses, with one having 8 in. (200 mm) of insulation and the other 14 in. (350 mm). Each hut contained five roof cavities—one reference cavity without insulation and four insulated. One of the insulated cavities was sealed with polyurethane foam at all of its bypasses and was hence subjected to little or no air leakage, while the other three cavities were exposed to both diffusion and air exfiltration conditions. The testing protocol was developed to reproduce wetting conditions slightly higher than typically found in these houses.

The humidity transfer was monitored using three methods: moisture content sensors in wood, relative humidity sensors in the insulation, and gravimetry for wood and cellulose specimens. The construction and the data collection are described in this paper. The difficulties in monitoring moisture transfer over long periods of time are also discussed.

Major results of the six-and-a-half month test program using seven simulated climatic conditions are presented. Wetting and drying curves for roof cavities are presented, and exposure time to moisture is compiled and presented. The reliability of the test procedure is discussed. This paper shows that the developed procedure permitted the assessment of the net moisture accumulation and the moisture exposure level after one complete wetting/drying cycle with precisely known conditions.

INTRODUCTION

A series of laboratory tests using a large-scale environmental chamber have been carried out on two flat roof models fully insulated with cellulose fiber. These two models represent typical flat roofs of urban houses, built in Montreal between 1930 and 1970. The insulating strategy consists of packing cellulose fiber to a density of approximately 4 lb/ft^3 (67 kg/m^3) in a single cavity roof between the roof planking and the ceiling plaster.

CONTEXT

Over the past two decades, research and on-site investigation have led to a better understanding of heat and moisture transfer in building envelopes. This broader understanding has led to the proposal of several novel insulating techniques and to the reconsideration of their energy saving potential and feasibility. One proposed solution suggests that cellulose insulation installed at a high density may reduce air movement to a level that avoids condensation problems. Although this approach has been used in some weatherization programs in

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the United States, it remains untested and undocumented in Canada. Insulating single-cavity flat roofs is not common practice in Canada. The consensus from published retrofitting reports (NRC 1990) is that insulating such roofs can lead to moisture accumulation.

One document (NRC 1990) states that if the interior of a flat roof is to be insulated, the most appropriate material is probably cellulose fiber blown in at a high density (3.5 lb/ft^3 to 4.5 lb/ft^3 [59 kg/m^3 to 76 kg/m^3]). It also states that the high density of the insulation combined with comprehensive air-sealing should reduce air movement to a level that avoids condensation. The use of densely packed cellulose in unvented flat roofs is not dealt with directly in the National Building Code of Canada (NBC 1990). For new construction, the code stipulates that, for the case of insulation installed under the roof decking, an air space of least 25 mm between the insulation and the roof deck must be provided and vented to the outside with uniformly distributed openings (art. 9.19.1.2.1 and 9.19.1.3.1 of the 1990 NBCC in effect at the time of the study). However, this provision can result in moisture accumulation when applied to existing houses that have no air/vapor barrier at the ceiling level, yet are retrofitted with insulation. Insulating with high density cellulose insulation would seem to be a better solution.

Moisture transfer through a building's envelope is a complex multi-dimensional process involving vapor diffusion, air movement, capillary flow, and moisture storage. Extensive research has been done on the subject, and several models and tools are currently available that allow steady-state and transient analysis. Currently available models are one-dimensional, limited to vapor diffusion and/or capillary flow, and were found to be limited in their capacity to predict the performance of flat roofs insulated with a hygroscopic material such as cellulose fiber. These models could not qualify nor characterize the air leakage to be expected within the assembly. This is crucial as air leakage dominates vapor diffusion as a moisture transport mechanism, even for relatively tight assemblies. Current research in this field aims to develop more sophisticated tools that allow two- or three-dimensional complex modeling incorporating diffusion, air movement, and storage. However, as these tools are not calibrated or validated against conditions similar to this project, the evaluation of this technique required a comprehensive experimental assessment. An in-situ study was considered, and some houses have been monitored. However, a full-scale experimental setup was found to be more suitable to determine the impact of variables like venting, insulation thickness, air leakage, vapor barrier, etc.

A new testing procedure had to be developed given the lack of published materials on works of similar scale. As stated by Stewart (1982), variations in daily cycling, solar radiation, etc., are rarely reproduced in laboratory conditions due to the long time constant of moisture accumulation. Most long-term work, e.g., Rose (1994), uses outside setups exposed to natural conditions. Ojanen and Simonson (1995) had a 50-day experiment but with constant conditions. Regarding test conditions, most projects select testing conditions arbitrarily. A calculation method is thus proposed to determine the testing conditions. This experiment included the evaluation of the impact of several parameters on the moisture performance of two full-scale unvented insulated single-cavity flat roofs for a complete wetting/drying season. The main variables were the mode of moisture transfer (diffusion, convection) and the air leakage geometry.

Most sources, e.g., the *Agriculture Handbook* (1987), agree that exact conditions leading to wood rotting are not yet determined. For this project, the concept of exposure level, i.e., the set of temperatures, moisture conditions, and time of exposure, was introduced as a set of parameters for evaluating results and is defined as follows:

1. Moderate level of exposure corresponds to moisture content between 20% and 25% for temperatures above 50°F (10°C) and moisture content above 20% with temperatures between 32°F and 50°F (0°C and 10°C).
2. Negligible level of exposure corresponds to range of moisture content and temperature below those in point 1 or temperatures above 104°F (40°C) or below 32°F (0°C).
3. High level of exposure corresponds to moisture content above 25% and temperatures between 50°F and 104°F (10°C and 40°C).

Objectives

The insulation technique consists of packing cellulosic fiber at high density in the entire cavity of a flat roof. The high density insulation is expected to prevent the convection of moisture-laden air. To evaluate this insulation technique, tests were carried out to determine:

1. whether there was a net moisture gain in the cavities after one complete wetting/drying cycle;
2. to what exposure level the cavities were subjected.

The experiment lasted 6.5 months: three periods of one month each simulated the conditions of November to March, and four periods simulated the spring and summer conditions of April to July. Each period consisted of an average day repeated over 24 hours. Two roof assemblies were tested in the environmental chamber.

The Facility

The recently commissioned environmental chamber has been designed to re-create climatic conditions to test building envelope performance. This facility can accommodate wall specimens of up to 13 ft, 6 in. by 23 ft, 6 in. (4.1 m by 7.2 m), which is equivalent to approximately two commercial stories or three residential stories high. It also permits the evaluation of roof specimens of 11 ft, 6 in. by 14 ft, 6 in. (3.5 m by 4.5 m). It allows for the study of the hygrothermal (air, moisture, and heat flows) aspects of building envelope performance, includ-

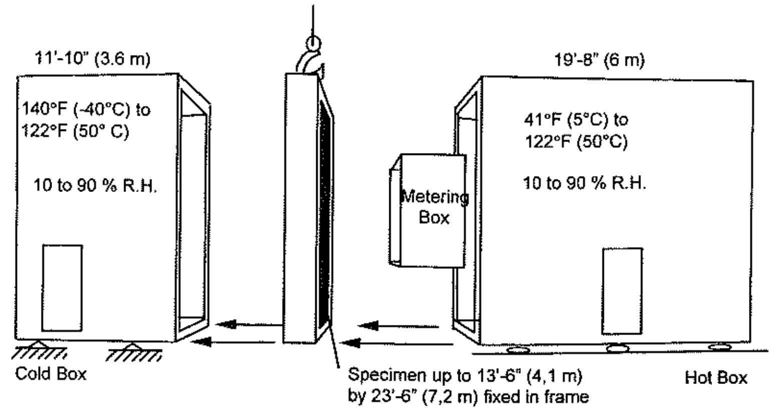

Figure 1 *Schematic representation of the environmental chamber.*

ing its interaction with the indoor environment and under controlled simulated outdoor and indoor conditions. Full technical details are given elsewhere (Fazio et al. 1997). The environmental chamber consists of two separate chambers representing indoor and outdoor conditions, denoted as hot and cold boxes, respectively (see Figure 1).

In one mode of testing, a hollow rectangular frame is sandwiched between the hot and cold boxes, in which building envelope components can be fixed or built up for steady-state or dynamic thermal tests. A metering box is located on the hot box side of the test specimen to measure heat flow for the thermal resistance measurement based on the guarded hot box method (ASTM C236). Without the metering box, this facility can be used for tests similar to the calibrated hot box method (ASTM C976).

A second mode of testing uses the facility as one large environmental chamber. The test presented here utilized this mode. The two boxes were joined, and two testing huts were built inside, one on top of the other (see Figure 2). Note that there is no heat transfer between the huts as they are separated by a 3 ft air space with free air movement.

THE EXPERIMENTAL PROCEDURE

Roof Construction

A database of 500 buildings, mostly built between 1930 and 1970, was compiled to determine the characteristics of the roofs. The majority of the roofs of these buildings had roof assemblies high enough to get proper ventilation above the added insulation. However, 25% of the buildings had roofs requiring complete insulation of the cavity and were of two types: 15% were of *thermos* type assembly, i.e., the joists are between the ceiling plaster and the roof planking, and 8% were of the *lambourde* type. This french word designates joists perpendicular to the main ones used to create the drainage slope to the roof. In the latter assembly, as in the first one, the joists and lambourdes are sandwiched between the ceiling plaster and the roof planking and membrane (see Figure 2 and Photos 1 and 2).

The structure of these houses is composed of superimposed horizontal wood timber sawn as rough 2 in. × 10 in. or 3 in. × 10 in. This urban adaptation of the log house, called carré de madrier (timber square) had to be covered by brick for fire protection. In the case of row houses, a masonry firewall would separate two houses. Of the 500 houses in the database, 50% were row houses and 40% were semi-detached. Roof joists are generally parallel to the front façade, and, thus, 50% of the joists rest on both ends in the masonry party wall and 40% have one end in the masonry wall and the other within the wood exterior wall. This is the basis of the geometry of the test hut. Each test hut measured 16 ft (4.8 m) long and had a load bearing wall 4 ft (1.2 m) from one end. The 4 ft (1.2 m) joists rested on an exterior wall that is considered to provide adiabatic indoor conditions, while the 12 ft (3.6 m) joists rested on the opposite wall, an exterior wall considered to be of the timber-on-timber type. This length of 12 ft (3.6 m) for a typical joist span is close to the averages of 12 ft, 4 in. (3.7 m), and

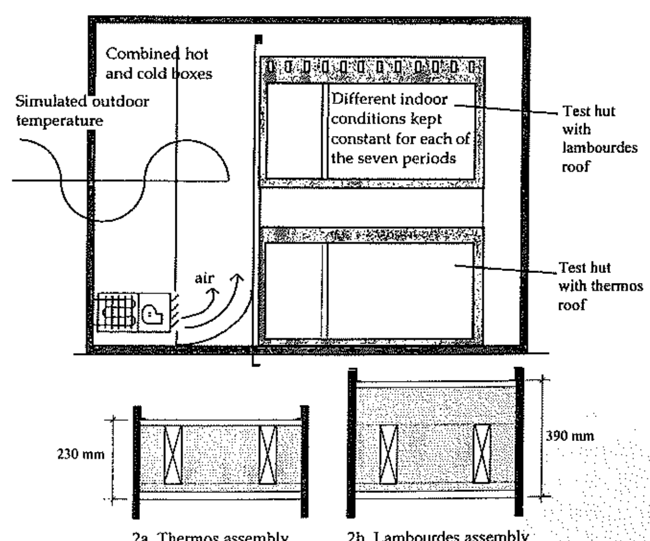

Figure 2 *Testing configuration for the flat roof test.*

Photo 1 *Typical thermos assembly during construction. The end of the cavity against the exterior wall is shown. Air leakage occurs in between wood members.*

Photo 2 *Typical lambourdes assembly during construction. Long joists receive cross members called lambourdes. Black panels are dividers between cavities.*

13 ft (3.9 m), given respectively for the thermos and lambourde by the database.

Each hut was divided into five longitudinal cavities. The average joist spacing measured on site was 16 ½ in. (409 mm) for thermos joists and 18 ½ in. (459 mm) for the lambourde joists; the median for both types was 16 in. (400 mm). A spacing of 400 mm was used in the test huts for each pair of joists. Four cavities had a width of 29 ½ in. (735 mm), leaving 6 in. (150 mm) of insulation on the nonmonitored sides of the joist, ensuring adiabatic conditions.

Furthermore, in accordance with the database, the ceiling finish consisted of plaster on wood lath, which was installed on ¾ in. (19 mm) furring strips. The roof planking was composed of ¾ in. × 6 in. (19 mm × 150 mm) planks covered with a membrane. Ninety percent of the roofs did not have fiber board. To simulate a built-up roof, a self-adhesive modified bituminous membrane was chosen because mopping hot asphalt might have been hazardous in the chamber.

The roof/wall junctions of the huts had the same construction as found on site, with main leakage paths at the intersection with the interior partition and with exterior walls. The air space due to the furring in the walls was connected with the roof space (see Photos 1 and 3). Expected air leakage was to enter into the roof through the middle partition, run horizontally through the roof insulation, and exit at the exterior wall. Diffusion-only cavities had all openings sealed with polyurethane.

The test huts are equipped with baseboard heating, an air-conditioning unit, a humidifier, and a dehumidifier. A pressurization setup was connected to each hut pumping air from the lab.

Each hut contains five roof cavities—one reference cavity without insulation and four insulated. Of these four, one is subjected to moisture diffusion only (little or no air leakage); the three others are subjected to both diffusion and air exfiltration. Table 1 summarizes the parameters as they were applied to the ten cavities.

Photo 3 *View of the cavity L5, which has lateral leakage all along the lateral wall. The furring on top of the polyethylene sheet leaves a space for air leakage behind the gypsum board. At the bottom right of the picture, the interior partition can be seen; leakage occurs through that partition as well.*

Conditions

In order to meet the objectives of the project, a testing procedure had to be developed that would expose the roofs to wetting and drying potentials slightly higher than those of roofs on site. The object was to study moisture transfer. Water penetration through the roof membrane was not examined as it would mask the effect of moisture diffusion and adsorption.

The first step was to determine the approximate duration of the wetting season and its corresponding wetting potential for a house located in Montreal. In order to do this, a computer

TABLE 1
Parameters Applied for Each Cavity

■ yes □ no

Cavities	Insulated	Diffusion	3 Points Exfiltration	Lateral Exfiltration	Renovated with Polyethylene and Gypsum Board	Goose Neck Opening
Thermos						
T1	□	■	■	□	□	□
T2	■	■	□	□	□	□
T3	■	■	■	□	□	□
T4	■	■	■	□	■	□
T5	■	■	■	■	□	□
Lambourdes						
L1	□	■	■	□	□	■
L2	■	■	□	□	□	□
L3	■	■	■	□	□	□
L4	■	■	■	□	□	■
L5	■	■	■	■	□	□

program was developed that calculates the approximate hourly condensation and drying rates due to diffusion and air leakage for a typical insulated flat roof based on its material properties and given indoor and outdoor conditions. A TMY Montreal weather file was used. The model considers stack effect and passive solar gains (through sol-air temperature). The model does not consider wind effects (which would tend to increase the positive pressure across a flat roof slightly), snow cover (which reduces the solar heat gains into the roof and acts as an insulator), and the impact of mechanical ventilation (which reduces the moisture load on the roof and raises the level of the neutral pressure plane that consequently reduces the positive pressure across the roof).

The material properties and characteristics of the flat roof simulated by the program were as follows:

- Surface: 90 m^2
- Distance to the neutral pressure plane: 3 m
- Vapor permeability of the roof (except membrane): 108 $ng/Pa \cdot s \cdot m^2$
- Vapor permeability of the membrane: 0 $ng/ Pa \cdot s \cdot m^2$
- Initial moisture content of cellulose at installation: 5%
- Airtightness of roof: 50 cfm to 200 cfm at 50 Pa

In order to determine the impact of different roof characteristics on the calculated duration, start date, and end date of the wetting and drying seasons, several simulations were performed by varying some of the parameters by as much as 50%. In all cases, the duration for both the wetting and drying seasons changed by only a few days. According to the results, the wetting and drying seasons are defined as follows:

- Wetting season:
  November 8 to April 8: 5 months approximately
- Drying season:
  April 9 to November 7: 7 months approximately

The next step was to determine if the wetting season could be compressed to three months by slightly increasing the humidity content of the indoor air while keeping it realistic. By using the model described above, increasing the indoor temperature from 21°C to 22°C - 24°C and increasing the indoor relative humidity from 40% to 50% - 55%, the wetting season could be reduced to three months of testing and still produce the same wetting potential as the five-month scenario. Further reduction of the wetting season was considered, but this risked the elimination of intermittent drying cycles that occur during the wetting season. The experiment's wetting season consisted of three periods of 30 days, each represented by a sinusoidal outdoor temperature profile and a set of other indoor and outdoor conditions. The three wetting periods are presented in the section "Running the Test" of this paper. The slightly above normal 40% and 35% relative humidity used for indoor conditions recognizes above average moisture generation due, for example, to humidifiers.

Due to the importance of the drying cycle, and the need to monitor the drying performance of each cavity closely, the drying season was not reduced or compressed. It consisted of four periods that simulated the outdoor conditions of April to July.

The test hut's indoor temperature and RH levels as compared to the typical site conditions are presented in Table 2. The schedule is found in Table 3.

Monitoring Plan

This monitoring plan includes the instrumentation used for heat, air, and moisture-transfer monitoring. All temperature measurement used thermocouples (type-T), copper, and constantan gauge 30, with 0.9°F (0.5°C) accuracy, with reference junction having 0.4°F (0.2°C) accuracy.

In the case of moisture, no device provides a direct measure of the flux of water molecules in a given area. What is done to measure diffusion through a small specimen is the dry cup/wet cup methods, where two different air moisture contents are separated by the tested material. To measure moisture transfer through a large-scale specimen is particularly complex since moisture can take different paths and follow different transfer mechanisms. Large-scale testing does not allow any direct measurements of moisture move-

TABLE 2
Typical vs. Tested Conditions

Period		Period Simulated		Procedure Requirements		Corresponding Site Conditions	
#	Duration	From	To	Indoor Temperature, °F (°C)	Indoor Relative Humidity	Indoor Temperature, °F(°C)	Indoor Relative Humidity
1	54 days simulated in 30 days	Nov. 8	Dec. 31	73.5 (23)	50%	70 (21)	40%
2	39 days simulated in 30 days	Jan. 1	Feb. 8	72 (22)	40%	70 (21)	35%
3	59 days simulated in 30 days	Feb. 9	April 8	73.5 (23)	55%	70 (21)	40%
4	21days	April 9	April 29	70 (21)	45%	70 (21)	45%
5	30 days	April 30	May 29	70 (21)	45%	70 (21)	45%
6	30days	May 30	June 28	73.5 (23)	50%	73.5 (23)	50%
7	14 days	June 29	July 14	73.5 (23)	50%	73.5 (23)	50%

TABLE 3
The Test Schedule

	Number of Days Into Test	Date of Actual Test	Planned Duration (Days)	Actual Duration (Days)
Preparation (−7.0°C to 0°C)	Days −5 to 0	April 2 - 7		5
Period 1 (−7.0°C to 0°C)	Days 0 to 28	April 7 to May 5	30	28
Period 2 (−11.0°C to −3.0°C)	Days 28 to 60	May 5 to June 6	30	32
Period 3 (−8.0°C to 6.0°C)	Days 60 to 91	June 6 to July	30	31
Period 4 (1.0°C to 20.0°C)	Days 91 to 112	July 7 - 28	21	21
Period 5 (9.0°C to 27°C)	Days 112 to 143	July 28 to August 28	30	31
Period 6 (13°C to 35°C)	Days 143 to 172	August 28 to September 26	30	29
Period 7 (16°C to 38.5°C)	Days 172 to 190	September 26 to October 14	As needed*	18
			Total	**190 days**

* Until all monitored moisture contents were below 10%.

ment. Since there exists no direct measurement technique for moisture transfer through an assembly, and in order to meet the project's objectives, the strategy for moisture monitoring utilizes three modes of investigation: measurement of the moisture content of the wood with moisture content pins, measurement of the relative humidity in the cellulosic fiber, and gravimetry measurement on samples comprising the planking, the joist, and the cellulosic fiber.

Wood Moisture Content Sensor. Moisture content in terms of percentage is defined as 100 times the ratio of weight of the moisture within a given volume of wood to the weight of the same volume of dry wood. The moisture content present within a material affects its electrical resistance. Studies have achieved specific correlation between the electrical resistance of wood and its moisture content for a set of wood species at a set temperature. Two pins acting as electrodes are inserted in the wood, at a specified distance one from the other, and the resistance to electrical current between the two pins is measured. The insulated pins are exposed at the tip to measure the electrical resistance, hence moisture content, in the wood at specified depths. Noninsulated pins are used to detect the highest moisture content in the area within the two pins. The pins are linked through a transmitter to the data acquisition system. To prevent any electrodeposition on the pins, the direction of the current is switched with a relay for each measurement and the current is maintained for only a few seconds. These probes are inserted in the planking of the roof and in the joists. A thermocouple is inserted with each pair of pins and at the same depth.

The pins measure moisture content ranging from 6% to fiber saturation (25% - 30%). Wood with very low moisture content has high electrical resistance. Readings at low moisture content are expected to be more accurate than at high moisture content (Table 4). Above the saturation point of the fiber, readings are of limited value.

Correction tables are available and list corrections to be made for temperature and for different wood species. The base

TABLE 4
Accuracy of Moisture Readings in Wood with Pins

from 6% to 12% moisture content	accuracy is within 0.5%
from 12% to 20% moisture content	accuracy is within 1%
from 20% to fiber saturation point	accuracy is within 2%

TABLE 5
Depths of Pins in this Study

Readings	Pins Inserted	Distance of Pins from Edge of Wood in Contact with Cellulosic Fiber	Distance from Air Leakage Site
In roof planking (19 mm thick)	From outside	6 mm	300 mm passed middle partition, and 300 mm before exterior wall
At top of joist	From outside	20 mm, at middle of joist	
At bottom of joist	From inside	6 mm	

curve is for Douglas Fir at 20°C. The wood used in our experiment is spruce, which demands a slight correction.

The local readings do not always reflect the general moisture distribution as several conditions may affect the moisture reading, e.g., the presence of sap. All the readings in these tests were taken perpendicular to the wood grain. The resistance to electrical current is greater across the wood grain than resistance parallel to the grain. For moisture content below 10%, readings are similar in the two directions. But for moisture content of 20%, readings across the grains are approximately 2% lower than readings taken parallel to the grain. Readings across the grain, by traversing many layers, provide an average moisture content, whereas readings parallel to the grain reflect one layer of wood cells and may, therefore, not be representative of the entire sample. The depths of readings for this project are given in Table 5.

Inorganic salts, like fire-retardant compounds, electrolyze rapidly and affect the readings by indicating a much higher moisture content than is actually present. The presence of borax in the cellulosic fiber was a concern for that reason. In order to prevent contact with the insulation, all the pins were either driven from the outside or inserted into the wood pieces. In case of very high moisture content, borax could be transported in the wood and affect the reading. This is one of the reasons that led to the gravimetric measurements to be done in parallel, as explained below.

Relative Humidity Sensor in Cellulosic Fiber. The relative humidity in the cellulosic fiber is measured using capacitance sensors. These probes are installed in the center of the insulated cavity with the transmitters on the warm side of the assembly. A thermocouple is integrated with the probe. The dielectric constant of the polymer thin film changes with atmospheric relative humidity, resulting in linear capacitance changes as a function of relative humidity. The sensor is not affected by water condensate and is immune to most chemically reactive vapors. This sensor had to be small so as to minimize its effect on the moisture distribution.

Gravimetry. Gravimetry is an indirect method of measuring moisture content that consists of comparing the weight of a specimen before and after it is oven dried. This can be done for a wall assembly or with small samples taken within the assembly. To monitor fluctuation in moisture content over time, the same sample can be weighed and replaced within the assembly to be dried only at the completion of the test (Forest 1989). This procedure allows long-term monitoring of moisture accumulation at regular intervals as a ratio of the dry weight of the wood specimen. As opposed to the electronic methods described above, the net weight of moisture within a volume can be obtained by gravimetry. The results from gravimetry are used to validate the results from the moisture pins and the relative humidity probes and to get reference data. The combination of the three methods was used to characterize moisture movement direction across the roof assemblies.

For this project, 40 samples of spruce wood and 80 samples of cellulosic fiber were measured at regular intervals during the experiment. Moisture content is determined at the end of the experiment by drying and weighing the specimens. Drying is not done before the completion since the moisture absorption properties of hygroscopic materials would be modified and therefore be different from the properties of the wood and cellulose remaining in the hut. For each weighing, the specimen is retrieved from the assembly, put into a plastic bag and brought directly to the weighing scale, weighed, and put back in place within 30 minutes. A tape is placed on the hole for the time of the weighing to prevent undue air exfiltration, as the test huts are under constant positive pressure. The cellulosic fiber is inserted into tea bags; this paper is highly permeable to vapor, does not absorb water, and is thermofusible. Specimens are all put back according to the same orientation and positioning.

Specimens were accessible either from inside or from outside the hut. In each case, one opening provides access to several specimens. For specimens situated on the cold side of the assembly, a wood specimen is cut directly in the planking at 200 mm from the moisture content sensors in the same plank. Two cellulose tea bags are positioned below, see Figure 3.

Access to specimens on the warm side of the assembly is provided through a gypsum board plug. These specimens

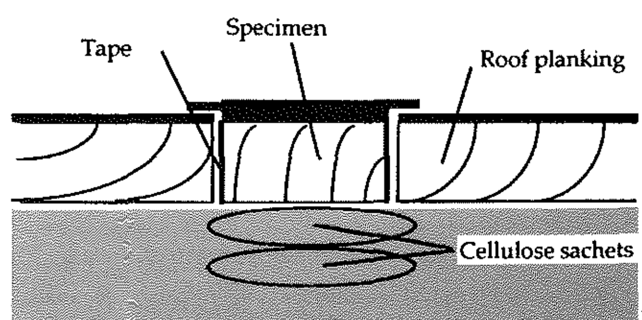

Figure 3 *Specimens on the cold side of assembly.*

TABLE 6
Synoptic Table of Test Progress*

	Duration (Days)	Indoor Temperature (°C)	Indoor RH (%)	Pressure Differential (Pa)	Average Outdoor Temperature (°C)	Average Outdoor RH (%)
Period 1						
Planned	30	23	50	3.1	−3.5	90
Actual	28	T 21.9, L 20.9	T 50.9, L 50.1	T 3.8, L 4.3	−3.6	64
Period 2						
Planned	30	23	40	3.6	−7.0	80
Actual	32	T 22.4, L 21.4	T 40.1, L 40.7	T 3.8, L 3.25	−6.7	64.4
Period 3						
Planned	30	23	55	3.1	−1.2	90
Actual	31	T 23.5, L 22.7	T 53.7, L 53.9	T 3.3, L 3.6	−1.4	70.9
Period 4						
Planned	21	21	45	0/3	14.5	45
Actual	21	T 21.9, L 20.9	T 46.5, L 48.4	T 1.7, L 1.3	10.6	56.6
Period 5						
Planned	30	21	45	0/2	18.2	40
Actual	31	T 21.9, L 20.7	T 45.1, L 44.3	T 1.3, L 2.2	18.3	48.8
Period 6						
Planned	30	23	50	0/1	24	50
Actual	29	T 21.9, L 21.2	T 47.7, L 45.5	T 0.2, L 0.1	25.2	46
Period 7						
Planned	As needed	23	50	0/0.5	27.4	72
Actual	18	T 21.6, L 21.5	T 47.3, L 46.6	T 2.5, L 2.7	27.3	41.8

* T refers to thermos assemblies and L refers to lambourdes assemblies.

include two cellulose tea bags and one wood cube that is inserted at the bottom of the joist. This cube is of the same wood species as the joist and is maintained in place with a rubber band. The cubes are at the same height as the wood moisture pins in the facing joist.

Running the Test

The test ran without interruption for 190 days. Only two out of the 262 sensors did not work properly. The conditions obtained compared very favorably with those required by the procedure, as shown in Table 6. Actual sol-air temperature profiles attained within the environmental chamber for each of the seven periods are presented in Figure 4. Differences between procedure and actual testing conditions were very minor for the indoor and outdoor temperatures and for the indoor relative humidity. The outdoor relative humidity was expected to vary with the cycling temperature, but the required average was determined for the procedure. During the cold periods, it was found to be impossible to raise the relative humidity as the humidity would condense on the cooling coil. Differences between 16% and 20% RH were experienced. As the exterior temperature was low, the difference in relative humidity was equivalent to a small difference of partial vapor pressure, and thus it is not expected to significantly affect the moisture accumulation rate. Periods 4, 5, and 6 had close to expected relative humidity. Period 7, being very warm, had the tendency to dry the air. Also, by that time, most moisture was out of the roof and could not contribute to keeping the relative humidity up. The pressure differentials required were very low and the conditions attained during the test were very acceptable, except for period 7 where a manual error occurred during a weekend. This happened at the end of the last period and had a nonsignificant effect. In periods 1, 2, and 3, the airflow provided by the air pump to maintain pressurization in the test huts varied from 9 cfm to 11 cfm (4 L/s to 5 L/s).

RESULTS

Major results are presented to demonstrate the test procedure and the performance of insulated flat roofs. Figures 5 and 6 show the average moisture content monitored in the planking of the five cavities of each test hut. From start to end of period 3, there is in all cases a steady increase in moisture content. From period 4 on, there is a continuous drying process.

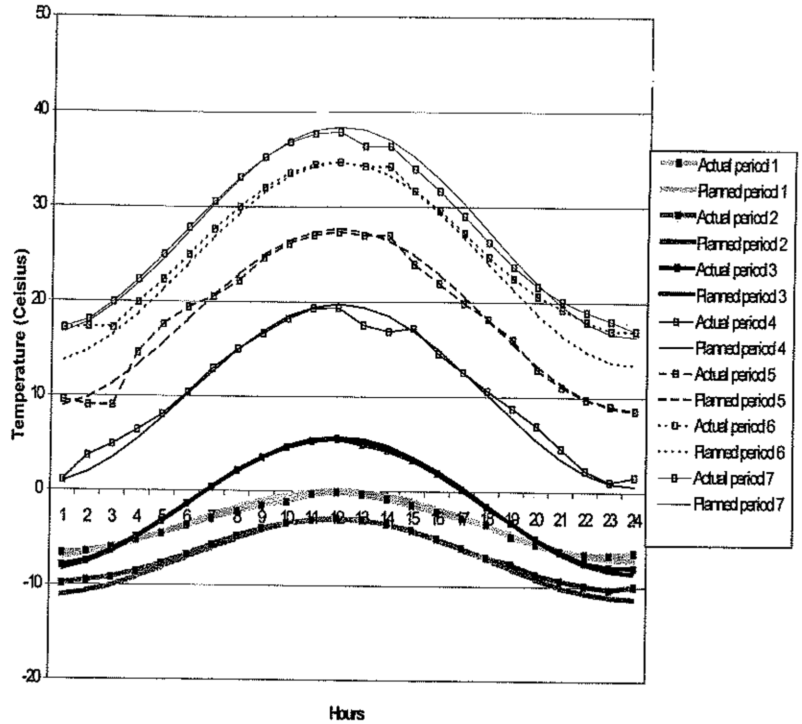

Figure 4 *Sol-air temperature profiles for periods 1 through 7. This shows obtained average conditions for each hour of each period vs. planned conditions.*

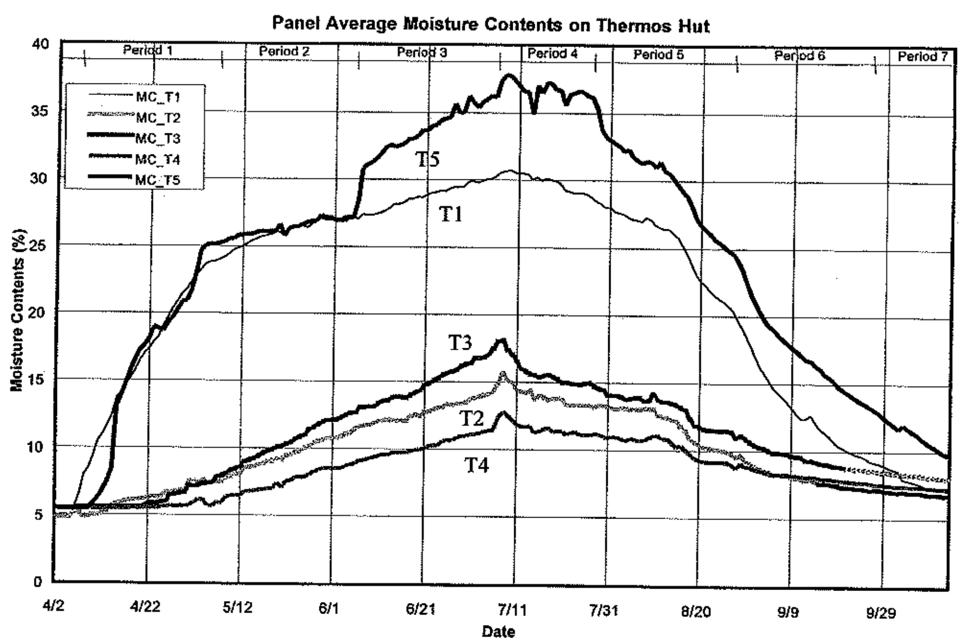

Figure 5 *Average moisture content in planking for length of test in the thermos hut.*

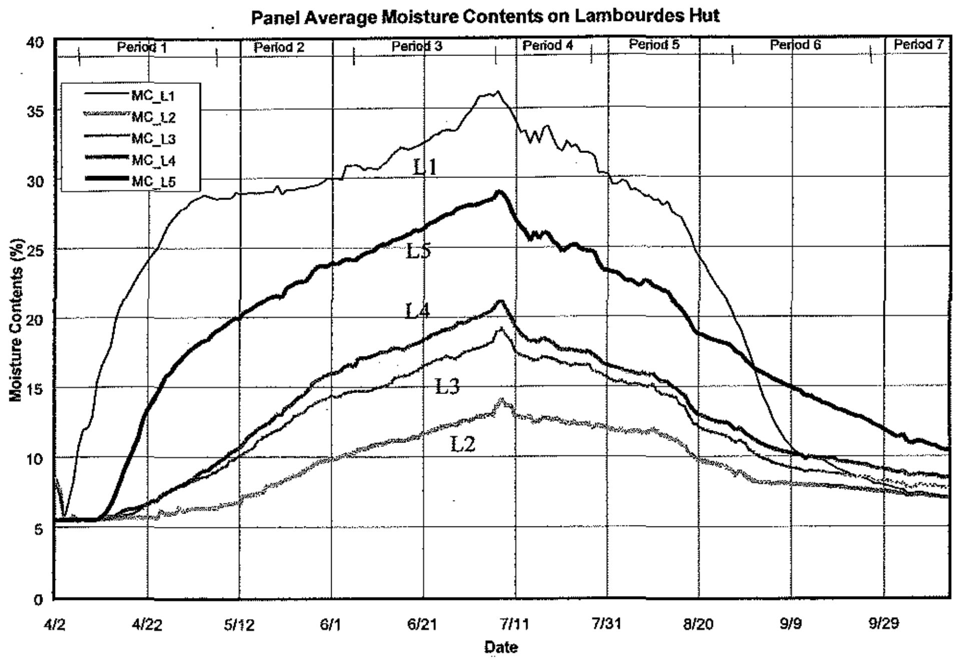

Figure 6 *Average moisture content in planking for length of test in the lambourdes hut.*

One may observe from Figures 5 and 6 that all cavities had dried by the end of the four drying periods. Therefore, there was no moisture accumulation after one complete cycle.

Regarding the second objective of the project, the determination of exposure level to moisture, the data were converted into bins of exposure levels for set temperature and moisture content intervals. These data were compiled and are presented in Table 7. This table shows a high level of exposure for the T1 and L1 noninsulated cavities. It must be taken into account that these cavities were exposed to interior conditions not usually found in poorly insulated houses, and, as such, the significance of these cavities is questionable. The other cavities were exposed to realistic but slightly above average wetting conditions given the extra airtightness and thermal resistance given by the added insulation. The extensive exposure of L5 and T5 to moisture conditions with temperature above 10°C and moisture content above 25% reflects the impact of exfiltration resulting from the lack of sealing of the joints between the exterior walls and the roof. T2 and L2 (diffusion only) and T4 (with polyethylene that restricted airflow) have a very low exposure to moisture conditions. The more leaky cavities are the ones that were most exposed to moisture as is also shown by the difference between cavities L3 and L4, which had the same construction, except for an extra gooseneck in L4. However, this has to be put in the context that, for all the insulated cavities, the air leakage path was built intentionally and, as such, is probably clearer than what is found on site.

TABLE 7
Hours of Exposure to Moderate and High Moisture Conditions

	Moderate Exposure to Moisture 20% to 25% Moisture Content Above 10°C; Above 20% Moisture Content, from 0°C to 10°C	**High Exposure to Moisture** Above 25%, Above 10°C
T1	579	670
T2	33	1
T3	91	4
T4	0	1
T5	574	721
L1	442	738
L2	23	0
L3	316	47
L4	408	90
L5	769	253

The above presentation of the data shows that the procedure provided meaningful results on ten cavities of different construction and air leakage pattern. It allows the assessment of the net moisture accumulation and the moisture exposure level after one complete wetting/drying cycle with precisely known conditions.

CONCLUSION

A test exposed two types of single cavity roofs, completely insulated with cellulosic fiber, to a full winter/summer heating/cooling cycle. A testing methodology was developed, and the environmental chamber proved to be a good facility for this type of test. The simulated conditions compared favorably with the conditions required by the procedure. A 98% data completeness ratio reflects the effectiveness of the data acquisition. The long duration of the test (190 days) provided for the required slow process of moisture accumulation and drying. Close monitoring of the conditions of the wood structure and the cellulosic fiber insulation was achieved by monitoring a total of 380 points on the cold and warm sides of the roof assemblies in a quasi-continuous mode with electronic instrumentation supplemented occasionally with gravimetry measurements. As the data are analyzed and the insulating technique is evaluated, the methodology developed is expected to contribute to the development of a standard test method for full-scale flat roof insulation.

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