Methods for the Assessment of Moisture Content of Envelope Assemblies

Dominique Derome, Ph.D. **Anik Teasdale-St-Hilaire** *Student Member ASHRAE* **Paul Fazio, Ph. D., P. Eng.**

ABSTRACT

Unlike heat transfer, the rate of transfer of moisture cannot be measured directly. Most methods are intrusive. Different materials react differently in the presence of moisture and the sustained presence of moisture can degrade the materials—a process that may affect the measurements. However, many studies focus on the impact of moisture within building envelope assemblies brought in either by diffusion, air leakage, capillarity, or water ingress.

In an effort to contribute to the development of more standard procedures to measure moisture for experimental applications, this paper presents a review of the various methods available to monitor the presence of moisture in envelope materials. These include gravimetry, electrical resistance techniques, dielectric techniques, neutron thermalization methods, thermal conductivity methods, ultrasonic methods, spectroscopic analysis, and thermal imaging. The advantages and disadvantages of each method are discussed, as well as a framework for the selection of the instruments and methods with respect to the testing protocol.

INTRODUCTION

The moisture performance of the building envelope refers to the capacity of the assembly to manage moisture so that no permanent damage is caused to the assembly and no temporary inconveniences are caused to the users of the building. To assess the moisture performance of walls and roofs there is a need to investigate the paths of moisture penetrating into the wall assembly, how long and where the moisture stays, and whether it causes temporary reduction of performance or permanent damage.

Currently, no tools can provide a moisture performance assessment that takes into account all the characteristics of the envelope. Designers rely on the state-of-the-art practices and rules of thumbs that come from experience, codes, and guidelines that emanate from research findings, such as the requirements for air and vapor barriers. In the research field, while numerical models are being developed and fine-tuned to simulate moisture performance of envelope assemblies, some complex problems are still better investigated experimentally.

The measurement of moisture in materials is intricate. The rate of transfer of moisture cannot be measured directly, but the content of moisture within materials can be monitored. Difficulties arise since methods are intrusive, different materials react differently in the presence of moisture, and the sustained presence of moisture can degrade the materials—a process that may affect the measurements. Nevertheless, many studies focused on the evolution of the moisture content within components of the building envelope assemblies brought in either by diffusion, air leakage, capillarity, or water ingress.

In an effort to contribute to the development of a more standard procedure to experimentally assess the moisture performance of building envelopes, this paper presents a review of the various instruments and methods available to monitor the presence of the moisture in envelope assemblies. A methodology developed by researchers at Concordia's Building Envelope Performance Laboratory (BEPL) that relies on the use of gravimetry and resistance moisture content sensors for wood and wood-based materials will be discussed

Dominique Derome is an assistant professor, **Anik Teasdale-St-Hilaire** is a student, and **Paul Fazio** is a professor with the Centre for Building Studies, Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, Quebec.

here, as well as other moisture content sensors found in literature. The advantages and disadvantages of each method will be discussed, as well as a framework for the selection of the instruments and methods with respect to the testing protocol.

DETERMINATION OF THE MOISTURE CONTENT OF MATERIALS

The moisture content of a material is the ratio of the mass of moisture within a given volume to the dry mass of the same volume, multiplied by 100. The moisture content can also be expressed as a volume fraction, which is the volume of moisture contained within a volume of dry material, in which case the density of the material must be known to convert it to a mass percentage. These moisture content (M) expressions are defined in the following equations:

$$\text{M (\% weight)} = \frac{\text{mass of moist sample} - \text{mass of oven-dry sample}}{\text{mass of oven-dry sample}}, \quad (1)$$

$$\text{M (\% volume)} = \frac{\text{volume of water within moist sample}}{\text{volume of dry sample}}, \quad (2)$$

$$\text{M (\% weight)} = \text{M (\% volume)} * \rho_w / \rho_{ds}, \quad (3)$$

where ρ_w and ρ_{ds} are, respectively, the densities of water and of the dry sample in kg/m^3.

Many methods can be used to determine the moisture content of porous, solid materials. Several methods will be described, namely, gravimetry, electrical resistance techniques, dielectric techniques, thermal conductivity methods, ultrasonic methods, neutron thermalization methods, spectroscopic analysis, and thermal imaging. Procedures that involve chemical analysis will not be discussed.

Gravimetry

Gravimetry is an indirect method of measuring the average moisture content of samples located within a specimen (Desmarais et al. 1998) and consists of comparing the weight of a specimen before and after it is oven dried. Gravimetry can be inaccurate when the oven drying process evaporates volatile substances within the material such as wood preservatives and extractives. The weight loss in such a case can be misinterpreted as being due to evaporated water. Therefore, when wood contains large amounts of volatile materials, other methods such as distillation are recommended (James 1975; Skaar 1972).

Gravimetry itself has been used differently in several building envelope studies. One method calls for weighing the entire assembly at the beginning and end of the experiment (Verschoor 1986) and another method calls for weighing the assembly continuously throughout the experiment (Desjarlais et al. 1998). Another practice entails weighing an assembly component or small samples at the beginning and end of the experiment once the assembly is deassembled. In Ojanen and Simonson (1995), moisture content monitoring was performed by placing small wooden samples at various locations in the envelope assembly and weighing and drying them at the end of the 50-day test period. However, to obtain a moisture distribution within envelope components, it is best to weigh small specimens integrated within the material, as shown in Figures 1 and 2, and to weigh them at regular intervals throughout the test. If the specimen to be tested is not readily accessible from the inside or outside environment, it is necessary to devise an access panel. Creating a single access location for more than one specimen facilitates the specimen-removal process and is especially useful for experiments of long duration and with a large number of samples. For example, an experiment at the BEPL required measuring 40 samples of spruce wood and 80 samples of cellulose insulation

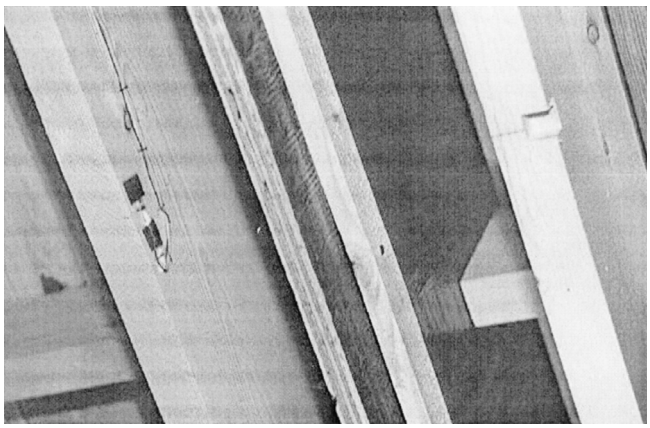

Figure 1 *Photo of bottom of the roof joists during preparation of the experimental setup. The notch on the right joist will receive a gravimetric wood sample. On the left side, a pair of moisture content pins has been inserted into the joist.*

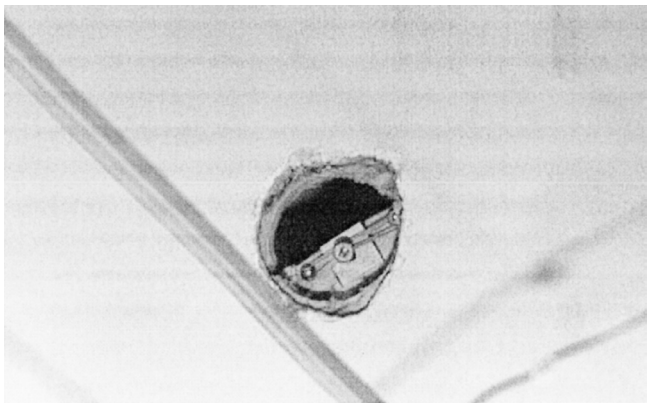

Figure 2 *Same view of the bottom of the joist, as shown in Figure 1, this time after completion of the assembly. An access port through the gypsum interior finish provides access to both a wood roof plank specimen, held in place with a rubber band, as well as two cellulose sachets, not present at the time of the photo.*

approximately every two weeks throughout an experiment that lasted about 6.5 months. The periodic removal of the specimens for weighing purposes was made easier by using the roof wood plank samples and gypsum board plugs as access ports for the cellulose specimen gravimetric sachets, as shown in Figures 2 and 4. Cutting out samples in envelope sheet materials, such as exterior sheathing and interior gypsum, is convenient but can potentially cause air leakage around the perimeter of the sample and unwanted air and moisture flow through the assembly. This problem was solved by cutting out the polyolefin membrane in front of each row of gravimetric samples and sealing the perimeter of the cutout to the fiberboard sheathing beneath. The access port was then covered between and during weighing with a rectangular piece of polyolefin membrane itself also sealed at its perimeter. This polyolefin piece can thus be removed when access to the gravimetric samples is required and extraneous air leakage due to the presence of a gravimetric sample in the exterior sheathing is prevented.

The determination of the moisture content of a sample by gravimetry entails cutting out a small specimen of the assembly component, as shown in Figure 1. It needs to be recognized that the cut produces a capillary break between the component and the specimen, which alters the capillary moisture migration into the specimen. The significance of this limitation depends on the capillary properties of the material in question and the importance of movement of liquid water within the material.

Electrical Resistance Techniques

Electrical resistance moisture probes, also called moisture content pins, can be used to find the local moisture content of wood using the principle that the electrical resistance of the material decreases with increasing moisture content (Duff 1968; Skaar 1988; Derome 1999). The probes, if insulated with their tip exposed, measure the moisture content at a specific depth while uninsulated probes increase the contact area and the moisture content measured is the highest moisture content over the area.

Although pure water exhibits a high resistivity, small quantities of dissolved ions can significantly reduce this value, and since the electrical resistance of most inorganic and organic nonconducting materials is relatively high, the moisture within the material carries most of the current. For example, the resistance of wood increases by a factor of roughly 10^7 over the range from the fiber saturation point (about 30%) to the oven dry state (Lagus 1994). The resistance moisture content methodology involves applying a voltage to the probes, which ionizes the material. The ionization is proportional to the number and the duration of the exposure to the voltage and causes corresponding errors in the readings (Desmarais 2000). A custom experimental setup was devised where the direction of the current is switched with a relay and the current maintained for only a few seconds for each measurement to prevent any electrodeposition on the moisture pins. The measured voltage is converted to a current (4 to 20 mA) signal that is read by the data acquisition system.

While stationary moisture measurement systems consisting of moisture probes connected to transducers and data acquisitions systems are appropriate for laboratory work, simple hand-held meters are useful for site investigations. This type of moisture measurement is now widely used in the wood industry. While Duff's (1968) early technique involved drilling a hole into the wood, placing an electric hygrometer made with small wood probes inside, and sealing the hole to prevent moisture loss, moisture probes can also simply be inserted directly into the wood to be tested (Duff 1968; Skaar 1972).

The accuracy of the electrical resistance readings typically decreases as the moisture content of the wood increases, and moisture level readings above the fiber saturation point of wood are of limited value (Derome 1999; Lagus 1994; Skaar 1988). Because the electrical resistance of wood decreases with increasing temperature (James 1975; Lagus 1994; Forsén and Tarvainen 2000), temperature corrections must be made. The resistance is also affected by the wood species, and more accurate results are obtained if the meter can be calibrated with respect to the wood species' exact place of origin (e.g., pine from Sweden) (Forsén and Tarvainen 2000). Corrections for temperature and wood species are typically provided by the moisture pin manufacturer. However, in some instances, more information might be required. For example, in Desmarais (2000), calibration curves were developed based on a method described by Zarr et al. (1995) for asphalt-impregnated sheathing fiberboard. Five 40 mm by 40 mm fiberboard samples were installed with moisture content resistance sensors and placed in a small conditioning chamber where the temperature and relative humidity were controlled. The temperature was held constant at 17ºC and the relative humidity maintained until the specimens reached moisture content equilibrium. The test was conducted at relative humidities of 50%, 75%, 85%, 90%, 95%, and 97%. The test was repeated at 4ºC and at relative humidities of 50%, 75%, 85%, and 92% for temperature-correction purposes. Voltage readings were taken from the moisture content sensors and the samples weighed immediately afterwards. The samples were oven-dried and weighed again at the end of the procedure. The actual moisture contents, determined by gravimetry, were plotted against the voltage readings to find the calibration curve from which the voltage readings taken during the actual experiment were converted into moisture contents, as shown in Figure 3. Unexpectedly, the maximum fiberboard moisture content measured during the experiment was greater than the maximum calibrated value, and, therefore, to obtain an accurate calibration curve at higher moisture contents, additional calibrations were performed.

While work by Stamm (1960) and James (1975) led many sources to state that the electrical conductivity of wood is greater in the direction parallel rather than perpendicular to the grain, recent extensive studies performed by Forsén and

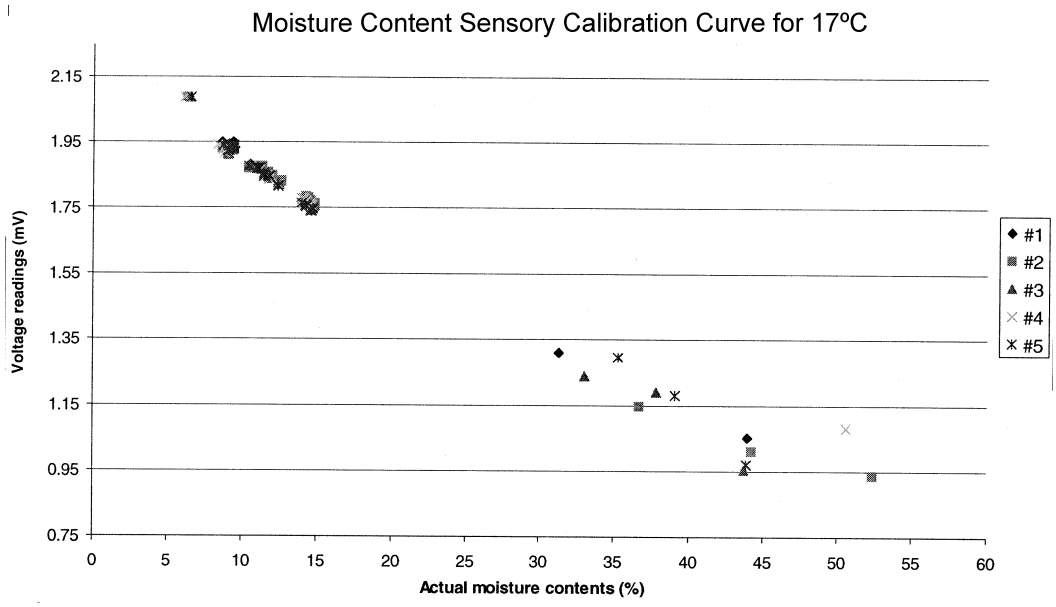

Figure 3 *Calibration of data points at 17ºC.*

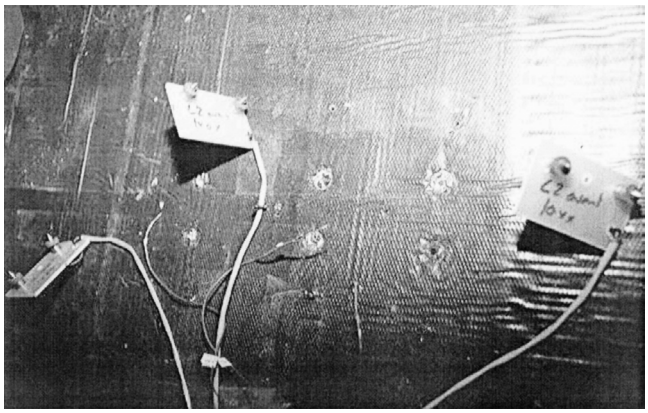

Figure 4 *Photo of dismounting of three pairs of moisture content resistance pins that had been installed from the exterior side of the roof assembly.*

Tarvainen (2000) at the Technical Research Center of Finland have revealed that the direction of the wood grain has no influence on resistance measurements. Forsén and Tarvainen's (2000) research also conveys that the wood density as well as the distance between the electrodes have minimal influence on the electrical resistance measured. However, the shape of the electrodes does alter the resistance measurement and, therefore, they recommend that only the pins provided by the manufacturer should be used with hand-held moisture meters.

Other factors may affect the readings. Dissolved salts (used as preservatives or fire retardants) can affect readings, especially at concentrations above 2000 ppm and at moisture contents above 8%, and the formation of corrosives can also be a problem when the pins are exposed to moisture for an extended period of time (James 1975; Lagus 1994; Zarr et al. 1995; Derome 1999). An experiment to evaluate the hygrothermal performance of cellulose-filled flat roofs at the BEPL involved a testing protocol that required monitoring the moisture content of wooden roof joists and wood roof planking covered with a bitumen membrane. The metal probes were installed into the wood planking from the exterior side of the assembly, as shown in Figure 4, to prevent contact between these and the borax-impregnated cellulose fiber beneath the wood planking. Borax is conductive when wet and can cause corrosion of the moisture pins and alteration of the moisture content readings. Such a measure could not be adopted for the wooden joists, however, because they were surrounded by cellulose insulation; consequently, another protective measure was undertaken. The aim was to measure the moisture content at a depth of approximately 1/4 of the thickness of the joist. Rather than insert a moisture probe through the closest face of the wood joist, a longer probe is driven deep into the opposite face of the joist such that its tip is located 6 mm from the surface of the joist in order to protect the probe from the borax-impregnated cellulose.

Some types of glue in plywood can act as conductors and affect measurements (James 1975). In addition, because of the large variation in properties within the same species and even within the same piece of wood, the electrical resistance of wood varies with constant moisture content (Forsén and Tarvainen 2000). It is therefore important to take several readings of a sample to obtain a representative average moisture reading. Also, gravimetry can be used as a base line—in the previously mentioned flat roof experiment at the BEPL, moisture content sensors were installed in the same plank that received the gravimetric wood sample. Below the fiber satu-

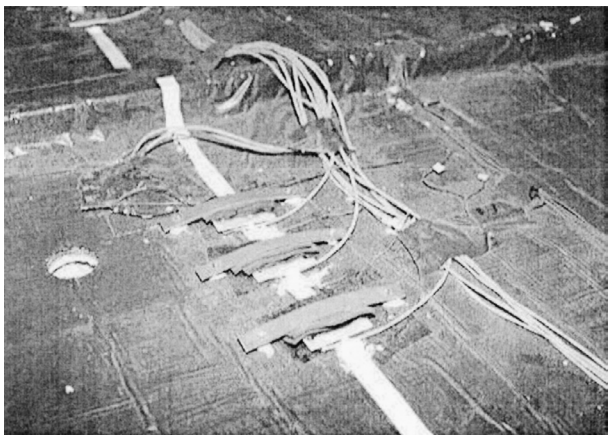

Figure 5 *Photo taken close to completion of the installation of the pins. PVC strips have been installed over the moisture content resistance probes to maintain contact between the probes and the wood. The round hole on the left allows the cellulose insulation to be seen. Two cellulose sachets were inserted and the original wood cut-out put back in place for gravimetric monitoring. The wood sample was taken in the same plank being monitored with the pins, so variation of properties within the same wood species would not be a factor when comparing data.*

ration point, data from the two methods could then be compared. Lastly, poor contact between the moisture probes and the sample, potentially caused by volumetric changes in the wood undergoing moisture content changes, can affect readings. To avoid these problems, PVC strips were installed over the probes in the wood planking, as shown in Figure 5, to provide constant pressure and, therefore, constant contact area between the probes and the wood.

Hand-held moisture content resistance apparatuses need further considerations. Because the temperature and wood species calibration curves are typically provided by the manufacturer, either in the electronic programming of the apparatus or in the form of tables, special consideration must be paid to the instrument's limitations. Extensive studies by Forsén and Tarvainen (2000) offer the following guidelines:

- correct temperature setting is important for resistance meters;
- pre-programmed temperature corrections for resistance meters do not apply at extreme temperatures, tested at temperatures ranging from –10ºC to 70ºC;
- resistance type meters are most accurate within the range 8% to 20%, and;
- hand-held resistance moisture meters are more accurate when they are exposed to a room temperature of around +21ºC

Dielectric Techniques

The dielectric constant, ε', is a measure of the polarization of atoms and molecules in a material under an applied voltage or voltage gradient (Skaar 1988). The amount of polarization and, hence, the dielectric constant, is a function of the frequency of the alternating electric field (Skaar 1972). Since the dielectric constant of water is 80 over a wide range of frequencies and temperatures, while that of most dry and solid materials ranges between 2 and 4, and since capacitance is proportional to the dielectric constant, capacitance measurement can be used to determine the moisture content of porous materials. It should be noted that the capacitance measured is proportional to the volume of water present, and thus the specimen density must be known to determine the moisture content as a weight percentage (Lagus 1994).

Another measurement factor to be considered in dielectric techniques is the power loss factor, tan δ, calculated as the ratio of the out-of-phase dielectric constant component, ε'', and the in-phase component, ε'. The power loss factor is due to the energy absorbed and subsequent heat lost by the dielectric material when it is placed in an electric field (James 1975). The power loss factor increases with moisture content, as does the dielectric constant. It can also increase and decrease with increasing temperature depending on the frequency and moisture content (Skaar 1988).

The dielectric properties are affected by numerous factors such as wood density, frequency of the current, grain orientation, and temperature. Forsén and Tarvainen (2000) performed extensive testing dealing with the influence of several factors including density and temperature on the capacitance of wood. They found that the most important influence on the dielectric property of wood is its density. This is likely because the cell wall volume is greater for denser woods and, therefore, these cells play a greater polarization contribution than in less dense woods. Although the effect is small, the dielectric constant of wood generally increases with increasing temperature except at high temperatures, where the reverse can occur (Forsén and Tarvainen 2000; James 1975).

Dielectric moisture meters are operated with alternating sinusoidal currents and usually at radio frequencies (Skaar 1972), although the frequency range has recently been extended into the microwave region (Kääriäinen et al. 2000; Schlemm and Leschnik 2000). There are two basic types of dielectric moisture meters. The first is a capacitance type, which, in essence, measures the dielectric constant of the wood. The capacitance is also affected by the electrode configuration. The second (and most common) is the power loss type, which measures both the increase in dielectric constant and power loss factor with increasing moisture content. The power loss type also depends on electrode configuration as well as the wood characteristics, which are, in turn, dependent upon moisture content, temperature, density, structural orientation, and frequency (Skaar 1972; Skaar 1988).

Errors frequently occur in practice when dielectric meters are used because the measurements are strongly influenced by

the wood density—density varies within a species and even within a sample but meters are calibrated for the average density for each species. Results of tests performed by Forsén and Tarvainen (2000), comparing the moisture content measurements of sapwood (more dense) and heartwood (less dense) using a capacitance meter, attest the role played by density in accuracy. Surface moisture may be another source of error.

Forsén and Tarvainen (2000) report that temperature correction charts or tables are typically not provided by the manufacturers of capacitance moisture meters.

Most dielectric meters are based on a fringing field concept. That is, the sample being tested is not placed between the capacitor plates, but rather it is placed in contact with the electric field formed by electrodes protruding from the body of the meter. Electrode penetration into the sample is not required and, therefore, the method is not intrusive. However, both Kääriäinen et al. (2000) and Schlemm and Leschnik (2000) report that their microwave moisture meters required inserting one or two small diameter rods into the test material, which can then be moved into the material at various depths to measure the moisture profile. Specimen dimensions are important because the field generated by the electrodes must be entirely within the material. Operating at higher frequencies can minimize the effect of dissolved salts (Lagus 1994).

Both Schlemm and Leschnik (2000) and Kääriäinen et al. (2000) conducted testing of the microwave sensor on several samples of concrete. Errors induced by wave scattering at aggregates and steel were recognized and required correction. Measuring the moisture distribution within more uniform materials will not likely require such corrections. Schlemm and Leschnik's (2000) experiments revealed that the linear regression produced a regression coefficient, r, equal to 0.958, which shows an excellent linear relationship between the real component of the dielectric constant, ε', and the volumetric moisture content. Kääriäinen et al. (2000) performed tests on wood (glue laminated pine) as well as a composite section of concrete, polystyrene insulation, and sand. The wood test showed an excellent correlation in the moisture range below 18% by volume but underestimated the moisture content at higher levels. Comparison of the average gravimetric and microwave moisture content in the concrete and polystyrene components of the composite sections showed good agreement.

Forsén and Tarvainen (2000) made several recommendations following their extensive experimental work on handheld capacitance moisture meters on wood specimens:

- capacitance meters show a much wider variance in accuracy compared to resistance meters;
- correct density setting is essential for capacitance meters;
- the dimensions of the sawn lumber, the moisture content level, and moisture gradient are other major factors affecting the accuracy of measurements and, therefore, the "correct" place to measure the *average* moisture content varies;
- extreme temperatures do not affect capacitance type meters, tested at temperatures ranging from –10ºC to 70ºC;
- many capacitance meters often indicate too low moisture contents because of their low measuring depth and the moisture gradient.

Thermal Conductivity Techniques

The thermal conductivity technique for moisture content determination of a porous medium has been used for many decades and is based on the material's decreased resistance to heat flow when moist. Generally, the temperature of the material is measured at a certain distance from a heat source or the temperature increase of the heat source is measured. The source can be cast into the material or inserted in the form of probes for less rigid porous materials such as insulation. Calibration is needed for each material used. The temperature sensor must also be at the same temperature as the material, and the ambient temperature should not change during the test (Lagus 1994).

This method has been applied to firebrick, concrete, and insulating materials (Lagus 1994). A modified version using small twin probes inserted into brick has been used for long-term monitoring of walls (Vos 1972). It should be acknowledged that the heat source should be active for only a short period of time; otherwise, the presence of heat could change the moisture distribution within the material.

Ultrasonic Techniques

Ultrasonic techniques have been applied to the determination of moisture content of soils and wood products. The basis for the technique is the altered propagation of acoustic waves in the megahertz region as they travel through moist solid materials. Wave velocity decreases as moisture content increases. The velocity of the acoustic wave traveling from the transmitter through a moist specimen is measured by an ultrasonic transducer in the receiver. This technique can be used to measure high levels of moisture content, and it has been applied to green wood with values up to 140% moisture content by weight. Dissolved salts do affect results, but the effects are minimized when high frequencies are employed. It may be difficult to apply this technique to the various types of materials found in building envelopes (Lagus 1994), as will be explained later.

Neutron Thermalization Methods

Skaar (1972) and Lagus (1994) discuss the use of neutron thermalization for the determination of moisture content of materials. The technology has been used in laboratory studies on concrete, qualitative field surveys of roofs and, more extensively, field technique for soils. The technology involves the thermalization of neutrons emitted by an americium-beryllium source by high-cross sectional elements such as hydro-

gen (found in water, for example). The neutrons, having an initial energy near 4.5 MeV, interact with the atomic nuclei in the sample, transfer kinetic energy, and are thermalized to an energy level of approximately 0.025 MeV. These low-energy neutrons are then back-scattered and detected by boron trifluoride in the meter.

Because the method determines the volumetric moisture content, the density of the material must be known to find its moisture content on a weight basis (Skaar 1972).

Commercial neutron moisture meters are designed to operate over a relatively large effective volume that ranges depending on the meter. Therefore, the technology is not applicable to samples that are limited in size in one or more dimension. Last, because this measurement technique does not lead to a point moisture content determination, the moisture distribution over a specimen cannot be found. These facts limit the applicability of the neutron thermalization method in building envelope testing (Lagus 1994).

Spectroscopic Analysis

Absorption spectrometers use a technology based on the interaction between matter and electromagnetic radiation. X-rays, beta rays, as well as gamma rays are typically used as radiation sources. X-rays are electromagnetic waves emitted when a metal target is bombarded by high-energy electrons, and they are moderately penetrating; beta rays are electrons emitted from certain isotopes during radioactive decay and are also moderately penetrating. These methods are limited by the fact that they are highly absorbed in dense materials such as wood and therefore may only be applicable to less dense materials or denser materials with small thicknesses. Gamma rays are electromagnetic waves emitted by radioactive nuclei such as cesium and are highly penetrating (Serway 1990; Skaar 1972). When gamma rays interact with matter their energy is partially or completely absorbed depending on factors such as the energy of the gamma ray photon, the nature of the absorbing material, and the distance that the radiation travels within the absorbing material (Kumaran and Bomberg 1985). Materials will absorb radiation selectively depending on the frequency of the radiation (ASHRAE 1997).

Much research has been done in the last two decades to develop a protocol for the experimental determination of moisture content using X-ray absorptiometry (Hansen et al. 1999) and, even more so, gamma spectroscopy using one or two sources (Kumaran and Bomberg 1985; Kumaran 1986; Kumaran et al. 1989; Cid et al. 1992; de Freitas and Castro 1999) for porous building materials with either a rigid solid matrix or a deformable porous medium. To obtain an overall time-dependant moisture distribution within a material, the intensity of the radiation transmitted through the material is tested at specific coordinates and at regular intervals both when dry and when wetted with a selected moisture transport process.

Research teams carried out gamma ray experimental validation for the dual-beam spectrometers by testing for known mass attenuation coefficients. Kumaran and Bomberg (1985) and Cid et al. (1992) determined the experimental mass attenuation coefficient of water for Cesium and Americium sources and they were found to agree well with the theoretical value. Kumaran et al.'s (1989) experiments reveal that the accuracy of moisture distribution in a material by gamma spectroscopy depends on the absolute value of the moisture concentration—the higher the concentration, the more accurately it is measured. The Hansen team experimentally determined the mass attenuation coefficient of two different combinations of aluminum and acrylic plastic, using an X-ray source, and their experimental values were found to agree with theoretical ones.

The advantages of the X-ray and gamma spectroscopy methods are the accurate determination of the volumetric moisture of a sample and the timing adjustability of the measurements for transient moisture distribution. In addition, these methods do not disturb the flow of moisture within the material because there are no intrusive measuring probes within the medium, and they require no manipulation of the medium, neither weighing nor cutting (Kumaran and Bomberg 1985; Cid et al. 1992). However, for gamma spectroscopy, dead time (i.e., the time during which the detector is not active nor counting photons), background radiation, and the Compton effect (i.e., the scattering as a result of collision between the gamma photon and a free electron in the specimen) must be recognized and corrected (Kumaran and Bomberg 1985; Cid et al. 1992).

There are several disadvantages of the gamma method, the first being cost. The logistics of X-ray and gamma spectroscopy necessitates the removal of the specimen from the envelope assembly for each test. The time required to measure the moisture content at each coordinate may cause redistribution of moisture within the sample and it may therefore be difficult to obtain an accurate "snapshot" of the moisture distribution in the entire specimen during transient moisture flow conditions. Also, the methodology described by Cid et al. (1992) requires that a deformable porous sample be placed in a cylindrical cell of a specified diameter. It is highly likely that manipulation of such a specimen could alter the moisture distribution within the sample by inherent squeezing.

These methods are best suited for laboratory work. The time needed to transport a field sample to a laboratory may cause a redistribution of the moisture within the sample, on account of which the spectrometry results would not be representative of true field conditions.

Thermal Imaging

While thermal imaging is a technique commonly used to determine the location of thermal breaks during laboratory work and field inspections, it can also be utilized to measure the moisture distribution within a material.

When a material has a moisture content higher than that of the surrounding environment, the moisture within the material will begin to evaporate, which causes the surface temperature of the material to decrease. The greater the moisture

content, the greater the evaporative heat loss and the measured temperature drop. Thus, if the temperature decrease is measured with an infrared camera with a high degree of precision, the moisture distribution on the surface of the material can be determined.

Before testing can begin on a specimen, a calibration procedure must be undertaken such that the temperature drop can be related to moisture content. This can be done by measuring the surface temperature of various specimens of known uniform moisture distributions with an infrared camera at known isothermal conditions. Once the temperature-moisture content relationship of the material has been ascertained, the method can be used to determine the moisture content of test specimens (Johansson 1999).

Tests performed at the Lund Institute of Technology using a sedimentary calcareous sandstone called Uddvide with moisture contents above 80-100 kg/m^3 revealed that the measuring accuracy is not sufficient in this particular case. The researchers hypothesize that the results may have been better if a lower relative humidity (below 33%) had been maintained within the laboratory. However, since the environmental conditions created in most laboratory tests aim to emulate field conditions, it may not be feasible to set low values of relative humidity to facilitate the measurement of moisture content of materials by thermal imaging.

Another critical limitation is the fact that the temperature-moisture relationship must be known for all relevant temperatures since the relationship is dependent upon the temperature of the sample. Also, the temperature distribution within a sample such as thermal insulation may not be uniform (Johansson 1999).

Other Methods

As technologies evolve, other methods and instruments are being developed. An example is a prototype for a non-destructive moisture sensor for low slope roofs, developed at the U.S. Army Cold Regions and Engineering Laboratory, and called the Passive Resonance Roof Moisture Detector (Yankeilun and Flanders 1997). The simple and inexpensive technology is based on an externally energized inductive-capacitive circuit whose plates are pushed close together in the presence of moisture, which causes the circuit to resonate at one frequency when it is dry and at another when it is wet. The researchers foresee two types of instrumentation to monitor the presence of water within a roof assembly. The first, called broadcast-induced resonance (BIR), consists of determining the presence of moisture within a wide roof area by establishing the presence of wet sensors, while the second, the swept frequency analyzer (SFA), consists of finding out which sensors are wet. The technology is still in the developmental stages and remains to be validated in the field.

ANALYSIS FOR SELECTION

This paper has discussed several methods to determine the moisture content of materials. Here, a framework for the selection of the methods and instruments is presented with regard to laboratory and field investigations of the moisture performance of envelopes.

Gravimetry is among the most accurate methods to determine the average moisture content of a material sample because it requires no temperature corrections and is valid for all moisture ranges. Thus, it is often used to calibrate other instruments. However, gravimetry is a destructive procedure, and oven drying and weighing the specimens at regular intervals to obtain a time-dependent moisture distribution of the assembly is a time-consuming process, especially if many samples are involved.

The electrical resistance technique provides a local moisture content measurement and can have a good degree of accuracy if readings are properly corrected for temperature and wood species. In a laboratory setting, it is especially useful in obtaining a transient moisture distribution "snapshot" because the resistance probes can be connected to a computer data acquisition system programmed to take measurements at specified time intervals. However, since measurements are reliable only for wood moisture content below fiber saturation point, it is often helpful to install a gravimetric sample adjacent to the moisture probes. A roof experiment run at the BEPL used moisture content data from moisture probes installed adjacent to gravimetric samples. The experimental data for the moisture probes alone, shown as a dark continuous line in Figure 6, tend to indicate that the moisture content in the wood deck reaches a maximum of 25%. However, a comparison with the adjacent gravimetric reading, shown as dark squares, demonstrates that the resistance measurements are false since the true moisture content value rises up to about 150% moisture content—a value that is outside the operating range of the electrical resistance technique.

Dielectric moisture meters, whether the capacitive type or the power loss type, can be quite accurate if great care is taken to compensate for specimen density, as well as frequency, structural orientation, and, less so, temperature. Hand-held capacitive and power-loss type dielectric moisture meters are not intrusive and are best suited for discrete measurements, while microwave dielectric methods, while intrusive, can be connected to a data acquisition system for continuous monitoring of building envelopes. Results of tests performed on concrete (Schlemm and Leschnik 2000) and wood (Kääriäinen et al. 2000) were reasonably accurate, although less so for wood above 18% moisture content by volume. Further validation could be done by comparing the results of integrated moisture distribution measurements using the microwave sensor and gravimetric measurements.

The thermal conductivity technique is another method presented for measuring the moisture content of materials. However, it is discounted for continuous moisture measure-

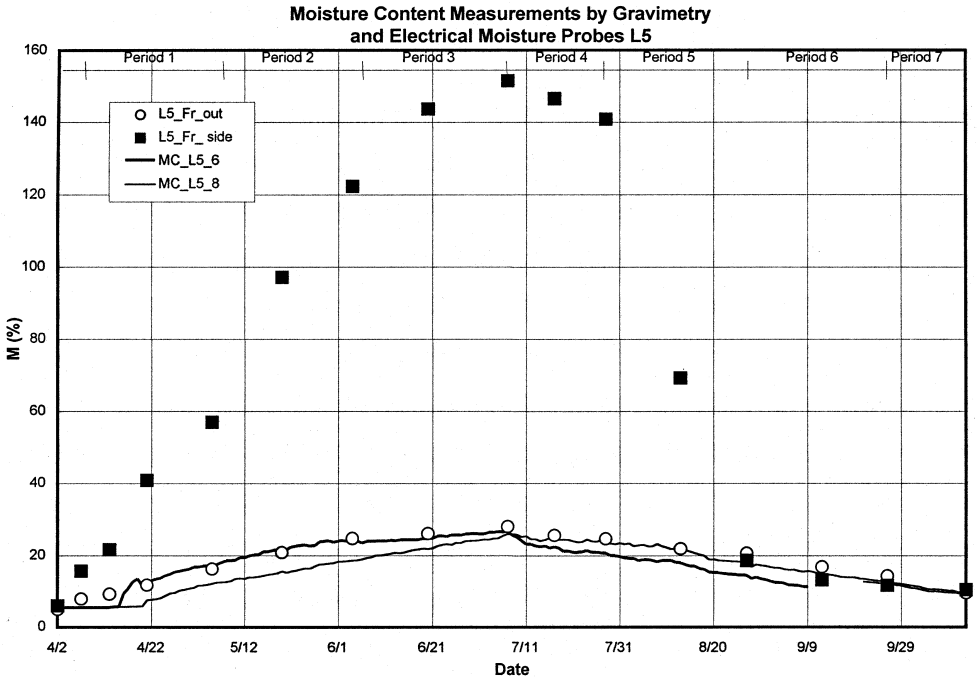

Figure 6 *An example of gravimetric readings outside of the operating range of electrical resistance probes.*

ment within building envelopes because of its slow response time (3 to 15 minutes) (Lagus and Trechsel 1994) and the possible disruptive effect of heat generation within a test assembly on the moisture distribution.

The ultrasonic technique has been utilized to determine the moisture content of wood up to 140% and has proven to be an accurate method. However, mechanical coupling of the instrumentation and the assembly and the fact that the specimen must be wholly contained between the transmitter and receiver may limit the applicability. It is best used on homogeneous materials as well because the presence of variability of density, the elastic moduli of inclusions, and cracks can influence results (Lagus 1994). Therefore, its applicability may be limited unless extensive corrections are performed on results.

The neutron thermalization method is discounted for several reasons. First, it is not very accurate (accuracy of approximately 5 $kg_{water}/m^3_{specimen}$ at best); second, it does not provide a point or local MC measurement; third, it is not applicable to specimens that are limited in size in any dimension; and fourth, the presence of hydrogen in any form (found in cellulose chains in wood, bitumens, and crystalline water of hydration in concrete, for example) as well as other elements such as boron, cadmium, and manganese chlorine iron may lead to results that overestimate the quantity of moisture within a sample (Lagus 1994). The instrument requires extensive calibration for this background (Skaar 1972).

A non-intrusive methodology that produces very accurate moisture distribution measurements is X-ray, beta, or gamma ray spectroscopy. While Kumaran (1986) successfully carried out moisture determination tests for medium-density glass fiber insulation, Cid et al. (1992) explained that the gamma spectroscopy method has not been utilized for highly porous materials because of the great difficulty in obtaining accurate measurement results for media with a small degree of absorption photons. However, the method is limited to laboratory work and requires expensive equipment and careful safety precautions due to the radiative sources.

The thermal imaging technique (Lagus 1994; Johansson 1999) appears viable for the determination of surface moisture content or of bulk moisture content of specimens at equilibrium moisture content. However, much research is required before the technique can be applied because of the need to determine the relation between infrared energy detected and moisture content at various equilibrium moisture conditions at a known temperature for the material in question. Experimental results of thermal imaging tests show that ambient RH conditions need to be controlled in order to produce accurate results (Johansson 1999), but this may not be possible in tests chambers that simulate actual field conditions. Because the material surface must be exposed to the camera when taking a reading (Johansson 1999), components within the assembly need to be removed for testing. To satisfy both conditions, the test material can be removed and taken to a small chamber with appropriate relative humidity for measurement purposes. Speedy testing procedures would be necessary to prevent moisture redistribution within the specimen.

The main points discussed above are tabulated for the different methods. Table 1 also includes the accuracy, operative range, and response time of the methods.

The discussion thus far relates information on the accuracy, physical setup, advantages, and limitations of the various

TABLE 1
Methods and Instruments for Measuring the Moisture Content of Materials

Instrument	Accuracy	Operative Range	Response Time	Source of Errors/Disadvantages
Gravimetry	Function of accuracy of weight scale and drying method	-	-	Evaporation of volatiles within material / Time consuming Destructive nature of test or access to samples
Electrical Resistance	Best is ±0.5%, most accurate within 8-20%*	< fiber saturation point (± 25- 30%MC)	Instantaneous	Dissolved salts, moisture gradients, electrode contact, correction for temperature, wood species
Dielectric (capacitance power loss)	Best is ±0.5%	Up to 96% wood MC**	Instantaneous	Dissolved salts, varying wood density, incorrect compensation for wood density; incorrect compensation for power-loss types / wide accuracy variations exist between different hand-held meters
Thermal Conductivity	No information	No information	3-15 minutes	- / Temperature must be constant during test
Ultrasonic	±1%	Has been applied for wood MC up to 140%	Instantaneous	Varying density, dissolved salts, elastic properties of material, cracks and variations in material / requirement for mechanical coupling, specimen wholly enclosed between transmitter and receiver
Neutron Thermalization	Varies; best is ±0.3 lb/ft^3 (5.34 kg/m^3)	No information	Fast	Influence of materials containing hydrogen and other elements / does not give a point MC measurement, not applicable to small specimens
Spectroscopy	Higher accuracy at higher MC; best is ±0.6%***	>5 g/100 cm^3****	Fast	Appropriate correction for dead time, background radiation, and the Compton effect / Need for radiation protection, expensive
Thermal Imaging	No info	0% to capillary saturation	Fast	- / Does not provide MC distribution at varying depths; temperature and RH affects accuracy
Microwave dielectric	Approximately 2% by vol.*****	< 18% MC for wood	Fast	Wave scattering due to inhomogeneities within specimen/ intrusive (borehole within material)

* From Forsén and Tarvainen's (2000) research on hand-held capacitance moisture meters.
** From Skaar (1988): Tests performed by Trapp and Pungs (1956) relating dielectric constant and power loss factor on European spruce for MC ranging from 0% to 96%, MC refers to moisture content.
***From Kumaran's (1986) experiment using gamma spectroscopy on a medium-density glass insulation sample.
****Estimated lower limit from Kumaran and Bomberg (1985).
*****From Kääriäinen et al. (2000).

TABLE 2
Application of Various Moisture Content Determination Methods with Respect to the Type of Test

Test to determine material properties	Hygrothermal tests on small-scale samples and large-scale panels	Field Studies
• Gravimetry • Electrical resistance • Capacitance • Ultrasonic • Spectroscopy • Thermal imaging***	• Gravimetry* • Electrical resistance • Dielectric** • Ultrasonic* • Spectroscopy*	• Electrical resistance* • Dielectric*

* Requires removal from the assembly.
** Discrete rather than quasi-continuous measurements are possible.
*** Accuracy is unknown.

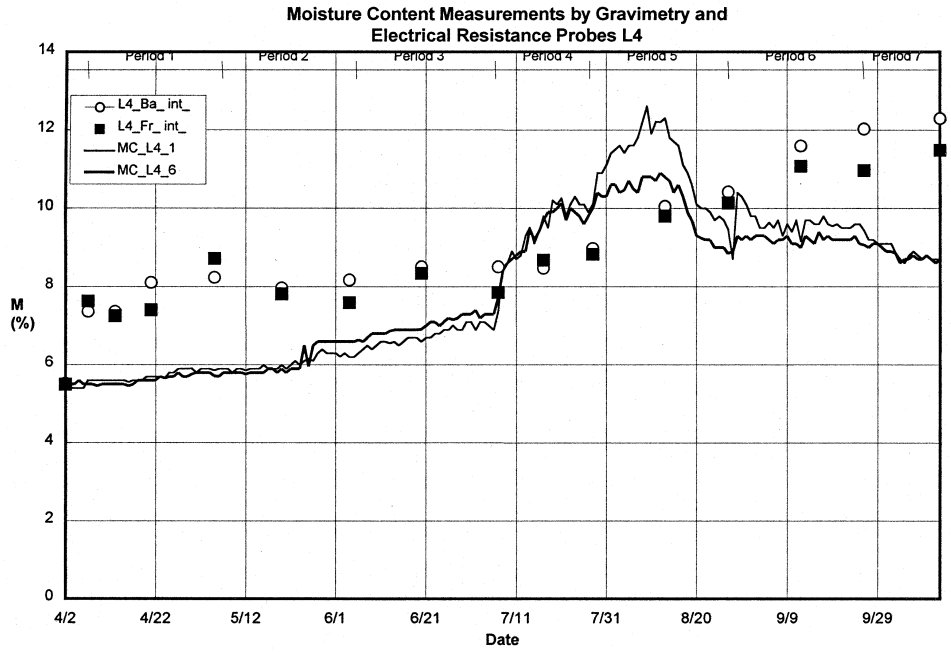

Figure 7 *Graph showing the difference in gravimetric and electric resistance measurements where the movement of moisture occurs in different directions.*

moisture content assessment methods. It is also useful to understand the methods most appropriate in various experimental contexts. Table 2 summarizes the application of the moisture content assessment methods with respect to different types of tests, namely, tests to determine the hygric properties of a material, small-scale or large-scale experiments, and field studies.

The previous discussion demonstrates that the gravimetric and electrical resistance and dielectric techniques are the most practical methods of measuring the moisture content of building envelope materials at present. They are also the most commonly used. As previously mentioned, electrical resistance measurements can be performed either as discrete measurements in a laboratory or a field setting with a handheld moisture content meter or as quasi-continuous measurements in a laboratory using moisture probes connected to transducers and a data acquisition system.

The next step in developing a monitoring protocol is to establish how many gravimetric samples and moisture content sensors to use and where to position them. This strongly depends on the objective and the complexity of the experiment. For example, if a moisture distribution over an envelope material is required, then it is appropriate to place the gravimetric samples and moisture content sensors in a grid-like pattern. They can also be placed at locations of interest, depending on whether the researcher wishes to monitor a one-dimensional, two-dimensional, or three-dimensional moisture transfer.

It should be noted that the position of individual gravimetric samples and sensors will affect the measurements. A case in point is the cellulose-insulated roof experiment previously discussed; a gravimetric sample and a pair of electrical resistance probes were placed in the same roof joist but resulted in very different moisture content readings. The gravimetric sample was placed in the corner of the bottom edge of the joist, as shown in Figure 1, while the moisture probes were positioned above the gravimetric sample on the vertical face of the joist. Gravimetric readings are shown as discrete points while quasi-continuous electrical resistance measurements are designated by lines; the dark line and square points, as well as the light line and circular points, correspond to the same joist, respectively. A comparison of the moisture content measurements showed that the gravimetric reading was, on average, much greater than that of the resistance probes, as shown in Figure 7. While the moisture probes show a slight increase in moisture content during periods 4 and 5, they indicate that the roof joists dry out in those locations afterward. However, this is not so for the gravimetric sample. In fact, the gravimetric samples indicate a continued increase in moisture content. The moisture probes measure the result of a moisture flux perpendicular to the surface of the joist, while the cubic gravimetric specimen is subjected to a moisture flux on both its exposed surfaces. Thus, while the moisture probes measure a decrease in moisture content at their tip starting in the middle of period 5, the gravimetric samples measure an increase in moisture content in the corner of the joist where moisture migrates toward the two exposed surfaces, which explains why the gravimetric measurements are greater than those of the probes.

The number of samples and sensors to be utilized is also important. If the temperature and moisture content distributions across a specimen are expected to be approximately uniform, and if little or no air movement is occurring, fewer sensors or gravimetric samples may be required. However, for an experiment attempting to monitor the hygrothermal effects of air exfiltrating through a wall cavity where natural and/or forced convection takes place, for example, a large number of moisture content sensors is necessary to obtain an accurate moisture distribution within the wall. For example, an experiment run at the BEPL to study the wetting of walls due to the exfiltration of moisture-laden air required 10 electrical resistance probes and 15 gravimetric samples to mark the migration of the air in each 400 × 2400 mm tested wall area. Whatever the case may be, the researcher must carefully optimize the placement and number of gravimetric samples and sensors, bearing in mind that while a larger number of sensors provide a more accurate picture of the moisture distribution within building components and assemblies, sensors and gravimetry do disrupt the behavior of building materials. In addition, the installation of sensors and the measuring procedure, such as the weighing of gravimetric samples, are labor-intensive tasks.

CONCLUSION

The experimental assessment of the moisture performance of envelope assemblies is based on the monitoring of moisture. This paper has presented moisture content measurement methods and instruments and has illustrated how they could be used for envelope studies. During selection, consideration should be given to whether a continuous or a discrete measurement methodology is preferred, whether the chosen method is appropriate for the material to be tested, and optimization of the number and location of the gravimetric samples and moisture content sensors to obtain the most pertinent data, based on the research objectives. Of the presented moisture content measurement methods and instruments, gravimetry and electrical resistance moisture content sensors and, to a lesser degree, dielectric, ultrasonic, and spectroscopic moisture content assessment techniques display the most potential.

A global framework for the development of experimental procedures investigating the moisture performance of assemblies has to encompass, in addition to the moisture content methods presented, methods for detecting and measuring condensation, rainwater ingress, relative humidity in air space within assemblies, as well as moisture content on surfaces. A complete portrait of the behavior of moisture that integrates all measurements could then be developed to rate and relay the moisture performance of assemblies, taking into account the materials used, the functions, and the location of the building.

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REFERENCES

ASHRAE. 1997. *1997 ASHRAE handbook—Fundamentals*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Cid, J., J.F. Alquier, and P. Crausse. 1992. Study of moisture transfer in a deformable porous medium through attenuation of two different energy gamma rays. *Review of Scientific Instruments* 63: 2057-2064. American Institute of Physics.

De Freitas, V. P., and J. Castro. 1999. Experimental study of the drying of cellular concrete. *Proceedings of the 5th Symposium on Building Physics in the Nordic Countries*, pp. 329-336. Göteborg, Sweden: Chalmers University of Technology.

Derome, D. 1999. Moisture occurrence in roof assemblies containing moisture storing insulation and its impact on the durability of building envelope, Ph.D. thesis, Concordia University, Montreal, Quebec.

Desjarlais, A. O., T.W. Petrie, P.W. Childs, and J.A. Atchley. 1998. Moisture studies of a self-drying roof: Tests in the large-scale climate simulator and results from thermal and hygric models. *Thermal Performance of the Exterior Envelopes of Buildings VII*, pp. 41-54. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Desmarais, G. 2000. Impact of added insulation on the hygrothermal performance of leaky exterior wall assemblies, master's thesis, Concordia University, Montréal, Quebec.

Desmarais, G., D. Derome, and P. Fazio. 1998. Experimental setup for the study of air leakage patterns. *Thermal Performance of the Exterior Envelopes of Buildings VII*, pp. 99-108. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Duff, J.E. 1968. Moisture distribution in wood-frame walls in winter. *Forest Products Journal* 18 (1): 60-64. Forest Products Research Society.

Forsén, H., and V. Tarvainen. 2000. *Accuracy and functionality of hand held wood moisture content meters*, rev. ed. Espoo, Finland: Technical Research Center of Finland.

Hansen, K.K., S.K. Jensen, L. Gerward, and K. Singh. 1999. Dual-energy X-Ray absorptiometry for the simultaneous determination of density and moisture content in porous structural materials. *Proceedings of the 5th Symposium on Building Physics in the Nordic Countries, Göteborg, Sweden*, pp. 281-288.

James, W. 1975. Electrical moisture meters for wood. Forest Products Laboratory, General Technical Report FPL-6. Madison Wis.: U. S. Department of Agriculture Forest Service.

Johansson, P. 1999. A thermal imaging method for measuring moisture distribution in porous building materials. *Proceedings of the 5th Symposium on Building Physics in the Nordic Countries*, pp. 297-304. Göteborg, Sweden: Chalmers University of Technology,

Lagus, P.L. 1994. In H.R. Trechsel, ed., *Moisture control in buildings*. Philadelphia, Pa.: American Society for Testing and Materials.

Kääriäinen, H., M. Rudolph, D. Schaurich, K. Tulla, and H. Wiggenhauser. 2000. Moisture measurements in building materials with microwaves. *Proceedings of the International Symposium on Non-Destructive Testing in Civil Engineering* (NDT-CE), pp. 199-207. Oxford: Elsevier Science.

Kumaran, M.K., and M. Bomberg. 1985. A gamma-spectrometer for determination of density distribution and moisture distribution in building materials. *Proceedings of the International Symposium on Moisture and Humidity*, pp. 484-490. Research Triangle Park, N.C.: Instrument Society of America.

Kumaran, M. K. 1986. *Gamma-spectroscopic determination of moisture distribution in medium-density glass fibre insulation*. Building Research Note, Institute for Research in Construction. Ottawa, Ontario: National Research Council of Canada.

Kumaran, M. K., G.P. Mitalas, R. Kohonen, and T. Ojanen. 1989. *Moisture transport coefficient of pine from gamma ray absorption measurements*. ASME HTD, vol. 123, *Collected Papers in Heat Transfer*, pp. 179-183.

Ojanen, T., and C. Simonson. 1995. Convective moisture accumulation in structures with additional inside insulation. *Thermal Performance of the Exterior Envelopes of Buildings VI*, pp. 745-752. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Schlemm, U., and W. Leschnik. 2000. Measurement of dielectric profiles at concrete with microwaves. *Proceedings of the International Building Physics Conference*, pp. 453-460. Eindhoven, the Netherlands: Eindhoven University of Technology.

Serway, R.A. 1990. *Physics for scientists & engineers with modern physics*. Philadelphia: Saunders College Publishing.

Skaar, C. 1972. *Water in wood*. Syracuse, N.Y.: Syracuse University Press.

Skaar, C. 1988. *Wood-water relations*. Springer-Verlag, Berlin Heidelberg, Germany, p. 274.

Stamm, A. J. 1960. Bound-water diffusion into wood in across-the-fiber direction. *Forest Products Journal* 10, pp. 524-528, quoted in Skaar, 1988. Wood-Water Relations. Springer-Verlag, Berlin.

Trapp, W., and L. Pungs, L. 1956. Einfluβ von Temperatur und Feuchte auf das dielektrische Verhalten von Naturholz im groβen Frequenzbereich. Holzforschung 10: 144-150, quoted in Skaar, C., 1988.

Verschoor, J. D. 1986. Measurement of water migration and storage in composite building construction. *ASHRAE Technical Data Bulletin*, vol. 2, No. 5, pp. 140-153.

Vos, B. H. 1972. Measuring moisture content and distribution in construction. *Building International*, quoted in Trechsel, H.R., ed., 1994, *Moisture control in buildings*. Philadelphia: American Society for Testing and Materials, pp.51-54.

Yankielun, N.E., and S.N. Flanders. 1997. Passive resonance roof moisture detector. *Journal of Thermal Insulation and Building Envelopes* 21: 45-67. Lancaster, Pa.: Technomic Pub. Co.

Zarr, R.R., D.M. Burch, and A.H. Fanney. 1995. Heat and moisture transfer in wood-based wall construction: Measured versus predicted. NIST Building Science Series 173. Gaithersburg, Md.: Building and Fire Research Laboratory, National Institute of Standards and Technology.