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Testing Water Vapor Transmission: Unresolved Issues

by M. Bomberg

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Résumé

Ce document passe en revue les questions clés dont on a discuté lors du symposium de l'ASTM sur les mécanismes et les mesures de la transmission de vapeur d'eau à travers les matériaux et systèmes. Il présente les questions qui n'ont pas été résolues dans les mesures en laboratoire et les futures méthodes d'essais de

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Testing Water Vapor Transmission: Unresolved Issues

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ABSTRACT: This paper reviews key issues addressed during the ASTM Symposium on Mechanisms and Measurements of Water Vapor Transmission through Materials and Systems. It presents unresolved issues in the laboratory measurements and postulates actions to be considered in the future development of ASTM test methods.

KEY WORDS: water vapor transmission, testing, laboratory testing

One of the most controversial topics in building science is that of moisture in walls and roofs. Johnson asked during a Building Thermal Envelope Coordinating Council (BTECC) symposium [1] "Do we have a moisture problem?" The question was repeated in the first session of the ASTM Symposium on Mechanisms and Measurements of Water Vapor Transmission Through Materials and Systems, and a few cases of possible moisture damage were discussed. These problems involved surface condensation in either hot and humid or cold climates as well as moisture enclosed during construction in walls with limited drying potential.

Current understanding of moisture in walls was put in perspective by Gavin [2], who stated: "Although wall moisture problems are not widespread, some that do occur are of sufficient gravity to generate concern, especially if the problem's cause cannot readily be determined. Moreover, measures being used to improve building energy efficiency, both in new construction and in retrofitting of existing structures, may increase the potential for moisture condensation in walls to become a problem."

Since the 1940s the condensation of vapor has been associated with vapor diffusion. More recently, this perception has begun to change. In his 1978 paper, reprinted as the introduction to this publication, Hutcheon states: "It was then possible to relate many known cases of corrosion, water damage, freeze-thaw breakdown of masonry, and icicle formation at the tops of tall buildings to condensation resulting from moisture carried by outward air leakage that was brought into contact with cold outer parts of the building enclosure under winter conditions."

Much has been learned about the mechanisms of moisture transfer in the past two decades. Twenty years ago, we were concerned with one material characteristic only. Today moisture in the building envelope is analyzed in the context of the system; moisture accumulation is seen as a result of heat, water vapor, rain water, and air movements influenced not only

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by material properties but also by interaction of materials and components forming the envelope system.

This improvement in understanding of the mechanisms of heat and moisture transfer has already made a significant impact on designers and builders. Yet it does not appear to have reached the manufacturers of building materials. Except for modernization of equipment, not much has changed in laboratory water vapor transmission (WVT) measurements since the early 1950s. There is, however, increased confusion about the scope and significance of WVT test methods, made worse by the number of modifications applied to the tests by different testing laboratories.

In reviewing laboratory WVT measurements, one must first define the objectives of WVT testing and then examine to what extent each method satisfies the objectives. Presentations and discussions during the ASTM Symposium on Mechanisms and Measurements of WVT through Materials and Systems and the existing technical literature permit such a review of laboratory WVT measurements. The present review comprises specific recommendations for the ASTM Subcommittees C16.31 and C16.33.

Factors Affecting WVT Rate

As part of a Scandinavian program of research on moisture in buildings [3], the Danish Building Research Institute studied moisture transfer through wall sections. Each wall section (1 by 1 m), was placed between warm and cold chambers that maintained constant temperature and humidity. The objective, described by Kjaer and Christensen [4], was to investigate the correlation between the results of dry and wet cup measurements performed on small specimens under isothermal conditions [5], and results for larger specimens tested under temperature gradients.

A cold chamber, 2.5 by 2.5 by 2.8 m, was temperature controlled to approximately $\pm 1^\circ\text{C}$; humidity fluctuated slightly around 90% relative humidity (RH) level. Three conditions of temperature, -20 , -10 , and 0°C , were applied. The warm chamber, built as an insulated, double steel box with inside dimensions of 1 by 1 by 1 m, had a constant temperature of $25 \pm 0.5^\circ\text{C}$. To maintain constant air humidity, four plastic trays of salt solutions were placed on a balance. The relative humidity of the air was measured with a lithium chloride (LiCl) sensor and recorded, as were surface temperatures.

Tables 1a and 1b show WVT measurements on 15- and 30-mm-thick layers of expanded polystyrene. It may be seen that the WVT coefficient changes with the applied temperature difference. It is approximately 50% higher with a temperature difference of 45°C than with one of 25°C . In addition to differences between various specimens, the change in specimen thickness from 15 to 30 mm (Tables 1a and 1b) alters the measured WVT coefficients.

The variation of results in the Danish tests (see differences between Tests 1 and 2 in Table 1b performed on different specimens) precludes the possibility of comparison with WVT

TABLE 1a—The WVT coefficient in $\text{g}/(\text{m}^2 \cdot \text{h} \cdot \text{mm Hg})$ for 15-mm-thick layer of expanded polystyrene determined by Kjaer and Christensen [4].

Cold Side		Warm Side		WVT Coefficient, $\text{g}/(\text{m}^2 \cdot \text{h} \cdot \text{mm Hg})$
$^\circ\text{C}$	%RH	$^\circ\text{C}$	%RH	
-20	90	25	48	0.16
-10	90	25	50	0.12
0	90	25	58	0.11

TABLE 1b—The WVT coefficient in $\text{g}/(\text{m}^2 \cdot \text{h} \cdot \text{mm} \cdot \text{Hg})$ for 30-mm-thick layer of expanded polystyrene determined by Kjaer and Christensen [4] (two separate tests).

Cold Side		Warm Side		WVT Coefficient, g/(m ² · h · mm Hg)
°C	%RH	°C	%RH	
TEST 1				
−20	90	25	54	0.10
−10	90	25	61	0.08
0	90	25	57	0.07
TEST 2				
−20	90	25.6	53	0.14
−10	90	25.0	57	0.12
0	90	25.3	58	0.11

coefficient determined by cup methods. The estimated WVT coefficients for polystyrene in the Norwegian tests were 0.23 and 0.08 $\text{g}/(\text{m}^2 \cdot \text{h} \cdot \text{mm} \cdot \text{Hg})$, respectively, for 15- and 30-mm polystyrene layers. (The Norwegian tests were, however, performed at 25°C to measure WVT as a function of relative humidity [5].)

Much has been learned in the intervening years. The significance of material variability is much better appreciated. For example, Zehendner [6] has demonstrated how resistance to water vapor flow through a material depends on the manufacturing mode (Fig. 1). The diffusion resistance coefficient in Fig. 1 relates the resistance of water vapor flow through the material to flow through a still air layer of the same thickness. For material with the same density, two to three-fold differences are apparent for each mode of polyurethane foam production. For boards cut from production blocks, this difference may even be as much as five or six-fold. One must recognize, moreover, that thermally driven vapor flow may contribute substantially to moisture transfer, (see Kumaran, in this volume).

Notwithstanding these limitations, the Scandinavian research [3-5] highlighted a number of factors affecting WVT rate:

1. mean temperature of the specimen (to be discussed by Schwartz et al. in this volume),
2. mean relative humidity (to be discussed later in this paper), and
3. temperature and humidity gradients associated with different thicknesses of test specimens.

If the WVT coefficient depends on so many factors, one must be careful not to compare WVT results obtained under different test conditions. One should therefore distinguish between tests aiming at:

1. comparing materials,
2. examining the effects of boundary conditions on the WVT, and
3. examining moisture accumulation during vapor diffusion.

To compare materials, one may use isothermal and easy-to-maintain testing conditions; for example, those specified by the ASTM Test Methods for Water Vapor Transmission of Materials (E 96-80) dry-cup procedure. To examine the effect of boundary conditions on the WVT rate, one must consider whether the test conditions correspond to the service conditions. Bringing the test conditions closer to the service conditions may, however, affect the property being measured, that is, WVT coefficient. The result of the test may be affected

FIG. 1—Diffusion resistance coefficient (ratio of the resistance of material to that of still air layer with the same thickness) in relation to density and manufacturing technology of polyurethane foams: open circles = boards, filled circles = boards cut from blocks, open triangles = poured foams, and filled triangles = spray foams. Source: Zehender [6], reprinted with permission.

not only by the physical process of water vapor transmission but also by the test procedure. In effect, one measures an apparent property. This was apparent in Tables 1a and 1b. Such is the case for non-isothermal methods, which should be discussed separately. Non-isothermal testing has been shown by Schwartz et al. to be necessary in examining moisture accumulation during vapor diffusion; non-isothermal testing will be discussed later in the paper.

Isothermal WVT Test to Compare Materials

The aim of this test method is to compare materials with the highest practicable precision. One cannot assume that the WVT coefficient determined in the test relates to actual field conditions, nor that when applied in a calculation this WVT coefficient will generate the actual flow rate for conditions different from those employed in the test.

Despite these limitations, this WVT test is useful. It may be used in research and development work to compare materials, calibrate dynamic and comparative WVT test equipment (as discussed by Pike in this volume), train laboratory personnel, and in studying small

changes in material performance, for example, the effect of aging in some membranes. The ASTM dry-cup test method is an example of such a test. Actually, ASTM E 96-80 lists two test methods: dry and wet cup. The wet-cup method is, however, much less reliable than the dry-cup method, particularly for hygroscopic materials. The wet-cup method is sensitive to changes in relative humidity and surface resistance on the high relative humidity side, see Joy and Wilson [7]. Moreover, when used for hygroscopic materials, it often gives an apparent WVT coefficient that includes a substantial contribution from flow in the adsorbed or condensed liquid phase, see Babbit [8,9].

The uncertainty of the dry-cup (desiccant) method is discussed by Toas, Hoffee, Hansen, and Bertelsen in this volume. The sources of uncertainty are as follows: (1) sealing edges, (2) relative humidity oscillations, (3) air flow, (4) insufficient surface area, (5) barometric pressure, (6) stabilization of vapor flux, and (7) calculation technique.

Sealing Edges—One of the most important sources of uncertainty in the dry-cup method is to ensure that the specimen is properly sealed to the dish. It is generally accepted that the following sealants are superior to any gasket seal: a monomeric sealant, a mixture of micro-crystalline wax with a refined crystalline paraffin wax (60 and 40%), a mixture of micro-crystalline wax with a plasticizer (90 and 10%), a mixture of waxes with melting points between 60 and 75°C (oil content, 1.5 to 3%).

Techniques to seal thick specimens with a wax mixture are discussed by both Toas and Hoffee in this volume. A technique to seal edges of thin membranes is described in the Appendix.

RH Oscillations—Uncertainties arising from temperature and humidity oscillations or insufficient sensitivity of the weighing balance were also discussed by Toas and Hoffee.

Air Flow—Another source of uncertainty, the velocity of air at the material surface, is often misunderstood. Originally, a high air velocity was required, for example, more than 2.5 m/s (TAPPI (1949) standard, see Chang [10]). Later, with the development of better chamber controls, moderate air velocities were recommended, for example, DIN 52615 requires less than 0.5 m/s [11]. To maintain uniform boundary conditions, however, air velocity must be higher than 0.05 m/s, see Joy and Wilson [7].

Insufficient Surface Area—An issue not discussed during this symposium was the significant difference in minimum surface area required by ASTM E 96-80 and some European laboratories [11,12], in which specimens with surface areas two or three times larger than those required by ASTM are used. The significance of a large surface area was observed in a comparative test series performed by a Canadian laboratory using the mylar film previously tested by Institute for Research in Construction/National Research Council of Canada (IRC/NRCC). Good agreement with NRCC measurements was observed when this laboratory used large cups ($\sim 80 \text{ cm}^2$), but agreement was poor when cups of 10 cm^2 surface area were used for WVT determination (by the same personnel).

Barometric Pressure—The effect of barometric pressure variations on the precision of WVT measurements has been discussed in a short presentation to the symposium by Wilkins and Pullan [13]. They observed that although the 1970 version of ASTM E 96-66 warned of buoyancy effects caused by changes in barometric pressure for specimens with a low WVT coefficient, there is no such mention in the current ASTM standard. Wilkins and Pullan showed how important this effect may be. Figure 2 shows weight changes recorded

FIG. 2—The effect of barometric pressure on weight changes during WVT test. Source: Wilkins and Pullan [13], reprinted with permission.

in a WVT test performed during a large change in barometric pressure, and Table 2 shows WVT coefficients calculated using either a single-variable regression (weight changes versus time) or a multi-variable regression (weight changes, pressure changes, and time).

The results (Table 2) show that multi-variable regression not only increased the correlation coefficient but, in many cases, also gave a different result for the WVT coefficient. Wilkins and Pullan concluded that for materials with low permeance, for example, less than 0.05 perms ($2.9 \text{ ng/Pa} \cdot \text{s} \cdot \text{m}^2$), one must account for the barometric pressure when calculating the WVT coefficient.

Stabilization of Vapor Flux—The effect of delay in the stabilization of flow rate is particularly significant for hygroscopic materials with relatively low permeability, for example,

TABLE 2—The WVT coefficient in $\text{ng}/(\text{Pa} \cdot \text{s} \cdot \text{m}^2)$ and correlation coefficient using single and multiple regress analysis. Results obtained by Wilkins and Pullan [13] on low permeance materials.

Test Code	Multivariable Regression		Single Regression	
	WVT	Correlation	WVT	Correlation
A	0.30	0.93	0.08	0.10
B	0.67	0.98	0.48	0.56
E	0.72	0.96	0.53	0.59
C	0.82	0.99	0.62	0.67
F	1.28	0.99	1.09	0.84
H	2.61	1.00	2.42	0.96
G	3.16	1.00	2.94	0.96
D	8.67	1.00	8.56	1.00

concrete [12]. The uncertainty regarding whether or not steady state has been reached may be reduced by an appropriate calculation procedure or by a test that records both inflow and outflow fluxes. An example of such a procedure, called a modified cup, is discussed by Schwartz et al. in this volume. Moreover, for materials with a low WVT coefficient, adsorption of water vapor to the surface of the cup may also introduce errors. (Plastic cups are not recommended for testing materials with a low WVT coefficient.)

Calculation Technique—Finally, as discussed by Hoffee, the uncertainty in the WVT coefficient may also be affected by the calculation technique.

ASTM Action Sheet

The following concerns should be addressed during revision of ASTM E 96-80.

1. introduce requirements for acceptable sealing compounds and specify techniques for sample preparation,
2. consider increasing minimum surface area of the specimen,
3. define a method for calculating the WVT coefficient,
4. relate requirements for the duration of the test and the barometric pressure correction to the value of the WVT coefficient,
5. define precision and bias in relation to the value of the WVT coefficient,
6. consider introducing limits on the method's application in terms of maximum and minimum WVT coefficients.

If these concerns can be resolved, it would improve the precision of the dry-cup WVT method and make it an excellent ASTM test for comparing different materials.

Isothermal WVT Test to Examine Effect of Varying Conditions

The effects of different boundary conditions on the WVT rate are important. The significance of relative humidity for the WVT coefficient of paints and coatings was shown by Yassen and Ashton [14] and again by Batdorf in the symposium. Equally important is the effect of temperature on WVT coefficient. Schwartz et al. show that changes in WVT as a function of temperature may cause moisture accumulation in cellular plastics. It is evident that one must examine how changing boundary conditions affect the isothermal WVT rate.

Ideally, one would like to measure a material characteristic as it changes with temperature and relative humidity. This material characteristic has been called "spot permeability" [7,15]. It was determined when using a narrow range of relative humidity difference across the specimen (for example, 20% difference of relative humidity). To maintain different conditions of relative humidity, one often uses specific salts that maintain a constant partial pressure above the surface of saturated solution. There are, however, two practical limitations to this approach:

1. precision of the spot permeability (test with a narrow relative humidity range) is much lower than that of the WVT coefficient determined when a broad range of relative humidity is applied across the specimen; and
2. unless a continuous recording and averaging of the relative humidity level at the surface of the specimen is undertaken, use of salt solutions may cause a large uncertainty in relative humidity level.

Errors in the Narrow Relative Humidity Range Cup Testing

Hens [12] examined the errors in cup methods in terms of uncertainties in thickness, relative humidity, temperature, and area of the specimen. Assuming that the absolute error of temperature in the chamber is about 0.2°C , the relative error of saturation partial pressure becomes about 1.2% and the relative error of the difference in relative air humidity becomes 3% (because of the uncertainty within the cup). Total errors may vary from 5% for a relative humidity difference of 90% to as much as 18% for a relative humidity difference of 20%.

To reduce the errors in cup methods, one must maintain as large a difference in relative humidity as possible; for example, the International Standards Organization (ISO) recommendation [16] proposed WVT testing between the desiccant on one side and $90 \pm 2\%$ relative humidity on the other side at two standard temperatures, $25 \pm 2^{\circ}\text{C}$ and $38 \pm 2^{\circ}\text{C}$.

Errors Caused by Uncontrolled Relative Humidity Above Salt Solutions

Salt solutions are capable of maintaining a precise level of partial pressure in the thin layer of air above the liquid solution, but only under equilibrium conditions. In actual testing, however, temperature and air velocity variations in the chamber may cause large oscillations in the actual relative humidity level. Fournier [16] described a study of the precision of the ISO/DIS 1663.2 method in which potassium nitrate (KNO_3) salts were assumed to give nominal 88.5% relative humidity. The actual relative humidity varied between 92% (with stirring of the salt solution) and 100%, with 94 to 96% relative humidity prevailing. Table 3 shows the WVT coefficient determined with the use of salt solutions and leads to the conclusion (reached by Fournier [16]) that use of the salt solutions may only be permitted in internal quality control tests in a given laboratory. A national standard must require the use of chambers with controlled temperature and humidity. On the other hand, the performance of desiccants appears to be more reproducible when their moisture content is small (see also Chang and Hutcheon [17]).

ASTM Action Sheet

If the use of salt solution is not recommended, how can one examine the effects of different boundary conditions on the WVT rate? The answer is twofold.

1. The effects of relative humidity may be examined with a transient method based on infrared detection, such as that discussed by Batdorf and Pike in this symposium.
2. The effects of temperature may be examined with a modified cup (proposed by Schwartz et al.); this method consists of dry and wet cups placed together.

The transient method should be carefully reviewed by the ASTM Subcommittee. It may be more difficult to calibrate the newer equipment, based on infrared detection, than the

TABLE 3—The WVT rate in $\text{ng}/(\text{s} \cdot \text{m}^2)$, at 38°C with nominal 0 to 88.5% RH as specified by ISO DIS 1663-2. Material tested was $16.2 \text{ kg}/\text{m}^3$ expanded polystyrene. Five replicas tested and averaged. Data from Fournier [16].

Test Number	Chamber Lab 1	Chamber/Solution Lab 2	Solution Lab 3
1	0.94	0.93/1.42	1.40
2	0.80	0.88/1.30	1.38
3	0.85	0.87/1.29	1.38

equipment discussed by Pike. The modified cup method may require a comparative study to determine its precision. The measurement of WVT is performed at a temperature different from that in the weighing room, and this may introduce uncertainties in addition to those previously discussed.

Non-Isothermal WVT Testing

A review of test methods comprising determination of both the WVT rate and the moisture absorption under steady or varying thermal gradient conditions has been given elsewhere [18]. Moreover, the results of selected test methods have been compared with moisture absorption under field conditions by Forgues [19].

Strzepek [20] provided a brief review of WVT under thermal gradients and an update on ASTM Committee C-16 activities in this area. He stated:

In the past, measurements of water vapor transmission have been made primarily under isothermal conditions (e.g., ASTM E 96 and DIN 52615). While such measurements are useful, it is important to recognize that in most applications in which water vapor transmission is of interest, temperature differences are present in addition to water vapor pressure differences. Therefore, it is quite appropriate—in fact, imperative—that standard techniques for measuring water vapor transmission through materials be developed that include thermal gradients.

The most important of the methods based on a thermal gradient appears to be one initiated in Germany for highway insulation testing and later specified in the Swiss standard SIA 279 [21] for thermal insulation on inverted roofs. A similar procedure was used by Tobiasson and Ricard of the Cold Region Research and Engineering Laboratory (CRREL), by Hedlin (NRCC), by Knab, Jenkins, and Mathey of the National Bureau of Standards (NBS) and

FIG. 3—Volumetric water absorption in different cellular plastics introduced by a thermal gradient. Results of modified SIA 279 test (water vapor diffusion under thermal gradient) for 50-mm-thick layer of different cellular plastics: a = open cell, b through g = closed cell plastics. Source: Strzepek [20], reprinted with permission.

others, however, with different boundary conditions in each case (see Tobiasson et al. [22]). The extent of the differences in water condensation and accumulation exhibited by various cellular plastics is shown in Fig. 3 (results were obtained by Dow Chemical) using a modified SIA 279 method on 50-mm-thick specimens. Materials b through g are different closed-cell cellular plastics. One may observe that substantial amounts of moisture accumulated in some closed-cell cellular plastics when exposed to vapor diffusion under thermal gradient, although these materials had negligible intake of moisture when submersed in water under isothermal conditions.

ASTM Action Sheet

Several authors [18–22] have discussed thermal gradient methods, each however using different boundary conditions. This does not permit any comparison. A task group of ASTM Subcommittee C16.31 should review the selection of boundary conditions better related to field conditions than are used by the SIA 279 standard. This task group should also perform a ruggedness test and then proceed to develop a precision and bias statement based on a round-robin program.

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APPENDIX

Technique to Seal Edges of Membrane Specimens

The following example illustrates a technique for cutting out the membrane specimen and mounting it in aluminum cups provided with a ledge. The preparation procedure contains two stages: first, a cardboard ring is attached to the membrane (to reinforce it and keep it wrinkle-free while cutting and sealing the specimen to the dish); second, the specimen is sealed with a wax mixture into the ledge of the cup. The following stages are used.

Stage 1—A stiff, thin cardboard ring of the same size as the ledge of the test dish is dipped into the molten wax (heated to a temperature of 100°C). The cardboard ring is then carefully placed on the membrane. When the wax has solidified, the specimen is cut out of the membrane (with the cardboard ring attached).

Stage 2—The specimen is placed on the ledge of the aluminum cup and a template placed on it. The molten wax is poured around the template. When the wax has solidified, the template is removed and a fine-tipped soldering iron is run around the wall of the cup.

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