HYGROTHERMAL SIMULATION OF DRYING PERFORMANCE OF TYPICAL NORTH AMERICAN BUILDING ENVELOPE

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ABSTRACT

Hygrothermal modeling of building envelope has received much attention and development in recent years; to increase its flexibility and accessibility is a consequential task. A powerful multi-physics simulation program, FEMLAB is applied to explore an efficient method of hygrothermal modeling. This paper presents a hygrothermal model and its application to analyze moisture behavior of typical North American building envelope systems. Comparison between simulation and experiment is made. It is shown that the model has satisfactory performance and great potential for further research purpose.

INTRODUCTION

In North America, wood is a major building material. Compared with mineral or synthetic materials, wood is clean and renewable, with its aesthetic and cultural value. However, wood based materials have the natural weakness to moisture invasion. Uncontrolled moisture penetration and accumulation could cause serious moisture related damages in wooden building materials, such as stain, deformation of enclosure components, decay of materials, and also indoor air quality deterioration. Some well-known cases, like the 'leaky condos' in Vancouver, have give rise to high research interest of the durability of envelope system in both construction and academic community. Experimental methods in laboratory and in the field have been applied widely in building envelope research. However, testing method usually requires extensive effort and time.

In addition to field investigations and laboratory experimentation, research efforts have also been made to model the moisture movement phenomena theoretically and to predict hygrothermal response of envelopes with computer simulations, and therefore, ultimately provide tools to design better envelope systems. With the development of numerical technique and computation capability provided by computer facility, computer simulation becomes a reachable research alternative, which can provide great time and cost saving.

In building envelope research, already many hygrothermal models are developed (Straube & Burnett, 2001), for example, especially in North America, the MOISTURE-EXPERT (Karagiozis, 2001) and the hygRIC (Maref, 2002). Before these modeling tools can be widely used, more research work is still required for validation, and increase in accessibility. In this paper, an advanced finite element method software, FEMLAB, is used to establish hygrothermal simulation models. It features built-in model for physical phenomena (unfortunately, not the hygrothermal mechanisms), interactive user interfaces; and is compatible with MATLAB functionalities (COMSOL, 2003). It has been used successfully to analyze moisture movements in bricks (Schijndel, 2002).

Moisture accumulation by rain penetration and vapor condensation in stud cavity of envelope is a major cause for envelope components decay. Methods or approaches were proposed to avoid or reduce moisture invasion, for example, the concept of four lines of defense, namely, deflection, drainage, drying and durable materials, were advocated by Hazleden and Morris (1999). The solution for moisture problems in terms of better design guidelines relies on full understanding and predication of the moisture behavior in stud cavity and drying mechanisms.

An experimental project is being carried out to evaluate the drying potential of sheathing materials and different envelope systems. A full-scale testing hut will be constructed in a large-scale environment chamber. Interior condition of the hut is set at indoor condition; and chamber condition is set at outdoor condition. Building envelope systems tested are installed as walls of the test hut. Temperature, relative humidity, moisture content sensors and gravimetric samples are installed on the sheathing and other components of the envelope. In the running period of the experiments, data from sensors and gravimetric samples will be recorded to monitor the hygrothermal response of envelopes. A preliminary test has been carried out to evaluate the experimental design.

As one part of this project, a hygrothermal model is developed in FEMLAB and applied to compare with experimental results and analyze factors that could affect experimental results.

DESCRIBTION OF HYGROTHERMAL MODEL

The driving potentials of the presented hygrothermal model are temperature (*T*) for heat transfer, and relative humidity (φ) for moisture transfer. The advantage to use relative humidity is that relative humidity maintains continuity across material boundaries (Galbraith et al, 1997). Moisture transfer mechanisms include vapor diffusion, surface diffusion and liquid capillary suction. Heat transfer mechanisms are thermal conduction, latent flow by vapor diffusion. Heat transfer caused by liquid flow is ignored, for its insignificant contribution to the enthalpy change. Heat and moisture resource in building components or boundary can also be accommodated.

Moisture transfer

Moisture transfer includes vapor transfer part (m_v) and liquid transfer part (m_l).

Vapor transfer

$$m_v = -\delta_p \nabla P_v \quad (1)$$

Liquid transfer

$$m_l = -\rho_o D_w \nabla u \quad (2)$$

where, δ_p is water vapor permeability, P_v is water vapor pressure, ρ_o is dry material density, D_w is liquid moisture diffusivity and u is water content.

Water vapor pressure is:

$$P_v = P_{sat} \cdot \varphi \quad (3)$$

where, P_{sat} is saturation vapor pressure. It is calculated by following equation (Bolton 1980).

$$P_{sat} = 611.2 \cdot e^{((17.67 \cdot T)/(243.5+T))} \quad (4)$$

The conservation equation for moisture in both gas and liquid forms is:

$$\rho_o \frac{\partial(u)}{\partial t} = -\nabla(m_l + m_v) + Q_m \quad (5)$$

where, t is time and Q_m is the source term for possible moisture source or sink.

Heat transfer

Heat transfer includes conduction part (q_λ) and latent flow part (q_v).

Heat conduction

$$q_\lambda = -\lambda \cdot \nabla T \quad (6)$$

Latent flow

$$q_v = -L_v \delta_p \nabla p_v \quad (7)$$

where, λ is effective thermal conductivity, L_v is enthalpy of evaporation/condensation.

The conservation equations for heat transfer are:

$$\rho_o (C_d + u \cdot C_w) \frac{\partial T}{\partial t} = -\nabla(q_\lambda + q_v) + Qh \quad (8)$$

where, C_d is dry specific heat of building material, C_w is specific heat of water and Q_h is the heat source or sink term.

MATERIAL PROPERTIES

Major material properties required for hygrothermal simulations are mass density (ρ_o), thermal conductivity (λ), specific heat capability (C_d), vapor permeability (δ_p), moisture diffusivity (D_w), and moisture storage curve, which builds the relation between moisture content (u) and relative humidity (φ). The Material properties used in the model are from published model WUFI (Kunzel, 1995), MOIST (Burch, 1997) and ASHREA report (Kumaran et al, 2002), and presented in Table 1. Weather barrier and vapor barrier are assumed no heat and moisture storage capability.

Table 1 Material properties in modeling

Materials	Hygrothermal properties
weather barrier (spun bonded polyolefin)	$\delta_p = 3.2e-9$
Plywood	$\rho_o = 500$ $\lambda = 0.075$ $c_d = 1214$

	$u = \frac{0.34\varphi}{(1+0.62\varphi)\cdot(1-0.83\varphi)}$ $\delta_p = (0.81e-12)+$ $(0.16e-14)\cdot\exp(9.8\varphi)$ $D_w = (0.23e-9)\cdot\exp(2.8u)$
Low-density glass fiber insulation	$\rho_o = 11.5$ $\lambda = 0.043$ $c_d = 840$ $u = \frac{0.014\varphi}{(1+10.4\varphi)\cdot(1-0.96\varphi)}$ $\delta_p = 1.72e-10$ $D_w = 0$
vapor barrier (polyethylene)	$\delta_p = 0.53e-15$
Gypsum board	$\rho_o = 625$ $\lambda = 0.16$ $c_d = 1089$ $u = \frac{0.0034\varphi}{1-0.90\varphi}$ $\delta_p = 0.64e-10$ $D_w = (0.79e-8)\cdot\exp(3.9u)$

BOUNDARY CONDITION

Effects of solar radiation and rain wetting are not considered in the modeling. The heat and moisture transfer on building envelope surface is through a thin layer of air, which creates a surface heat and moisture transfer resistance.

Heat flow through building envelope surface is

$$q=\alpha\cdot(T_a-T_s) \quad (9)$$

where, q is heat flux density through building surface, α is heat transfer coefficient, including convection and long wave radiation effects, T_a is ambient air temperature and T_s is surface temperature of building component.

Surface heat transfer coefficient α is

$$\alpha = \alpha_c + \alpha_r \quad (10)$$

where, a_c is convective heat transfer coefficient, α_r is long-wave radiation heat transfer coefficient.

Similarly, vapor transfer is calculated by:

$$m_v = \beta_p(P_u - P_o) \quad (11)$$

where, m_v is water vapor flux density through building component surface, β_p is water vapor transfer coefficient, P_o is ambient water vapor pressure and P_u is water vapor pressure on the building component surface.

The convective water vapor transfer coefficient is calculated by analogy relation with convection heat transfer coefficient a_c.

$$\beta_p = 7.7\cdot 10^{-9} a_c \quad (12)$$

Since the testing hut is installed in the environmental chamber and the temperature difference between ambient surrounding and the envelope panel is very small, the radiation heat transfer coefficient is ignored in calculation. Thus, the surface heat transfer coefficient is simplified as the convective heat transfer coefficient.

Dimensional analysis is applied to calculate convective heat transfer coefficients. The dimensionless Reynolds number (*Re*), Nusselt number (*Nu*), Prandtl number (*Pr*) and Grasshof number (*Gr*) are used to determine the flow status on the surface of envelope.

The convective heat and moisture transfer coefficients in the presented modeling are:

Exterior surface

a_c = 5.6 $W/m^2.^oC$

β_p = 4.31e-8 $kg/m^2\cdot s\cdot Pa$

Interior surface

a_c = 2.4 $W/m^2.^oC$

β_p = 1.85e-8 $kg/m^2\cdot s\cdot Pa$

In the cavity below insulation, water vapor evaporates from water tray and is absorbed by sheathing board and insulation, seen in Figure 1. The heat and moisture transfer coefficients applied on sheathing surface is

a_c = 0.25 $W/m^2.^oC$,

β_p = 1.925e-9 $kg/m^2\cdot s\cdot Pa$.

Since low density insulation is open porous material, the convective resistance on the surface of insulation is set at zero.

APPLICATION AND ANALYSIS

Application of the model is described in this part. The moisture distribution in sheathing is investigated by comparison between experimental result and simulation. Then, the influence of vapor barrier and convective heat and mass transfer coefficients are investigated by simulation.

The assumptions of simulation are described as following: the simulation is two-dimensional, and two axles are the height (y) and thickness (x) of the panel; the construction is airtight and convection doesn't exist in materials; effect of air convection is considered in calculation of convective heat and moisture transfer coefficients, weather barrier and vapor barrier have vapor resistance, but no thermal resistance and heat and moisture storage capability.

Preliminary experimental setup

The structure of the tested panel in the preliminary test is shown in Figure 1. A water tray is put at the bottom of stud cavity, works as moisture source. The upper space of the water tray in stud cavity is filled with insulation material, same as a normal envelope.

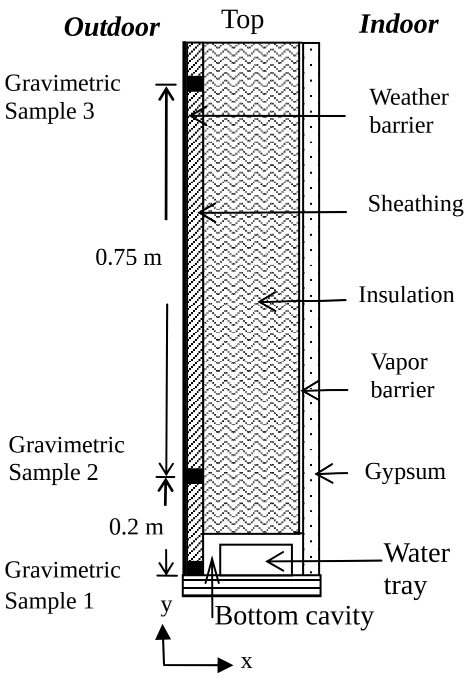

Figure 1 Sketch of experimental setup, a water tray is put at the bottom of stud cavity

The materials of a typical envelope panel are shown in Table 2. Envelope panel is installed on a test hut in a large-scale environmental chamber. The inside space of the test hut is conditioned at indoor condition: 21^{o}C, 60% relative humidity and air flow is natural convection; the outside space of the test hut is conditioned at outdoor condition: 13.5^{o}C, 60% relative humidity and air flow pattern is natural convection. Temperature, relative humidity, and moisture content sensors are installed on sheathing and other envelope components. Gravimetric samples, with a diameter of 0.039m and thickness of 0.019m, are cut at different locations on the sheathing. Figure 1 indicates the locations for the three gravimetric samples at different heights. Before testing, the plywood sheathing is conditioned to the initial moisture content of around 10% by mass. The experiment runs for a period of 72days,

Table 2 Composition of the base case wall section

Envelope components
The panel is assumed as 1 m high.
1. spun bonded polyolefin membrane with crinkled surface as weather barrier
2. plywood sheathing, 19 mm
3. fiberglass insulation, 140 mm
4. polyethylene vapor barrier,
5. interior gypsum board, 19 mm

Moisture distribution in sheathing board

Moisture distribution in sheathing board is a major question in the research project. Through experiment and simulation, moisture migration direction and amount in sheathing board in a certain wetting or drying process is investigated. This information will be used to develop moisture defense strategy.

The relative humidity contour profile at the end time of simulation is presented in Figure 2. The dense lines around the water tray cavity illustrate the gradient of relative humidity, which indicates higher moisture concentration in the lower part of plywood sheathing than upper part.

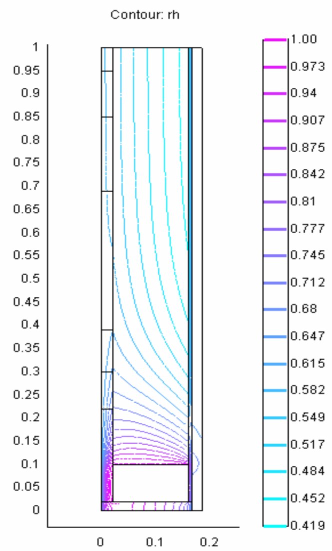

Figure 2 Contour of relative humidity in envelope

In the testing, vapor pressures in stud cavity are calculated using temperature and relative humidity measured. The stud cavity is filled with loose insulation material. The sensors are fixed in the middle thickness of stud cavity and at three heights: 0.1m, 0.5m, and 0.95m. Vapor pressure at the end of testing period is compared with simulation results, shown in Figure 3. Both experiment and simulation show a water vapor pressure gradient along the height of stud cavity. The water vapor pressure is higher at the lower part of stud cavity than that at higher part, and the gradient indicates an upward moving direction of moisture. A vapor pressure gradient also exists across the stud cavity, which drives vapor flow from stud cavity to exterior, especially near the water tray. At the top part of stud cavity, the horizontal vapor pressure gradient is small due to very small vapor resistance of the insulation.

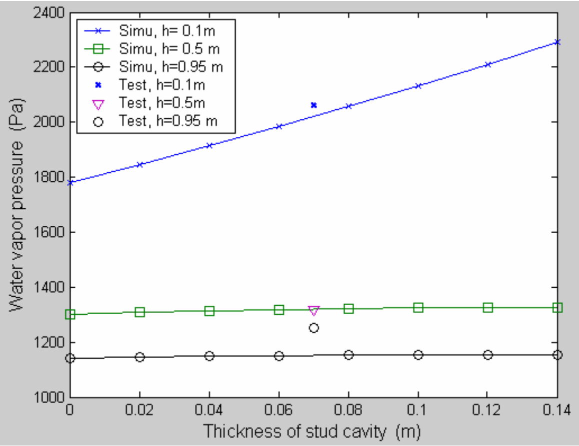

Figure 3 Comparison of Vapor pressure in study cavity by simulation and test

Moisture distribution in plywood sheathing is investigated by gravimetric samples and simulation, shown in Figure 4. Sample 1 is at the bottom of sheathing. Because interior surface of sample 1 is exposed to water vapor evaporation from the water tray, significant moisture increase is observed. It reaches stable moisture content around 16%. Further away from the moisture source, sample 2 absorbs less moisture than sample 1, and reaches a stable moisture content of 13.5%. Sample 3 is at the top of sheathing, is not much affected by the water tray. Its moisture content should decrease to reach equilibrium with the ambient air, as the prediction of simulation. In testing, the moisture content of gravimetric sample 3 shows a small oscillation and then falls down slowly, the possible reason is that the influence of air convection is not considered in simulation. Generally, the simulation presents the same moisture movement tendency with gravimetric measurement.

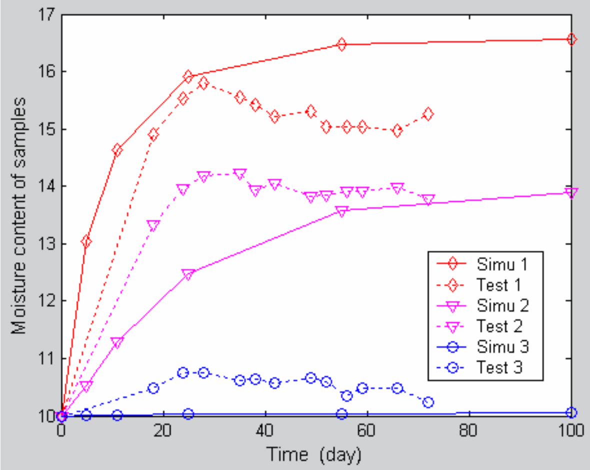

Figure 4 Comparison of Moisture contents of sheathing panel from gravimetry and simulation

Uneven moisture distribution in gravimetric samples at different heights is observed from experimental result. A further analysis of moisture distribution in sheathing is provided by simulation. In Figure 5, moisture distribution at the end of a 100days simulation period, through the thickness of plywood at different height is plotted. Each line is the moisture content at a certain height. All lines show the moisture content near the exterior surface is lower than that near interior surface. The gradient of moisture content indicates a drying direction from interior to exterior. Moreover, the moisture concentration at lower part of sheathing is higher than that at upper part. Lines 1 & 2 present a moisture content level more than 20% by mass near the interior surface of sheathing, which signifies the vulnerable location to mold growth and material decay.

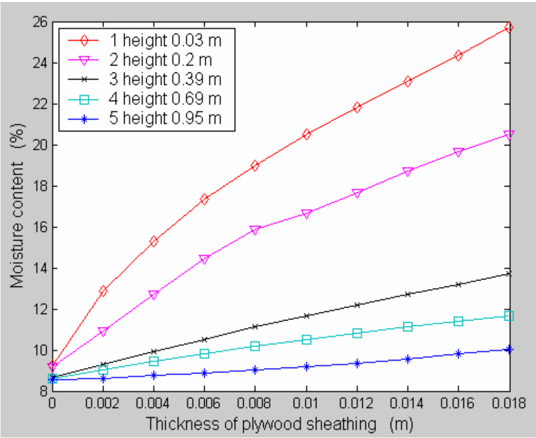

Figure 5 Moisture distribution through the thickness of plywood sheathing at different height

The influence of vapor barrier

Vapor barrier is widely used to prevent vapor condensation in walls. Its influence to the drying process is investigated by modeling. The material properties and boundary condition of simulation are same as the preliminary experiment. And the initial moisture content of plywood sheathing is set at 8%. Under this setting, the indoor water vapor pressure is higher than the vapor pressure in materials and outdoors, so vapor diffusion direction is from indoors to outdoors. Two cases, with and without vapor barrier (polyethylene), are shown in Figure 6. The average moisture content of the entire plywood sheathing with a vapor barrier is lower than the case without a vapor barrier in the whole period of modeling. It demonstrates that vapor barrier could protect sheathing material from moisture accumulation due to diffusion from indoor space.

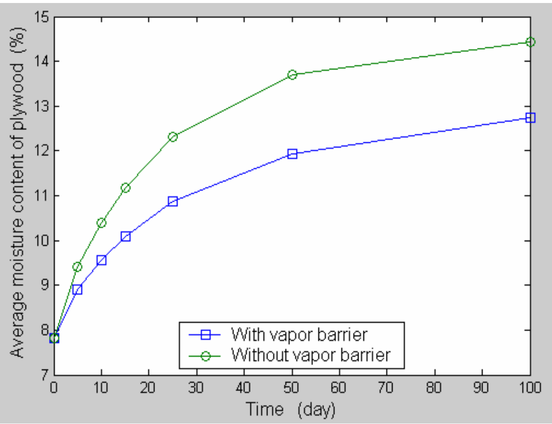

Figure 6 Average moisture content of sheathings with and without vapor barrier

Convective heat and moisture transfer coefficients on sheathing surface

In the preliminary experiment, the sheathing panel is covered by a layer of weather barrier (spun bonded polyolefin membrane with crinkled surface), without any cladding. But, in the subsequent full-scale experiment, a cladding (wood siding or stucco) is added on sheathing to emulate the real situation of building. The influence of this change is investigated by simulation. A third case, forced convection on exterior surface of sheathing board, also is simulated for the purpose of comparison.

In Table 3, the convective transfer coefficients of the exterior surface of sheathing are set at three possible convection conditions. Other settings are same as the preliminary experiment.

Table 3 Convection coefficients in simulation

Sheathing is exposed under natural convection. a_c = 5.6 $W/m^2 \cdot {}^oC$; β_p = 4.31e-8 $kg/m^2 \cdot s \cdot Pa$
Sheathing is exposed under forced convection. a_c = 9.5 $W/m^2 \cdot {}^oC$; β_p = 7.32e-008 $kg/m^2 \cdot s \cdot Pa$
Sheathing is covered by cladding and natural convection occurs in air gap, it is assumed that air condition in air gap is the same as outdoors. a_c = 1.31 $W/m^2 \cdot {}^oC$; β_p = 1.008e-8 $kg/m^2 \cdot s \cdot Pa$

Simulation result is shown in Figure 7, the stronger the convection on surface is, the more moisture the sheathing absorbs in the same period. The faster increase in the moisture accumulation by sheathing in turn implies a faster drying rate of the envelope in removing the moisture from inside the insulation cavity. Convection is a positive factor to increase drying capability of sheathing.

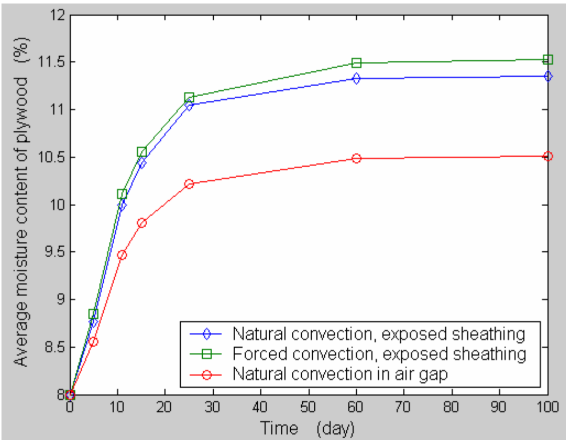

Figure 7 Average moisture content of plywood sheathing under various convective conditions

CONCLUSION

Computational simulation of hygrothermal phenomena of building envelope is an important research field with the great benefit of time and cost saving. Accurate modeling needs well developed database of material properties and boundary settings, and in-depth knowledge to choose suitable physics mechanisms and numerical methods.

Hygrothermal modeling is carried out in this paper to compare with preliminary experimental results. The simulation and experiment show general agreement of moisture accumulation rate and distribution in sheathing board. Other simulation work includes investigation of the influence of vapor barrier and the air flow pattern on exterior surface of envelope.

Also, it is demonstrated in this paper that FEMLAB program is a flexible and accessible tool to ease the computation aspect of simulation.

NOMENCLATURE

C_d ($J/kg{\cdot}^oC$) dry specific heat of building material

C_w ($J/kg{\cdot}^oC$) specific heat of water

D_w (m^2/s) liquid diffusivity

Gr (-) Grasshof number

L_v (J/kg) enthalpy of evaporation/condensation

m_v ($kg/m^2 \cdot s$) water vapor flux rate

m_l ($kg/m^2 \cdot s$) water liquid flux rate

Nu (-) Nusselt number

P_{sat} (Pa) Saturation vapor pressure

p_v (Pa) water vapor pressure

P_o (Pa) Ambient water vapor pressure

P_u (Pa) Water vapor pressure on the building component surface

Pr (-) Prandtl number

q (W/m^2) heat flow rate

q_λ (W/m^2) heat flow rate by conduction

q_v (W/m^2) heat flow rate by vapor diffusion

Re (-) Reynolds number

t (s) time

T (° C) temperature

T_a (° C) ambient air temperature

T_s (° C) surface temperature of building component

u (%, kg(moisture)/kg(dry material)) moisture content

α ($W/m^2{\cdot}^oC$) surface heat transfer coefficient

a_c ($W/m^2{\cdot}^oC$) convective heat transfer coefficient

α_r ($W/m^2{\cdot}^oC$) long-wave radiation heat transfer coefficient

β_p ($kg/m^2 \cdot s \cdot Pa$) surface water vapor transfer coefficient

δ_p ($Kg/m{\cdot}s{\cdot}Pa$) water vapor permeability

φ (%) relative humidity

λ ($W/m{\cdot}^oC$) effective thermal conductivity.

ρ_o (kg/m^3) dry material density

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