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A Computer Analysis of Wall Constructions in the Moisture Control Handbook

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ABSTRACT

A computer model, called MOIST, is used to investigate the moisture performance of recommended wall constructions given in the Moisture Control Handbook (1991). These wall constructions are intended to minimize moisture accumulation, thereby preventing material degradation, mold and mildew growth, and loss in thermal performance.

For the heating climate (northern United States) and mixed climate (central United States), all the wall constructions in the Moisture Control Handbook were found to perform satisfactorily. That is, when the surface relative humidities of the construction layers were plotted versus time of year, the peak relative humidities were always found to be within acceptable limits that preclude material degradation and mold and mildew growth.

For the cooling climate (south-eastern United States), one of the walls had risk of mold and mildew growth behind an interior vapor retarder. During the summer, moisture from the outdoor environment diffused inwardly into this construction. Upon reaching the interior vapor retarder, moisture was significantly retarded and accumulated, thereby causing the surface relative humidity to rise above the critical 80% level for mold and mildew growth. An interesting finding was that moisture accumulated during the winter at exterior layers having low permeability, thereby giving rise to relative humidities above a critical level (80%). However, this moisture accumulation occurred at relatively low outdoor temperatures, which would slow mold and mildew growth.

For a cooling climate, a permeable wall (i.e., without vapor retarding layers and low-permeability materials) was found to perform satisfactorily. During both winter and summer periods, moisture passed through the construction and did not significantly accumulate within construction layers.

KEY WORDS

material degradation, moisture, moisture control guidelines, moisture transfer model, mold and mildew growth, vapor retarders, vinyl wallpaper, and wall construction.

INTRODUCTION

In cold heating climates (northern United States), the absolute humidity of the air within a residence is considerably higher than that of the outdoor environment during the winter. In this situation, moisture from the indoor environment permeates outwardly through walls by way of diffusion and, more importantly, air exfiltration through openings and cracks in the construction. This moisture is absorbed and may condense at exterior layers of the construction. Duff (1968) has observed that the moisture content at the siding and sheathing increases during cold winter periods and subsequently decreases during warm summer periods. Seasonal variations in moisture content of exterior construction layers have been predicted by Burch and TenWolde (1993).

In cooling climates (south-eastern United States), moisture from the outdoor environment is transferred inwardly into wall construction by way of diffusion and, more importantly, by air infiltration during the summer. When a low-permeability wallpaper is installed at the interior surface, moisture accumulates within the adjacent gypsum board. The surface relative humidity may approach a saturated state, thereby providing a conducive environment for mold and mildew growth. Characteristic pink and chartreuse splotches develop on the back side of the wallpaper. In addition, mold and mildew colonies emit fungal spores which may cause an indoor air quality problem (e.g., musty odor) and health related problems (e.g., respiratory illness). Such mold and mildew problems have been documented in field studies by Lstiburek (1992a, 1992b) and in computer analysis by Burch (1993).

In a mixed climate (central United States), walls experience both of the above problems, but to a lesser extent. In mixed climates, it is difficult to determine which problem dominates. Therefore, the construction should accommodate both problems to achieve satisfactory performance.

Moisture accumulation within insulation materials increases the heat transmission in building envelopes in two ways. First, the presence of moisture within the pore structure of an insulation increases the steady-state heat conduction (see Knab, Jenkins, and Mathey 1980). Second, an outdoor diurnal temperature cycle may cause liquid water to evaporate from one part of a construction and condense in another part, thereby giving rise to a latent heat transfer effect (see Hedlin 1988).

Lstiburek and Carmody (1991) recently prepared a Moisture Control Handbook to provide guidance to architects and building designers. This handbook recommends walls, foundations, and roof constructions for three different climatic regions of the United States (see Figure 1). These constructions are intended to minimize moisture accumulation, thereby preventing degradation of materials, mold and mildew growth, and loss of thermal performance. The selection of walls for the handbook was achieved through consensus of a panel of experts from Government and industry. In some cases, wall constructions were included in the handbook for which a minority of the panel had concerns regarding their moisture performance.

In this report, a computer model, called MOIST, is used to investigate the performance of all the recommended wall constructions given in the Moisture Control Handbook. Program MOIST predicts the one-dimensional transfer of heat and moisture in a multi-layer building construction under nonisothermal conditions. The analysis is limited in that it does not include the effects of convective transport of moisture by air infiltration or air exfiltration, and wetting by rain is neglected. The program inputs hourly ASHRAE weather data (Crow 1981), and predicts the relative humidity (or moisture content) and temperature of the construction layers as a function of time of year. This program includes moisture transfer by diffusion, capillary flow, and one-dimensional algorithms to approximate convective transfer of moisture. The moisture-transfer resistance offered by vapor retarders and paint layers are readily included in simulations.

DESCRIPTION OF COMPUTER MODEL

Theory

Within each layer of a wall construction, moisture transfer is governed by the following one-dimensional conservation of mass equation[1]:

$$\frac{\partial}{\partial y}\left[D_\gamma(\gamma,T)\frac{\partial \gamma}{\partial y}\right] + \frac{\partial}{\partial y}\left[D_T(\gamma,T)\frac{\partial T}{\partial y}\right] = \frac{\partial \gamma}{\partial t} \qquad \textbf{(1)}$$

The selection of moisture content (γ) and temperature (T) as potentials has the advantage that the same mathematical formulation represents both diffusion transfer and capillary transfer. This formulation is equivalent to using water-vapor pressure as the moisture transfer potential in the diffusion regime and suction pressure in the capillary flow regime with a single required diffusivity.

Heat transfer is governed by the one-dimensional conservation of energy equation:

$$\frac{\partial}{\partial y}\left[k(\gamma,T)\frac{\partial T}{\partial y}\right] = \rho_d\left(C_d + \gamma C_w\right)\frac{\partial T}{\partial t} \qquad \textbf{(2)}$$

Latent transport of heat is included at the boundaries of the layers. The other components of enthalpy transport by moisture movement are generally small and are therefore neglected in the analysis. In the term $\rho(C_d + \gamma C_w)$ the heat capacity of dry material is given by ρC_d and the heat capacity of the accumulate moisture is given by $\rho\gamma C_w$.

In the preceding two governing equations, strong couplings exist between heat and moisture transfer. Both the diffusivity for the moisture gradient (D_γ) and the diffusivity for the temperature gradient (D_T) are strong functions of moisture content and temperature. The thermal conductivity (k) can also be a function of moisture content and temperature, but for the present analysis it is assumed to be constant.

When the moisture content of a material is below fiber saturation, the diffusivity for the moisture gradient (D_γ) and the diffusivity for the temperature gradient (D_T) are calculated by the relations:

$$D_\gamma = \frac{\mu(\phi)P_{vg}(T)}{\rho_d\frac{\partial f(\phi)}{\partial \phi}} \quad \text{and} \quad D_T = \frac{\mu(\phi)\phi\frac{\partial P_{vg}(T)}{\partial T}}{\rho_d} \qquad \textbf{(3)}$$

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[1] Symbols are defined in the Nomenclature Section.

The above equations may be derived by introducing the sorption isotherm function $f(\phi)$ and applying the chain rule to Fick's steady-state diffusion equation with the gradient of the water-vapor pressure as the driving-force potential.

When the moisture content of a material is above fiber saturation, a liquid diffusivity (D_γ) is used in Equation (1). It is calculated using procedures given in Burch and Thomas (1991). The diffusivity for the temperature gradient (D_T) is calculated using the second relation of Equation (3).

The model also has a provision for including non-storage layers (e.g., an air space, glass-fiber insulation, a vapor retarder, etc.) that may be sandwiched between two storage layers. In a non-storage layer, the storage of heat and moisture is neglected, and the transfer of heat and moisture is assumed to be steady-state. The model includes one-dimensional algorithms to model a constant flow rate of indoor or outdoor air to the non-storage layer.

The MOIST model has recently been verified in the hygroscopic regime by way of comparison to a series of laboratory experiments (Zarr, et al. 1995). A more detailed description of the model is given in Burch and Thomas (1991).

Solution Procedure

Equations (1-2) were recast into finite-difference equations using a uniform nodal spacing within each layer. An implicit solution technique with coupling between the two conservation equations was used to solve the equations. A FORTRAN 77 computer program, called MOIST, with a tridiagonal-matrix solution algorithm was prepared. At each time step, the calculation proceeds by first solving for the temperature distribution, after which a set of moisture contents is calculated. The relative humidity is calculated from the sorption isotherm relation.

When the computer program was run on a Model 386 personal computer with a 33 Mhz clock speed, equipped with a math co-processor, about 30-60 minutes of computer time was required to simulate one year of real time, depending on the wall construction. Program MOIST can be obtained at no cost from the National Institute of Standards and Technology[2].

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[2]Copies of the MOIST Program is available from Kimberly Whitter, National Institute of Standards and Technology, Building 226, Room B320, Gaithersburg, Maryland 20899, Fax (301) 990-4192, E-mail Whitter@micf.nist.gov (via Internet).

MOISTURE PROPERTY DATA

Water-vapor permeances of the hygroscopic construction materials are plotted versus relative humidity in Figure 2. For the wood-base materials and concrete block, the permeance increases by more than a factor of ten from a dry to a saturated state. In these instances, it is very important to include property variations in hygrothermal analysis. Sources for these permeances data are given in Table 1.

Table 1
Sources for Permeances of Hygroscopic Materials

No.	Description	Source
1	Wood Siding	Burch, Thomas, Fanney (1992)
2	Exterior-Grade Plywood	Burch, Thomas, Fanney (1992)
3	Gypsum Board	Burch, Thomas, Fanney (1992)
4	Asphalt-Impreg. Sheathing	Burch, Thomas, Fanney (1992)
5	Cement Parge Coat	Tveit (1966)
6	Concrete Block	Int. Energy Agency (1991)
7	Stucco Finish	Engineering Estimate
8	Brick	ASHRAE (1993)
9	Extruded Polystyrene	ASHRAE (1993)
10	Glass-Fiber Board	Burch (1995)

The permeability (product of permeance and thickness) of hygroscopic materials were fit to an equation of the form:

$$\mu = \exp(A_0 + A_1\phi + A_2\phi^2). \tag{4}$$

The coefficients (A_0, A_1, and A_2) were determined by regression analysis. The permeability equations were included in Program MOIST.

In the computer analysis, the storage of moisture was small and therefore neglected in several of the construction materials either because they were very thin layers or because they were weakly hygroscopic and did not absorb much moisture. Permeances of these relatively non-hygroscopic materials are given in Table 2.

Table 2 Permeance of Relatively Non-Hygroscopic Materials			
Material	Permeance		Source
	Perm[2]$_{SI}$	Perm[2]$_{IP}$	
19-25 mm Vert. Air Space	9,300	162	See Footnote 3
Vinyl Wallpaper	26	0.45	Burch, et al. (1992)
Latex Paint	575	10	Based on ASHRAE (1993)
Oil-Base Paint	115	2	Based on ASHRAE (1993)
Vapor Retarder	57	1	ASHRAE (1993)

[2] A $perm_{SI}$ equals $ng/s{\cdot}m^2{\cdot}Pa$, and a $perm_{IP}$ equals $grain/h{\cdot}ft^2{\cdot}inHg$.
[3] The permeance of a vertical air space (h_w) was calculated using the Lewis relation:

$$Le = 0.622 \frac{h_c}{h_w C_a P_{atm}}$$

where the Lewis number ($Le = 0.927$), the convective conductance of the air space ($h_c = 1.4$ $W/m^2{\cdot}°C$), the specific heat of air ($C_a = 1000$ $J/kg{\cdot}°C$), and atmospheric pressure ($P_{atm} = 1.01 \times 10^5$ Pa).

HEATING CLIMATE ANALYSIS

Program MOIST was first used to predict surface relative humidities at the construction layers versus time of year for all the walls of the heating climate. The indoor temperature was assumed to be 21°C (70°F). Separate computer simulations were carried out for indoor relative humidities of 35% and 50%. Hourly outdoor temperatures, relative humidities, and solar radiations were obtained from ASHRAE WYEC weather data for Madison, WI (Crow 1981). Winter moisture problems tend to become worse in colder climates. For these results and all subsequent results, six months of pre-conditioning weather data were used to initialize the simulations so that the results would be less dependent on assumed initial moisture content and temperature.

Description of Wall Constructions

The wall constructions analyzed for the heating climate are given in Figure 3. With the exception of Wall 6, an interior vapor retarder was installed in all the wall constructions. In Wall 4, the vinyl wallpaper served as an interior vapor retarder.

In these results and the results that follow, the walls faced north, and the solar absorptance of the exterior surface was 0.7. The effect of wood-framing members was neglected.

Discussion of Results

In the heating climate analysis, program MOIST was first used to simulate the performance of Wall 1 without an interior vapor retarder. In the Moisture Control Handbook, Wall 1 has an interior vapor retarder. In the first simulation, the vapor retarder is omitted for illustration purposes. A plot of the surface relative humidity at the construction layers versus time of year is given in Figures 4a and 4b for relative humidities of 35% and 50%, respectively. The horizontal broken line depicts a saturated relative humidity (97%) above which liquid water exists within the pore structure of a material[3]. When the indoor relative humidity was 35%, the relative humidity at the inside sheathing surface was saturated for 1.5 winter months. When the indoor relative humidity was 50%, the sheathing was saturated for 3-4 winter months, and inside wood surface approached saturation for 2 months.

Program MOIST was next used to predict the performance of Wall 1 with a vapor retarder (as it is in the Moisture Control Handbook). The results are given in Figures 5a and 5b for an indoor relative humidity of 35% and 50%, respectively. The surface relative humidity at all locations of the construction is seen to be significantly below saturation (97%). These results indicate an interior vapor retarder is effective in reducing the ingress of indoor moisture inwardly into wall construction, thereby preventing moisture accumulation in exterior

[3]In the MOIST computer model, capillary water exist within the pore space of a material when the interstical relative humidity is above 97%.

construction layers.

Results for Walls 2-6 are given in Figures 6 and 7, for indoor relative humidity of 35% and 50%, respectively. In all cases, the surface relative humidity at all locations within the construction was significantly below saturation (97%). In Walls 2-5, the interior vapor retarder is effective in reducing moisture accumulation within exterior construction layers. In Wall 4, vinyl wallpaper performed as an interior vapor retarder. It is note worthy that Wall 6 performed satisfactorily, even though the construction did not contain an interior vapor retarder.

Wall 6 performs well because the temperature at the inside surface of the polystyrene is relatively high (high R-value) and thus the surface relative humidity stays low. The satisfactory performance of walls with foam sheathing exposed to winter climate has been demonstrated by Sherwood (1983).

MIXED CLIMATE ANALYSIS

Program MOIST was next used to predict surface relative humidities at the construction layers versus time of year for all the walls of the mixed climate. As in the case of the heating climate results, the indoor temperature was assumed to be 21°C (70°F), unless indicated otherwise. Separate computer simulations were carried out for an indoor relative humidity of 35% and 50%. Hourly outdoor temperatures, relative humidities, and solar radiations were obtained from ASHRAE WYEC weather data for Washington, DC (Crow 1981).

Description of Wall Constructions

The five wall constructions for the mixed climate are given in Figure 8. Note that Walls 1-3 have an interior vapor retarder, while Walls 4-5 do not. Water-vapor permeances of the materials are given in Tables 1 and 2.

Discussion of Results

In each of the plots, the dashed horizontal line depicts a saturated relative humidity (97%) considered in this analysis to coincide with material degradation during cold winter periods. The solid horizontal line depicts a critical relative humidity (80%) considered to coincide with mold and mildew growth during hot and humid periods. The International Energy Agency (IEA 1990) has recently published Guidelines and Practices (Volume 2) for preventing mold and mildew growth at building surfaces. This consensus document indicates that a monthly mean surface relative humidity above 80% is conducive to mold and mildew growth. Some experts in the United States (e.g., Philip Morey 1994) believe that this critical relative humidity should be lower.

Results for Walls 1-5 are given in Figure 9 for an indoor relative humidity of 35%. During the winter months, the surface relative humidity was always below saturation (97%). In Walls 2-3, the surface relative humidity at the exterior surface of the vapor retarder reached the threshold relative humidity (80%) for mold and mildew growth during the summer months. This behavior is shown below to be an artifact of maintaining an indoor temperature of 21°C (70°F) during the summer.

A special computer simulation was carried out for Wall 2 with separate winter and summer indoor setpoint temperatures 21°C (70°F) for winter and 24°C (76°F) for summer). The results are given in Figure 10. The higher summer setpoint temperature caused the relative humidity at the vapor retarder to decrease below the critical 80% level.

Similar results for Walls 1-5 are given in Figure 11 for an indoor relative humidity of 50%. Here the higher indoor relative humidity causes more moisture to be transferred from the indoor into the wall constructions. In Walls 4 and 5 (without an interior vapor retarder), the surface relative humidity at the insulated sheathing briefly reaches saturation in January. This is believed to pose little or no risk to the construction. Walls 4-5 were believed to perform satisfactorily without an interior vapor retarder because the temperature at the inside surface of the foam sheathing is relatively high (high R-value) and the surface relative humidity stays low, thereby preventing surface condensation.

COOLING CLIMATE ANALYSIS

Program MOIST was next used to predict surface relative humidities at the construction layers versus time of year for all the walls of the cooling climate. The indoor temperature and relative humidity were assumed to be 24°C (76°F) and 50%, respectively. Hourly outdoor temperatures, relative humidities, and solar radiations were obtained from ASHRAE WYEC weather data for Lake Charles, LA (Crow 1981).

Description of Wall Constructions

The ten wall constructions for the cooling climate are given in Figure 12. Note that Walls 1-5, and 7 have permeable latex paint applied at the interior surface, while Walls 6, 8, 9, and 10 have vinyl wallpaper installed at the interior surface. Wall 4[4] has an interior vapor retarder. Walls 6-8 have an exterior vapor retarder. It is worth mentioning that Walls 6 and 8 are difficult to construct and therefore may not be cost effective. Water-vapor permeances of the materials are given in Tables 1 and 2.

Discussion of Results

The surface relative humidities at the construction layers are plotted versus time of year in Figures 13. In each of the plots, the solid horizontal lines depicts a critical relative humidity (80%) for mold and mildew growth.

Summer Moisture Accumulation. During the summer, the relative humidities at all locations within the construction were below the critical 80% level, except for Wall 4. In Wall 4, moisture from the outdoor environment permeated inwardly through the construction. The high water-vapor transfer resistance of the interior vapor retarder caused moisture to accumulate at that location. A similar situation occurred in Wall 10 where moisture accumulated behind the vinyl wallpaper installed at the interior surface. Here the relative humidity approached, but did not exceed, the critical 80% level, thereby providing a limited potential for mold and mildew growth. Theses results indicate that an interior vapor retarder provides a surface which may develop high relative humidity during the summer.

Walls 6-8 have interior vinyl wallpaper, yet the surface relative humidity behind the vinyl wallpaper remain substantially below the critical 80% level for mold and mildew growth. This satisfactory performance is achieved by the use of an exterior vapor retarder which reduces the ingress of moisture from the outdoor environment into the interior layers of the construction. However, moisture permeating from the indoor environment can accumulate at these exterior vapor retarders during the winter, as will be shown in the next section.

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[4]Wall 4 was a contentious wall in that Joe Lstiburek, the lead author of the Moisture Control Handbook, had concerns regarding the performance of this wall.

Winter Moisture Accumulation. In Walls 1-3 and 5-8, the surface relative humidity at exterior constructions layers was observed to rise above the critical 80% level for mold and mildew growth. Here the critical relative humidity is taken to be 80% instead of saturation (97%) because the temperature of exterior layers experiences mild temperatures during the winter. An explanation is that moisture from the indoor environment permeates outwardly through the construction. When exterior layers offer high resistance to water-vapor transfer, moisture accumulates at these locations, thereby causing the relative humidity to rise.

It is worth mentioning that the surface relative humidity at exterior construction layers in Figures 13a, 13b, 13c, 13g, and 13h tend to be slightly higher in January (beginning of plot) than in December (end of plot). This is caused by lower temperatures in January composed to December.

Another issue warranting discussion is that the amount of moisture accumulation in exterior construction layers during the winter depends on assumed indoor relative humidity. In this analysis, the indoor relative humidity was assumed to be 50% during the winter. As the indoor relative humidity decreases, less moisture accumulates in the building envelope. The authors believe that a relative humidity below 50% is unlikely during the winter because natural ventilation with mild temperature outdoor air has considerably reduced capacity to remove moisture from the indoor space compared with a very cold climate.

The problem of high relative humidity at exterior construction layers was most pronounced for Wall 5 (see Figure 13e). The relative humidity at the plywood sheathing is seen to rise above 90% in January. Moisture, transferred from the indoor environment, is significantly retarded by the polyethylene vapor-diffusion retarder and accumulates within the plywood sheathing.

It is interesting that the above problem did not occur in Wall 9 (Figure 13i), even though this construction had a low-permeability exterior construction layer (i.e., extruded polystyrene). This wall performed well in the winter because the temperature at the inside surface of the foam is relatively high (high R-value) and thus the surface relative humidity stays low. During the summer, Wall 9 performs better than Wall 10 because the extruded polystyrene insulation in Wall 9 significantly limits the ingress of moisture from the outdoor environment into the construction.

AN ADDITIONAL WALL CONSTRUCTION FOR COOLING CLIMATE

A permeable wall (i.e., a wall without vapor retarders and low-permeability layers) was selected as having potentially good performance in a cooling climate. During the summer, outdoor moisture diffusing into the construction readily passes through and is removed by the air conditioning equipment, instead of accumulating at interior construction layers. This moisture diffusion produces only a small increase in the latent cooling load because the latent cooling load is dominated by moisture transport by air infiltration. During the winter, indoor moisture permeating the construction passes through to the outdoor environment and does not accumulate at exterior construction layers.

An example of a permeable wall is shown in Figure 14. Here each of the construction layers has high water-vapor permeability. The air gaps between overlapped aluminum siding pieces were assumed to provide high water-vapor permeability.

Program MOIST was used to predict the surface relative humidity at the construction layers versus time of year for the permeable wall. The results are given in Figure 15. The relative humidity at all locations was observed always to be below the critical relative humidity (80%) for mold and mildew growth.

CAVEATS AND CAUTIONS

It should be pointed out that the analysis conducted in this study assumed that the wall constructions were well constructed and therefore air tight. The convective transport of moisture by air infiltration and air exfiltration was neglected. In addition, the cyclical wetting of the wall constructions by rain was neglected. This later wetting mechanism can be especially important for walls with exterior masonry construction, especially when the wall receives direct solar radiation. The above wetting mechanisms warrant further investigation.

It is perhaps worth mentioning that if the above wetting mechanisms had been included in the analysis, the predicted results would have been more pessimistic. That is, there would have existed a potential for more of the wall constructions to have a moisture problem.

SUMMARY AND CONCLUSION

A detailed computer model, called MOIST, was used to predict the surface relative humidity at the construction layers versus time of year for all the wall constructions given in the Moisture Control Handbook. These wall constructions are intended to minimize moisture accumulation, thereby preventing material degradation, mold and mildew growth, and loss of thermal performance.

For the heating climate (northern United States), all the walls in the Moisture Control Handbook were observed to perform satisfactorily. That is, the peak relative humidity at all locations within the construction was always observed to be considerably below saturation, thereby indicating little or no risk of material degradation. The satisfactory performance was primarily achieved by an interior vapor retarder which significantly reduced the ingress of moisture into the construction from the indoor environment.

For the mixed climate (central United States), all the walls were also observed to perform satisfactorily. Several of the walls did not contain an interior vapor retarder, but contained insulated sheathing. In these walls, the interior surface temperature of the sheathing was raised, thereby decreasing moisture accumulation at this location of the construction. When the indoor relative humidity was 50%, the surface relative humidity of the sheathing approached a saturated state during a brief winter period, but this was considered to pose little or no risk to the construction.

For the cooling climate (south-eastern United States), one of the walls had risk of mold and mildew growth behind an interior vapor retarder cooled by the indoor air conditioning. During the summer, moisture from the outdoor environment permeated inwardly through this construction and accumulated at the interior vapor retarder, and the surface relative humidity approached and rose above the critical 80% level for mold and mildew growth.

Several of the walls for a cooling climate contained an exterior vapor retarder which decreased moisture transfer to the interior construction layers. The relative humidity behind interior vapor retarders was decreased below the critical level (80%). However, during the winter, moisture from the indoor environment permeated outwardly through the wall construction and accumulated at exterior vapor retarders where the relative humidity rose above the critical level (80%).

For a cooling climate, the MOIST model was used to find another good performing wall construction. A permeable wall (without vapor retarding layers and low-permeability materials) was found to perform satisfactorily. During both winter and summer periods, moisture passed through the construction and did not significantly accumulate within construction layers.

The analysis presented in this report was limited in that it did not include moisture transfer by air movement and it did not include cyclical rain wetting. These effects warrant further study.

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NOMENCLATURE

Symbol	Units	Definition
A_0, A_1, A_2		Coefficients of permeability equation
C_a	J/kg·°C	Specific heat of air
C_d	J/kg·°C	Specific heat of dry material
C_w	J/kg·°C	Specific heat of water
D_γ	m^2/s	Diffusivity for moisture gradient
D_T	$m^2/°C \cdot s$	Diffusivity for temperature gradient
$f(\phi)$		Sorption isotherm function
h_c	$W/m^2 \cdot °C$	Convective heat transfer coefficient
h_w	$kg/s \cdot m^2 \cdot Pa$	Permeance of vertical air space
k	W/m·°C	Thermal conductivity of porous material
Le		Lewis number
P_{atm}	Pa	Atmospheric Pressure
P_{vg}	Pa	Water-vapor saturation pressure
t	s	Time
T	°C	Temperature
y	m	Distance from inside surface of wall
γ	kg/kg	Moisture content on dry basis
μ	kg/s·m·Pa	Water-vapor permeability
ρ	kg/m^3	Density of dry material
ϕ		Relative humidity

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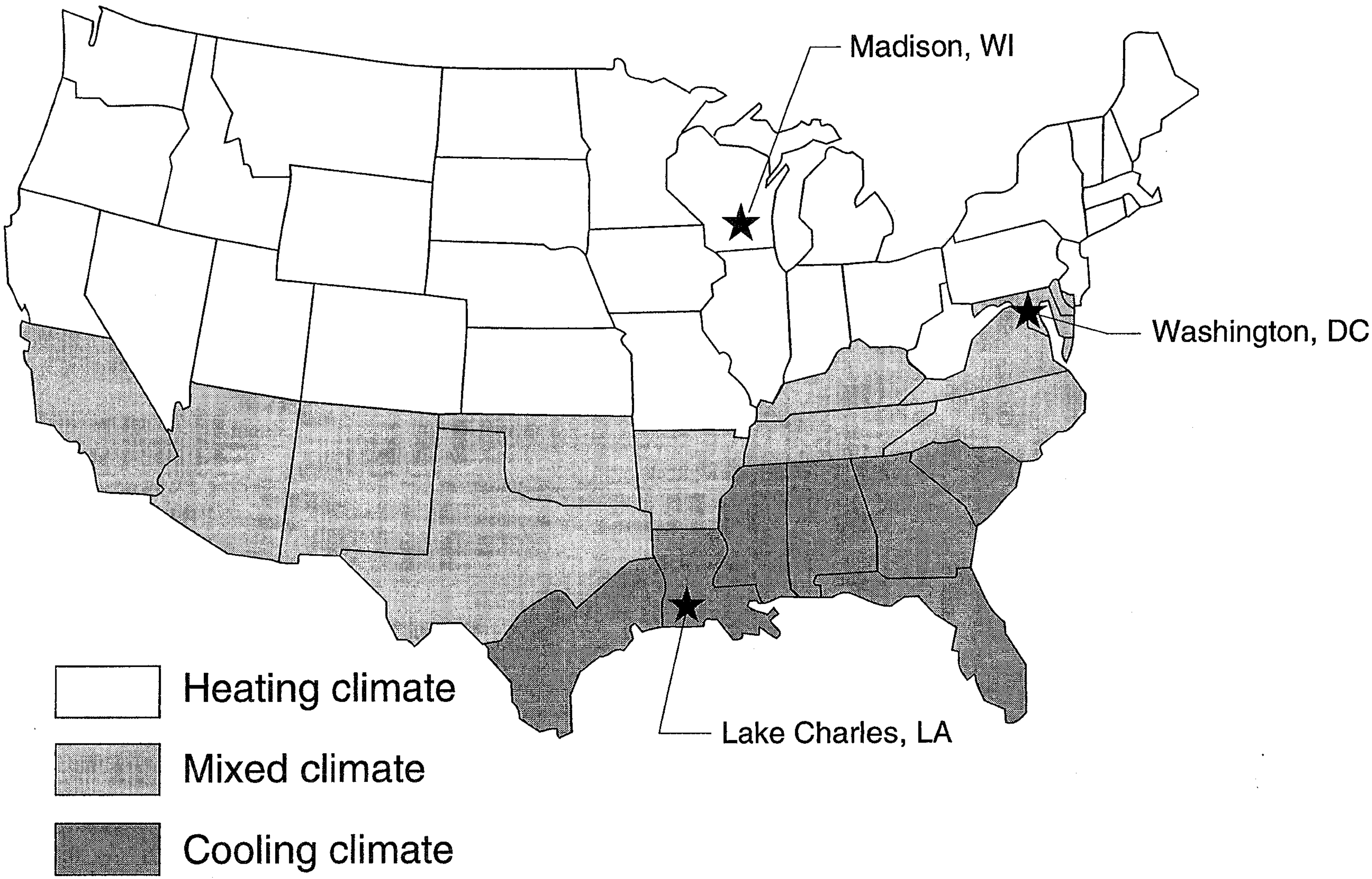


Fig. 1. Climate regions of the United States showing cities used in the analysis.

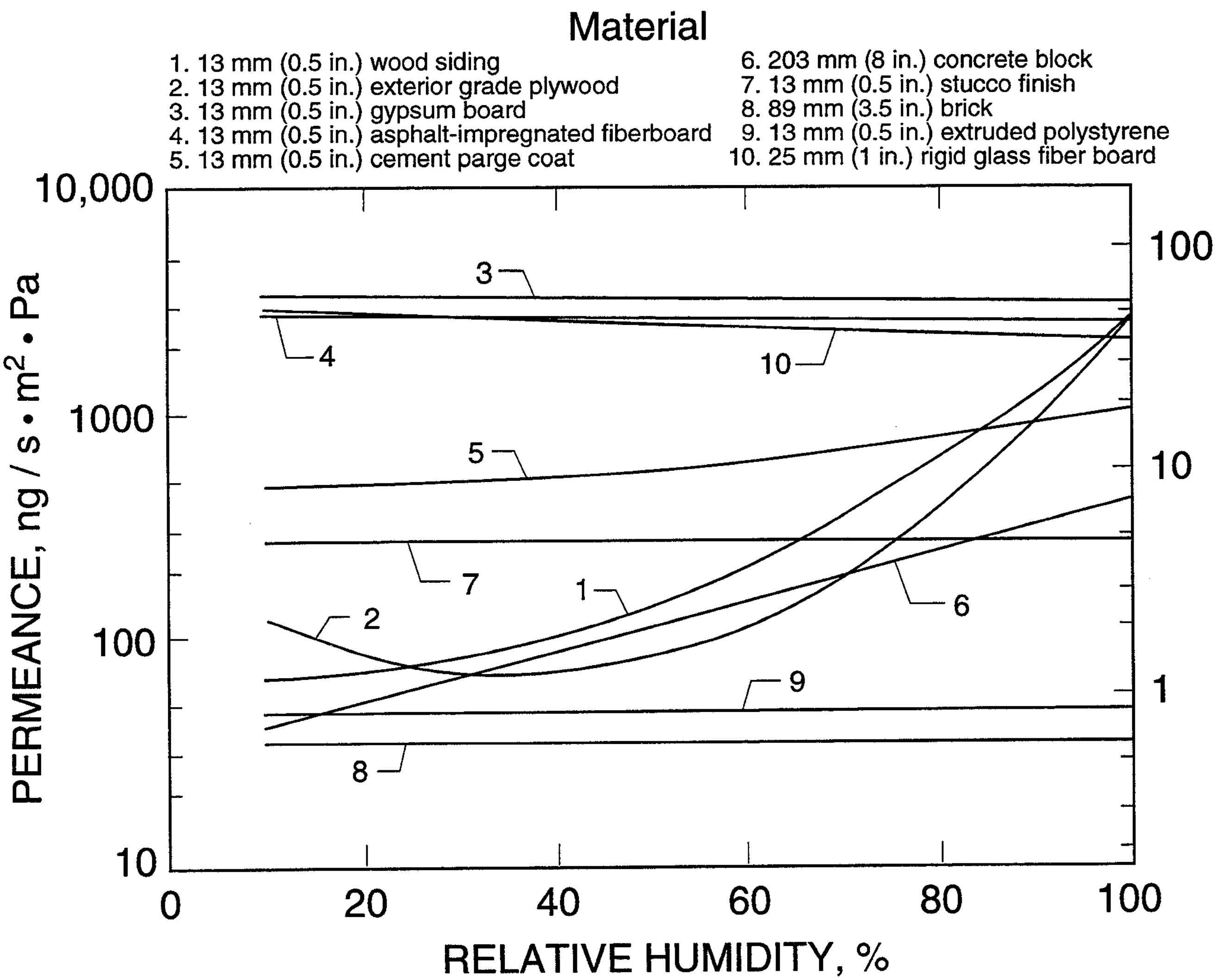


Fig. 2. Plot of permeance of materials versus relative humidity.

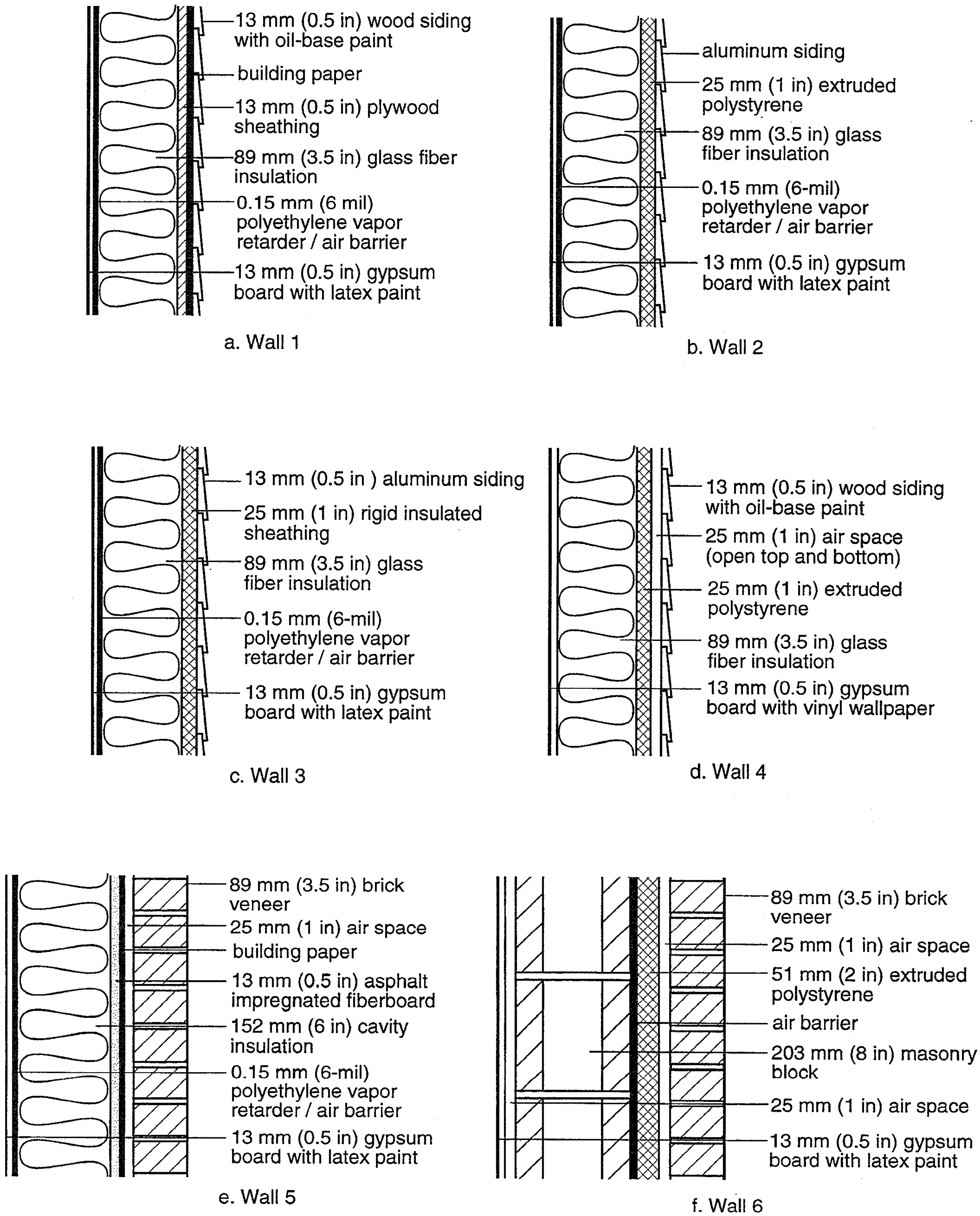


Fig. 3. Wall constructions analyzed for the heating climate

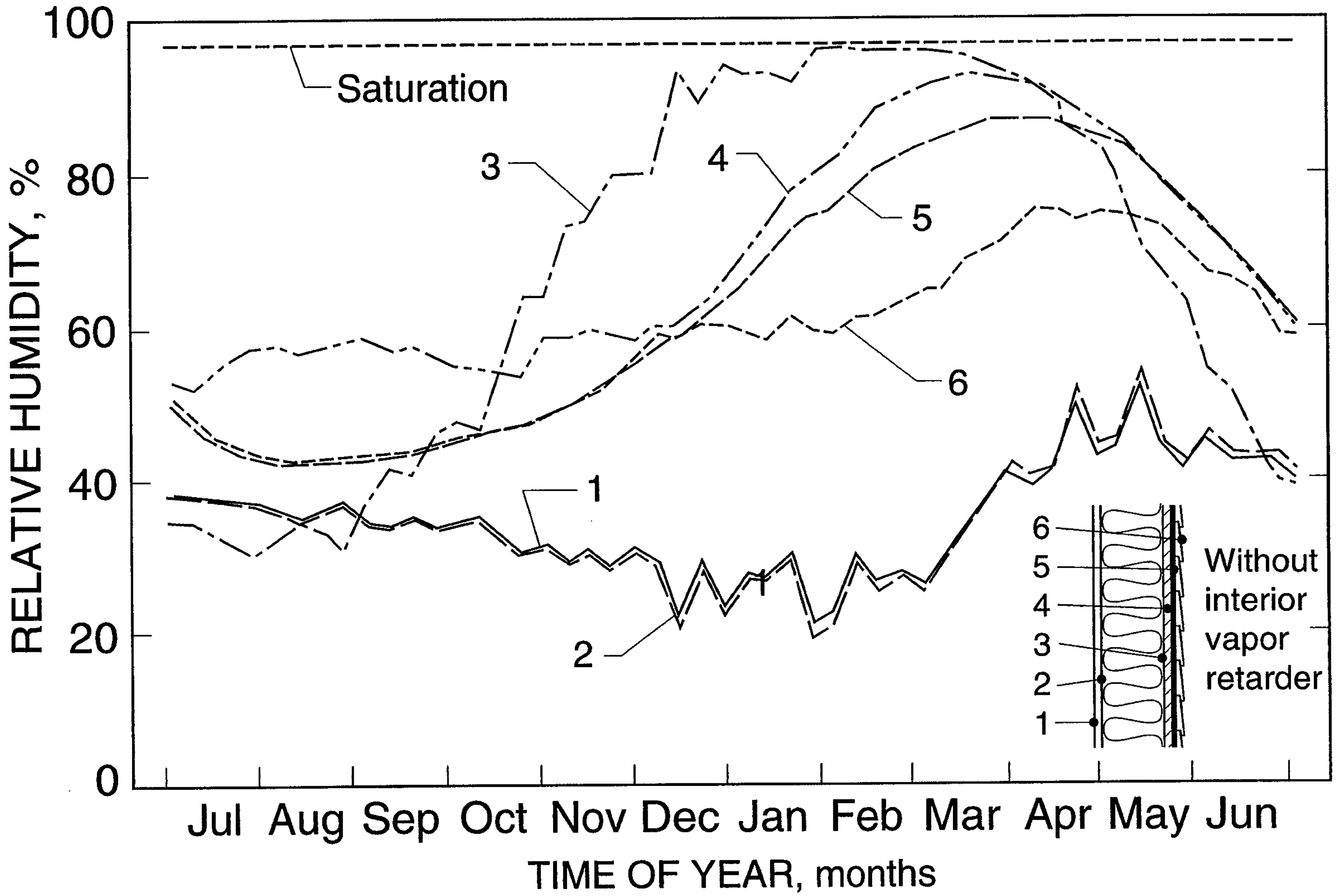


Fig. 4a. Relative humidity at layer surfaces versus time of year for heating climate Wall 1 without interior vapor retarder (Indoor relative humidity of 35%)

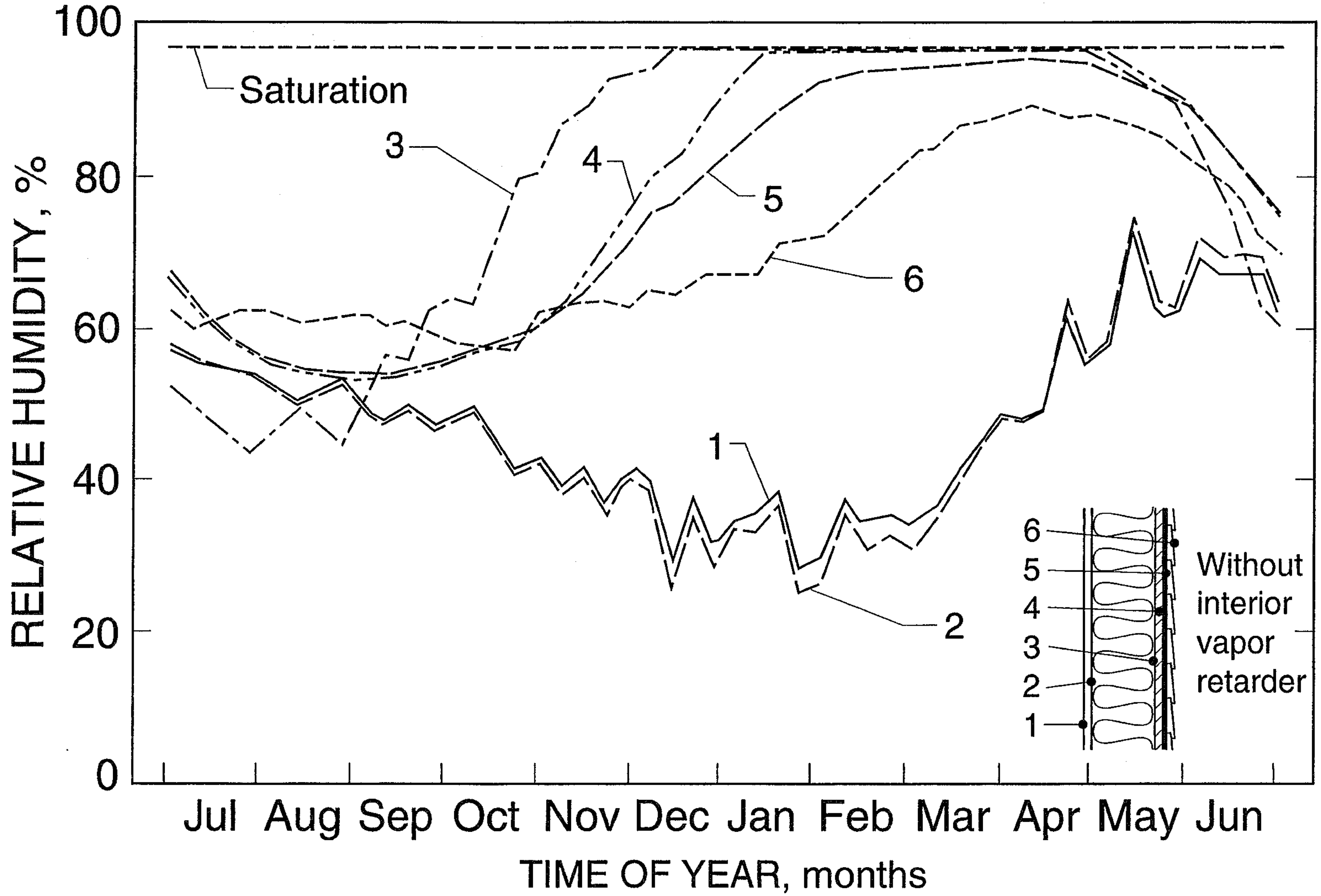


Fig. 4b. Relative humidity at layer surfaces versus time of year for heating climate Wall 1 without interior vapor retarder (Indoor relative humidity of 50%)

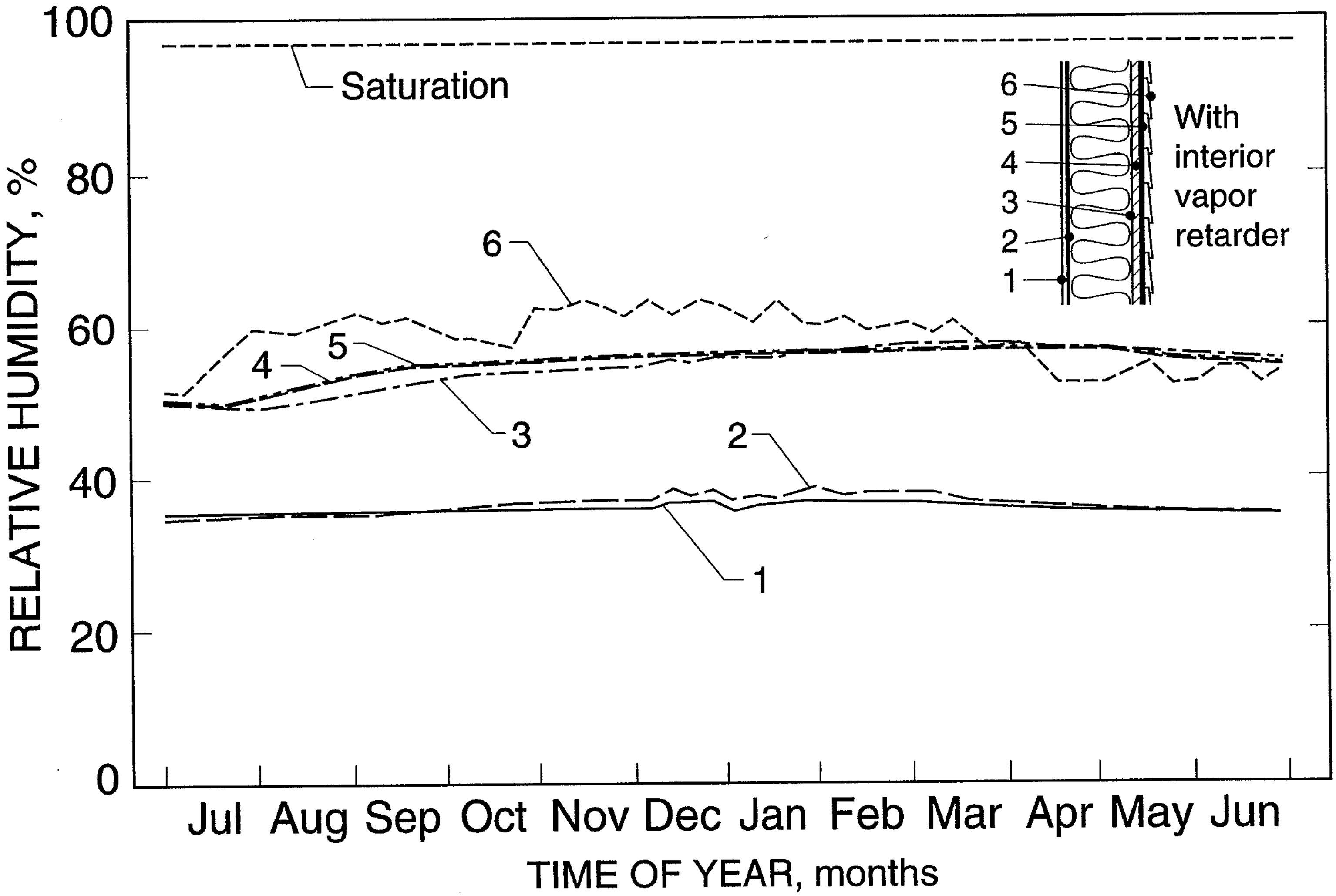


Fig. 5a. Relative humidity at layer surfaces versus time of year for heating climate Wall 1 with interior vapor retarder (Indoor relative humidity of 35%)

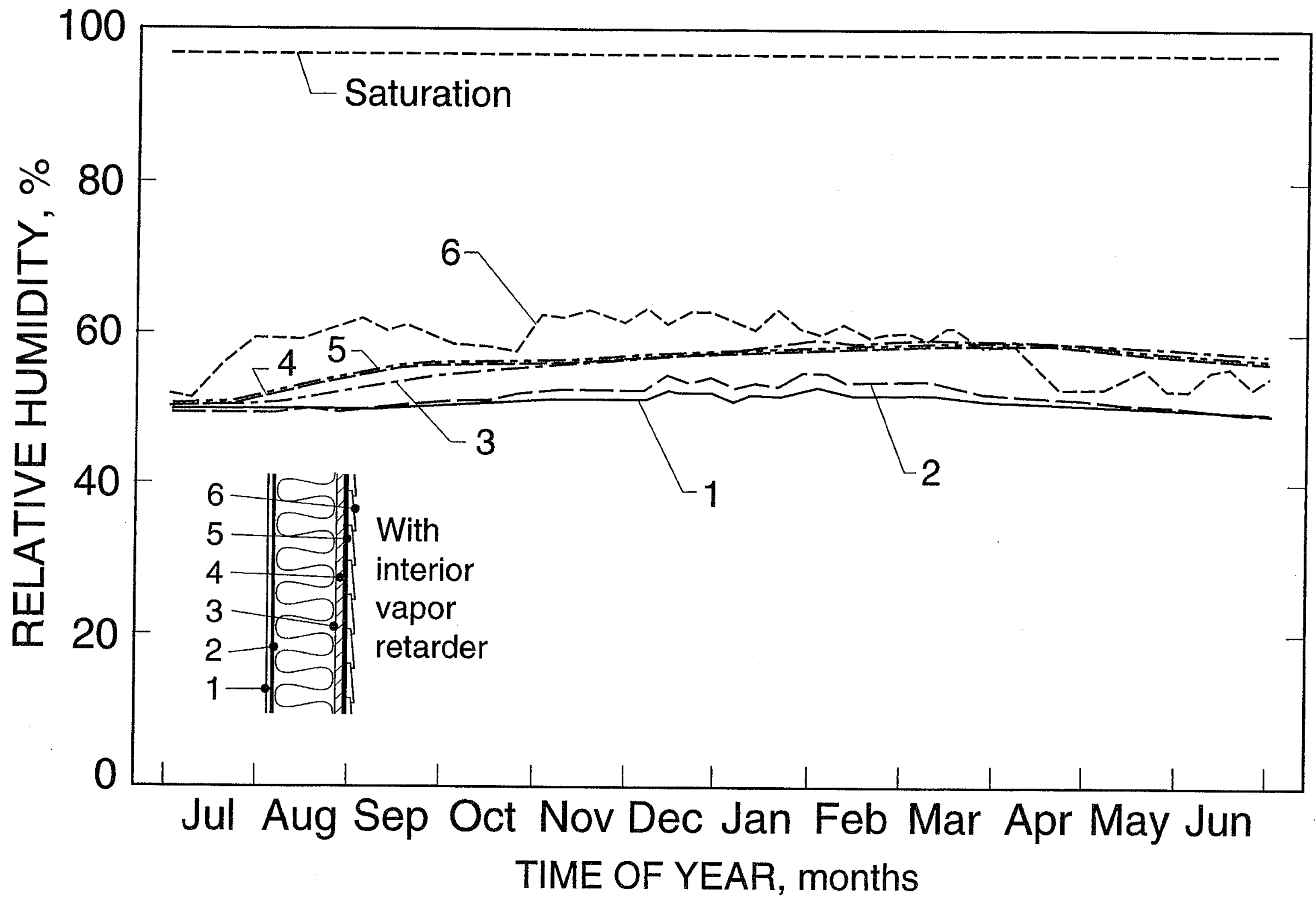


Fig. 5b. Relative humidity at layer surfaces versus time of year for heating climate Wall 1 (Indoor relative humidity of 50%)

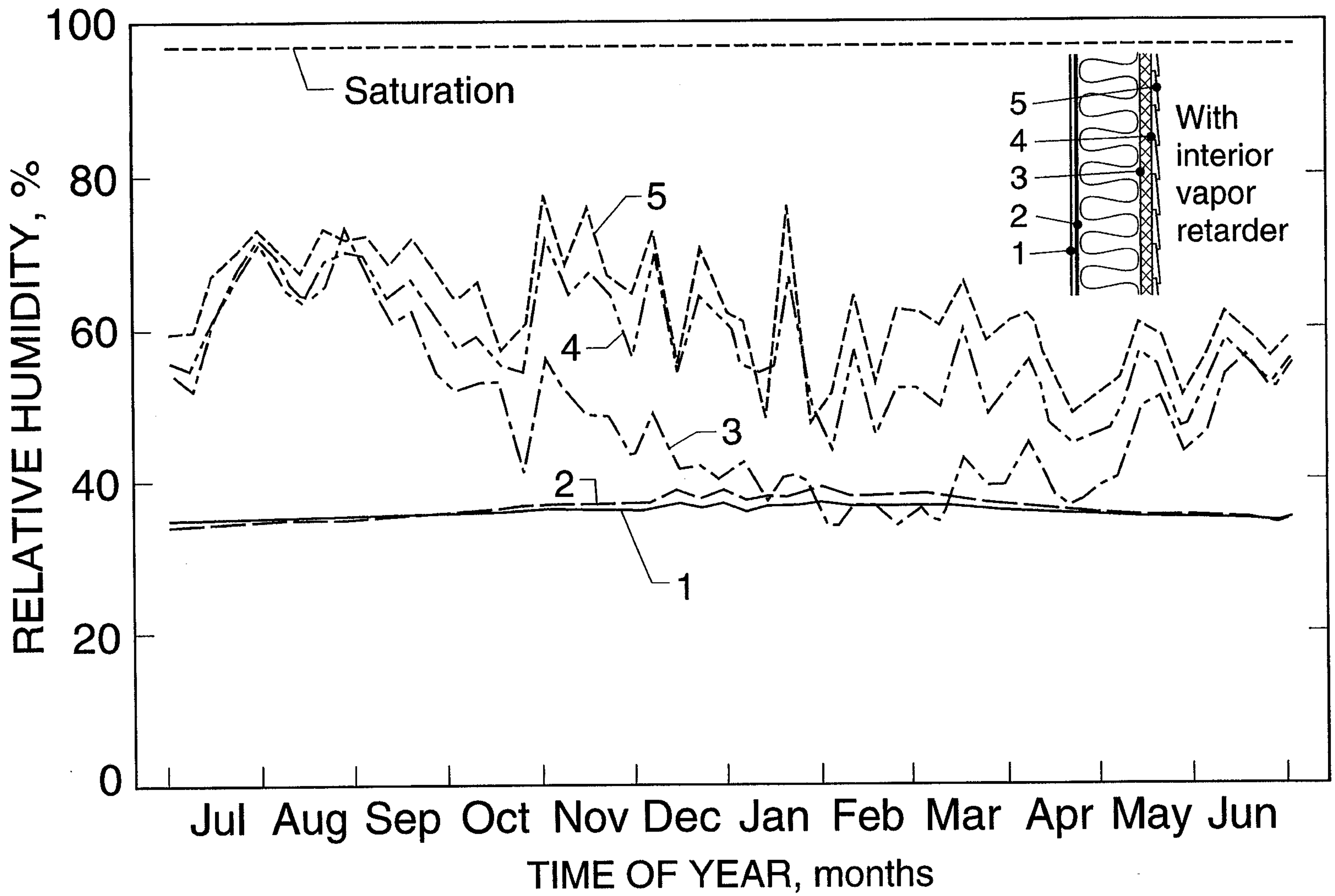


Fig. 6a. Relative humidity at layer surfaces versus time of year for Wall 2 of heating climate (Indoor relative humidity of 35%)

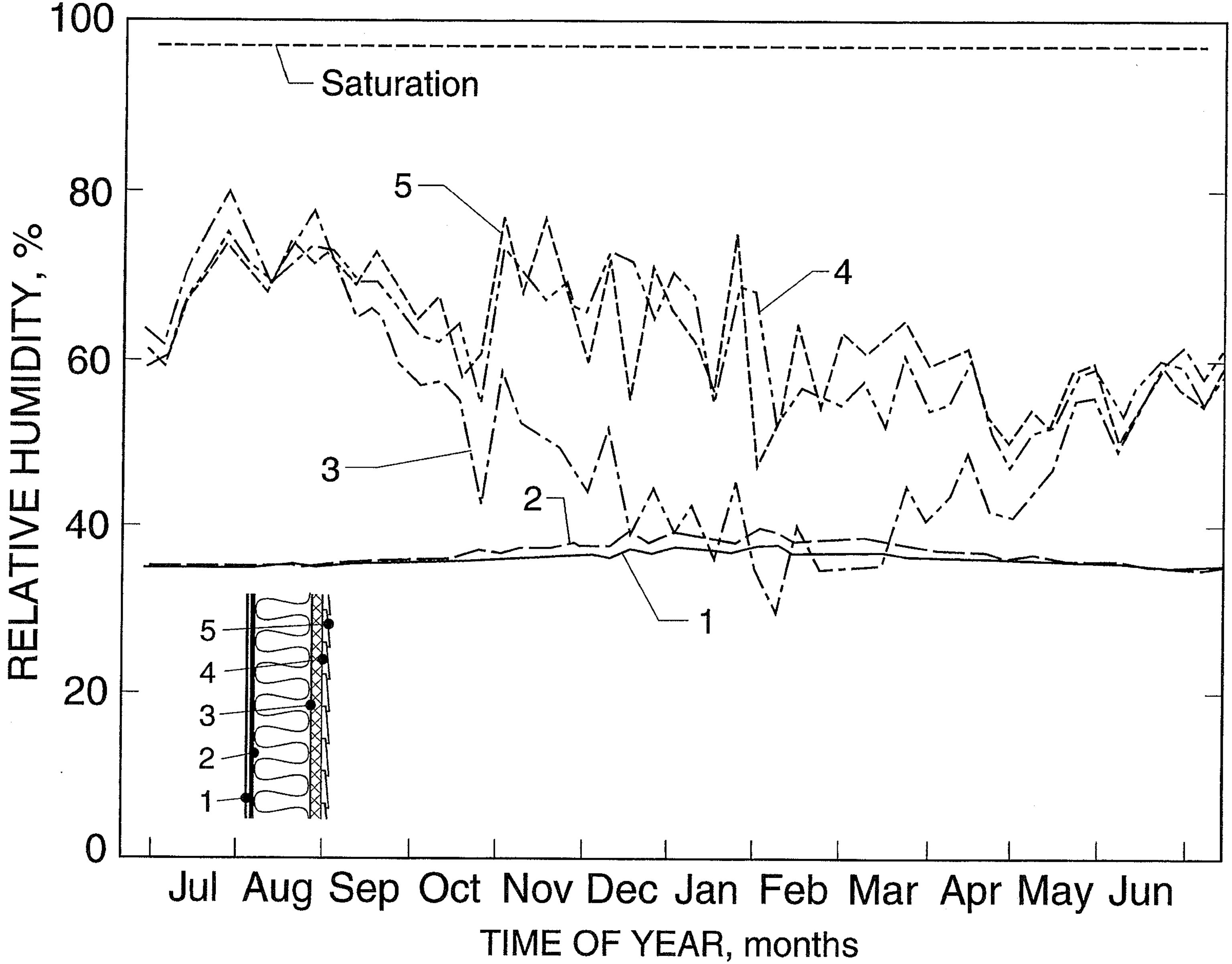


Fig. 6b. Relative humidity at layer surfaces versus time of year for Wall 3 of heating climate (Indoor relative humidity of 35%)

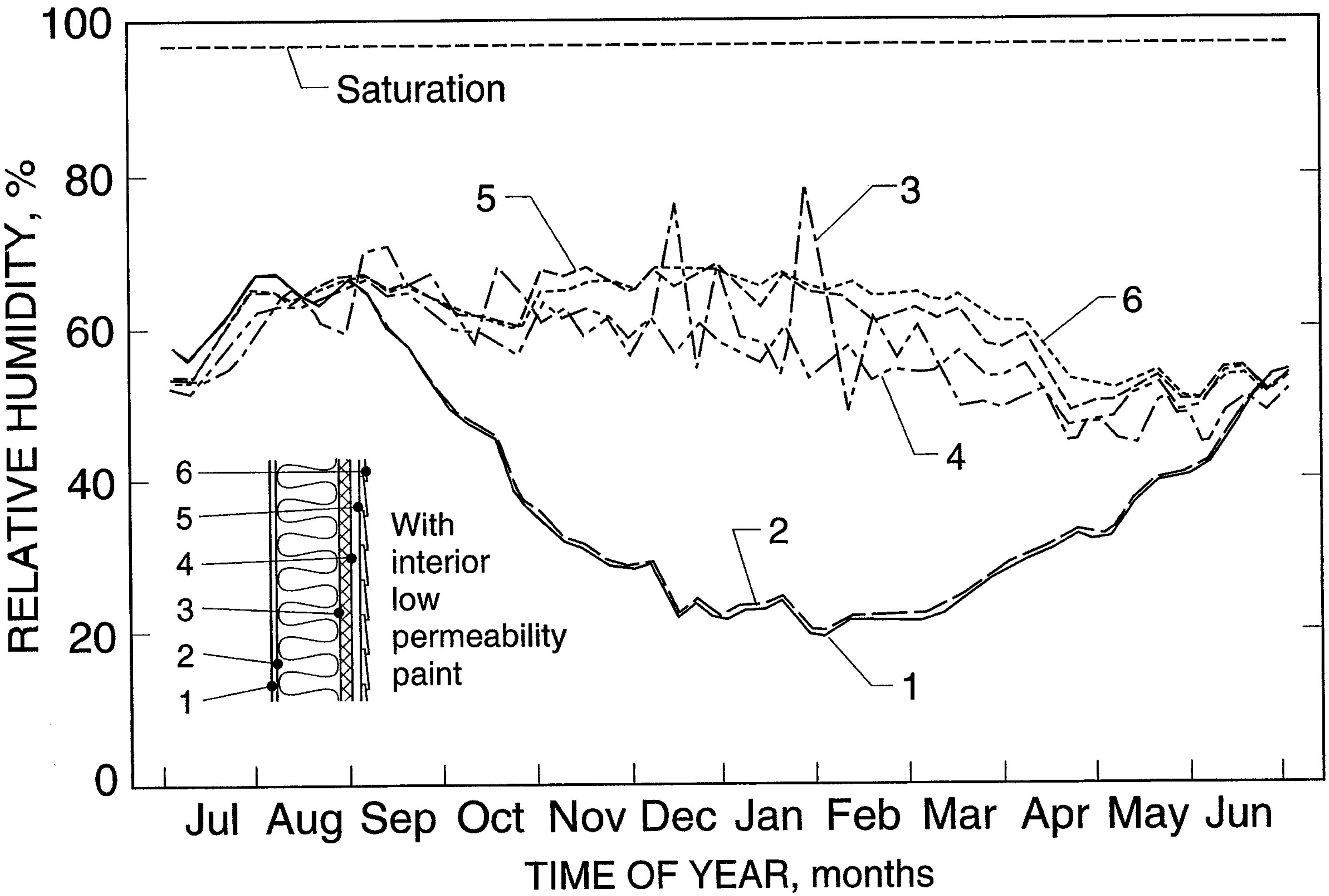


Fig. 6c. Relative humidity at layer surfaces versus time of year for Wall 4 of heating climate (Indoor relative humidity of 35%)

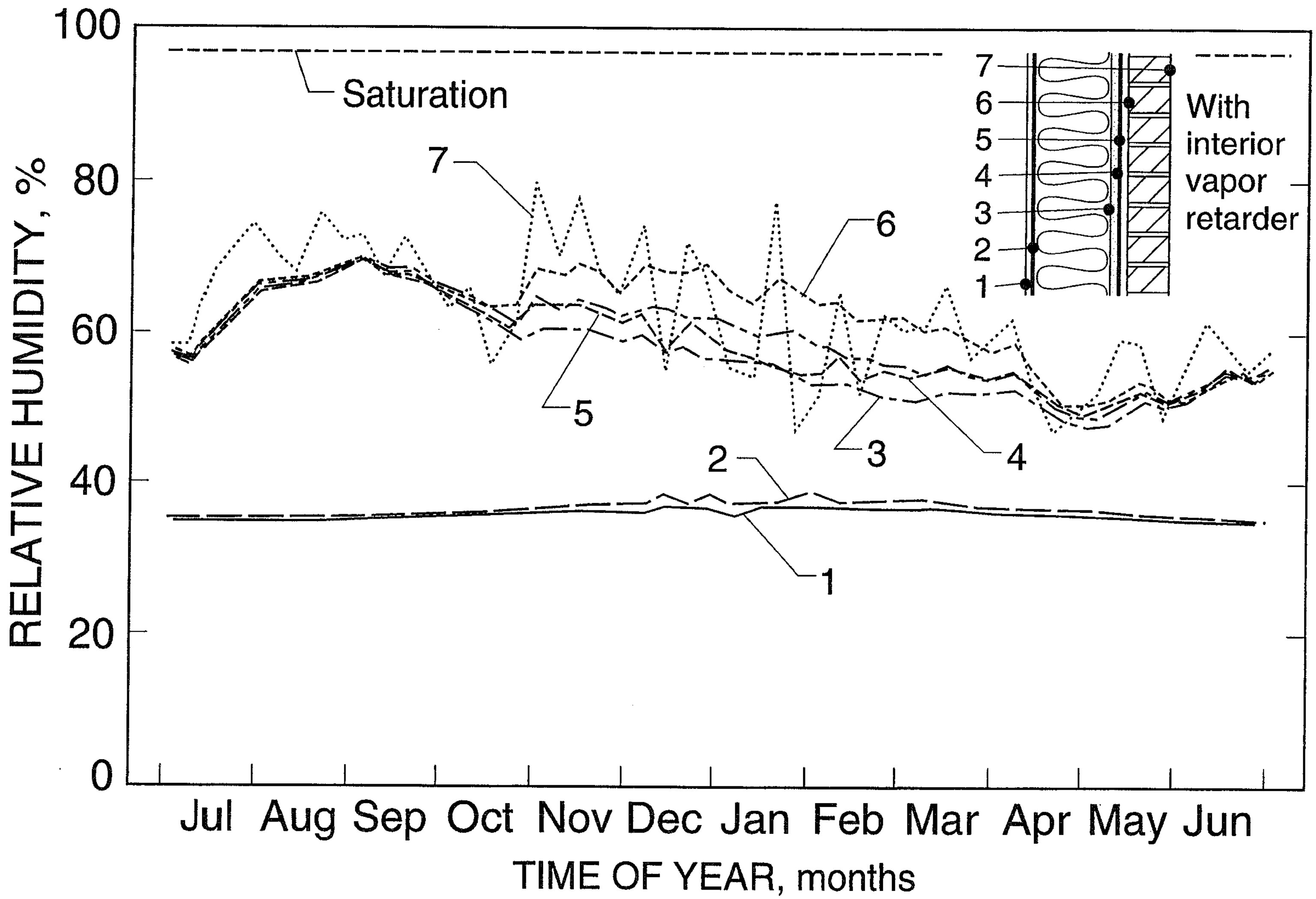


Fig. 6d. Relative humidity at layer surfaces versus time of year for Wall 5 of heating climate (Indoor relative humidity of 35%)

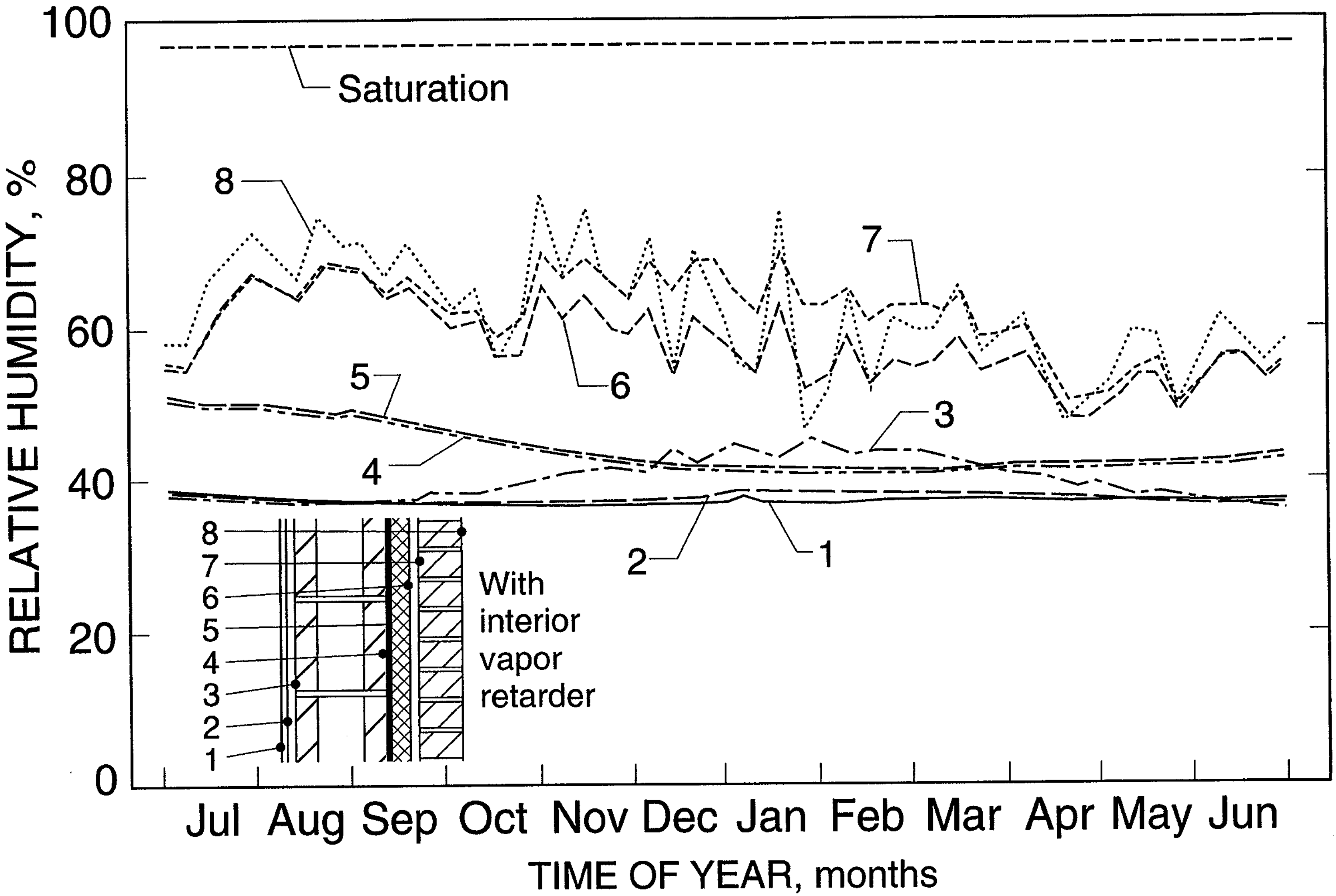


Fig. 6e. Relative humidity at layer surfaces versus time of year for Wall 6 of heating climate (Indoor relative humidity of 35%)

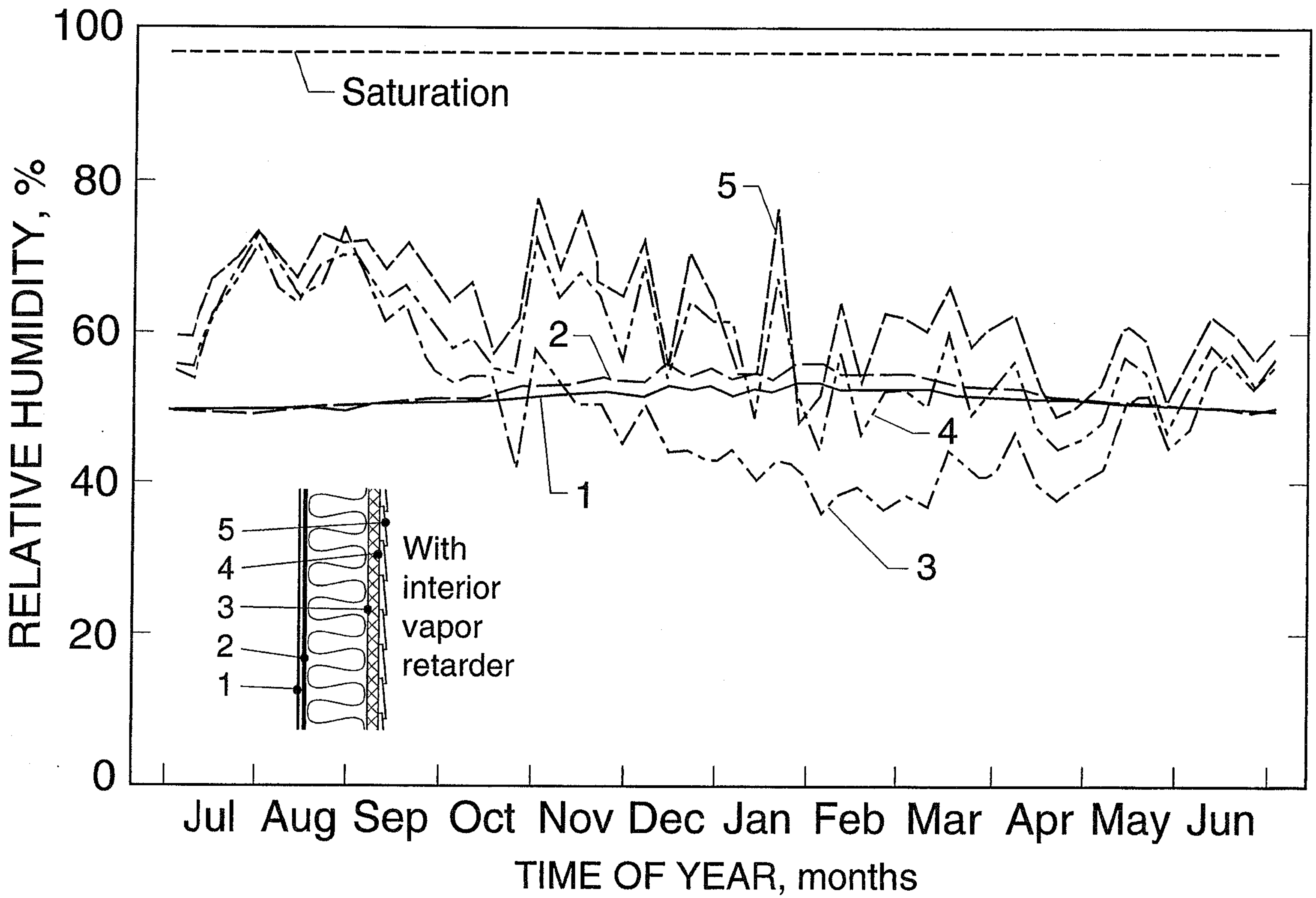


Fig. 7a. Relative humidity at layer surfaces versus time of year for Wall 2 of heating climate (Indoor relative humidity of 50%)

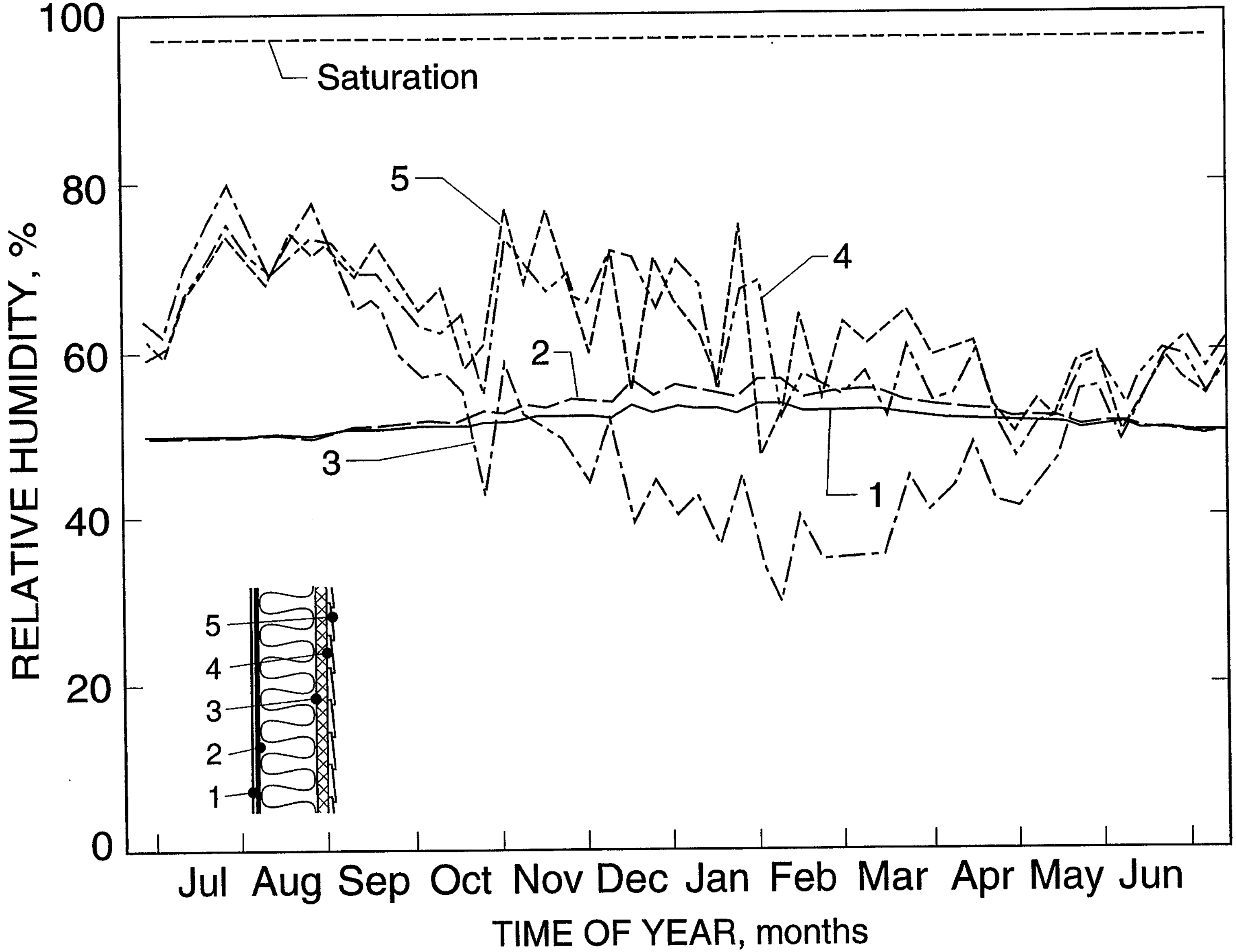


Fig. 7b. Relative humidity at layer surfaces versus time of year for Wall 3 of heating climate (Indoor relative humidity of 50%)

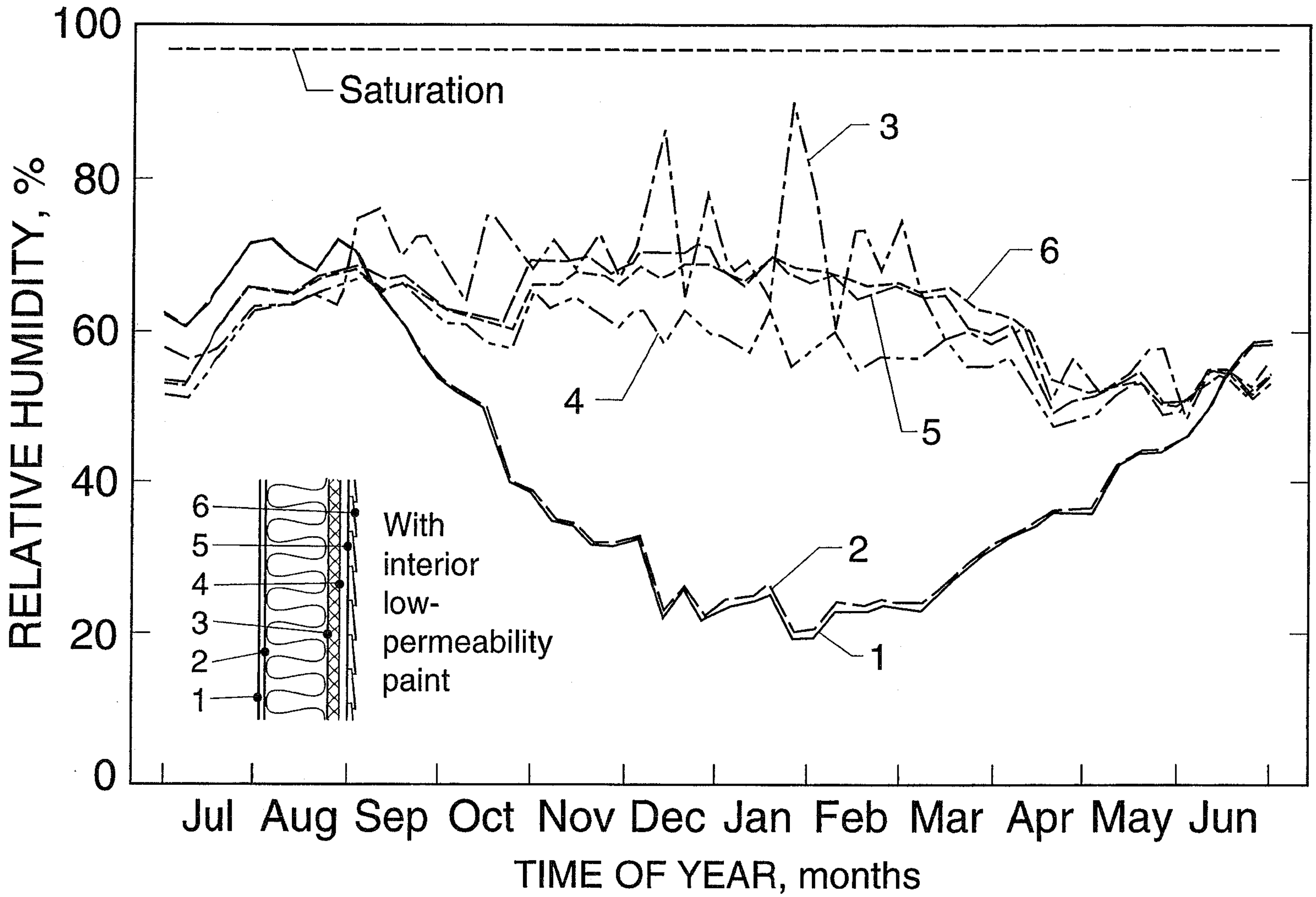


Fig. 7c. Relative humidity at layer surfaces versus time of year for Wall 4 of heating climate (Indoor relative humidity of 50%)

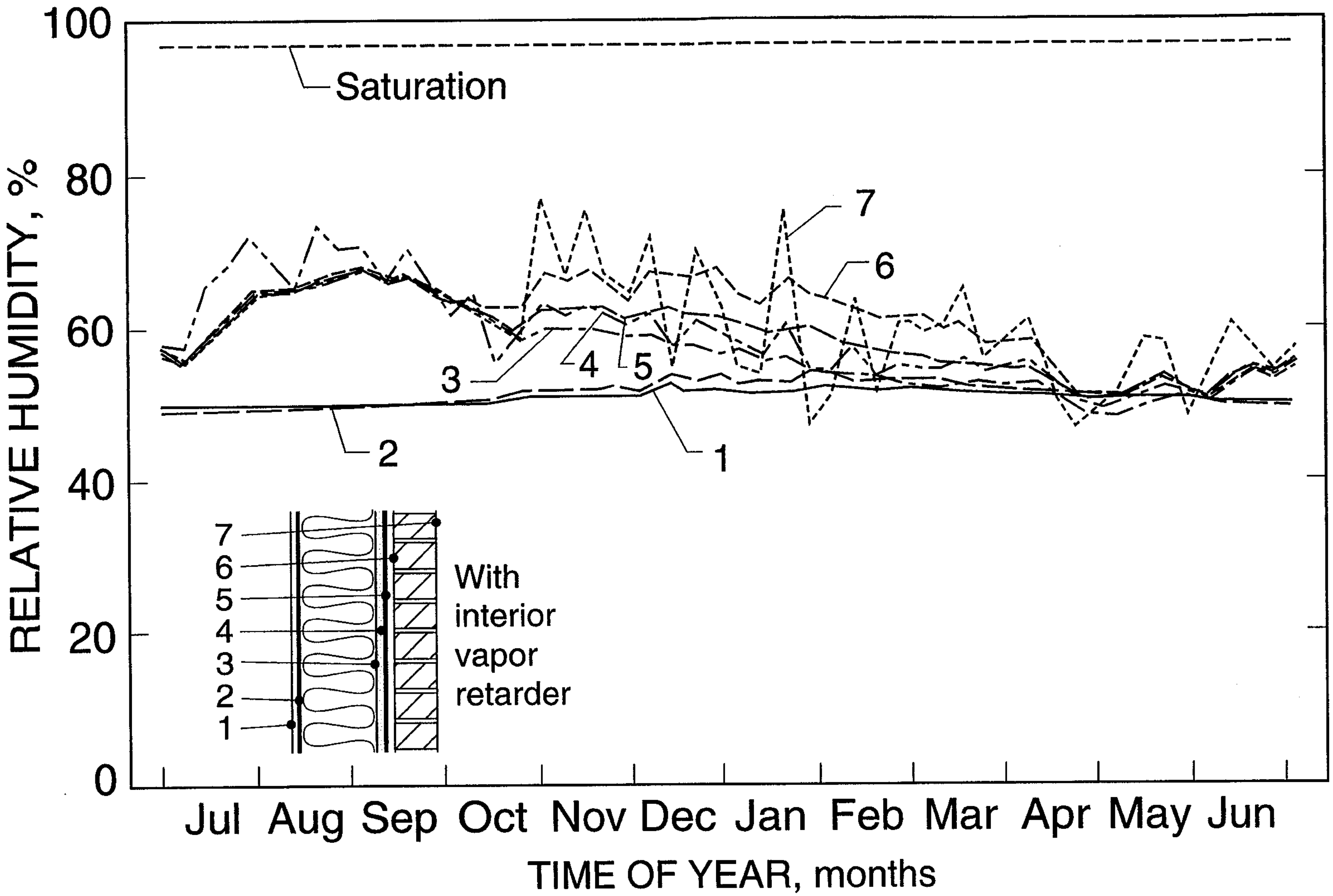


Fig. 7d. Relative humidity at layer surfaces versus time of year for Wall 5 of heating climate (Indoor relative humidity of 50%)

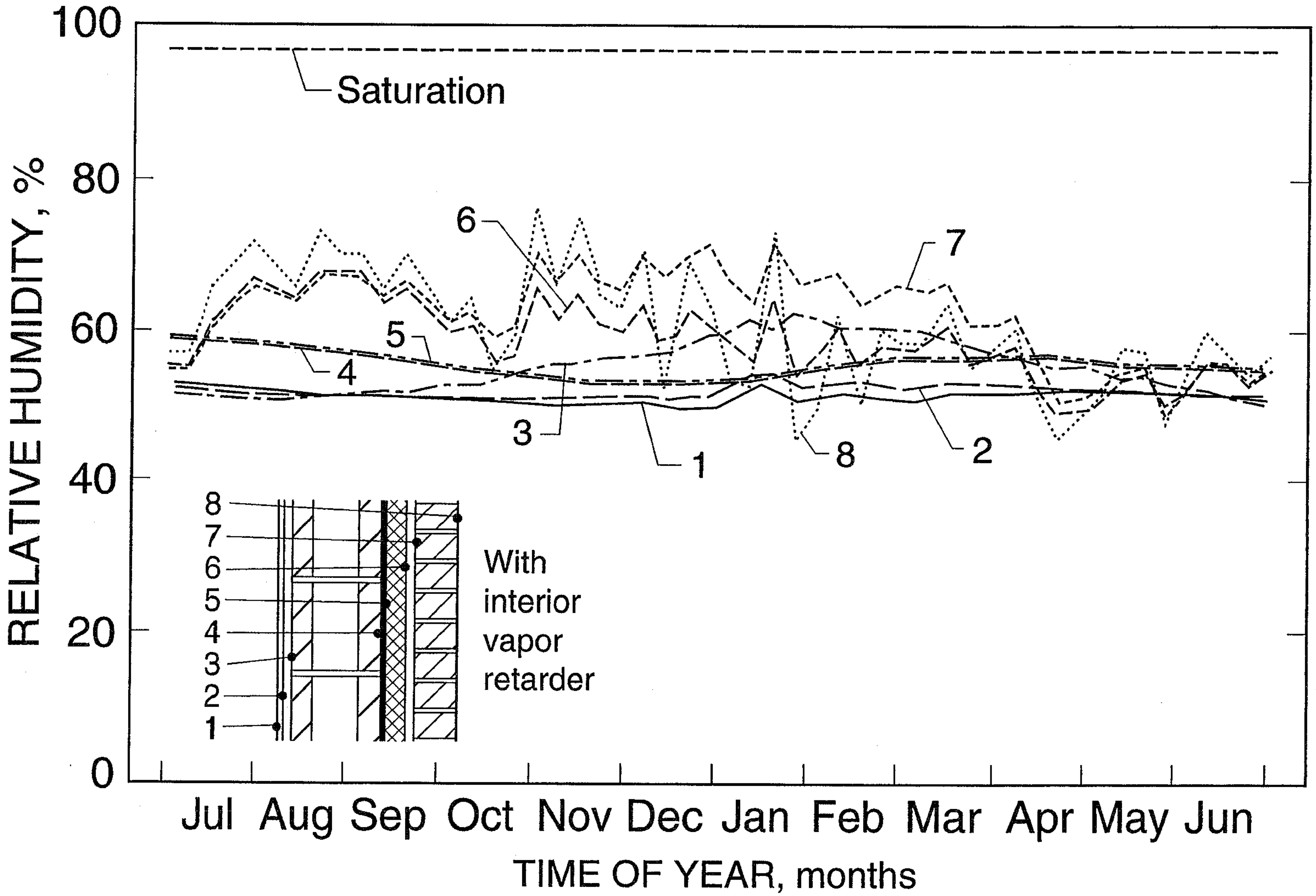


Fig. 7e. Relative humidity at layer surfaces versus time of year for Wall 6 of heating climate (Indoor relative humidity of 50%)

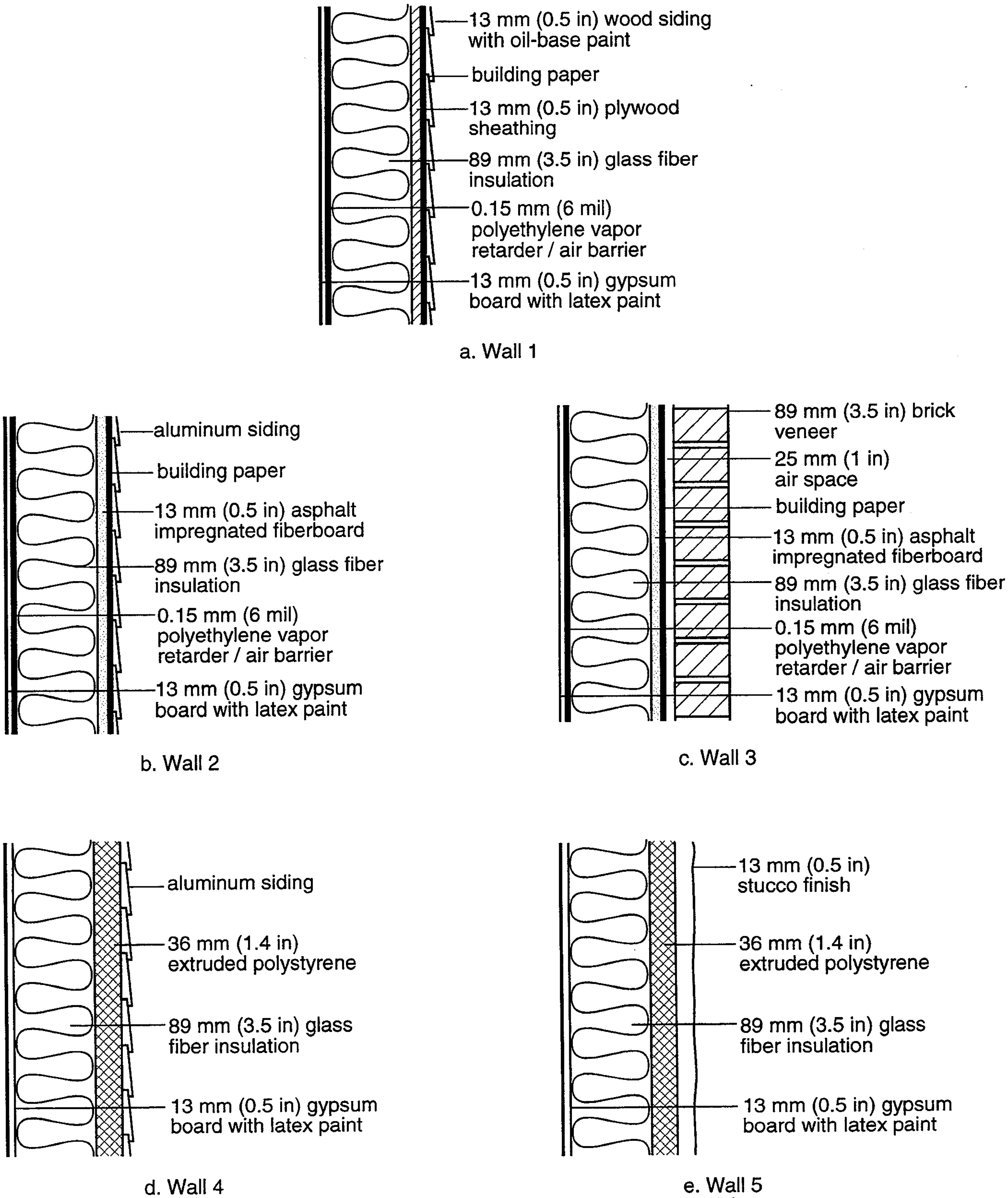


Fig. 8. Wall constructions analyzed for mixed climate.

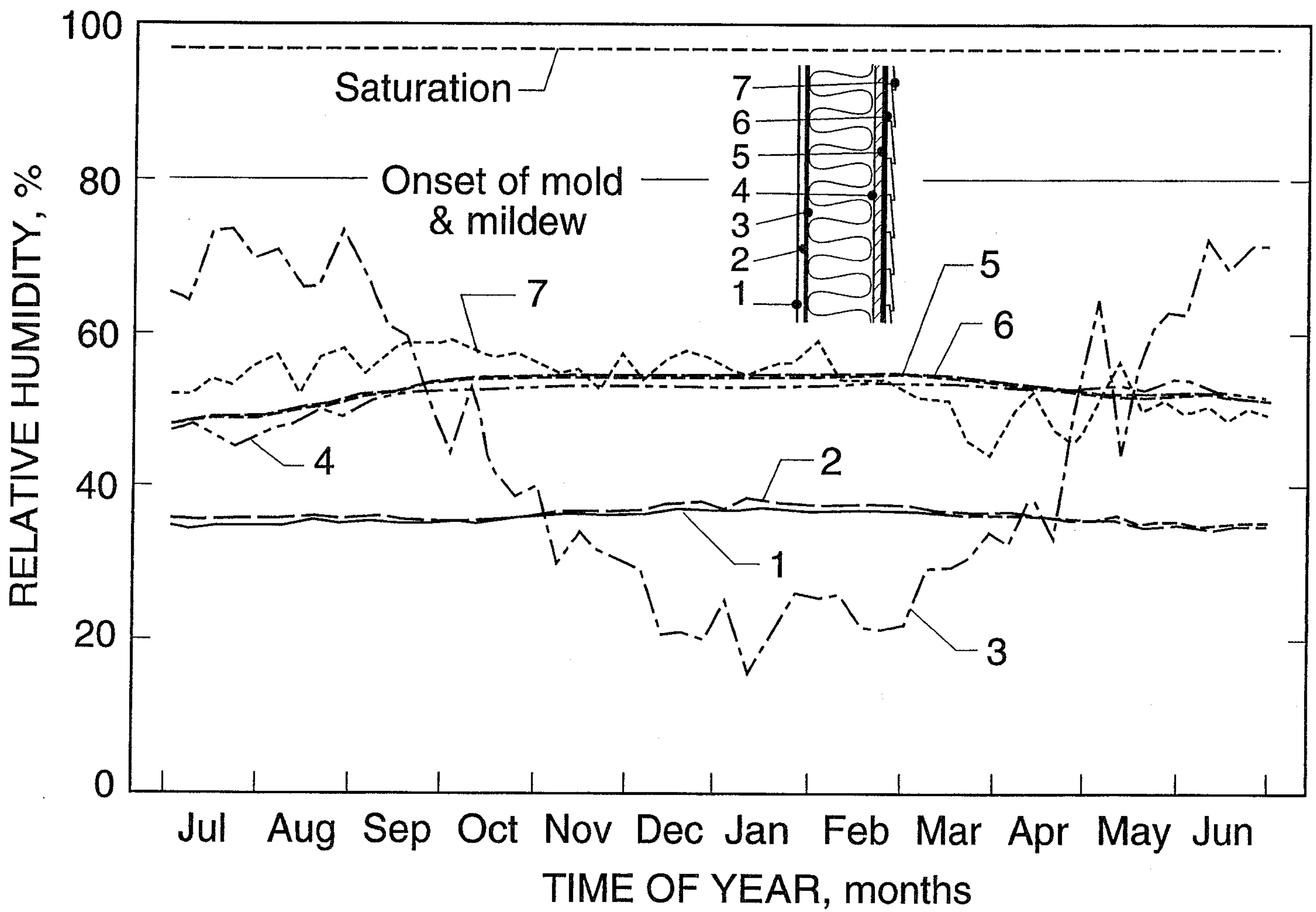


Fig. 9a. Relative humidity at layer surfaces versus time of year for Wall 1 of mixed climate (indoor relative humidity of 35%)

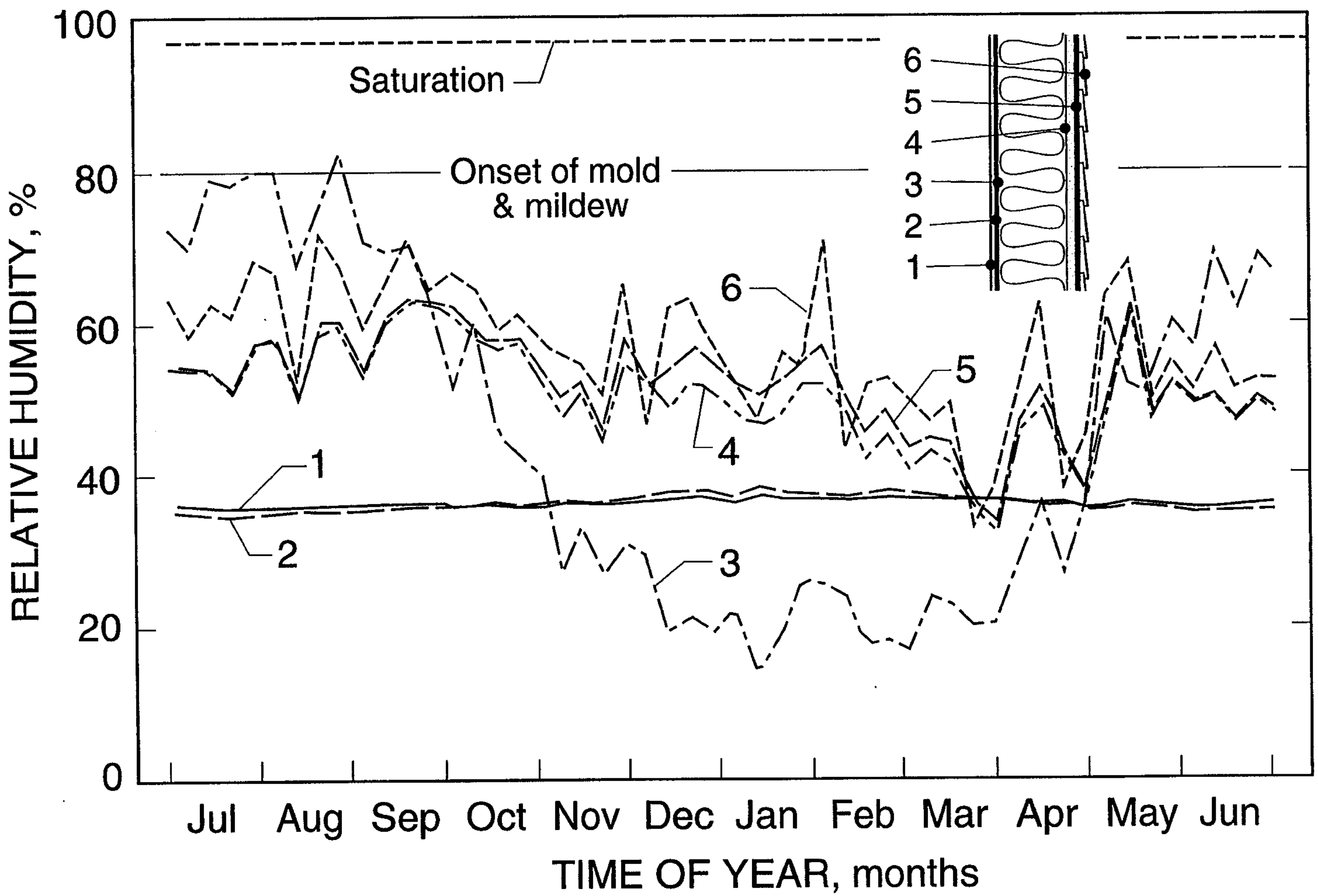


Fig. 9b. Relative humidity at layer surfaces versus time of year for Wall 2 of mixed climate (indoor relative humidity of 35%)

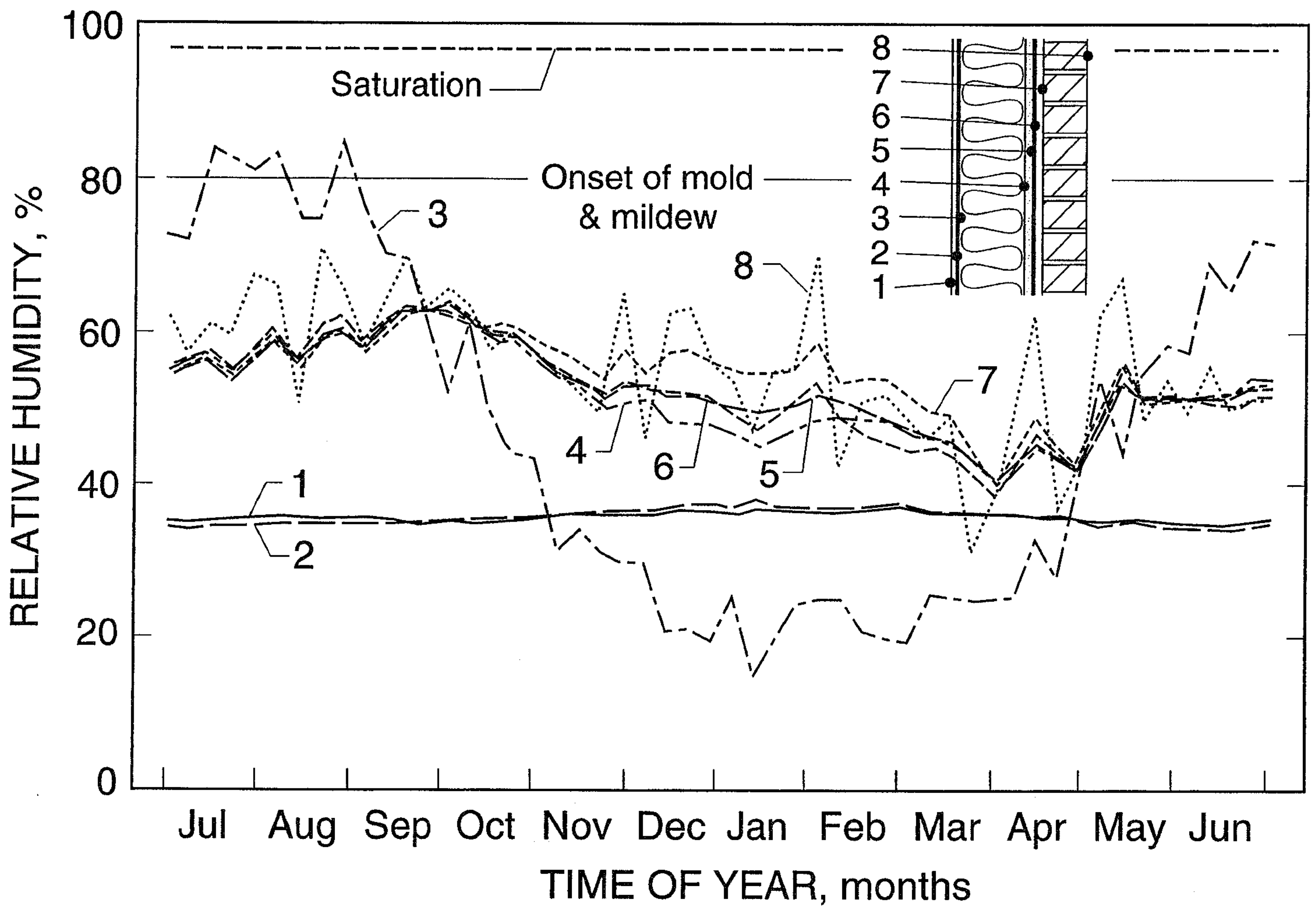


Fig. 9c. Relative humidity at layer surfaces versus time of year for Wall 3 of mixed climate (indoor relative humidity of 35%)

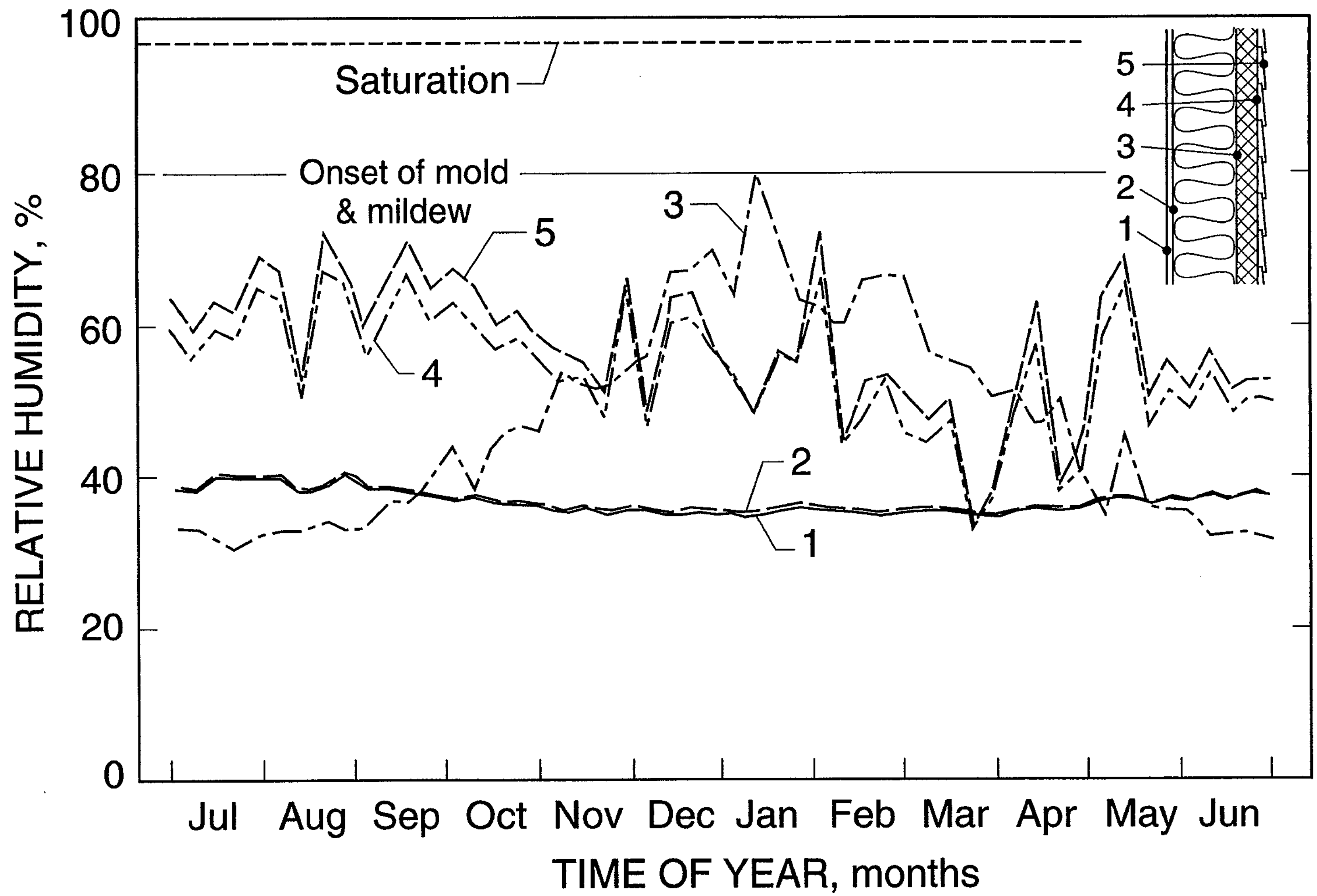


Fig. 9d. Relative humidity at layer surfaces versus time of year for Wall 4 of mixed climate (indoor relative humidity of 35%)

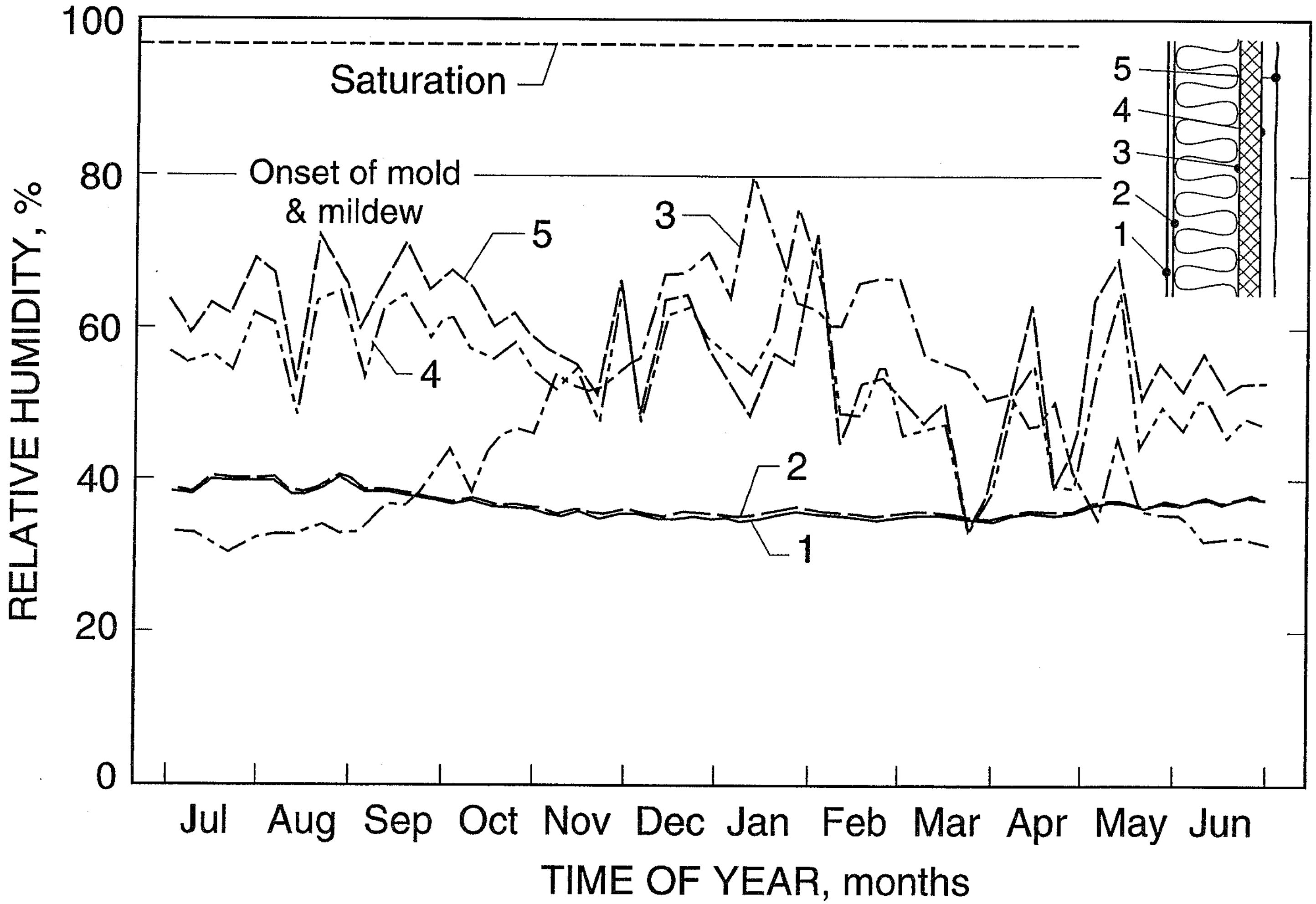


Fig. 9e. Relative humidity at layer surfaces versus time of year for Wall 5 of mixed climate (indoor relative humidity of 35%)

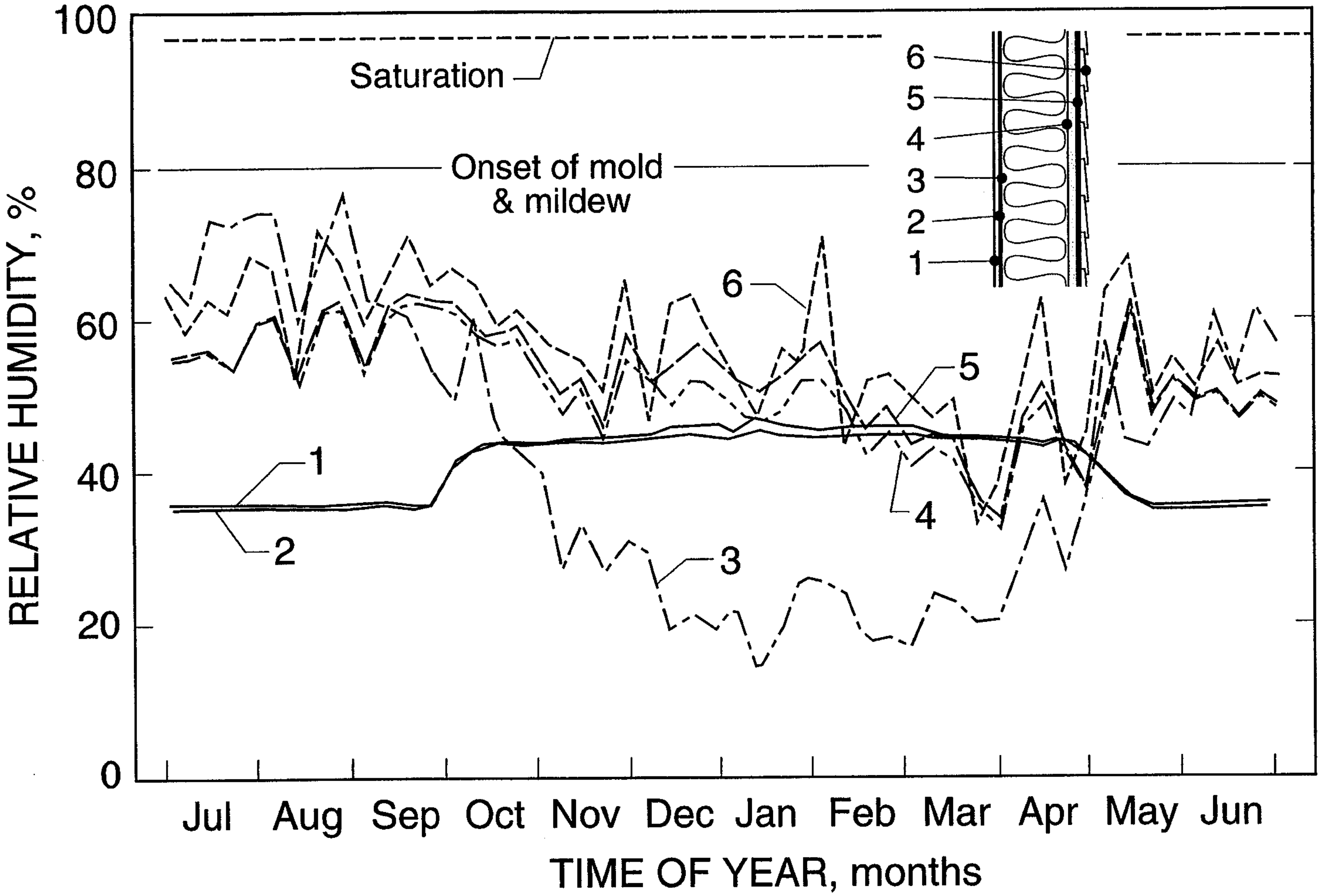


Fig. 10. Computer simulation of wall 2 of mixed climate with winter setpoint of 21.1°C (70° F) and summer setpoint of 24.4°C (76° F)

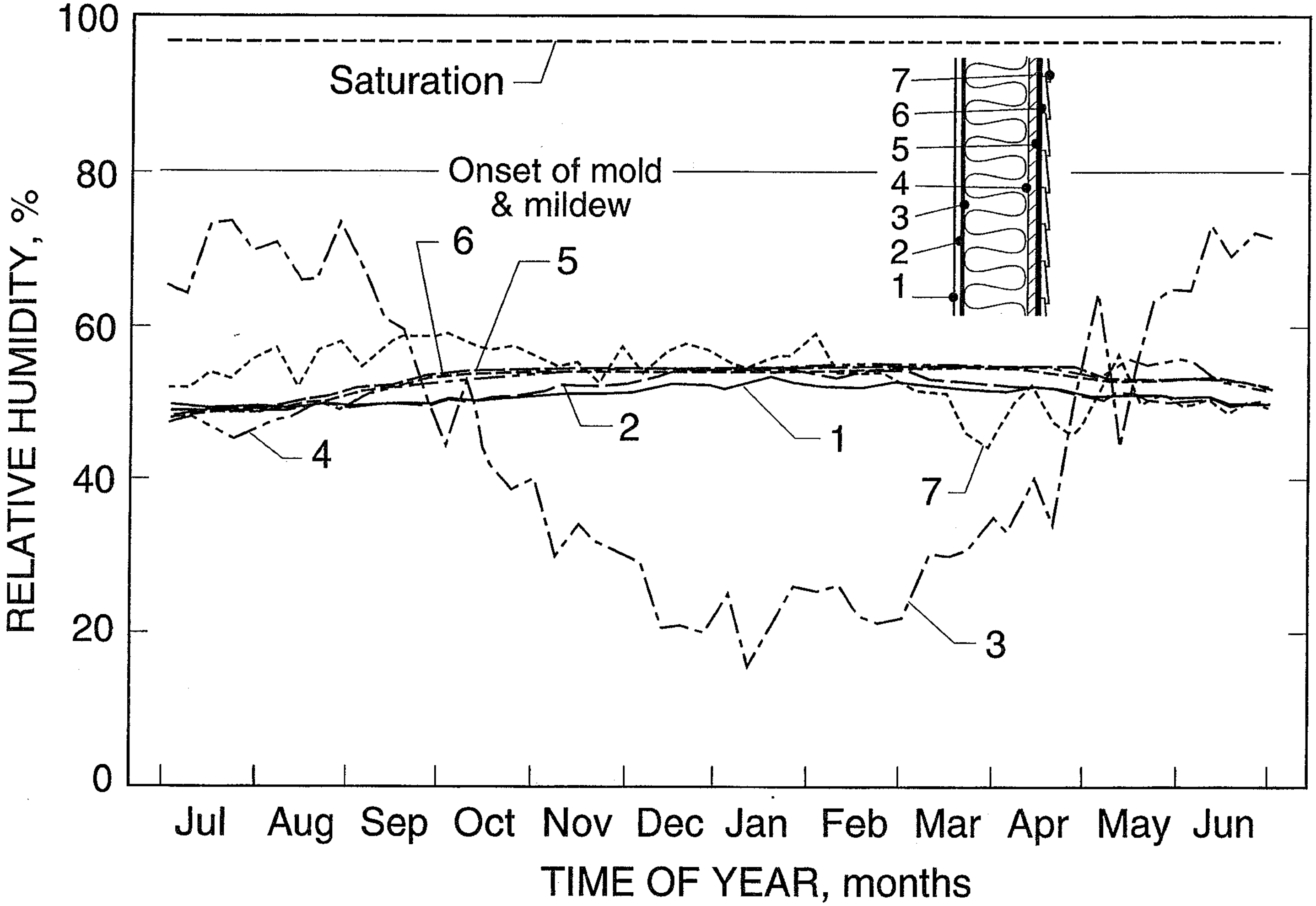


Fig. 11a. Relative humidity at layer surfaces versus time of year for Wall 1 of mixed climate (indoor relative humidity of 50%)

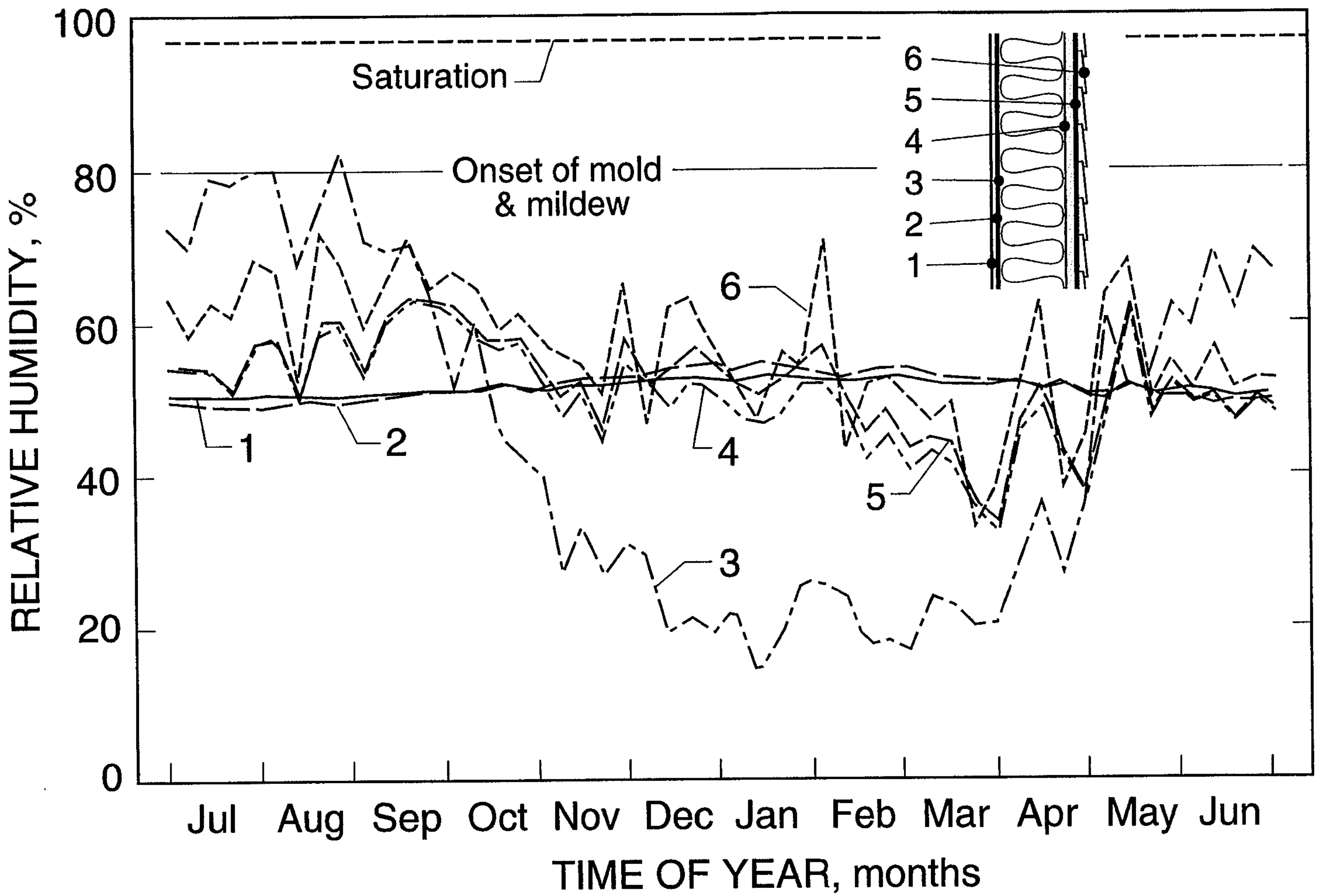


Fig. 11b. Relative humidity at layer surfaces versus time of year for Wall 2 of mixed climate (indoor relative humidity of 50%)

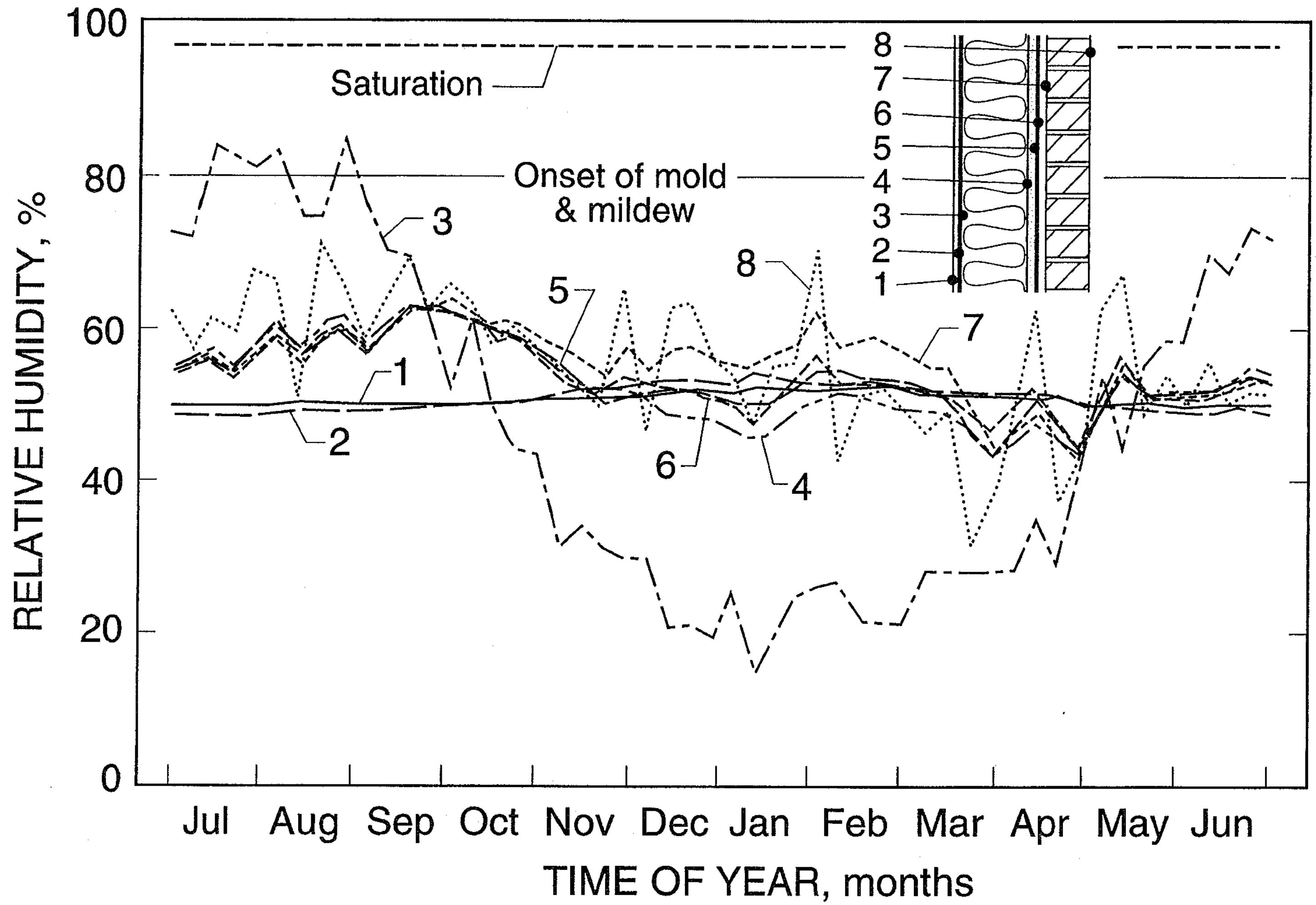


Fig. 11c. Relative humidity at layer surfaces versus time of year for Wall 3 of mixed climate (indoor relative humidity of 50%)

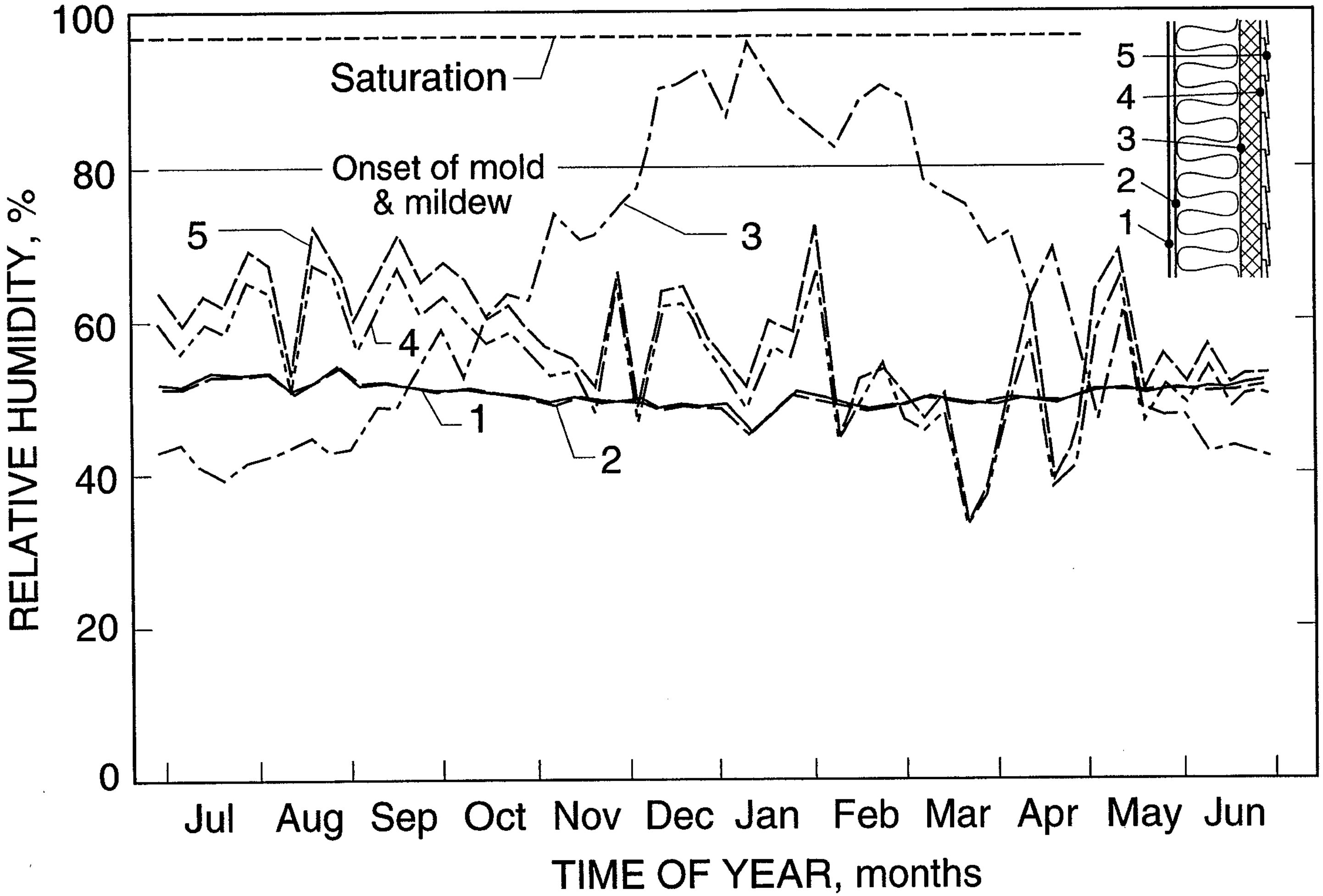


Fig. 11d. Relative humidity at layer surfaces versus time of year for Wall 4 of mixed climate (indoor relative humidity of 50%)

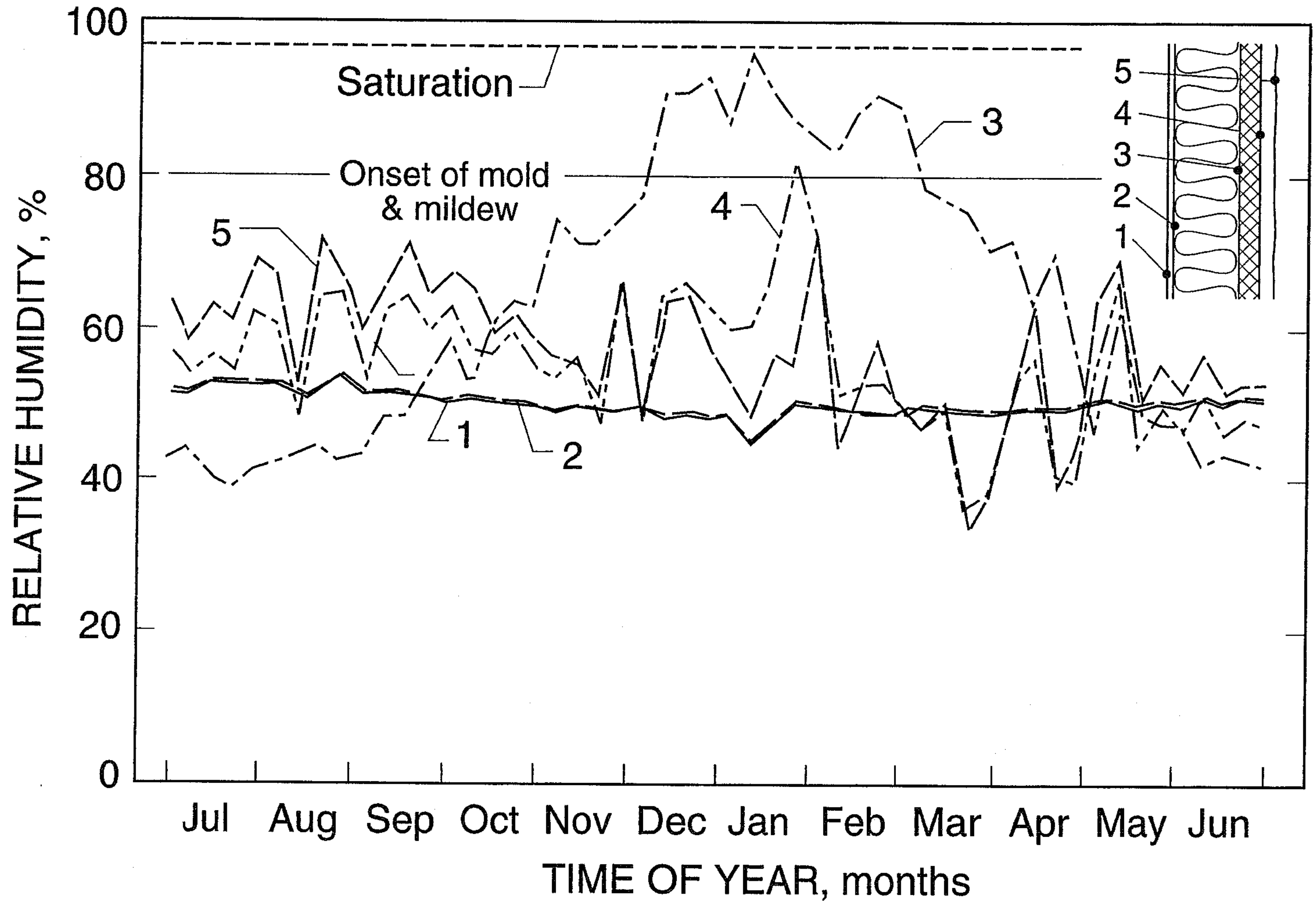


Fig. 11e. Relative humidity at layer surfaces versus time of year for Wall 5 of mixed climate (indoor relative humidity of 50%)

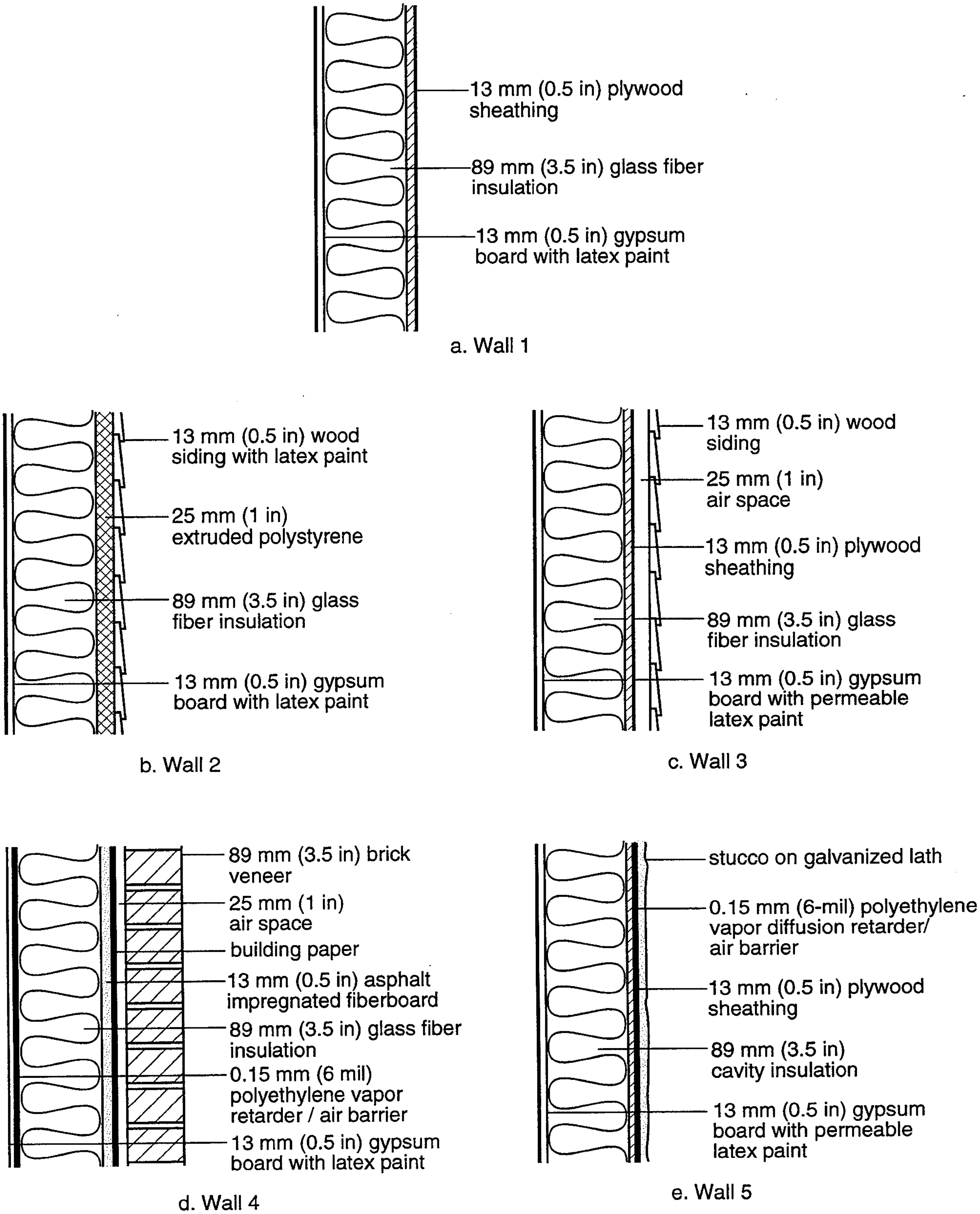
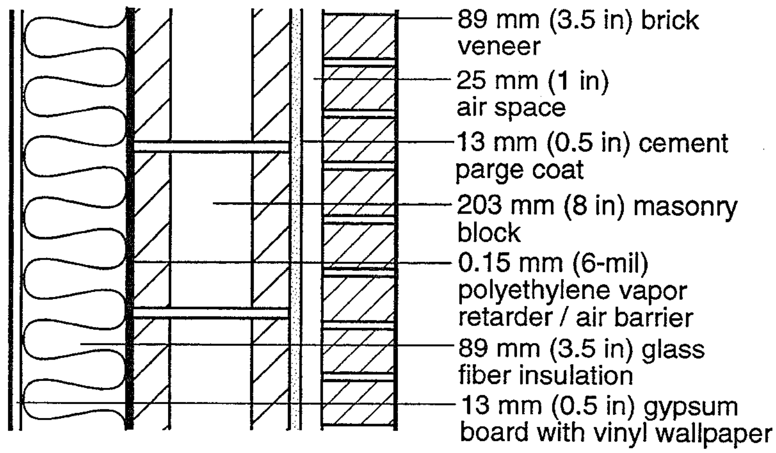
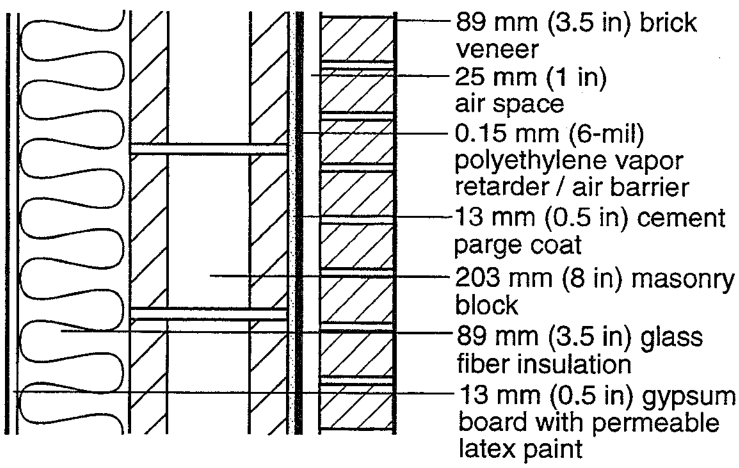


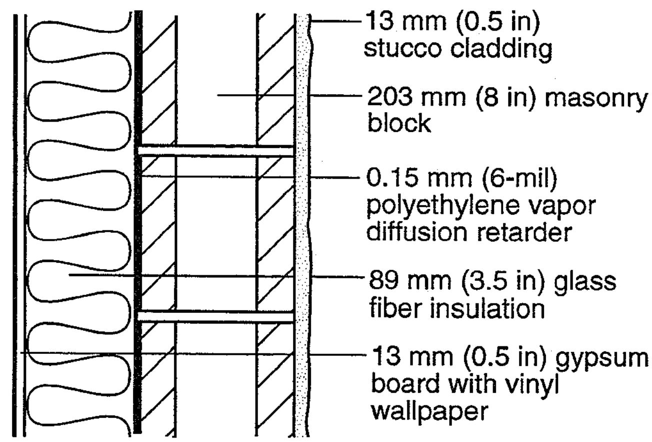
Fig. 12a. Wall constructions analyzed for cooling climate.



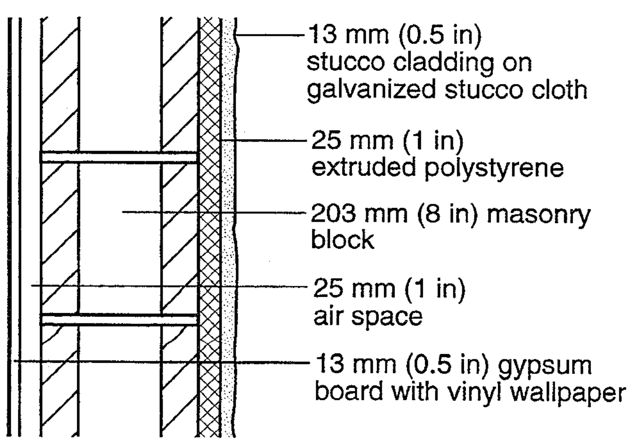
f. Wall 6



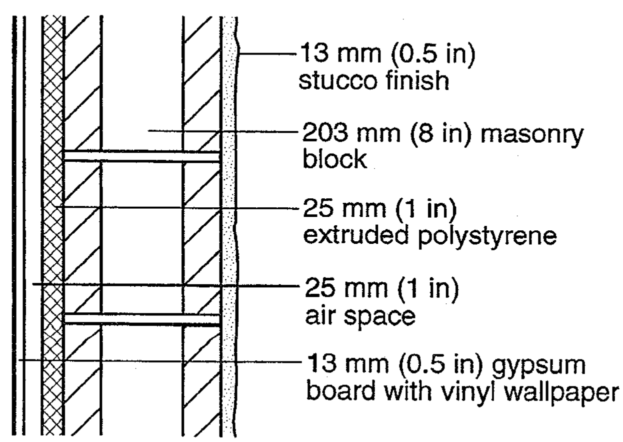
g. Wall 7



h. Wall 8



i. Wall 9



j. Wall 10

Fig. 12b. Wall constructions analyzed for cooling climate.

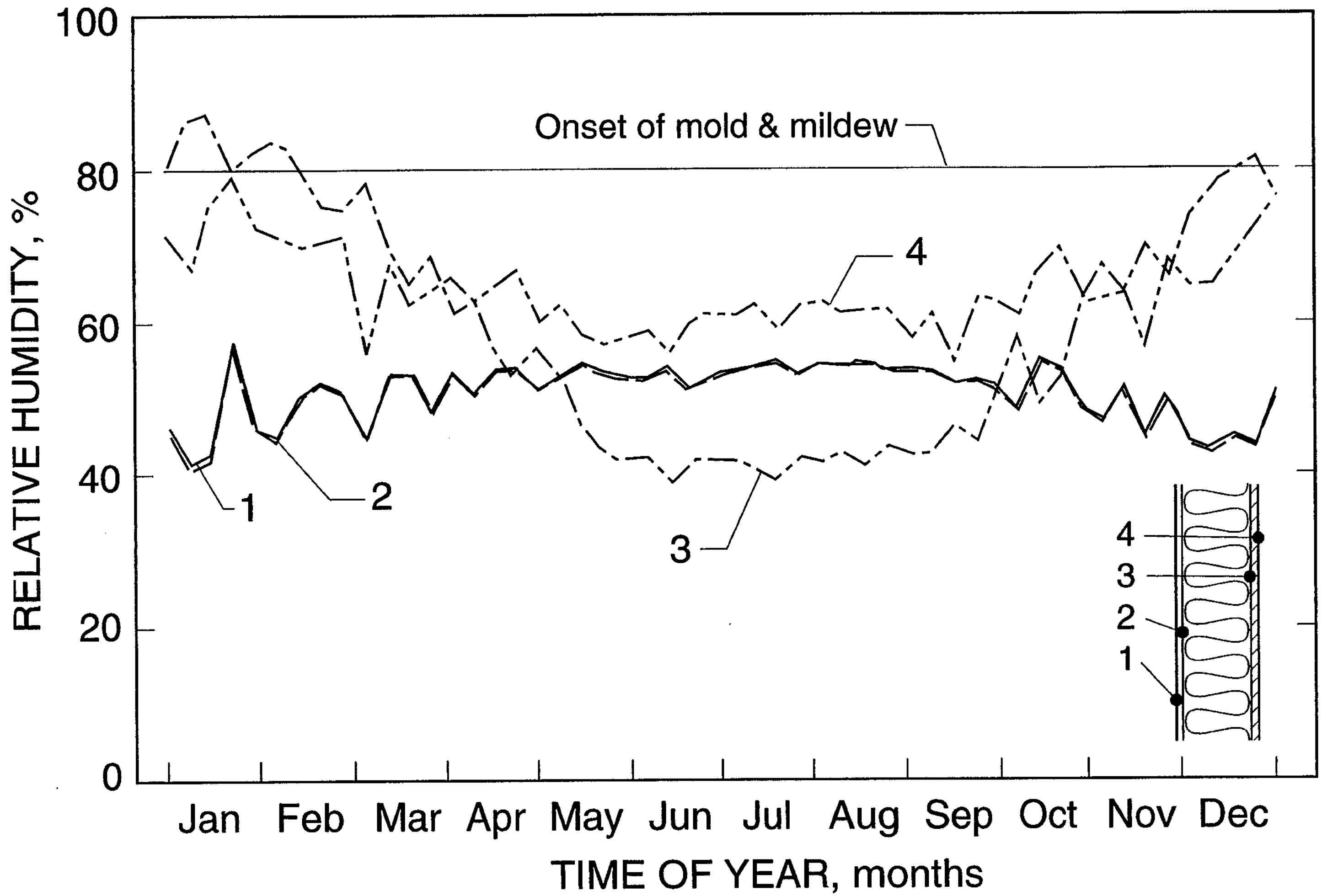


Fig. 13a. Relative humidity at layer surfaces versus time of year for Wall 1 of cooling climate (indoor relative humidity of 50%)

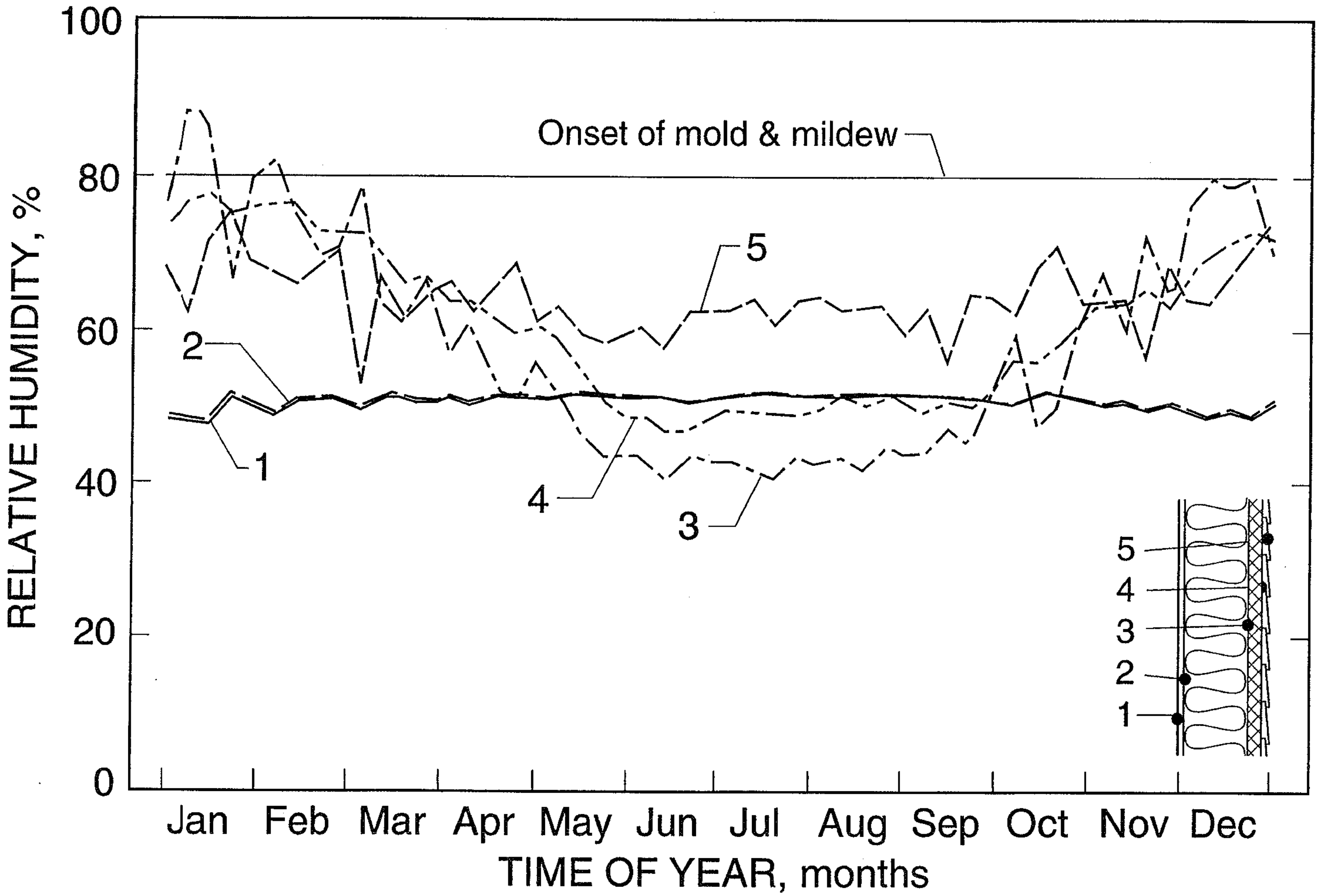


Fig. 13b. Relative humidity at layer surfaces versus time of year for Wall 2 of cooling climate (indoor relative humidity of 50%)

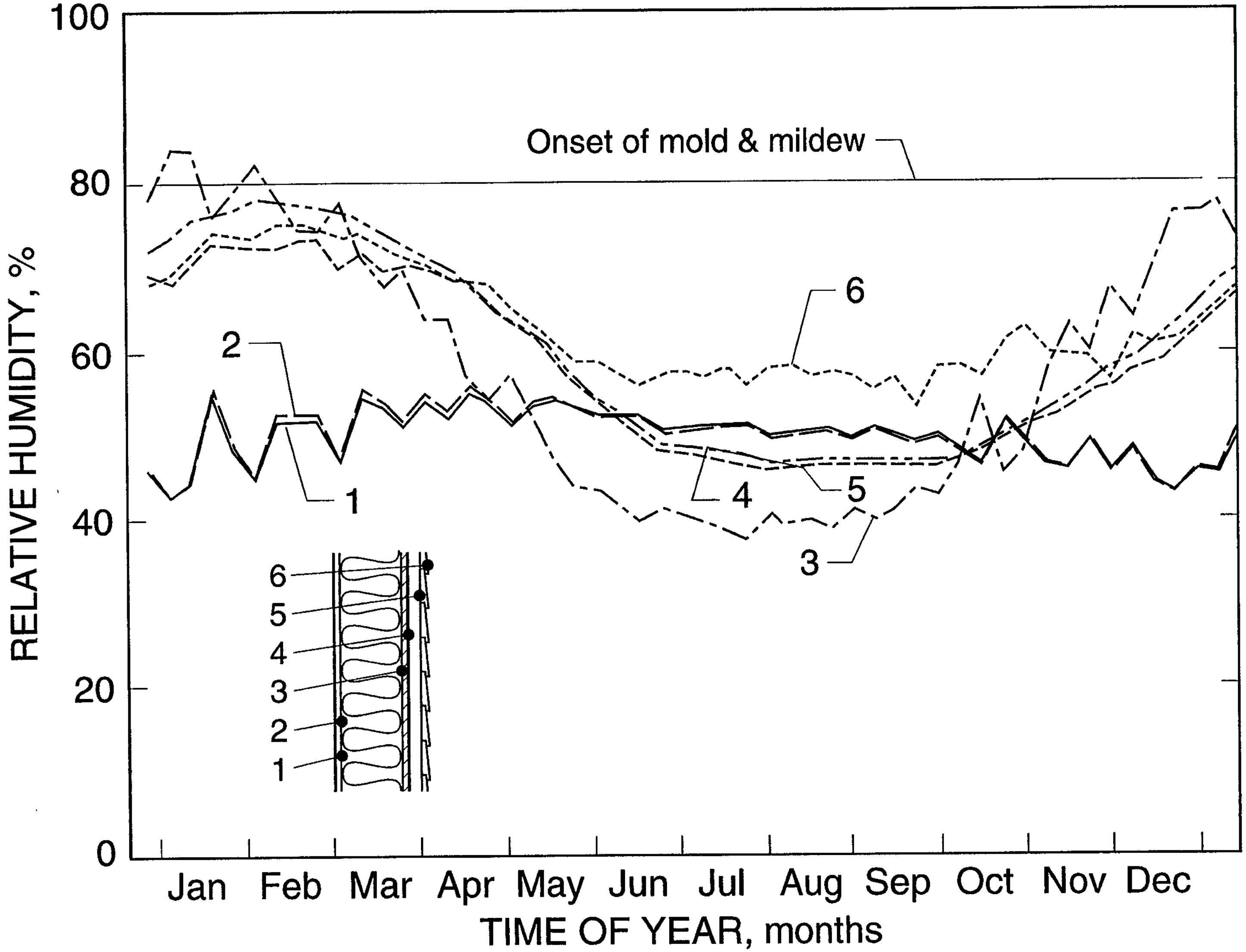


Fig. 13c. Relative humidity at layer surfaces versus time of year for Wall 3 of cooling climate (indoor relative humidity of 50%)

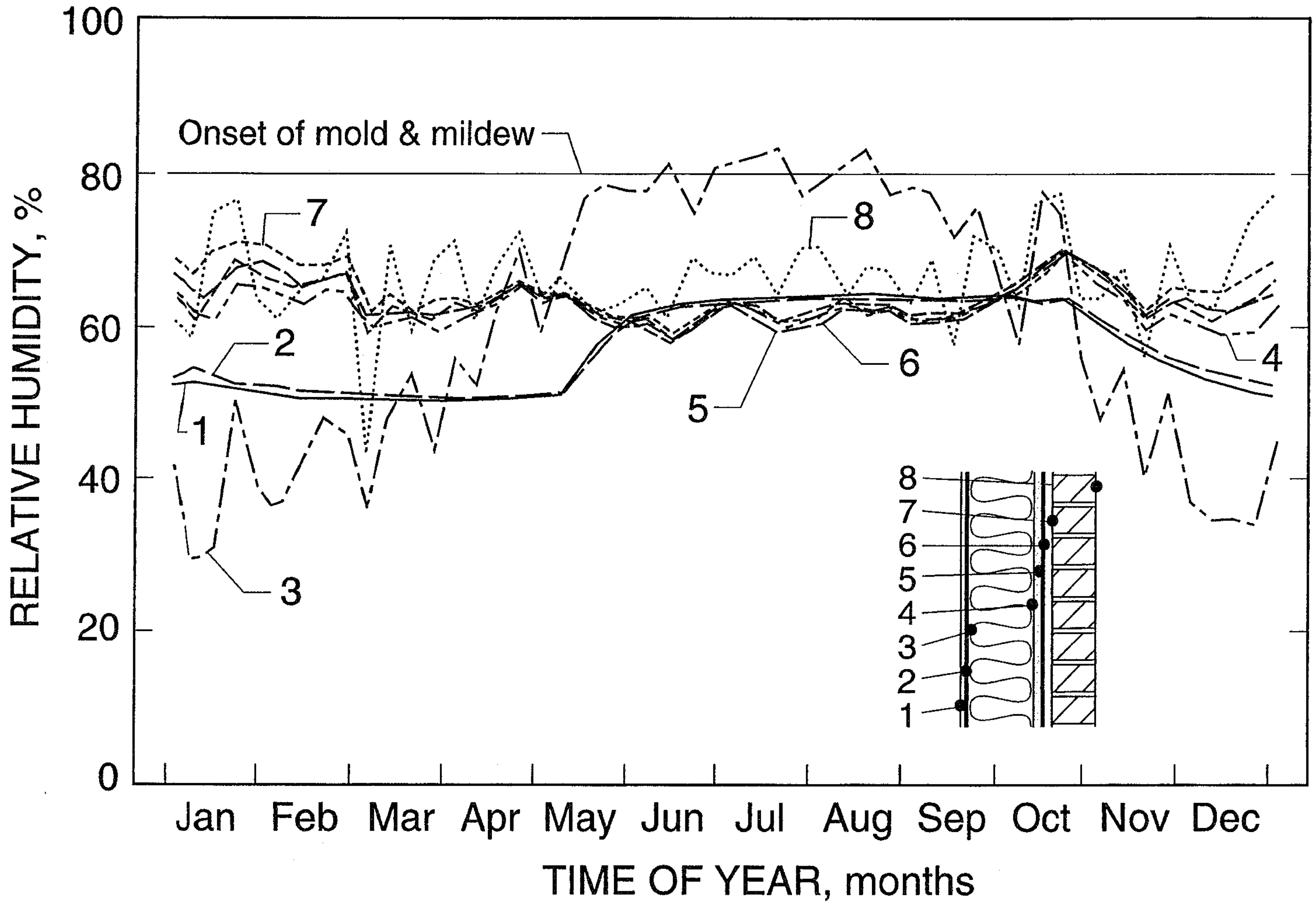


Fig. 13d. Relative humidity at layer surfaces versus time of year for Wall 4 of cooling climate (indoor relative humidity of 50%).

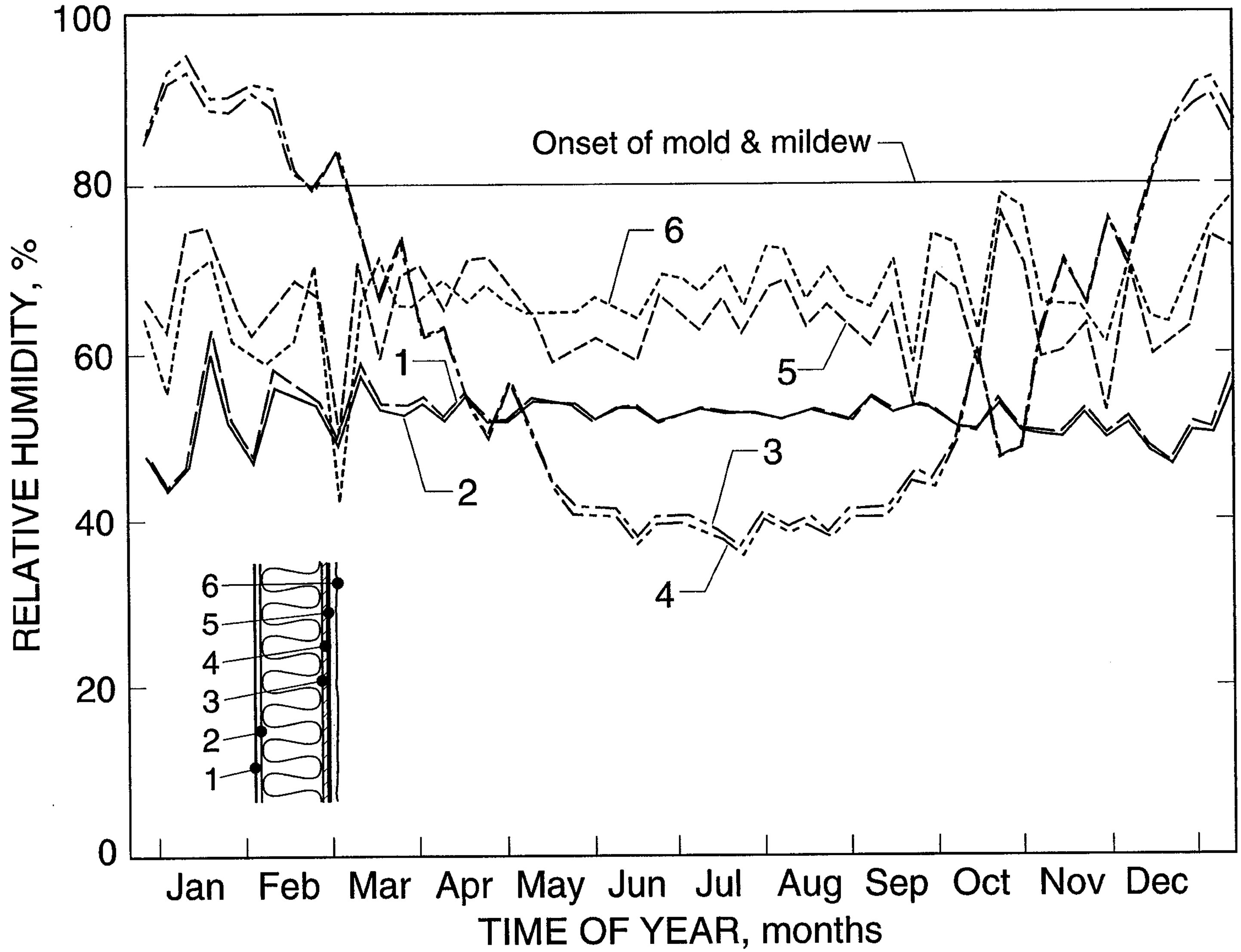


Fig. 13e. Relative humidity at layer surfaces versus time of year for Wall 5 of cooling climate (indoor relative humidity of 50%)

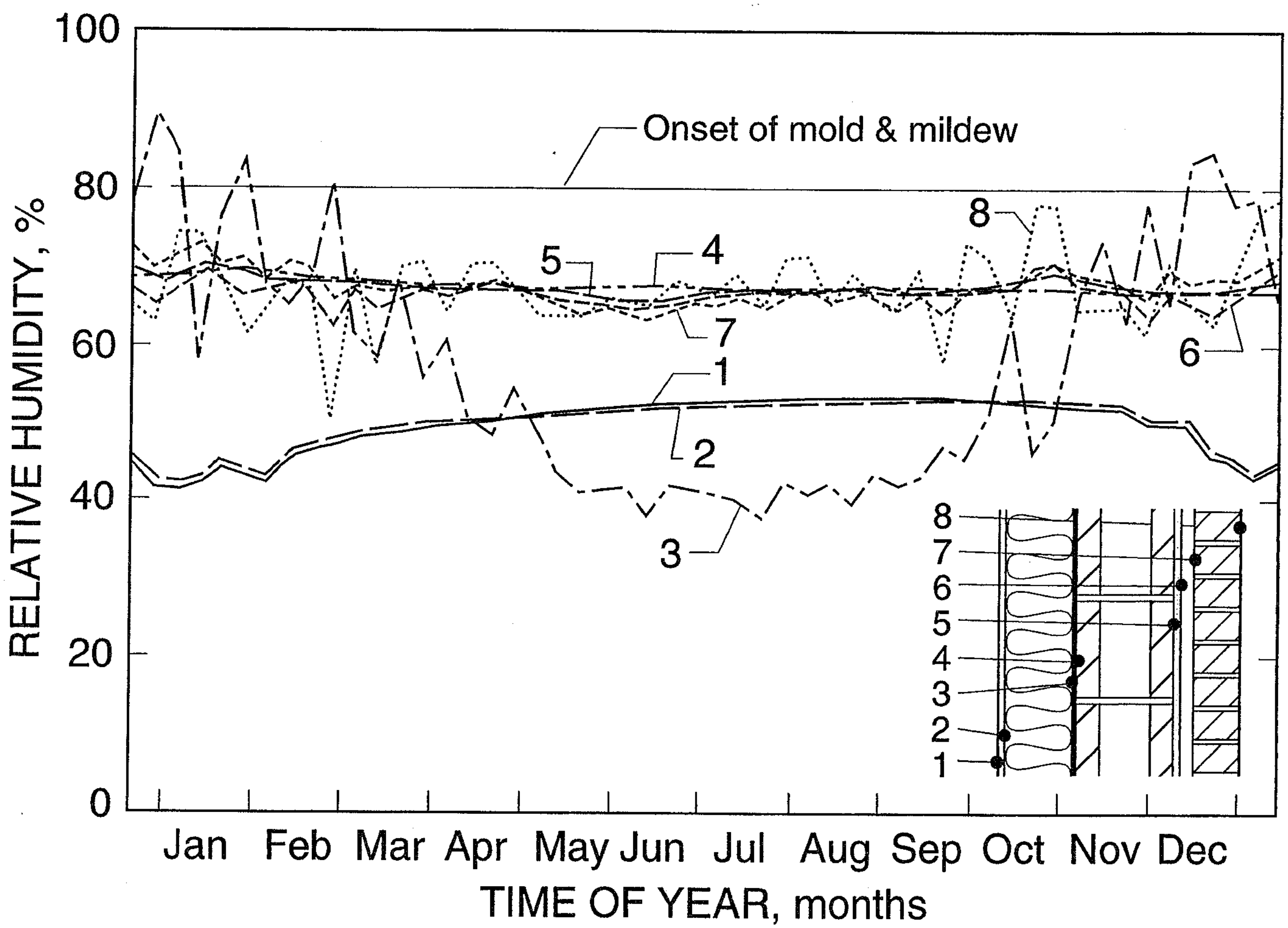


Fig. 13f. Relative humidity at layer surfaces versus time of year for Wall 6 of cooling climate (indoor relative humidity of 50%)

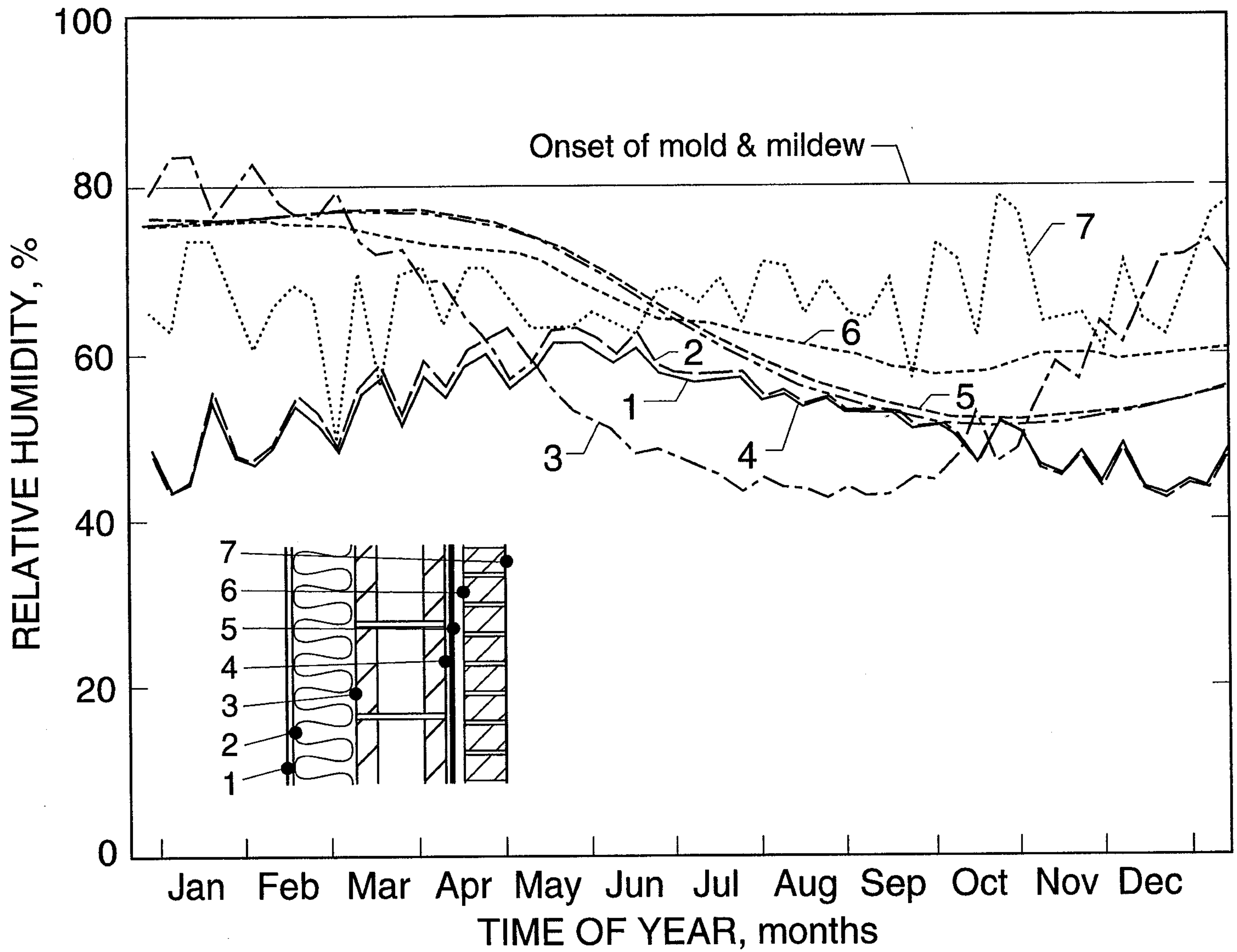


Fig. 13g. Relative humidity at layer surfaces versus time of year for Wall 7 of cooling climate (indoor relative humidity of 50%)

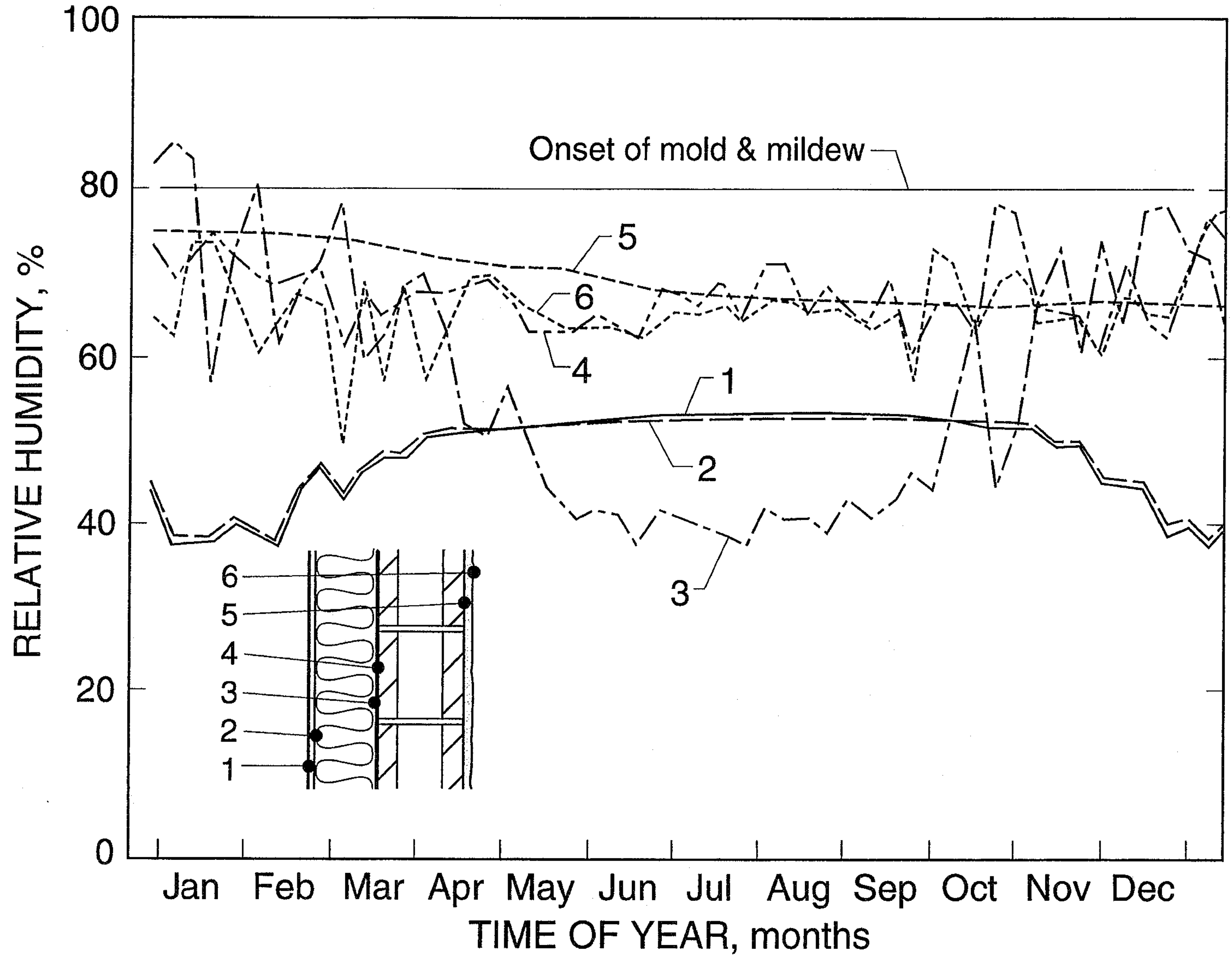


Fig. 13h. Relative humidity at layer surfaces versus time of year for Wall 8 of cooling climate (indoor relative humidity of 50%)

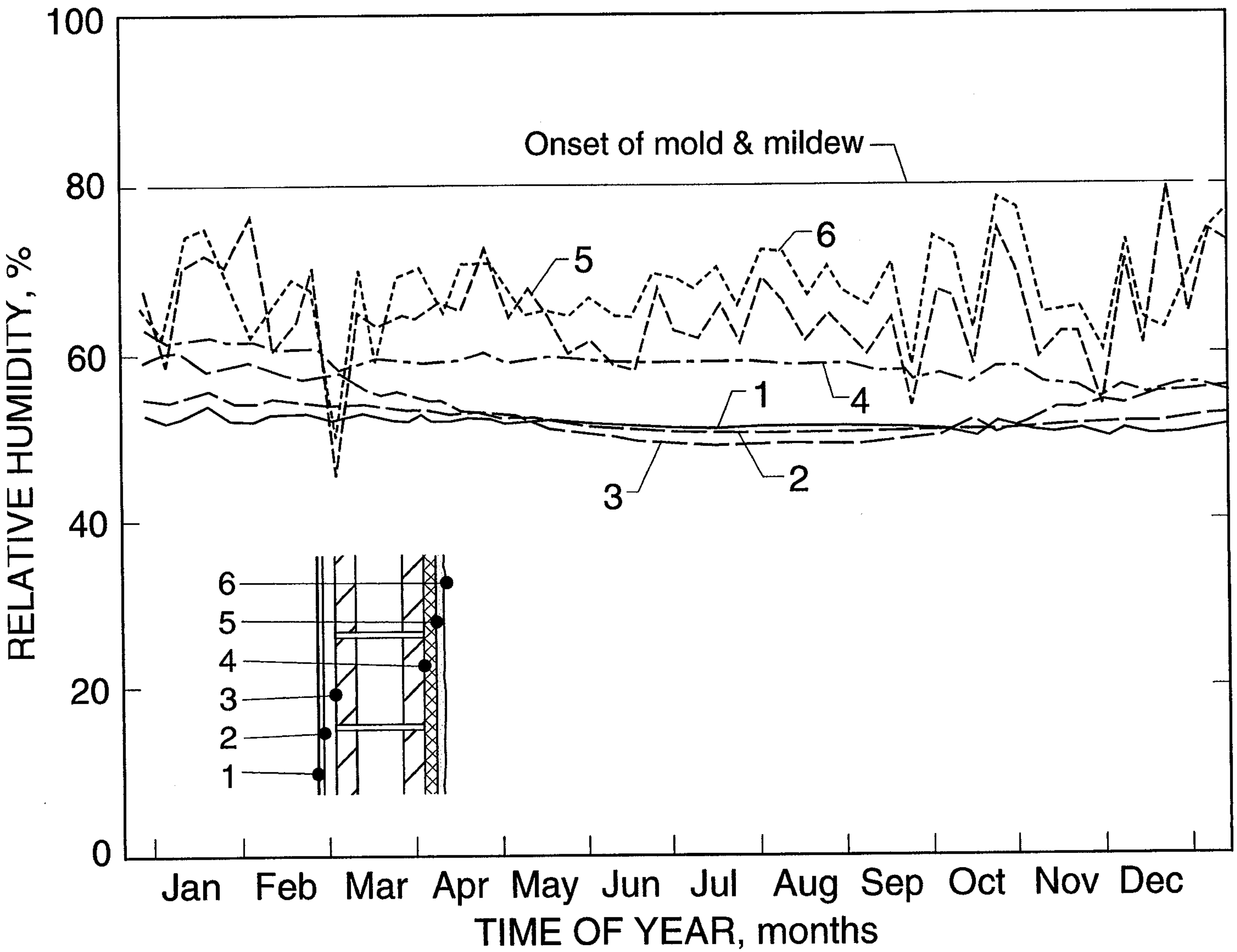


Fig. 13i. Relative humidity at layer surfaces versus time of year for Wall 9 of cooling climate (indoor relative humidity of 50%)

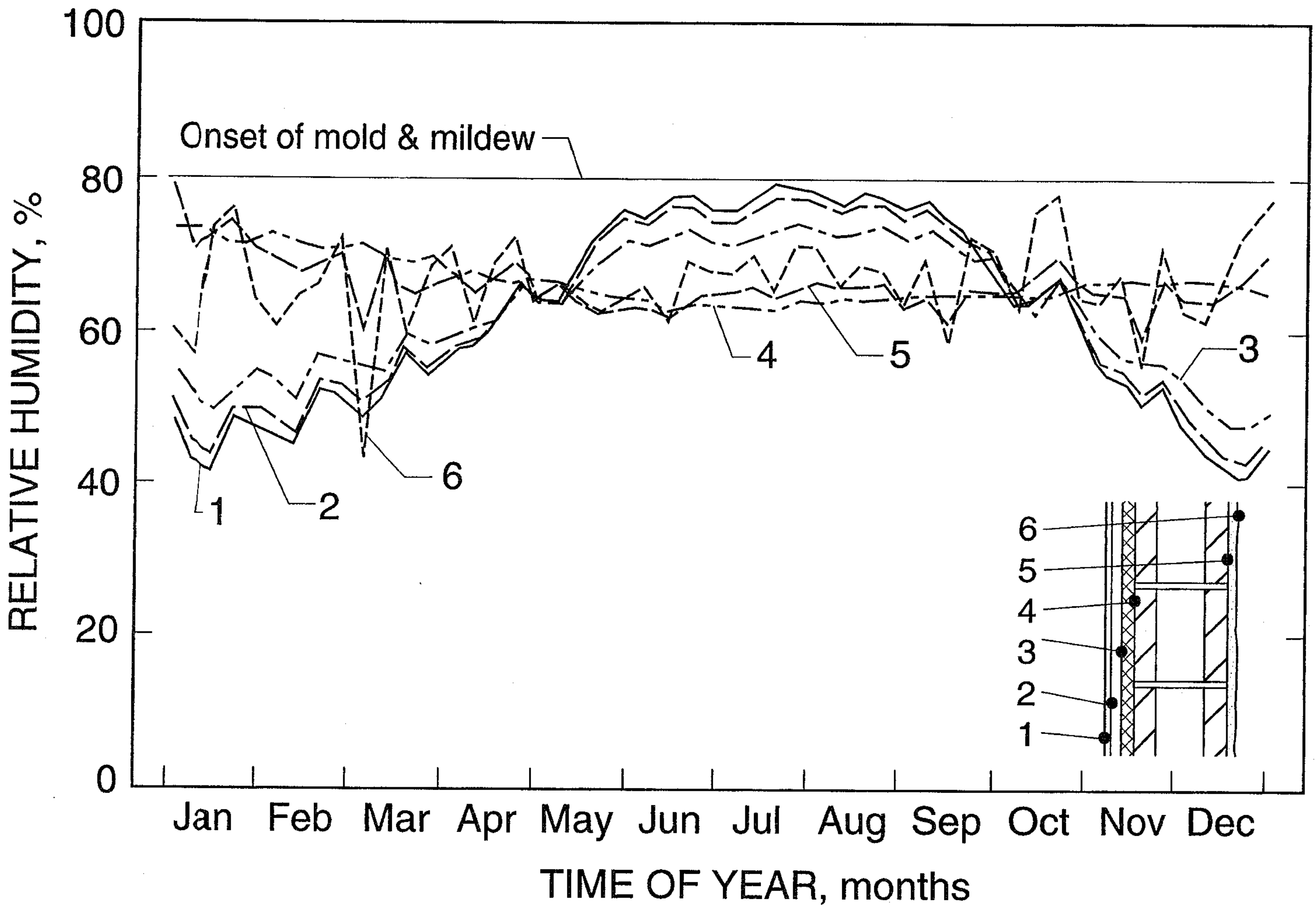


Fig. 13j. Relative humidity at layer surfaces versus time of year for Wall 10 of cooling climate (indoor relative humidity of 50%)

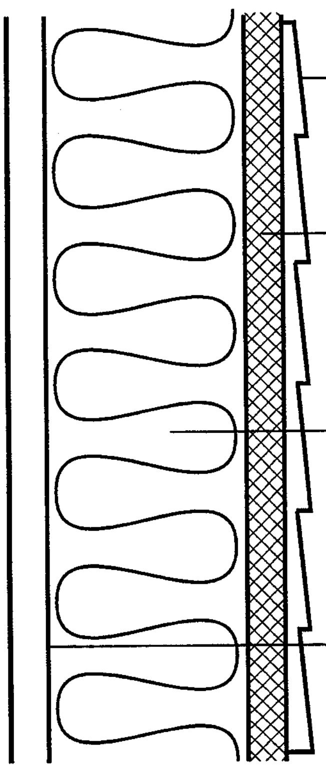


Fig. 14. A permeable wall for cooling climate

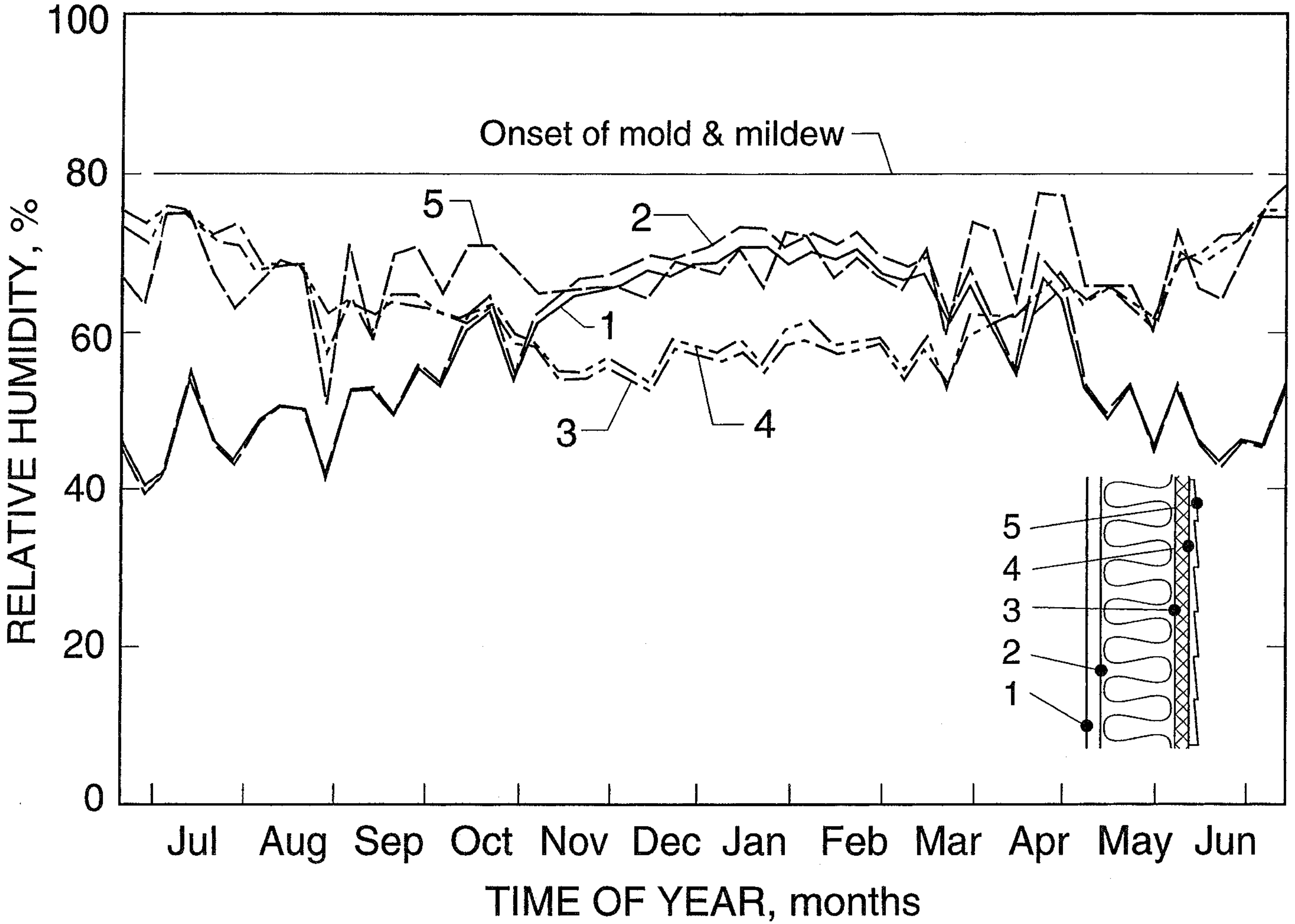


Fig. 15. Computer simulation of permeable wall construction for a cooling climate.