Hygrothermal Performance of Masonry Cavity Walls with Very Low U-Factor: A Test House Evaluation

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ABSTRACT

The Kyoto agreement obliges the industrialized world to increase investments in energy efficiency. As building usage generates 35% to 40% of the total annual energy consumption, the construction of Low Energy and Low Pollution (L²EP) buildings and L²EP retrofits should rank high on the list of priorities. L²EP presumes a well-insulated building enclosure with opaque whole wall U-factors close to 0.2 W/(m²·K).

That U = 0.2 W/(m²·K) requirement will alter the design of the traditional masonry cavity wall in Western Europe quite drastically. To gain a better view of the criteria to be set, a test house campaign on six pairs of 1.8 m wide and 2.7 m high masonry cavity walls with U = 0.2 W/(m²·K) as an intended U-value was initiated. For each pair, one wall faced southwest, the other northeast. The walls differed in terms of capillary properties of the brick veneer, the application of a full or a partial cavity fill, the use of fiberglass or extruded polystyrene as a filling material, the level of workmanship, and the air permeability of the inside leaf. During two years, temperature gradients, relative humidity profiles, heat flow rates, and moisture content in the brick veneers were measured. Major differences in thermal performance were found, with workmanship as the most determining factor. Moisture tolerance was found to be very high for all cavity walls tested.

This paper closes with a discussion of the design and workmanship criteria that were highlighted by the research.

INTRODUCTION

The Kyoto agreement is obliging the industrialized world to invest more in energy efficiency. As building usage represents 35% to 40% of the total annual energy consumption (IEA 1994), the construction of Low Energy and Low Pollution (L²EP) buildings and L²EP retrofits should rank high on the list of priorities. L²EP presumes a well-insulated building enclosure, with opaque whole wall U-factors close to 0.2 W/(m²·K).

For decades, U = 0.6 W/(m²·K) figured as the whole wall U-factor threshold in moderate climates. A masonry cavity wall, which had that U-value imposed, consisted of a 9-cm-thick brick veneer, a 5- to 7-cm-wide cavity, and a 14-cm-thick inside leaf, finished with a gypsum plaster. The cavity was partially or fully filled with a thermal insulation. For the inside leaf, typically perforated blocks with dimensions ranging from T x H x L = 14 x 14 x 29 cm (bricks and concrete) to T x H x L = 14 x 59 x 89 cm (cellular concrete and sand-lime stone) were used. The calculated clear wall U-factor of such a design laid between 0.45 and 0.55 W/(m²·K) for a wall thickness of 30 cm (Künzel 1983; Künzel 1991).

In the early days of insulation activity, the thermal bridge flaws (mentioned in Table 1 under D1 and D2) and design mistake and workmanship imperfections (described in Table 1 under D3, W1, and W2) were common in cavity wall construction. To ensure that the intended U = 0.6 W/(m²·K) was effectively realized at the whole wall level, practitioners were therefore instructed, in a very systematic way, how to eliminate thermal bridges D1 and D2 (Hens 1984; Standaert 1985; Knapen and Standaert 1985; Anon. 1992; Hens and Mohamed 1995; Anon. 1996a; Anon. 1996b; Hens 1999). Also, rules of

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TABLE 1
Common Design and Workmanship Flaws

	Design
D1	Cavity closers around windows and doors, lintels insulated at the inside
D2	Concrete floors touching the outer leaf
D3	No inside gypsum plastering
	Workmanship
W1	Partial fill not pressed against the inside leaf, the fill starting above the lower flashing, a gap left at the top of the wall (Figure 3)
W2	Header joints in the inside leaf insufficiently filled

good workmanship were published and critical details were assessed with, as one of the objectives, the elimination of the design mistake D3 and the imperfections W1 and W2. Flaw D3, in fact, facilitates air infiltration and exfiltration through the wall, while the imperfections W1 and W2 both induce buoyancy around the cavity fill—a main cause of bad thermal performance (Bankvall 1972; Lecompte 1989; Anon. 1992; Hens 1999). Of course, the four ties per m^2 between the inside leaf and the brick veneer could not be eliminated. Figure 1 shows that their impact, as a thermal bridge, on the whole wall U-factor is too marginal to be considered.

DESIGNING A U = 0.2 W/(M²·K) MASONRY CAVITY WALL

Downscaling the clear wall U-factor from 0.6 to 0.2 $W/(m^2{\cdot}K)$ occurred in steps. First, the cavity was broadened from 6 cm to 11 cm, which added 5 cm to the wall thickness. With a 10-cm-thick mineral fiber full fill, that first move reduced the clear wall U-factor to 0.30 $W/(m^2{\cdot}K)$. A partial fill, with a 7.5-cm-thick PU-board, with an aluminum liner at both sides, brings the U-factor down to 0.25 $W/(m^2{\cdot}K)$. An additional decrease without extra thickness came from bricklaying the inside leaf with perforated lightweight groove-and-tongue building bricks with a density below 800 kg/m^3 and an equivalent thermal conductivity of 0.16 $W/(m{\cdot}K)$. That measure lowered the clear wall U-factor to 0.27 $W/(m^2.K)$ for a 10 cm mineral fiber full fill and to 0.22 $W/(m^2{\cdot}K)$ for an aluminum-lined PU partial fill. A lightweight groove-and-tongue building brick inner leaf of 19 cm, resulting in a wall thickness of 40 cm, gave a further decrease to 0.25, respectively, 0.21 $W/(m^2{\cdot}K)$ (i.e., very close to the 0.2 $W/(m^2{\cdot}K)$ objective). However, if the cavity is widened to 16 cm and filled with 15 cm mineral fiber or a 12.5-cm-thick PU-board, while keeping the inside leaf 14 cm thick, the clear wall U-factor reaches 0.19, respectively, 0.15 $W/(m^2.K)$, underlining that the new benchmark is realizable with a wall thickness of 40 cm (Hens 1999). The 10 cm extra compared to the U = 0.6 cavity wall nevertheless invoke secondary costs that should be considered when evaluating the economics of the solution (Rudbeck 2000). The wider

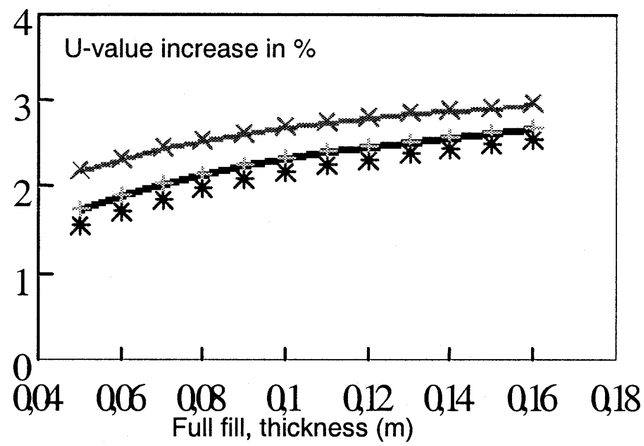

Figure 1 *Increase of the U-value in percentage when four ties per square meter of wall are used. Lowest line for U = 0.6 W/(m²·K), highest is for U = 0.2 W/(m²·K).*

cavity also has consequences for buildability. Ties, for example, must be redesigned.

At the whole wall level, most practitioners today are aware of the negative impact of thermal bridges—refer to flaws D1 and D2 in Table 1. Most try to eliminate structural thermal bridging by a consequent application of thermal breaks. Design flaw D3 and workmanship imperfections W1 and W2 in Table 1, however, are more persistent. Inside plaster is still considered by some designers as a useless asset that hinders their vision of esthetics, while workmanship in relation to W1 and W2 remains troublesome on many building sites, mainly because the professionals do not understand the consequences of these imperfections. Hence, the U = 0.2 $W/(m^2{\cdot}K)$ constraint may increase the risks related to these flaws in terms of unfit thermal and hygric wall behavior compared to the actual U = 0.6 $W/(m^2{\cdot}K)$ wall, risk being defined as the probability of a flaw, mistake, or imperfection is committed multiplied with the weighted severity of its consequences.

The flaw D3 and the imperfections W1 and W2 from Table 1 facilitate air movement in filled masonry cavity walls. These movements combine four basic patterns: (1) air in and exfiltration, (2) air intrusion, (3) ventilation and wind washing, and (4) buoyancy induced air flow. Infiltration and exfiltration stay for outside or inside air moving through the wall from one side to the other. The flow developing that way is governed by the air permeance of the wall (refer to the default values of Table 2) (Hens and Mohamed 1995). That table confirms the importance of an inside plaster to realize acceptable air tightness. Intrusion points to inside air that enters the wall somewhere and leaves it at another place after having bridged a distance along the cavity. Ventilation and wind washing are caused by outside air permeating into the cavity.

TABLE 2
Default Values for the Air Permeances of Cavity Walls

Brick veneer with two open butt joints per meter	$K_a = 2\ 10^{-3} \Delta Pa^{-0.45}$
Inside leaf, masonry blocks, not plastered	$K_a = 4\ 10^{-5} \Delta Pa^{-0.25}$
Inside leaf, no fines concrete blocks, not plastered	$K_a = 4\ 10^{-4} \Delta Pa^{-0.25}$
Inside leaf, no fines concrete blocks, plastered	$K_a = 1\ 10^{-5} \Delta Pa^{-0.2}$

Figure 2 *The test building with the six masonry cavity walls facing northeast.*

If the airflow stays at the exterior surface of the fill, the pattern is called *ventilation*. When the airflow intrudes into the fill and moves along the cavity surface of the inside leaf, the term *wind washing* applies. Buoyancy flow finally addresses cavity air flowing around the insulation layer, a consequence of the temperature difference that exists between both of its sides.

The consequences of these airflow patterns, in terms of degrading thermal performance, were analyzed in Hens et al. (1999). Normally, the U-factor is given by

$$U = \frac{1}{1/h_i + \sum_{j=1}^{n} R_j + 1/h_e} \qquad (1)$$

where h_i is the inside surface film coefficient, h_e is the outside surface film coefficient, and R_j is the thermal resistance of all layers composing the wall. Air infiltration and exfiltration delete the U-factor calculated that way as an energy-efficiency indicator. Infiltration also facilitates rain leakage, decreases noise reduction, and promotes drafting in the interior space. Exfiltration, in turn, may cause excessive interstitial condensation. As Lecompte (1989) analyzed in great detail, buoyancy flow lifts the effective U to a multiple of the value calculated with Equation 1.

TABLE 3
The Six Pairs of Test Walls

Veneer	Cavity Fill	Inside Leaf
Brick masonry, capillary, d = 9 cm	**Fiberglass, d = 14 cm, full fill, poor workmanship**	**Concrete blocks, d = 14 cm, quite air permeable**
Brick masonry, hardly capillary, d = 9 cm	Fiberglass, d = 14 cm, full fill, correct workmanship	Perforated bricks masonry, d = 14 cm, more air retarding
Brick masonry, hardly capil-lary, d = 9 cm	**XPS, d = 10 cm, partial fill, poor workmanship, rest cavity ventilated**	**Concrete blocks, d = 14 cm, quite air permeable**
Brick masonry, capillary, d = 9 cm	XPS, d = 10 cm, partial fill, correct workmanship, rest cavity ventilated	Perforated bricks masonry, d = 14 cm, more air retarding
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A TEST HOUSE EVALUATION OF U = 0.2 SI MASONRY CAVITY WALLS

Experimental Set up

To quantify the risks poor workmanship, design errors, and mistakes may cause, a test building experimental program on U = 0.2 W/(m²·K) cavity walls was initiated in 1996 (Janssens et al. 1997, 1999). Six pairs of walls, each wall being 180 cm wide and 270 cm high, were constructed in the facade ridges of the test building (Figure 2). One wall per pair faced southwest, the other northeast. Table 3 and Figure 3 list the six sections. In the table, the walls exhibiting poor workmanship are printed in bold. *Poor* included a 1-cm-thick air space between the cavity fill and the inside leaf, open joints between the 60-cm-high insulation panels in the cavity and a 10-cm non-insulated cavity space at the top and the bottom of the fill. At a height of 54, 135, and 216 cm above floor level, all 12 walls had Cu-Co thermocouples fixed on the inside and outside surface, in the interfaces between brick veneer and cavity and between cavity and fill and at the cavity side of the inside leaf. Relative humidity sensors were fixed at the same heights in the middle of the cavity between the fill and the brick veneer (partial fill) or the air space between the fill and the brick veneer (full fill). At the inside, a heat flow meter was attached on the wall's surface, 135 cm above floor level.

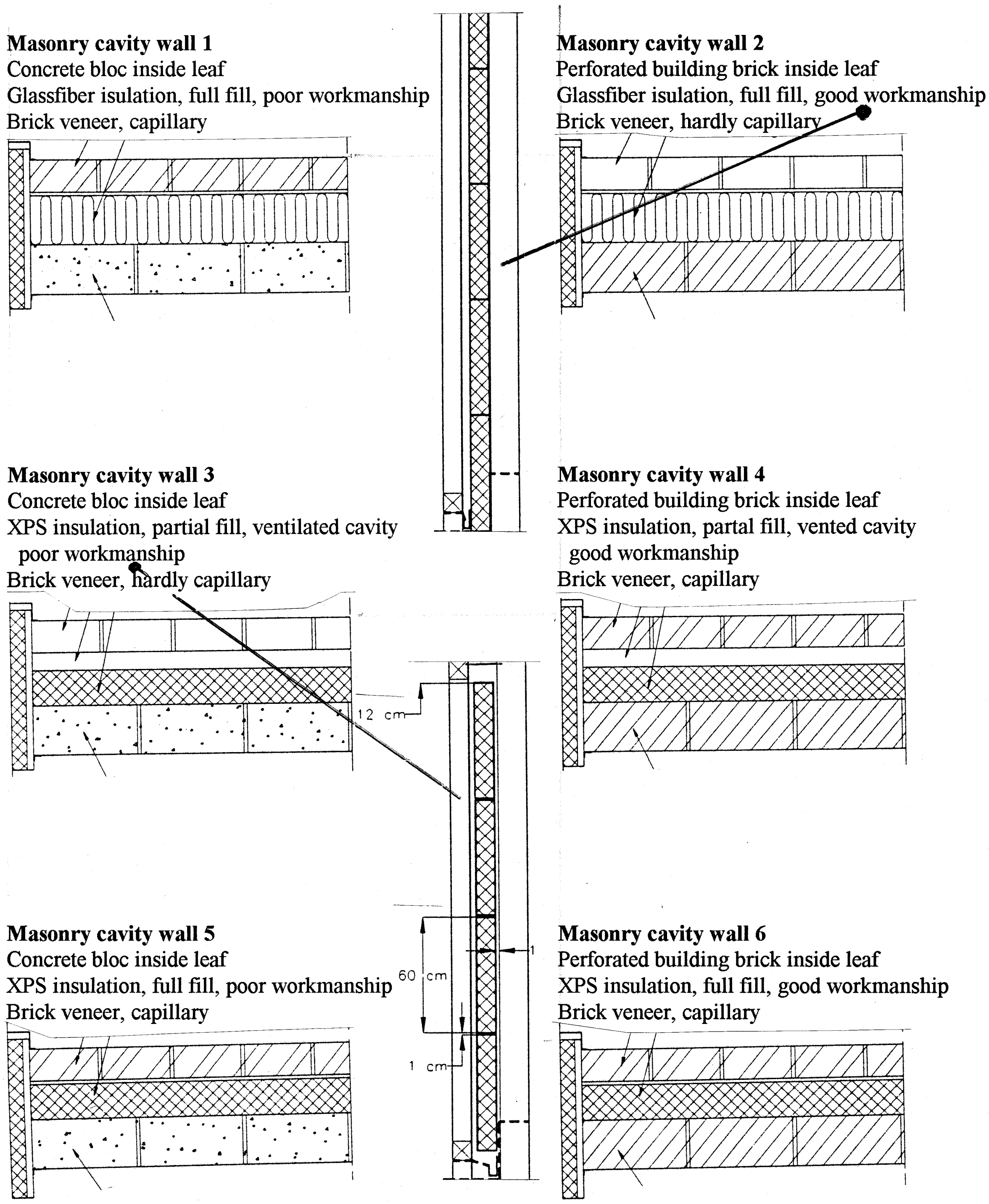
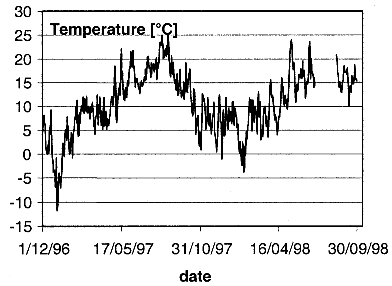
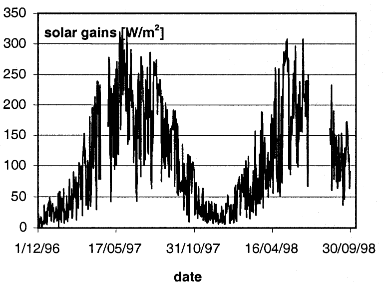


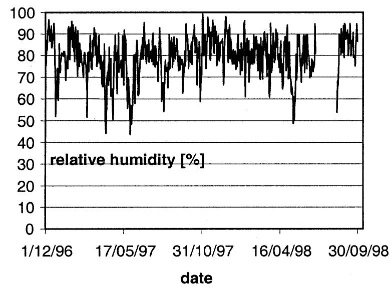
Figure 3 *The wall sections.*



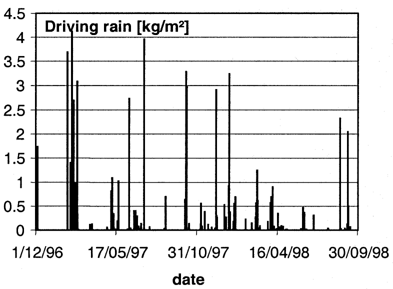
Daily average air temperature in °C



Daily average solar gains on a horizontal surface in W/m²



Daily average relative humidity in %



Daily average wind driven rain in the center of the south West oriented facade in kg/(m².day)

Figure 4 *Outside climate during the test period.*

During two consecutive winters, from the end of December 1996 to September 30, 1998, temperature fields, relative humidity, and heat flow rates were monitored continuously. Each week, a loose panel that had perimeter jointing to minimize adventitious air ingress in the cavity was removed from each of the brick veneers, weighed on a precision balance, and reinstalled. At the end of the second winter, cores were taken from each veneer, and their moisture content compared with the value measured in the loose panels.

At the test house site, exterior temperature, exterior relative humidity, the solar gains on a vertical and a horizontal surface, wind direction, wind velocity, and precipitation were scanned every 10 ft and stored for further analysis. In the test house, an inside climate class 3 situation, with an air temperature around 21°C and an inside-outside vapor pressure excess of some 600 Pa, was maintained. Inside climate class 3 is representative for small dwellings, constructed in Western European countries under the denominator *subsidized housing* (Sanders 1996).

PERFORMANCES TESTED

The cavity walls were evaluated according to the *Annex 32 Array of Level 3 Envelope Performances* (Hendriks and Hens 2000). Table 4 gives the performances that were analyzed using the measured data.

TABLE 4
Excerpt of the Annex 32 Array of Level 3 Envelope Performances

Topic	Performances
Heat and mass	Airtightness – Air permeance – Ventilation and wind washing – Buoyancy flow around the fill
	Thermal insulation – Clear and whole wall U-factor
	Moisture response – Rain penetration – Interstitial condensation
Service life	Physical attack (stress and strain due to moisture and temperature gradients, frost attack, salt attack)

RESULTS

Exterior Climate

Figure 4 summarizes some daily average climatic data measured at the test site: air temperature, relative humidity, solar gains on a horizontal surface, and wind-driven rain in the middle of the southwest facade. The values are typical for the cool, wet climate of Western Europe—moderate winter temperatures with some lonely cold spells, moderate summer

TABLE 5
Intended and Measured U-Values, First Winter

Cavity Wall	Fill		Intended U, W/(m^2·K)	Measured U, W/(m^2·K)	
	Partial	Full		SW	NE
Poor workmanship		MF	0.22	0.37	0.32
Good workmanship		MF	0.22	0.22	0.21
Poor workmanship	XPS		0.21	0.86	0.86
Good workmanship	XPS		0.21	0.23	0.21
Poor workmanship		XPS	0.21		0.51
Good workmanship		XPS	0.20	0.21	

temperatures, high relative humidity, few solar gains in wintertime, and quite some wind-driven rain.

Performances

Airtightness. The air permeance of the 12 walls was measured shortly after construction using an airtight box that had the same surface as the wall (180 x 270 cm). The box was sealed against the inside wall surface, coupled to a calibrated fan, and equipped with an air pressure gauge that measured the pressure difference between the box and the inside environment. Although some perimeter leakage disturbed the measurements, there was a clear difference in air leakage between the walls with a concrete block inside leaf and those with a perforated building brick inside leaf. On average, the first gave a leakage rate of 2.74 $m^3/(m^2 \cdot h)$ at 10 Pa air pressure excess, the second a leakage rate below 0.7 $m^3/(m^2 \cdot h)$.

Thermal Insulation. Using the winter average values of the measured heat flow rates in the center of the inside surface of each wall and the winter average values of the inside and outside surface temperature measured at the same spot, the clear wall U-factor was calculated using the formula

$$U = \frac{1}{\dfrac{\bar{\theta}_{si,\,central} - \bar{\theta}_{se,\,central}}{\bar{q}_{central}} + 0.17} \qquad (2)$$

where $\bar{q}_{central}$ is the average heat flow rate, $\bar{\theta}_{si,\,central}$ is the average surface temperature in the center of the inside surface, $\bar{\theta}_{se,\,central}$ is the average surface temperature in the center of the outside surface, and 0.17 is the sum of the standardized surface resistances on both sides of the wall. An analysis, in advance, with a two-dimensional combined heat and airflow computer model showed that the heat flow rate at the center of the inside surface was representative for the surface-averaged heat flow rate, even when wind washing and buoyancy flow intervened. The pronounced change of heat flow rates and surface temperatures with height in that case did not allow calculating U using a surface-averaged value of the surface temperatures. The differences between the mortar joint and masonry surface temperature were also too small to get any upgrade of Equation 2 when using weighted averages. In fact, it did not care which of the two temperatures was applied, as long as it was logged nearby the heat flow meter.

TABLE 6
Measured Thermal Resistances of the Different Layers in the Walls

Layer	Thickness (m)	Measured R-value, air dry material, $0 < \bar{\theta} < 30$°C $m^2 \cdot kW$
Hardly capillary bricks ($A = 0.014$ kg/($m^2 \cdot s^{0.5}$))	0.085	$0.12 - 2.2\ 10^{-4}\bar{\theta}$
Capillary bricks ($A = 0.2$ kg/($m^2 \cdot s^{0.5}$))	0.085	$0.16 - 1.2\ 10^{-4}\bar{\theta}$
Concrete blocks	0.14	$0.10 + 2.0\ 10^{-4}\bar{\theta}$
Perforated building brick	0.14	$0.28 - 2.1\ 10^{-4}\bar{\theta}$
Fiberglass, 40.5 kg/m^3	0.14	$4.21 - 0.014\bar{\theta}$
Extruded polystyrene 33.4 kg/m^3	0.10	$4.19 - 0.0145\bar{\theta}$

The winter of 1996-1997 included the months of January and February 1997. The winter of 1997-1998 was divided into two periods—the first one ranging from October 1997 to January 1998 and a second combining the months of February and March 1998. Table 5 gives the measured and intended clear wall U-factors for the winter of 1996 to 1997. The last were calculated with the conduction-based steady-state clear wall U-factor of Equation 1. The thermal resistances R_j of all layers were measured beforehand on separate 60×60 cm samples using a calibrated heat flow meter apparatus. For the results, see Table 6.

The intended clear wall U-factors all group around 0.2 W/(m^2·K). Observation of the measured results reveals major differences between good and poor workmanship. Good workmanship ensures the intended values are realized. Poor workmanship instead lifts the measured U-factors to unexpected heights. The partially filled Wall 3, for example, experiences an increase in clear wall U-factor of just around 310%. Such large increases cannot be caused by moisture-induced latent heat flow. On the contrary, if that was the reason, all southeast oriented walls, and, respectively, northeast oriented walls, should show a similar restricted increase in measured U-factor (between 4% and 10%—the main reason being drying of the wet veneer to the exterior). The only causes left that could explain the major increases are buoyancy flow and wind washing. A comparison with the U-factors of Lecompte (1989), measured in a hot box on cavity walls that suffered from buoyancy flow around a 5-cm-thick cavity fill, shows that 310% is greatly beyond the 140% he noted as a maximum. His test walls had an intended U-factor of 0.35 W/(m^2·K), a 25-mm-wide air space at both sides of the cavity fill, and gaps

TABLE 7
Measured U-factors, Second Winter, Before and After Airtightening

Cavity Wall	Fill		Intended U, W/(m²·K)	Measured U, W/(m²·K)			
				Before air-tightening		After air-tightening	
	Partial	Full		SW	NE	SW	NE
Poor work-manship		MF	0.22	0.39	0.33	0.44	0.35
Good work-manship		MF	0.22	0.21	0.21	0.22	0.22
Poor work-manship	XPS		0.21	0.86	0.86	0.94	1.03
Good work-manship	XPS		0.21	0.23	0.21	0.27	0.21
Poor work-manship		XPS	0.21	0.60	0.79	0.68	0.94
Good work-manship		XPS	0.20	0.22	0.22	0.22	0.22

TABLE 8
Average Exfiltration Rate, Second Winter, Before Airtightening

Cavity Wall	Fill		Inside Leaf	Average Exfiltation Rate, m³/h	
	Partial	Full		SW	NE
Poor workmanship		MF	Concrete blocks	0.30	0.12
Good workmanship		MF	Bricks	0.06	0.06
Poor workmanship	XPS		Concrete blocks	0.48	1.08
Good workmanship	XPS		Bricks	0.24	0
Poor workmanship		XPS	Concrete blocks	0.48	0.93
Good workmanship		XPS	Bricks	0	0

of 18 mm below and on top of the fill. The more negative results registered here may suggest two things: (1) the lower the intended U-factor, the higher the impact of buoyancy flow; (2) wind washing may reinforce the effect of buoyancy flow quite substantially, as was calculated by Hens et al. (1999). Wall 3, in fact, behaves thermally as if the 10-cm-thick EPS cavity fill shrank to a 1.4-cm-thin layer!

Some results are unexpected. A poorly installed fiberglass full cavity fill (Wall 1), for example, performs better than a poorly installed XPS full cavity fill (Wall 5). The reason for this only became clear the day the walls were demolished. The smooth fiberglass boards succeeded in closing part of the gaps between the boards and the air spaces between fill and inside leaf, while the stiff XPS did not.

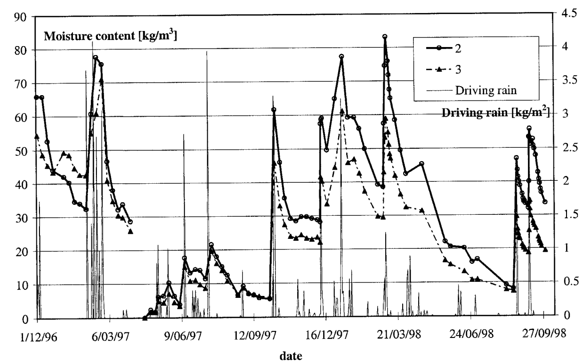
As mentioned, the second winter included two periods, one before and one after early February 1998. During the first days of that month, the inside surface of all walls was covered with an airtight, but vapor permeable, film. The purpose of that intervention was to separate the impact of air exfiltration, if active, on the clear wall U-factor calculated from the conductive heat flow rate measured in the center of the inside surface from the impact of wind washing and buoyancy. The minimization of air exfiltration by the film should give an increase in heat flow rate at the inside, resulting in a measured U-factor that is higher with then without exfiltration. Table 7 lists all results. Yet practically all U-factors measured after airtightening lay above those measured before, indicating that exfiltration indeed was active before airtightening, which is not unexpected, as all walls were air leaky, those with a concrete block inside leaf more so than the ones with a perforated building brick inside leaf.

The measured apparent U-factors before and after airtightening were used to calculate the average air exfiltration rates of Table 8 using the formula

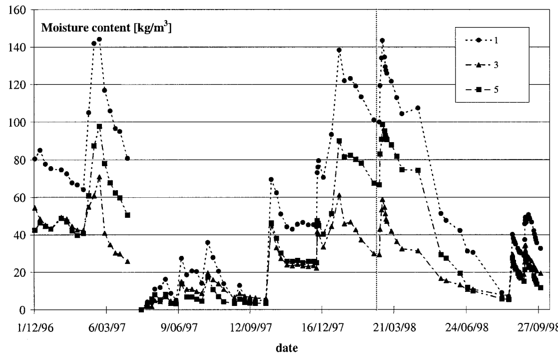
$$\frac{1}{\dfrac{c_a g_a}{U_{before}}} = \left| \frac{1}{1 - \exp\left(\dfrac{c_a g_a}{U_{after}}\right)} \right| \qquad (3)$$

where c_a is the specific heat capacity of air in J/(kg·K) ($\approx$1010 J/(kg·K)) and g_a is the exfiltration rate in kg/(m²·s). The apparent U-factors U_{before} and U_{after} stand for the measured mean conductive flow rates in the center of the inside surface per degree temperature difference between the inside and the outside environment. They do not equal the wall property U defined by Equation 1. Equation 3 emanates from solving the steady-state differential equation for combined one-dimensional heat and air flow. Table 8 confirms the results of the direct air leakage measurements—the walls with a concrete block inside leaf are definitely more air permeable than those with a perforated building brick inside leaf.

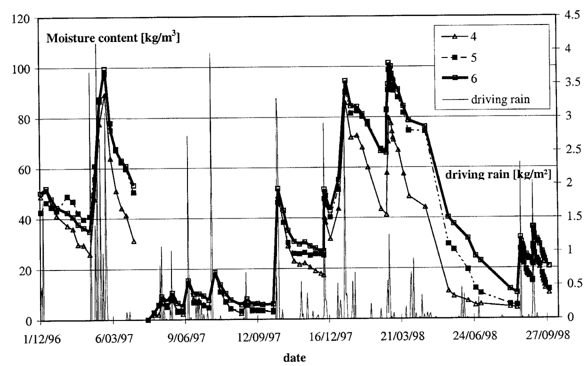
How does one translate these measured results into risk? From multiple building site controls, we know bad workmanship, as tested, is a common imperfection, a fair guess being that one on two new constructions with a partial cavity fill suffer from it. Some eight on ten new buildings have partially filled cavity walls. That gives a probability of 0.4. The negative consequences of the imperfection are twofold—a higher energy consumption for heating and possibly mold inside, close to the basis of the wall. For most building users, mold



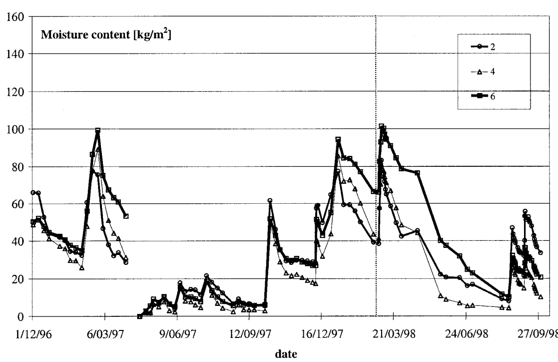
Partially filled walls with ventilated cavity versus fully filled walls
2: fiberglass, full fill, hardly capillary brick, 3: XPS, partial fill, hardly capillary brick



Cavity walls, poor workmanship.
Cavity and veneer: 1=fiberglass, full fill, capillary brick, 3=XPS, partial fill, hardly capillary brick, 5=XPS, ful fill, capillary brick.



Partially filled walls with ventilated cavity versus fully filled walls
4: XPS, partial fill, capillary brick, 5: XPS, full fill, capillary brick, 6: XPS, full fill, capillary brick.



Cavity walls, good workmanship.
Cavity and veneer: 2=fiberglass, ful fill, hardly capillary brick, 4=XPS, partial fill, capillary brick, 6=XPS, full fill, capillary brick.

Figure 5 *Southwest-facing brick veneers, moisture content in the removable panels.*

ranks much higher on the list of unwanted consequences than energy. A ratio of importance of 100 to 1 seems acceptable. If the temperature ratio at the basis drops below 0.7, then the likeliness for mold passes 0.05, giving a weighted severity on a scale from 0 to 1 of 100*0.05/10 = 0.5. Energy consumption for heating at the building level may increase some 30% (i.e., a weighted severity of 0.03). Total risk (in relative terms!) is consequently $0.4 \times 0.53 = 0.21$. That number gets a clear meaning only when compared with the risk other imperfections represent. However, 0.21 is quite high.

Moisture Response. As far as moisture response is concerned, rain penetration and interstitial condensation are the events that bother practitioners most in the case of a cavity wall.

In Western Europe, wind-driven rain typically comes from the southwest. Cavity walls are normally very rain-penetration tolerant. The combination of a capillary active brick veneer, with a cavity that acts as capillary break and air pressure equalizing volume, and the use of an airtight inside leaf with high moisture storage capacity creates several lines of defense. To mention the safe ones: outside surface runoff, storage in the veneer, and veneer backside runoff. The last makes the penetration risk negligible, on condition that a correctly mounted cavity tray is included at the wall's base (Straube 1998). In the case being discussed, all walls had such a tray. Walls 1, 2, 5, and 6, however, had a fully filled cavity. In case that fill touches the veneer's backside, the drainage plane there may get short-circuited by cavity ties sloping down to the inside leaf and by open joints between insulation boards, as is the case in the Walls 2 and 5. Walls 1, 3, and 5, in turn, have an air permeable inside leaf. The brick veneers of Walls 2 and 3 also show poor suction with a moisture absorption coefficient A of only 0.014 kg/(m²·s$^{0.5}$) and a capillary moisture content w_c of 67 kg/m^3, compared to A = 0.196 kg/(m²·s$^{0.5}$), and w_c = 194 kg/m^3 for the bricks in the other veneers. A low moisture absorption coefficient reduces the water uptake rate by the veneer, resulting in faster and more abundant water runoff at the outside surface under wind-driven rain conditions. The low capillary moisture content simultaneously limits the storage capacity and enhances water conduction through the head joints to the veneer's backside. Combining all these factors, Walls 1, 2, 3, and 5 should be more prone to rain penetration than Walls 4 and 6.

During the two years, the southwest facade of the test building received large amounts of wind-driven rain. Rain penetration through one of the walls was never recorded. At some moments, however, the cavity tray in Wall 2 collected some runoff from the veneer's backside. Yet, as Figure 5 illustrates, all veneers absorbed large amounts of water.

TABLE 9
Correlation between the Moisture Content in the Brick Veneer and All Factors Favoring Rain Uptake by the Veneer (Southwest)

Wall	Rainwater Uptake	Position	Brick Veneer		Fill		Inside Leaf	
			Capillary	Less capillary	Partial, cavity ventilated	Full	Less air leaky	Air leaky
1	Highest	Corner	X			X		X
2	Lowest+1	Corner+1		X		X	X	
3	Lowest	Corner+2, larger overhang		X	X			X
4	Lowest+2	Middle-2, larger overhang	X		X		X	
5	Highest-1	Middle-1	X			X		X
6	Highest-1	Middle	X			X	X	

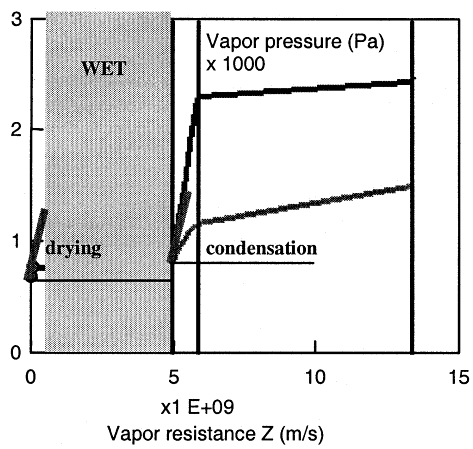


Figure 6 *Vapor pressure gradient in winter in a masonry cavity wall with wet brick veneer. The highest line represents the water vapor saturation pressure, the lowest represents the vapor pressure.*

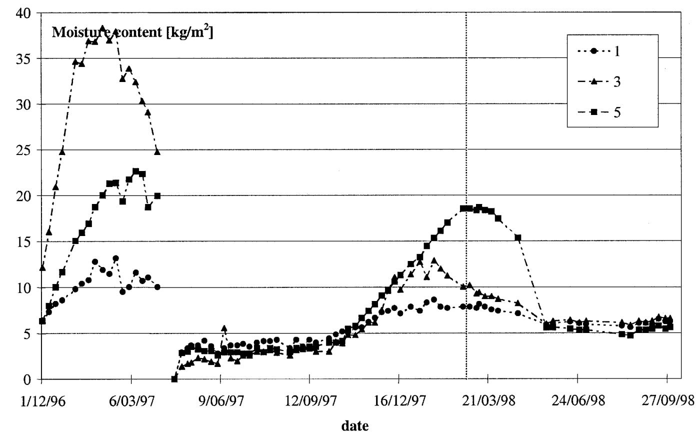
The figure shows a net seasonal behavior. There was hardly any drying in the winter and nearly complete drying in the summer—both cases alternated with moisture peaks by wind-driven rain. The condensation-drying balance of the veneer easily explains the nondrying effect in the cold season. In winter, condensing moisture is deposited at the veneer's backside by equivalent vapor diffusion and air exfiltration. Between two driving rain events, the same two driving forces activate drying from the moisture front in the veneer to the outside. Hence, as soon as the drying rate equals the condensation rate, or vice versa, the change in moisture content in the veneer stops and a moisture residue is left (Figure 6). In summer, instead, the veneer dries both to the outside and to the inside, permitting the residue to drop to the hygroscopic equilibrium for the average relative humidity in the veneer between succeeding driving rain events.

Going back to Figure 5, the veneer of Wall 1, fiberglass, full fill, collects the highest moisture content. There are three reasons for this. The wall is situated at the southwest corner of the building, the location where the highest wind-driven rain deposits were collected. Its inside leaf is simultaneously quite air leaky, resulting in more exfiltration and larger amounts of condensed moisture. The brick veneer is also of the capillary type (i.e., absorbs most of the rain). Cavity ventilation may have helped in keeping the average moisture content in the veneer of Walls 3 and 4 lower. Yet, by coincidence, both stood in the middle of the facade under a somewhat larger overhang, which resulted in the lowest wind-driven rain deposit measured. That disturbed a clear judgment on the effects of cavity ventilation.

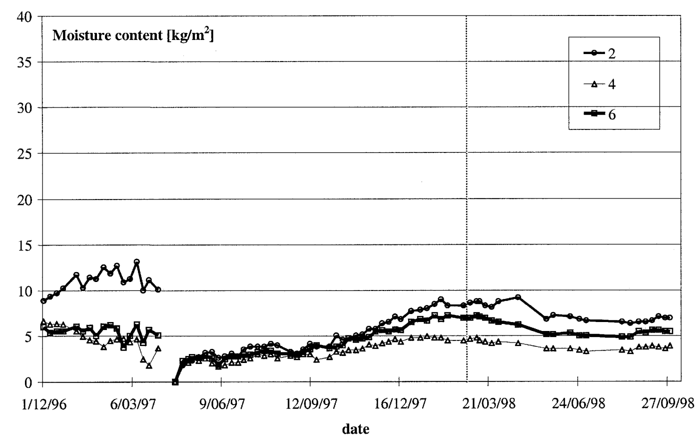
Table 9 summarizes the conclusions. Position and type of brick clearly overrule all other parameters, such as cavity ventilation and lack of airtightness of the inside leaf.

Moisture measurements on the fill and a blotting paper at the cavity side of the inside leaf showed no signs of summer condensation, proving that this is a minor risk in masonry cavity walls in cool climates. In fact, a moisture increase in the fill or wetting of the blotting paper was never recorded. That conclusion, however, only holds as long as the inside leaf has enough moisture storage capacity and/or if the brick veneer is not finished with a vapor-retarding paint. Damage cases showed that paints retard drying of the veneer more than they hinder capillary suction through cracks in the paint. That keeps the veneer wet even under summer conditions. In such cases, summer condensation may wet a vapor permeable cavity fill. The usage of a vapor retarder at the backside of the fill, which is sometimes advocated as a solution, only aggravates that problem (Anon 2001).

We simulated the measured moisture behavior with an advanced, commercially available one-dimensional heat and moisture calculation tool (Künzel 1994). The results were disappointing. Calculated moisture uptake was lower and drying proceeded much faster than measured. The reasons are



Cavity walls, poor workmanship.
Cavity and veneer: 1=fiberglass, full fill, capillary brick, 3=XPS, partial fill, hardly capillary brick, 5=XPS, ful fill, capillary brick.



Cavity walls, good workmanship.
Cavity and veneer: 2=fiberglass, ful fill, hardly capillary brick, 4=XPS, partial fill, capillary brick, 6=XPS, full fill, capillary brick.

Figure 7 *Northeast facade, moisture content in the brick veneer loose panels.*

obvious. A brick veneer is not a one-dimensional capillary porous system. Indeed, not only does it act as a parallel circuit of bricks and mortar joints, but the butt joints also form a complex system of micro-cracks and voids. That results in accelerated capillary suction by the joints and gravity flow through the joints when driving rain runoff develops, resulting in local water drainage at the backside of the veneer and capillary suction by the brick from all sides. The tool also does not consider airflow. In reality, exfiltration, wind washing, and buoyancy flow developed in the walls, turning each cavity wall into a complex three-dimensional heat, air, and moisture system. No tool exists that is able to simulate such complex reality.

The northeast facade did not receive any wind-driven rain at all. Hence, moisture content in the brick veneer was the result of interstitial condensation of vapor, permeating from inside, and surface condensation by undercooling from outside. Figure 7 summarizes the measured moisture contents. Although too high to be caused by diffusion-related interstitial condensation only, the moisture content nevertheless remained lower than in the case when driving rain causes the wetting. Again, a clear winter-summer cycle exists, with higher moisture contents in winter than in summer. Walls 1, 3, and 5, all with an air-permeable inside leaf and poorly installed cavity fill, reach higher winter values than Walls 2, 4, and 6, with less air-permeable inside leaf and correctly installed cavity fill. The veneer of Wall 1, fully filled with fiberglass, did not experience the highest moisture deposit. That was Wall 3, with a vapor retarding XPS partial fill the first winter, and Wall 5, with a vapor retarding XPS full fill the second winter. These observations correlate well with the average exfiltration

TABLE 10
Minimum and Maximum Outside Surface Temperature Measured on the Brick Veneers During the Two Years of Testing

Wall	Minimum and Maximum Outside Surface Temperature					
	Northeast			Southwest		
	Min.	Max.	Remarks	Min.	Max.	Remarks
1	-5.6	43.6		-7.3	61.3	
2	-9.4	36.1	*	-9.1	54.7	*
3	-7.3	37.0	*	-7.1	54.4	*
4	-8.4	42.5		-8.4	61.1	
5	-6.2	41.4		-8.5	60.8	
6	-5.8	40.7		Failing sensor		

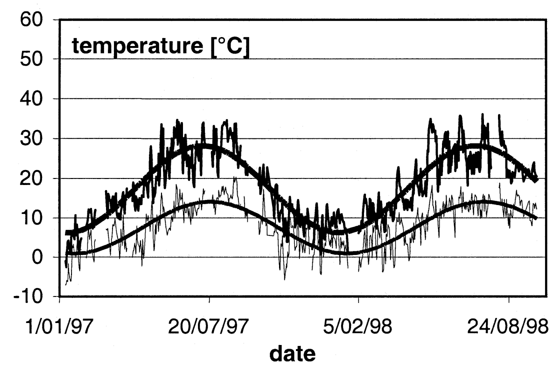
* Hardly capillary bricks.

rates listed in Table 8—Walls 3 and 5 being more air permeable than Wall 1.

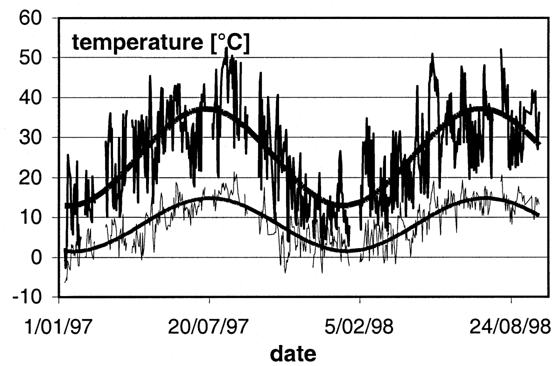
Service Life. Four aspects were analyzed: temperature, moisture content, freezing load, and efflorescence. Table 10 gives the measured minimum and maximum temperature in the center of the exterior surface of each brick veneer. Figure 8 shows the evolution for Wall 2 of the daily minimum and daily maximum and their harmonic best fit over the whole test period. Figure 9 gives the cumulated distribution of the daily difference between the minimum and maximum for all walls. The table and the figures clarify that orientation, followed by the type of brick (the hardly capillary brick is lighter colored than the capillary brick) explain most of the differences. Other factors, such as poor workmanship, full or partial fill, and more or less air-permeable inside leaf, have a much smaller impact.

Moisture content in the brick veneers was discussed above. A point of interest is the relative humidity in the cavities. Table 11 gives an overview. Rain absorption increases the relative humidity (see southwest orientation). Air exfiltration does the same, although buoyancy flow lowers it since the phenomenon results in higher cavity temperatures. Any relative humidity whatsoever is too high to allow moisture-sensitive and hygroscopic insulation materials to be used as a cavity fill.

The number of freeze-thaw cycles recorded in the brick veneers and cavities at 1/5 and 4/5 of the height are summarized in Table 12. The number remains significantly lower than in the air. The reason for that is undercooling, which causes the surface temperature to drop below zero even when the air temperature swings above zero for a short period of time. The number of cycles recorded in the cavities at 4/5 of the height further reflects buoyancy flow. Zero or close to in Walls 1, 3, and 5 with poorly installed fill, different from zero in Walls 2, 4, and 6 with correctly installed fill. Yet, the number of cycles recorded did not result in any damage. There were at least two reasons for that. First, indirect testing revealed that



North east orientation



South west orientation

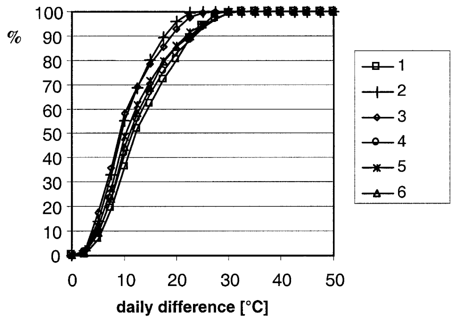
Figure 8 *Daily minimum and maximum temperature at the center of the outside surface of the veneer of cavity wall 2 (fiberglass full fill, good workmanship).*

the bricks were absolutely frost-resistant. Secondly, the moisture content in the brick veneers remained too low to give frost problems.

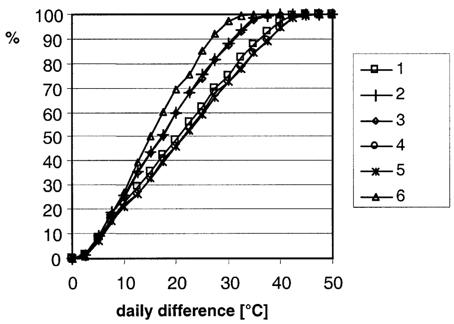
After both winters, salt efflorescence appeared on the veneers of the northeast-oriented Walls 1, 3, and 5 (i.e., the air permeable walls with poorly installed fill). These walls also suffered the most from exfiltration-induced interstitial condensation, resulting in moisture contents that allowed capillary transport of moisture and dissolved salts to the outside surface of the veneer where the moisture evaporates and the salts crystallize without being washed by driving rain. Again, these salt efflorescences did not result in physical nor structural damages.

CONCLUSIONS

The research confirmed that a U = 0.2W/(m²·K) masonry cavity wall is a construction with a substantial risk of deficient thermal performance. Simultaneously, the wall demonstrates high moisture tolerance, excellent durability, and a low risk of moisture performance problems. The whole wall U-factor



North east orientation



South west orientation

Figure 9 *Cumulative distribution of the daily difference between the minimum and the maximum temperature in the center of the outside surface of the veneer of all cavity wells.*

degrades dramatically if the cavity fill is not correctly pressed against the inside leaf, if open joints between the separate boards exist, and if the top and bottom of the cavity are not filled with great care. Rain penetration risk is low, even when some of the lines of defense are eliminated, such as a hardly capillary instead of a capillary brick veneer, a full fill that may short-circuit the drainage plane at the back of the veneer, or a lack of airtightness. Some lines of defense, however, should not be abandoned. Cavity ties must slope down to the veneer and not vice versa—all joints between the insulation boards of a full fill should be closed carefully and the cavity trays above and below lintels must be positioned with great care. Winter interstitial condensation is a minor problem. Summer condensation is even less of a problem, except for some specific applications (painted or glazed brick veneers). Service life is threatened neither by frost damage nor by salt efflorescence on condition that the bricks and mortar used have an absolute frost resistance and a low salt content.

The research results helped in refining the design and workmanship criteria for a U = 0.2 W/(m²·K) masonry cavity wall:

- The inside leaf should have very low air permeability. An inside plaster, in combination with joint caulking where needed (around windows and doors, at the skirting, around electrical boxes), is a necessity to fulfill that requirement.
- The cavity fill must be mounted in a way that wind washing and buoyancy flow is excluded. Different options are possible—sticking the fill against the inside leaf, using boards with a soft backside and a stiff front layer and fixed with screwed cavity ties, or applying a full fill. In any case, the wall should be constructed from the inside to the outside, first by bricklaying the inside leaf, next by mounting the cavity fill-in stretching bond with all joints between boards carefully closed and fix-

TABLE 11
Relative Humidity in the Cavities: 10%, Median, and 90% Values

Wall	Relative Humidity, 1/5H				Relative Humidity, 4/5H			
	% time	10%	50%	90%	% time	10%	50%	90%
Northeast								
1	84	43	82	100	84	65	87	97
2	67	74	100	100	84	68	100	100
3	75	57	77	99	75	53	67	79
4	54	51	70	82	75	46	67	83
5	36	57	74	99	84	54	88	100
6	37	69	100	100	82	61	76	85
Southwest								
1	58	75	100	100	85	70	90	100
2	56	59	91	100	85	65	95	100
3	85	53	71	97	85	49	65	76
4	85	37	67	93	85	47	68	88
5					85	65	81	96
6	84	60	83	100	84	58	84	100
Outside climate					93	67	80	90

TABLE 12
Number of Freeze/Thaw Cycles in the Brick Veneer and the Cavity

Wall	Number of frost/thaw cycles					
	Northeast			Southwest		
	Outside surface	Cavity 1/5	Cavity 4/5	Outside surface	Cavity 1/5	Cavity 4/5
1		28	1	25		
2	40	30	31	33	28	18
3		18	0	31	8	1
4		21	17	38	11	9
5	30	8	0	36	8	0
6	36	23	19			
Air	68					

ing it with down-sloping ties into the inside leaf, and finally, by brick laying the veneer and plastering the inside leaf. The windows should be fixed before the insulation work starts.

- The fill should consist of a highly moisture-tolerant, nonhygroscopic insulation material.
- No vapor retarder at the inside is needed in cool climates. On the contrary, its usage may create moisture problems instead of preventing them.
- Cavity trays must be mounted with great care. They should drain all cavity-side runoff back to the outside. For that purpose, two open butt joints per meter are needed in the veneer, at the basis of the cavity, just above the trays.
- All construction details, such as veneer-floor contacts, lintels, window reveals, window sills, and balconies, should be designed so that the continuity of the cavity fill and the air retarding layer (i.e., the inside plastering) is guaranteed. At the same time, details may facilitate neither rain penetration nor interstitial condensation. If thermal bridging at those spots is left, the risk of ghosting, fungal defacement, surface condensation, and local cracking increases substantially.
- Only frost-resistant capillary bricks and mortars, both with very low salt content, should be used for the veneer.
- Painting the brick veneer or using glazed bricks is not recommended. If it has done, then the application of a partial fill with a close cell insulating material diminishes the risk of summer condensation.

The criteria listed are not new. However, since the negative consequences of poor design and poor workmanship are more severe for a U = 0.2 W/(m²·K) masonry cavity wall than for a U = 0.6 W/(m²·K) masonry cavity wall, they should be applied much more meticulously.

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