Condensation Risk Assessment

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ABSTRACT

The methodology of risk analysis and assessment is reviewed and applied to study the reliability of condensation control measures in lightweight building envelopes. It is generally recognized that airtight construction is an essential part of condensation control. Nowadays, different air barrier systems are developed and documented to prevent air leakage and moisture accumulation in the envelope. But does this mean that the condensation risk is sufficiently minimized and that the protective system is reliable? Considering the high occurrence of human error in the building process, the possibility of air barrier defects during the service life of a building envelope may be high.

To define the reliability of the condensation control system, the consequences of air barrier failure are quantified using a two-dimensional numerical control volume model for the calculation of combined heat, air, and vapor transfer in multilayered building envelope parts. A set of failure modes and design calculation conditions is defined for an exemplary wood frame insulated roof, and a failure effect analysis is performed in order to predict the condensation risk as a result of air barrier defects. The effectiveness of redundant design measures to improve the reliability of the condensation control system is studied.

RISK ANALYSIS METHODOLOGY

Risk analysis, as applied in this work, is a method to study the effects of uncertain events or unintentional actions on the serviceability of a design in order to prevent or reduce the negative outcome of these effects (Ang and Tang 1984; Ansell et al. 1991). In this definition, risk not only refers to the probability of failure but also incorporates a notion of the magnitude of the failure. The techniques to identify and reduce risks were developed in the 1960s in the nuclear and chemical industries (Kletz 1992). The analysis provides a systematic and structured framework with three main stages:

1. Risk identification
2. Risk assessment
3. Decision making

The first step to be addressed at the design stage of a project is the recognition and identification of the range of risks to which a system is subject. The ultimate aim of risk identification is to link the possible problems that a system might experience directly to external factors and events involving component failures and human errors. The second stage implies the use of probabilistic calculation and assessment methods in order to predict the system performance and the probability of failure as a result of the unintentional events. In industrial risk analysis, risk is generally determined as the product of the frequency and the size of the consequence of the event (Ansell et al. 1991; Kletz 1992). Risk is accepted when events that happen often have no or low consequences or when events involving serious problems are rare.

When the predicted risk cannot be justified, decisions should be taken to eliminate or minimize the risk, either by preventing the event or by reducing the consequences in case of occurrence. These decisions often imply redesign of the system by the introduction of protective measures. There are generally three types of strategies, with decreasing order of effectiveness: inherent, engineered, and procedural safety measures. The reliability of protective systems is often improved through some duplication of components. This is called "redundancy" if the protective components are the same or "diversity" if they are different. In a nonredundant system, the failure of the protective component leads inevitably to the failure of the entire system.

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Consider the example of fire risk prevention in buildings. A building is constructed with inflammable or fire-retarding materials whenever possible and affordable (inherent safety). Recognizing that fire risk is rarely eliminated, a sprinkler installation may be designed and installed in the building (engineered safety). Finally, to prevent casualties, a fire alarm and escape may be added (procedural safety). The reliability of the fire protection may be increased by installing two or more fire alarms (redundancy) or adding both sprinkler and alarm systems (diversity).

There are similarities between the design of a hazard protection and a building envelope system. The building envelope may be regarded as a multicomponent protective system to eliminate or minimize the discomfort of the environment. The application of the redundancy concept is a common element of building envelope design. For instance, the reliability of rain control in the building envelope is often improved by adding redundant components, such as drained cavities, multilayered membranes, etc. Because of these similarities, the methodology of risk analysis may well be applied to the performance analysis of building envelope systems.

In some recent publications on moisture control, the concepts of risk analysis are implicitly present. It is recommended that designers incorporate moisture control measures to ensure the performance of the envelope system in the case that something goes wrong during construction or operation, for instance, by accidental wetting or by human error. This subsystem is called "the second line of defense" (Lstiburek and Bomberg 1996).

UNCERTAINTIES IN CONDENSATION CONTROL

Condensation Control Systems

TenWolde and Rose (1996) presented two major approaches to moisture control in the building envelope. The first is to design and construct the building envelope for a high tolerance for moisture. The second is to limit the moisture load on the envelope. Designing the envelope for a high moisture tolerance implies the use of measures to control the migration of moisture into the construction, to control moisture accumulation in building materials, or to enhance removal of moisture from the building assembly (Lstiburek and Carmody 1993). The limitation of the moisture load often involves control strategies on the level of building design and operation, e.g., ventilation, dehumidification, or depressurization. Table 1 categorizes potential condensation control strategies for the building envelope. Table 2 lists measures to restrict the moisture load by proper building design and operation. The individual measures may be combined to create an effective condensation control system. The problem is to find out which combination of condensation control measures is the most reliable to reduce the condensation risk.

TABLE 1
Condensation Control Strategies for the Building Envelope*

Strategy	Aim	Measure
Control of moisture access	Eliminate air leakage	Air barrier
	Restrict vapor diffusion	Vapor retarder
Control of moisture accumulation	Raise temperature of condensing surface	Insulation outside of condensing surface
	Allow harmless accumulation	High moisture capacity at condensing surface
Removal of moisture	Promote drying	Vapor permeable layers
		Capillary active layers
		Cavity ventilation
	Remove condensation	Drainage
Reduction of moisture load	Limit construction moisture	Initially dry materials

*after Lstiburek and Carmody (1993) and TenWolde and Rose (1996)

TABLE 2
Reduction of Moisture Load by Building Design and Operation*

Aim	Design	Operation
Limit vapor in interior air	Natural ventilation system	Mechanical ventilation
		Dehumidification
Control air pressure differentials	Airtight floor separations (limit thermal stack height)	Depressurization

*after Lstiburek and Carmody (1993) and TenWolde and Rose (1996)

Uncertainties in Air Barrier Performance

It is generally recognized among building researchers that airtight construction is an essential part of any condensation control system. Without effective control of air leakage, other condensation control measures such as vapor retarders are completely ineffective (ASHRAE 1997). Nowadays, different air barrier systems are developed and documented, and material and system requirements are prescribed (Di Lenardo et al. 1995). However, in terms of risk analysis, the air barrier is a nonredundant protective component. If airtightness requirements are not met in practice, there is a risk of serious condensation problems. This implies that the uncertainties in condensation control are primarily related to uncertainties in air barrier performance.

The authors have conducted a survey of recent cases of serious condensation problems in lightweight roofs (Janssens 1998). They found that most problems were caused by a failure of the air barrier due to human errors. *ASHRAE Fundamentals* (ASHRAE 1997) lists some of the most frequently observed leakage paths in lightweight wall and roof systems.

They may be divided into four categories: (1) joints between different sheets or boards of the air barrier, (2) interfaces with other envelope systems, such as the wall-roof and wall-window interface, (3) junctions around structural penetrations (columns, joists, trusses, etc.), and (4) electrical and plumbing penetrations. Air barrier defects at these locations may be caused by a combination of design and construction errors. Different parties in the design team and different trades in the construction team may contribute to the defects. Considering the high occurrence of human error in the building process, it is evident that the likelihood of air barrier defects is not negligible. Some redundancy in the design of the condensation control system may become necessary.

To decide in which condition changes in design are necessary and to find out which measures are effective in reducing condensation risk, it is necessary to quantify the effects of air leakage on the moisture performance of building envelope systems.

CONSEQUENCES OF AIR BARRIER DEFECTS

Analytical Study of Condensation Due to Air Leakage

Let us first consider the simple case of one-dimensional heat, air, and vapor flow. In steady-state conditions, this problem may be solved analytically (Hens 1996). The solution may help in understanding the conditions when air leakage causes condensation problems. It may also give a first idea of the potential measures to prevent problems. The condensation rate at a material interface in air permeable envelope systems is calculated according to Equation 1:

$$g_c = -g_a\xi_a\left[\frac{p_i - p_{sat}(\theta_c)}{1-\exp(g_a\xi_a Z_i^c)} - \frac{p_{sat}(\theta_c) - p_e}{\exp(-g_a\xi_a Z_c^e) - 1}\right] \tag{1}$$

where

g_c = condensation flow rate (kg/m^2/s),

g_a = airflow rate (negative sign in case of exfiltration) (kg/m^2/s),

ξ_a = vapor capacity of air = 6.2×10^{-6} kg/kg/Pa,

p_i = interior vapor pressure (Pa),

p_e = exterior vapor pressure (Pa),

$p_{sat}(\theta_c)$ = saturation vapor pressure at the condensation plane (Pa),

Z_i^c = sum of the vapor diffusion resistances between interior and condensation plane,

Z_c^e = sum of the vapor diffusion resistances between condensation plane and exterior.

With even moderate air exfiltration rates (negative sign), the denominators with the exponential terms become unity and infinity, respectively. Equation 1 reduces to Equation 2:

$$g_c = -g_a\xi_a(p_i - p_{sat}(\theta_c)) \tag{2}$$

The condensation flow rate per unit flow of air is independent of the vapor transfer properties of the envelope system. Condensation will occur whenever the indoor vapor pressure exceeds the saturation vapor pressure of the condensation plane or when

$$\Delta p > p_{sat}(\theta_c) - p_e \tag{3}$$

where

Δp = vapor supply in the building (Pa),

p_i = $p_e + \Delta p$.

The left-hand side of Equation 3 characterizes the indoor climate, the right-hand side, the exterior climatic conditions.

Equation 2 shows that when exfiltration through the envelope is not stopped, there is only one way to prevent condensation: by increasing the temperature of the critical interface so as to lower the difference between the indoor vapor pressure and the saturation vapor pressure at the interface. This is practically done by applying insulated sheathing or by changing the envelope design with the principles of a warm deck construction.

Going back to Equation 1, it is possible to define a second type of potential protective measure. Suppose that the saturation vapor pressure at the condensation plane is above the exterior vapor pressure and that the vapor diffusion resistance to the outside Z_c^e is at least one order of magnitude smaller than the diffusion resistance to the inside Z_i^c. For a certain range of air exfiltration rates, Equation 1 reduces to

$$g_c = -g_a\xi_a\left[\Delta p - \frac{p_{sat}(\theta_c) - p_e}{1-\exp(g_a\xi_a Z_c^e)}\right]. \tag{4}$$

This shows that measures to enhance moisture drying to the outside may be capable of preventing condensation problems, even when a perfect airtightness is not achieved. On the other hand, the use of vapor retarders is ineffective when air leakage is not stopped.

Failure Effect Analysis: Insulated Wood Frame Roof

Calculation Model. The authors developed a two-dimensional numerical control volume model for the calculation of combined heat, air, and vapor transport in multilayered building envelope parts (Janssens 1998). The model considers airflow in porous material and laminar flow in cracks and air layers only. As a consequence, the equations for the conservation of momentum reduce to the linear Darcy and Hagen-Poiseuille flow equations. Airflow is driven by external pressures or thermal stack. The equations for the conservation of mass, momentum, and energy are iteratively solved. Underrelaxation techniques are applied to improve and accelerate the convergence of the solution. The heat and vapor flow equations are integrated using the exponential differential scheme. Condensation flows are calculated iteratively by changing variables whenever the calculated vapor pressure rises above the saturation vapor pressure. Eventually, in every calculation node, the airflow rates, temperatures, relative humidities, and condensation flow rates are defined. Thus, the model makes it possible to assess the effect of air leakage on the thermal and moisture performance of the building envelope.

Description of Boundary Conditions, Envelope System, and Failure Modes. A preceding comparison between the results of transient and steady-state calculations showed that steady-state calculations are a good check for the moisture performance of lightweight envelope systems with nonhygroscopic layers (Janssens 1998). Unlike moisture accumulation as a result of vapor diffusion, condensation linked to air leakage is a fast and short-term phenomenon. The one-dimensional transient calculation was performed using a climate file of Manchester, U.K., with hourly averaged data. The results showed typical condensation periods of a couple of days to a week. A common characteristic of the boundary conditions during these periods was the negative net radiation to the exterior surface, in addition to the conditions described above. From this analysis, a set of weekly average design boundary conditions was composed for the two-dimensional steady-state calculation of condensation problems linked to air leakage. They are listed in Table 3. The air pressure is imposed at the lowest point of the boundary.

TABLE 3
Design Boundary Conditions for Condensation Risk Assessment (Weekly Averages)

Boundary	Temp.	Vapor Pressure	Surface Coefficient	Net Radiation	Air Pressure
Interior	18°C	950 Pa	8 W/(m^2·K)	0 W/m^2	2 Pa
Exterior	−2.5°C	450 Pa	19 W/(m^2·K)	−30 W/m^2	0 Pa

As an exemplary case, a failure effect analysis is performed on an insulated wood frame roof that has, from inside to outside, the interior finish, a glasswool insulation layer, an air cavity, the underlay, and tiles. The interior finish also includes the air/vapor barrier. It is assumed that the tile layer, due to an intensive mixing of air around the tiles, affects the temperature distribution in the roof only. Its thermal resistance is included in the underlay. Table 4 lists the material properties. The length of the roof is 3 m, and the slope is 45°. The U-value is 0.22 W/(m^2·K). The moisture performance of the roof design is acceptable according to existing standards (e.g., DIN 4108, 1981). Under the above conditions, a Glaser calculation predicts a condensation amount of 0.01 L/m^2 per week.

The calculation domain is discretized into a rectangular grid with dimensions of 19 × 75 in the x and y direction, respectively. The first calculation assumes that no defects are present in either of the envelope layers. The underlay and internal lining are essentially airtight, and airflow may develop in the air permeable fiberglass insulation only, due to thermal stack.

TABLE 4
Material Properties

Layers	d m	λ_x/λ_y W/m^2/K	R_x m^2·K/W	μd m	K_x/K_y m^2
Internal lining	0.01	0.1	0.1	5.0	1e-12
Fiberglass	0.14	0.035/0.040	4.0	0.2	4e-9/6e-9
Cavity	0.01		0.12		
Underlay	0.01	0.14	0.07	1.5	1e-12

Then a set of failure modes is defined, and all possible combinations are included in the envelope geometry (Figure 1). Table 5 lists the set of failure modes. One particular mode may consist of two or more defects that are supposed to occur together, for instance, air layers on either side of the thermal insulation or overlaps in the underlay. Some of them are not necessarily defects but may be inherent in the envelope design, for instance, overlaps in the underlay or cavity vents.

In total, 256 combinations (= 2^8) are calculated and the resulting heat flow, air flow, and condensation flow rates are statistically processed.

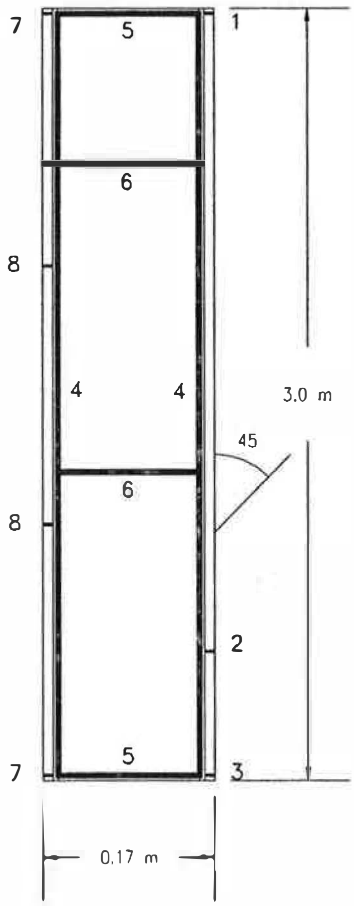

Figure 1 Failure modes.

TABLE 5
Set of Failure Modes

Layer	Failure Mode	Width (mm)	Position from Bottom	Simulated Defect
Internal lining	1	1	3.0 m	Crack—unsealed junction
	2	1	0.5 m	Penetration (equivalent Ø8 mm)
	3	1	0.0 m	Crack—unsealed junction
Thermal insulation	4	5	-	Air layers
	5	5	0.0/3.0 m	Junction with eaves and ridge
	6	5	1.2/2.4 m	Joints between boards
Underlay	7	2	0.0/3.0 m	Junction—vent
	8	2	1.0/2.0 m	Overlap—joint

Moisture Performance. The calculation results are represented by means of the cumulated distribution function (CDF). This is a common statistical function to show the variation of a collection of different data. The function defines the fraction of calculation results falling below a certain value. Since the distribution of calculation results characterizes the potential variation in system properties, the CDF may be considered a response property of the system to a set of defects. Figure 2 shows the cumulated distribution function (CDF) of the average condensation flow rate of all 256 calculated cases. In this case, the condensation rate in a roof without defects coincides with the 10% percentile of the CDF (see Table 6). Thus, the consequences of defects in the envelope layers are serious and may jeopardize the roof performance. Experiments have shown that condensate starts to run off when it amounts to approximately 0.1 L/m^2 (Janssens 1998). In more than 70% of the failure combinations, the weekly condensation mass is higher. The two curves in the graph represent the effect of the thermal radiation from the outside boundary (net radiation $q = 0$ vs. $q = -30$ W/m^2).

Figure 3 gives more information about the conditions leading to condensation. The condensation flow rate is plotted as a function of the total air exfiltration rate. There is no unambiguous relationship between both variables. Roughly, three zones may be distinguished. The first one, with no air exfiltration, contains all failure combinations without a continuous airflow path between the boundaries of the construction. The condensation amounts are limited but may still be 30 times more than in a roof without defects. This is the case when at least two defects occur in the internal lining.

When air leaks exist in both the internal and external lining, humid indoor air exfiltrates through the envelope and the condensation amounts are more substantial. The relationship between condensation and exfiltration rate, however, depends strongly on the minimum length of the airflow path in the construction. The second zone in the graph, with the highest condensation amounts, contains all combinations with defects in the internal lining and central overlaps in the underlay (failure mode 8). The third zone, with the highest exfiltration rates but clearly lower condensation amounts, contains the combinations with defects in the internal lining and at least

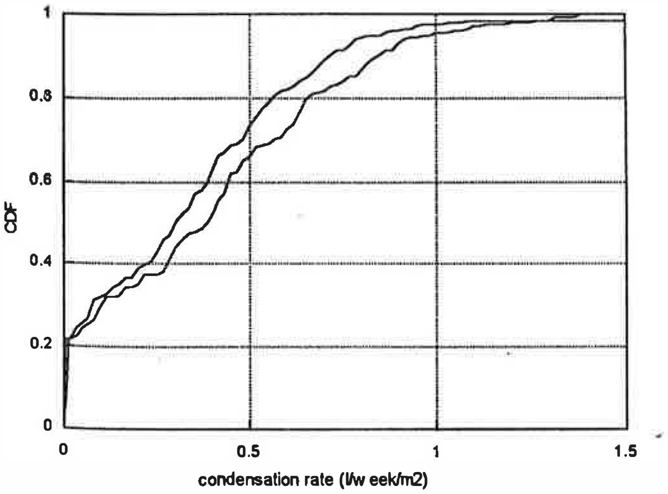

Figure 2 *CDF of condensation rate (L/m^2/week).*

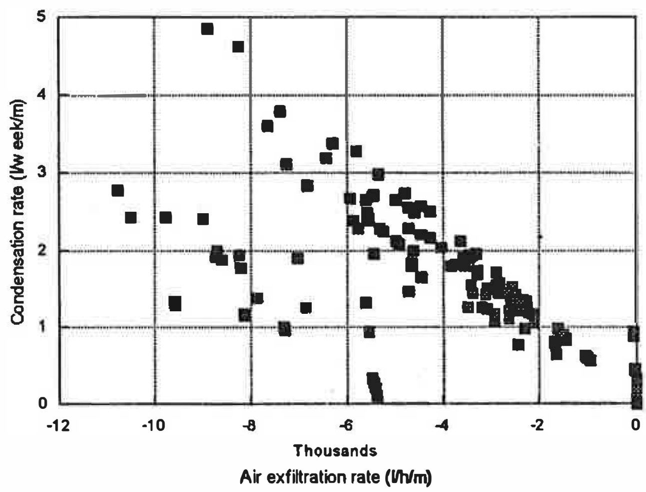

Figure 3 *Condensation vs. air exfiltration rate.*

TABLE 6
Distribution of Roof Performances as a Result of Roof Defects

Percentile %	$U_{APPARENT}$ W/m²/K	E_{LEAK}/E_0	$V_{a,ROOF}$ m³/h/m	g_c kg/m²/week
10	0.15	1.01	0.0	0.01
50	0.20	1.09	2.4	0.38
90	0.26	1.27	7.3	0.84

the outer overlaps in the underlay (failure mode 7). In this case, the airflow path is shorter, the exfiltrating humid air is cooled down less effectively, and, consequently, less moisture is deposited in the cavity.

Thermal Performance. The effects of air leakage on the thermal performance of the roof is represented in two ways. First, the apparent U-factor of the roof is calculated by dividing the total conductive heat loss at the internal boundary by the roof area and the temperature difference between inside and outside (case with no radiation to the exterior surface). Table 6 lists the statistical distribution of the calculated apparent U-factors. The U-factor of a roof without defects coincides with the 60% percentile of the CDF.

The analysis of the consequences of defects on the energy efficiency of the roof is incomplete without considering the air leakage rate through the roof and the associated enthalpy loss. For a correct interpretation, these extra heat losses should be studied on the scale of the building. Let's consider, for example, a dwelling with a vertical section as in Figure 4. The U-factor of the roof U_0 is 0.22 W/m²/K, and the average U-factor of the other envelope parts U_1 is 0.82 W/m²/K. This way, the dwelling fulfills the Flemish insulation requirements (insulation level K55). Suppose that the ventilation air change rate n is 0.5 h^{-1}; then the energy consumption of the dwelling is E_0:

$$E_0 = (2AU_0 + A_1U_1 + 0.34nV)(\theta_i - \theta_e) \quad (5)$$

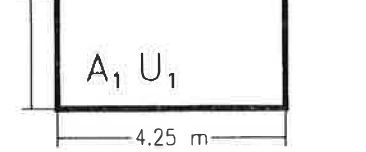

Figure 4 *Dwelling section.*

In the case with defects, air leakage through the roof n increase the air change rate of the building and contribute the ventilation heat losses. As a worst estimate, let's add the leakage rate $V_{a,ROOF}$ to the ventilation air change rate n. T energy consumption of the dwelling becomes E_{LEAK}:

$$E_{LEAK} = (2AU_{APPARENT} + A_1U_1 + 0.34(nV + 2V_{a,ROOF}))(6$$

The increase in energy loss in the dwelling due to defe in the roof is estimated from the ratio E_{LEAK}/E_0. Figur shows the CDF of the energy loss increase. The two cur represent the effect of radiation from the outside boundary all calculation cases, the roof failure modes have a negat effect on the energy demand of the dwelling. In the worst ca it may be increased with a factor of 1.45.

REDUNDANT PROTECTIVE MEASURES I CONDENSATION CONTROL

Redundancy

The failure effect analysis clearly demonstrates that e small defects in the air barrier or in one of the other layers the envelope system may seriously affect the thermal a moisture performance of the envelope part. The most pr lematic for the serviceability of the envelope and the build is the risk of condensation problems. This risk cannot be ju fied, as we have shown, because of the high possibility of barrier defects and because of the potentially important effe of air barrier failure. Therefore, it is necessary to look for so redundancy in the envelope design, directed toward preve ing or minimizing the condensation risk. Performance requi ments could be established in order to define whether condensation risk of a design solution is acceptable or not. I instance, the performance check could exist of a failure eff analysis with a design set of failure modes and design cal lation conditions. The condensation risk of an envelope des

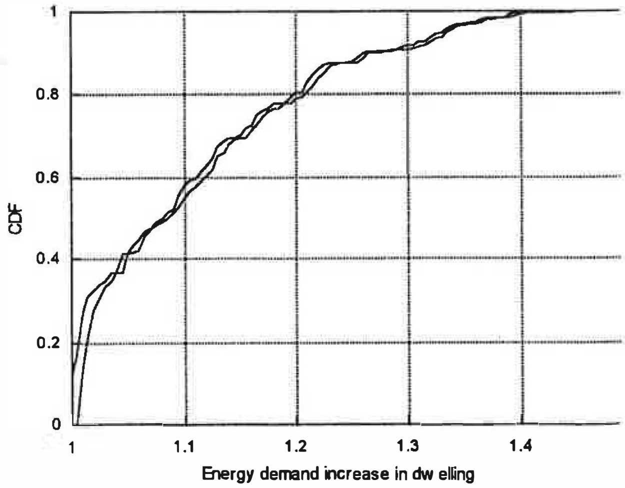

Figure 5 *CDF of energy demand increase.*

could be acceptable if the 90th percentile of the calculated condensation amounts would be smaller than a critical level, i.e., 0.1 kg/m^2.

An obvious way to improve the reliability of the air barrier system and to reduce the condensation risk is the duplication of the air barrier, for instance, by applying the underlay or the sheathing according to air barrier requirements. However, a second air barrier also is susceptible for damage. Once a continuous airflow path in the envelope develops, the condensation problems are essentially as problematic as in the case with a single air barrier. Protective measures to reduce condensation amounts even though air barrier defects occur would be more effective.

Diversity

In the introductory calculation example, two potential measures were defined to reduce the condensation rates in leaky envelope parts: the use of thermally insulating or vapor permeable materials at the cold side of the structural cavity. The effectiveness of these measures in reducing condensation risk is studied more in detail here by failure effect analysis.

The analysis is done for a roof with the same properties as listed in Table 5 but with different underlay properties. Figure 6 shows the CDF of the condensation rate in a roof with a vapor permeable underlay with diffusion thickness 0.02 m, together with the CDF for the original roof design. The condensation risk is reduced, as expected, but is not acceptable yet. In the same graph, the results are shown for a calculation that does not account for thermal radiation to the outside surface ($q = 0$ instead of -30 W/m^2). The influence of radiation on the condensation rate is more important in the case with a vapor permeable underlay. The results with no radiation largely underestimate the condensation risk. This demonstrates the importance of including radiation at the outside surface in condensation calculations. The failure effect analysis also confirms that a vapor barrier is completely ineffective in reducing the condensation risk: the CDF is essentially the same no matter whether the diffusion thickness of the internal lining is 0.5 m, 5 m, or 50 m.

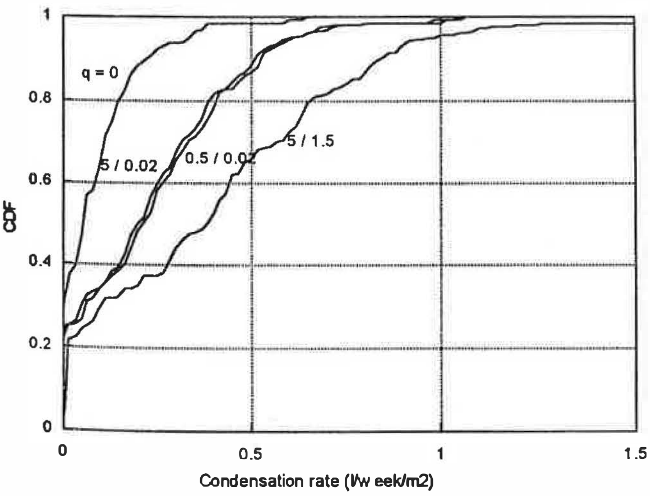

Figure 6 *Effect of vapor permeable underlay, parameter* = μd *internal lining* / μd *underlay (in m).*

Figures 7 and 8 show the effect of exterior insulation on the condensation risk. The thermal resistance of the layers at the cold side of the structural cavity is the parameter in the failure effect analysis. The analysis is performed for the original roof design and for the design with vapor permeable underlay.

In the original roof design, an exterior insulation with high thermal resistance is needed in addition to the cavity insulation in order to reduce the condensation risk to the desired level. The 90% percentile of the condensation rate CDF becomes lower than 0.1 kg/m^2/week when a thermal resistance of 2 m^2·K/W is added to the structural framing, the equivalent of 6 cm of extruded polystyrene (Table 7).

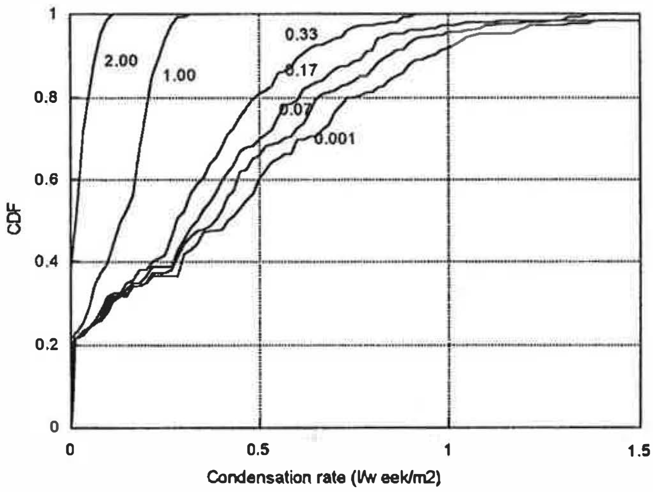

Figure 7 *Effect of exterior insulation (*μd *= 1.5 m), parameter = thermal resistance of layers at cold side of structural cavity (in m*^{2}*·K/W).*

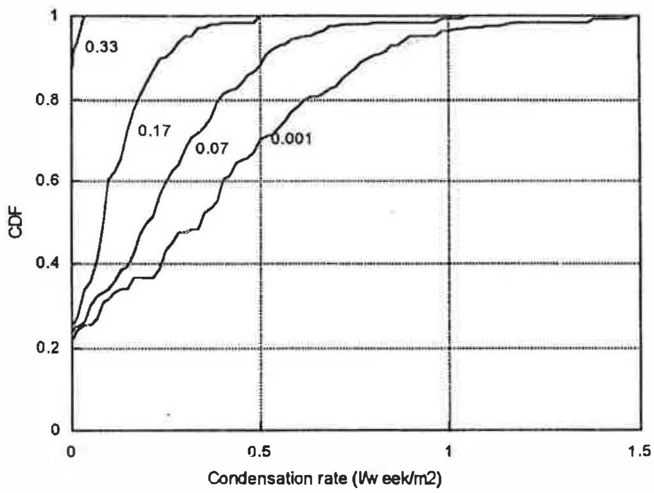

Figure 8 *Effect of insulating and vapor permeable sheathing (*μd *= 0.02 m), parameter = thermal resistance of layers at cold side of structural cavity (in m*^{2}*·K/W).*

TABLE 7

Distribution of Condensation Rate as a Result of Roof Defects (kg/m²/week)

Percentile (%)	Properties of Layers at Cold Side of Structural Cavity							
	Diffusion Thickness μd = 1.50 m				Diffusion Thickness μd = 0.02 m			
	Thermal Resistance ($m^2 \cdot K/W$)				Thermal Resistance ($m^2 \cdot K/W$)			
	0.001	**0.07**	**1.0**	**2.0**	**0.001**	**0.07**	**0.17**	**0.33**
10	0.01	0.01	0	0	0	0	0	0
50	0.42	0.38	0.13	0.01	0.34	0.20	0.08	0
90	0.95	0.84	0.24	0.07	0.78	0.51	0.23	0.005

A vapor permeable underlay or sheathing is unable to reduce the condensation risk without additional thermal resistance. However, the combination of a high vapor permeance with a thermal resistance even as small as that of an air cavity is very effective in minimizing condensation risk. These results indicate that very simple and inexpensive design measures are capable of creating reliable condensation control systems in lightweight building envelopes.

CONCLUSIONS

The methodology of risk analysis and assessment has been reviewed and applied to study the reliability of condensation control measures in lightweight building envelopes. It is generally recognized that lack of airtightness is the more important cause of serious condensation problems, but in terms of risk analysis, the air barrier protective system is a nonredundant condensation control system. Considering the high occurrence of human error in the building process, it has been shown that the possibility of air barrier defects during the service life of the building envelope is high. To define the reliability of the condensation control system, the consequences of air barrier failure have been quantified using a two-dimensional numerical control volume model for the calculation of combined heat, air, and vapor transfer in multilayered building envelope parts.

A set of failure modes and design calculation conditions has been defined for an exemplary wood frame insulated roof, and a failure effect analysis has been performed to predict the condensation risk as a result of air barrier defects. The analysis has demonstrated that the condensation risk cannot be justified because of the potentially important effects of air barrier failure. Therefore, the effectiveness of redundant protective measures to reduce the condensation risk has been studied. The results have shown that the use of thermally insulating or vapor permeable materials at the cold side of the structural cavity are capable of creating reliable condensation control systems in lightweight building envelopes. The use of a vapor barrier, on the other hand, is completely ineffective in reducing the condensation risk.

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