Building Material Problems Caused by Condensation at an Enclosed Swimming Pool and an Enclosed Ice Rink

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ABSTRACT

Enclosed swimming pools and ice rinks in winter climates have the potential for high indoor relative humidities and cold building materials. These elements can contribute to condensation and premature deterioration of building materials. This paper presents case histories of an enclosed swimming pool and an enclosed ice rink with condensation problems.

An evaluation was performed after roof leaks were reported around some skylights of a newly constructed indoor swimming pool in a Chicago suburb. After a preliminary inspection, it was evident that the reported leaks were related to building moisture problems rather than a roof leak. Exterior brick masonry exhibited heavy efflorescence in the area of the swimming pool, and water streaks were visible on the exterior walls below the eaves. The evaluation included laboratory testing of the solution causing the streaks, a visual inspection, field tests and measurements, and analyses for condensation potential. Results of the evaluation indicated the presence of condensed moisture, as a direct cause of the observed water stains, and masonry efflorescence. Recommended corrective actions included installation of a continuous air and vapor retarder and providing negative indoor air pressure.

A 54-year-old enclosed ice rink in New England was investigated to determine the cause of a deteriorated wood deck roof. The building had no dehumidification or air-handling system. The building was heated to 13°C (55°F) only when occupied. The evaluation included visual inspection and analyses for condensation potential. Results of the evaluation indicated condensation within the wood decking and insulation during winter months and high relative humidities that prohibited drying during the spring, summer, and fall. These conditions over an extended number of years resulted in fungi attack and decay of the wood decking.

INTRODUCTION

Enclosed swimming pools and ice rinks in winter climates have the potential for high indoor relative humidities and cold building materials. These elements can contribute to condensation and premature deterioration of building materials. Buildings with lower relative humidities in these climates tend to be more forgiving because they have opportunities to dry out. Moisture due to rain or floods penetrating the building envelope tends to evaporate from buildings with low relative humidity in the winter. Moisture due to indoor moisture migrating outward during the winter tends to evaporate in the summer months. Buildings with high interior relative humidities throughout the year do not have these forgiving seasons and must be carefully designed to prevent moisture problems. This paper presents case histories of an enclosed swimming pool and an enclosed ice rink with condensation problems.

ENCLOSED SWIMMING POOL

An evaluation was performed after roof leaks were reported around some skylights of a newly constructed indoor swimming pool. After a preliminary inspection, it was evident that the reported leaks were related to building moisture problems rather that a roof leak. Exterior brick masonry exhibited heavy efflorescence in the area of the swimming pool, and water streaks were visible on the exterior walls below the eaves.

The evaluation included a visual inspection, fourier transform infrared spectrometry (FTIR) analysis on water stains on the masonry walls, borescope inspection through roof and wall assemblies, measurements of interior relative humidities and temperatures, measurement of interior-exterior pressure differentials, and exploratory openings made through the roof assembly. Analyses were performed to evaluate condensation

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potential through the roof and wall assemblies under actual and design conditions. Condensation rates were calculated for each case. Results of the evaluation indicated that the presence of condensed moisture was the direct cause of the observed water stains, reported leaks, and masonry efflorescence.

Building and Materials

The indoor swimming pool facility is located in a Chicago suburb and was completed in fall 1994. The building includes an indoor swimming pool area, workout room, offices, and a second floor lounge. The swimming pool area also includes a large whirlpool.

The swimming pool area structure has a steep roof and consists of masonry load-bearing walls supporting laminated wood trusses and laminated tongue-and-groove wood decking. The tongue-and-groove wood decking is exposed to the inside of the swimming pool area. Design drawings indicate a rigid insulation layer placed over the tongue-and-groove wood decking. Prefabricated ventilated deck boards consisting of two oriented strand boards (OSB) with a 16 mm air gap were attached over the rigid insulation. The ventilated deck boards and rigid insulation were provided as a preassembled system. Roofing felt and asphalt shingles were installed over the ventilated deck boards. Several rectangular skylights were installed over the roof. In some areas, such as roof ridges and areas adjacent to skylights, a layer of ice and water shield protection membrane was substituted for the roofing felt. A layer of asphalt felt was reportedly placed over the tongue-and-groove wood deck prior to placement of the rigid insulation.

The walls in the pool area consist of cement plaster interior surfaces installed over concrete masonry units (CMU), 50 mm (2 in.) rigid insulation on the outer face of the CMU, and face brick. Exterior windows are wood framed and have insulated glass panes. Skylights are aluminum framed and reported to have argon-filled insulated glass panes. The building's HVAC system is reportedly designed to provide negative interior pressure during the winter months and to maintain an indoor relative humidity of approximately 40%.

Concern was due to apparent water leaks at the skylights during cold winter days, brown-colored water stains that had appeared on the masonry surfaces at the eaves of the roof in the pool area, and efflorescence of exterior masonry surfaces around the pool area. These symptoms became evident during a cold January immediately following completion of the building.

Scope of Evaluation

The scope of evaluation included field investigation, laboratory testing, and analysis for condensation potential. Available design drawings and specifications were reviewed to evaluate possible design deficiencies. Fourier transform infrared spectrometry (FTIR) analysis was performed on brown-colored water samples removed at the roof eaves and water-soluble compounds of the roof deck components.

A visual review of the building's interior and exterior surfaces was performed. The interior area adjacent to a skylight was inspected from a scaffold. A 38 mm (1½ in.) hole was drilled through the tongue-and-groove wood deck, insulation, and bottom layer of OSB to evaluate the absence of a vapor retarder and the condition of the ventilated deck board above. Relative humidities and temperatures were measured at several locations inside the building and at one location outside the building. Pressure differential between the outside and inside of the building was measured twice during our fieldwork. Borescope inspections were performed at two locations of the exterior pool area walls to evaluate the wall construction and to verify absence of a vapor retarder.

In order to evaluate the effect of the predicted condensation on the roofing system components, shingles were removed from the exterior roof surfaces to expose the OSB boards. Shingles were removed in several areas including an area adjacent to a skylight and an area in the field of the roof.

A steady-state water vapor diffusion analysis was performed for the typical roof and wall sections to verify the potential for condensation in the existing structure. The analysis was also performed for the proposed repairs to investigate their potentials for condensation. The analyses provided the location of the surfaces on which condensation potentially occurs, as well as the quantity of condensed water. Analyses were performed in accordance with Annex A1 of *ASTM C 755-85, Standard Practice for Selection of Vapor Retarders for Thermal Insulation.* Analyses were performed for the following outdoor temperature and relative humidity conditions: ASHRAE winter design, average January, average February, conditions observed on March 1, 1995, during the field investigation, ASHRAE summer design, and average July. The indoors was assumed to be at standard indoor pool conditions of 27°C (80°F) and 95% RH.

Field Investigation and Laboratory Testing Results

Laboratory testing of the brown-stained water samples taken at pool area roof eaves indicated that the source of the brown-colored material was the OSB of the ventilated deck boards.

Review of the design drawings indicated no effective vapor retarder was provided on the inner, or warm, surfaces of the roof and walls in the pool area. The ice and water shield protection installed over the ventilated deck boards did not act as an effective vapor retarder. Designers had attempted to prevent condensation by use of the ventilated deck boards. The air gap between the deck boards was intended to be ventilated through continuous eaves and ridge vents. However, this ventilation was ineffective due to wood blockings specified at the eaves immediately above the eave vents. In addition, the lower OSB of the ventilated deck became cold enough in

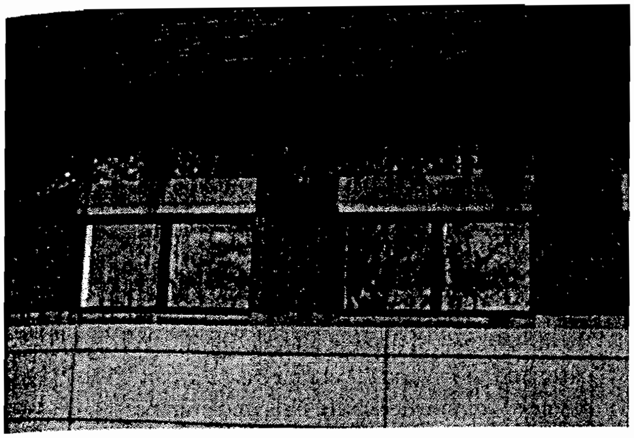

Figure 1 *Stains on brick masonry below pool area roof eaves.*

winter to cause condensation. Therefore, ventilating the upper deck panels would not eliminate condensation. Design drawings did not indicate an asphalt felt above the tongue-and-groove wood deck. The design of exterior walls did not provide an effective vapor retarder within the wall system.

Visual review of the building exterior confirmed the presence of several brown stains on the brick masonry immediately below the pool area roof eaves (Figure 1). These stains were not limited to the areas below the skylights and appeared uniformly distributed. It appears that the staining was caused by condensed water that formed on the outside surfaces of the ventilated deck boards. This condensed water would dissolve brown, water-soluble compounds within the OSB and would flow down the roof deck, discharging at the eaves.

Observations within exploratory openings into the exterior roof surface revealed water damage to the OSB boards in all cases. The water damage was accompanied with mildew in areas adjacent to the skylight (Figure 2). This condition was attributed to the presence of the ice and water protection membrane placed over the outer OSB board in those areas. The presence of this relatively impermeable layer slowed the evaporation of the condensate from the OSB boards and promoted mildew growth. In all exposed areas, the damage caused by the condensation was severe enough to adversely affect the physical characteristics of the OSB boards.

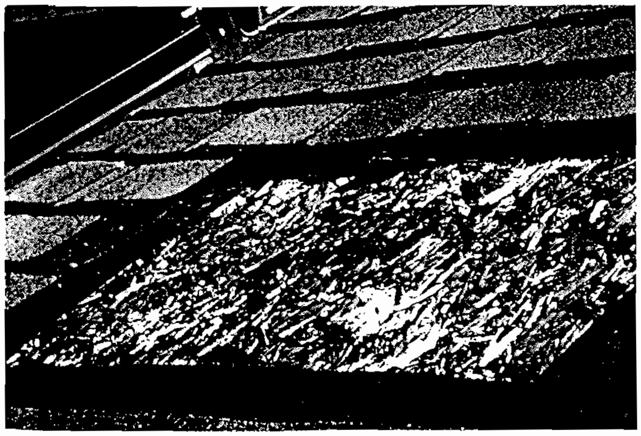

Figure 2 *Mildew on OSB board in roof areas adjacent to the skylight.*

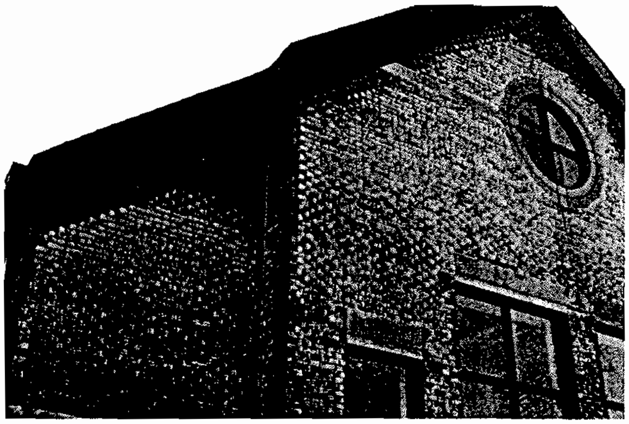

Figure 3 *Efflorescence on exterior masonry surface.*

Severe efflorescence was observed on exterior masonry surfaces at the north wall (Figure 3). Efflorescence was also observed on the east and west walls of the pool area, as well as the fireplace chimney on the east elevation. The fireplace was located in a lounge area adjacent to the pool area.

Measured relative humidities and temperatures during the afternoon of March 1, 1995, were as follows:

- Indoor relative humidities in the pool area ranged from 34% to 38%.
- Indoor temperatures in the pool area ranged from 26°C (78°F) to 27°C (81°F).
- Outdoor relative humidity was 41%.
- Outdoor temperature was −5°C (23°F).

The exploratory hole drilled adjacent to a skylight revealed the following:

- No vapor retarder or asphalt felt was found directly above the tongue-and-groove wood deck.
- The OSB of the ventilated deck board was notably moist.

Two measurements of pressure differential between the outside and inside of the building taken with a digital micromanometer indicated that the interior pool pressure was 5 Pa (0.02 in. of water or 0.0007 psi), lower than that of the outside. This minor pressure differential was induced by the HVAC system.

Borescope inspection of the exterior pool area walls at one north-facing location and one west-facing location indicated the absence of a vapor retarder immediately underneath the interior plaster finish. Based on these two observations, the walls were assumed to consist of cement plaster on metal lath, kraft paper, a 45 mm (1¾ in.) air space, CMU, kraft paper, 50 mm (2 in.) of rigid insulation (assumed to be polyisocyanurate), and face brick.

Results of Analyses

A steady-state vapor diffusion analysis was performed assuming the wall dimensions and materials cited above and the following roof dimensions and materials: a 50 mm (2 in.) thick tongue-and-groove wood deck, a 7 kg (15 lb.) asphalt felt, 65 mm (2 9/16 in.) thick polyisocyanurate insulation, two layers of 11 mm (7/16 in.) OSB separated by a 21 mm (13/16 in.) nonventilated air space, 7 kg (15 lb.) asphalt felt, and asphalt shingles. The air gap between the two OSBs was assumed to be nonventilated because wood blockings installed at the eaves would prevent airflow through the gap. In addition to existing conditions, analyses were performed for the assumed repairs of adding a vapor retarder to the roof and wall assemblies. Results are presented in Tables 1 and 2 and indicate the following:

1. The existing roof was predicted to have condensation between the insulation top surface and OSB for all winter conditions analyzed. Condensation was also predicted to occur beneath the insulation for the winter design case, the average January case, and the average February case. The condensation rates were considered low (underestimated) due to gaps in the wood deck and insulation boards.
2. The existing wall was predicted to have condensation between the insulation and brick for all winter conditions analyzed.
3. The assumed roof repair was the addition of a continuous warm side 0.15 mm (6 mil) polyethylene vapor retarder with a ventilated air space beneath the vapor retarder. This repair indicated condensation potential at the interface between the top of the insulation and the bottom of the OSB for the severe ASHRAE winter design, the average January case, and the average February case when 95% RH was assumed for the indoor air. No condensation potential was indicated when the ASHRAE winter design, the average January case, and the average February case were assumed to have indoor relative humidities of 22%, 46%, and 53%, respectively. The ASHRAE winter design condition is a severe case for condensation and is anticipated to be exceeded 2.5% of the hours in the months of December, January, and February, which is 54 winter hours. Condensation predicted to occur only under these conditions is frequently able to evaporate during other periods and not cause damage. The predicted relative humidity to prevent condensation potential for the average January and Febru-

TABLE 1
Results of Steady-State Vapor Diffusion Analysis to Determine Condensation Potential of Swimming Pool Roof

Component	Case	Indoor Condition			Outdoor Condition			Condensation		
		Temperature		Relative Humidity %	Temperature		Relative Humidity, %	Surfaces(s) with Condensation	Condensation Rate*	
		°C	°F		°C	°F			g/day/m²	grains/day/ft²
Existing Roof†	Observed 3/1/95	26	78	38	−5	23	41	top of insul./bot of OSB	1.5	2.2
	Winter Design	27	80	95	−17	2	70	bot. of insul & bot of OSB	8.9	12.8
	Avg. January	27	80	95	−6	21	70	bot. of insul & bot of OSB	7.8	11.2
	Avg. February	27	80	95	−3	26	70	bot. of insul & bot of OSB	7.5	10.8
	Summer Design	27	80	95	32	91	70	None	–	–
	Avg. July	27	80	95	23	73	70	None	–	–
Assumed Repaired Roof	Observed 3/1/95	26	78	38	−5	23	41	None	–	–
	Winter Design, 95% RH	27	80	95	−17	2	70	top of insul./bot. of OSB	0.8	1.1
	Winter Design, 22% RH	27	80	22	−17	2	70	None	–	–
	Avg. January, 95% RH	27	80	95	−6	21	70	top of insul./bot. of OSB	0.5	0.7
	Avg. January, 46% RH	27	80	46	−6	21	70	None	–	–
	Avg. February, 95% RH	27	80	95	−3	26	70	top of insul./bot. of OSB	0.5	0.7
	Avg. February, 53% RH	27	80	53	−3	26	70	None	–	–
	Summer Design	27	80	95	33	91	70	None	–	–
	Avg. July	27	80	95	23	73	70	None		–

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[*] Approximately 7000 grains is equivalent to 1 pound.

[†] Condensation potential and rates for the existing roof are probably low (underestimated) due to gaps in the wood deck and insulation board.

TABLE 2
Results of Steady-State Vapor Diffusion Analyses to Determine the Condensation Potential of Swimming Pool Wall

Component	Case	Indoor Condition			Outdoor Condition			Condensation		
		Temperature		Relative Humidity %	Temperature		Relative Humidity, %	Surfaces(s) with Condensation	Condensation Rate*	
		°C	°F		°C	°F			g/day/m²	grains/ day/ft²
Existing Wall	Observed 3/1/95	26	78	38	−5	23	41	insul./brick	1.5	2.2
	Winter Design	27	80	95	−17	2	70	insul./brick	10.1	14.6
	Avg. January	27	80	95	−6	21	70	insul./brick	9.1	13.0
	Avg. February	27	80	95	−3	26	70	insul./brick	8.5	12.1
	Summer Design	27	80	95	33	91	70	None	–	–
	Avg. July	27	80	95	23	73	70	None	–	–
Assumed Repaired Wall	Observed 3/1/95	26	78	38	−5	23	41	None	–	–
	Winter Design, 95% RH	27	80	95	−17	2	70	insul./brick	0.5	0.7
	Winter Design, 39% RH	27	80	39	−17	2	70	None	–	–
	Avg. January, 95% RH	27	80	95	−6	21	70	insul./brick	0.0	0.1
	Avg. January, 88% RH	27	80	88	−6	21	70	None	–	–
	Avg. February	27	80	95	−3	26	70	None	–	–
	Summer Design	27	80	95	33	91	70	None	–	–
	Avg. July	27	80	95	23	73	70	None	–	–
								None		–

* Approximately 7000 grains is equivalent to 1 pound.

ary cases was greater than the reported design RH of 40%. This repair was considered adequate for the conditions assumed.

4. The assumed wall repair was a continuous 0.15 mm (6 mil) polyethylene vapor retarder placed on the existing wall surface and a water-resistant wallboard placed on the inside surface of the vapor retarder. It was also assumed that a vapor-retarding paint was applied to the interior surfaces of the wallboards. This repair indicated condensation potential at the interface of the insulation and brick for the severe-ASHRAE winter design and average January cases when 95% RH was assumed for the indoor air. No condensation potential was indicated when the ASHRAE winter design and average January cases were assumed to have indoor relative humidities of 39% and 88%, respectively. The predicted RH to prevent condensation potential for the average January case is greater than the reported room RH of 40%. This repair was considered adequate for the conditions assumed.

5. No condensation was predicted for the summer conditions assumed for the wall or roof as they existed or as they were proposed to be repaired.

As mentioned previously, ASHRAE winter and summer design conditions are often severe cases for condensation. Condensation predicted to occur only under these conditions is frequently able to evaporate during other periods and not cause damage. However, continuous condensation with no drying periods will result in the accumulation of moisture in the building envelope.

Calculation assumptions may not replicate field conditions. The analytical method is a steady-state first-order method used to show the potential for condensation. The method does not consider the dynamic effects of daily temperature changes, solar effects, and material absorption. Therefore, condensation rates are approximate and are better suited as rough approximation rates for comparison purposes rather than actual volumes of water.

Findings

In general, the roof and walls were constructed in accordance with design plans. The reported leaks in the skylights in the pool area were attributed to condensation in the roof assembly. The brown stains at the exterior walls were also attributed to this condensation. As water condensed on the ventilated deck boards, it either leaked to the interior at the skylight openings or ran down over the surfaces of the OSB and discharged at the eaves. Condensation at the skylights was further exacerbated by the presence of steel support angles around the perimeter of the skylights. These steel angles caused thermal bridging that resulted in their low surface temperatures. The warmer, humid inside air condensed as it came in contact with the cooler steel surfaces.

The condensation in the roof assembly was caused by lack of an effective vapor retarder on the interior surfaces of the roof assembly. It is possible that continued condensation has caused damage to the ventilated deck boards or other roof assembly components.

The efflorescence observed on the exterior masonry was also attributed to lack of a vapor retarder. In the absence of an effective vapor retarder, warm, humid air from the pool area penetrated the porous plaster finishes, CMU, and rigid insulation. As it reached the colder surfaces of the exterior brick, it condensed. This condensed moisture was continuously driven toward the outside by higher water vapor pressure on the inside. As it passed through the porous mortar, it dissolved water-soluble salts such as calcium carbonate and brought these salts to the outside surfaces of the brick. Eventual evaporation of the moisture left these salts on the masonry surface in the form of the observed efflorescence.

In most indoor swimming pool buildings, controlling the indoor relative humidity and reducing interior atmospheric pressure minimizes the moisture drive from interior building surfaces to the outside. Reduction of interior atmospheric pressure is accomplished by a negative pressure HVAC system. Although indoor relative humidity of the facility was well controlled, its atmospheric pressure was not maintained at a significantly lower pressure than that of the outdoors.

Recommendations

The only effective method to prevent condensation in such a building is to provide a continuous vapor retarder on the interior surfaces of the pool area. For long-term prevention of moisture problems, recommendations were to install the vapor retarder in the walls between the pool area and the workout room, offices, and second floor lounge. The vapor retarder was designed to provide a continuous barrier against moisture migration. Areas around the skylights and other penetrations should be carefully detailed to prevent thermal bridging by the support angles and lintels.

Recommendations for installing a vapor retarder in the roof assembly were to remove all components down to the tongue-and-groove wood deck and to rebuild them. The new roof assembly should contain a ventilated air gap between the top of existing tongue-and-groove decking and a new vapor retarder. Adequate insulation, nailer boards, and roofing materials should then be placed over the vapor retarder.

Recommendations were to provide a continuous vapor retarder in the exterior wall assemblies by installing a vapor retarder over the existing interior surfaces. Rough surfaces should be smoothed to prevent puncturing the vapor retarder. A layer of moisture-resistant wallboard (such as cement board) or cement plaster can then be installed over the vapor retarder. The interior surfaces of the wallboards should be finished and painted with a vapor retarding paint.

Vapor retarders in the roof assembly and exterior walls need to be continuous. Recommendations were to include the building envelope vapor retarder in the whirlpool area roof.

ENCLOSED ICE RINK

An analysis was performed to determine the potential for condensation within the roof materials of an enclosed ice skating rink as it was originally constructed in 1938. An elastomeric membrane was spray-applied on the exterior roof surface in 1987. The purpose of the analysis was to determine whether enough condensation was present to be absorbed by the insulation and wood deck to cause significant deterioration of the wood deck prior to the application of the membrane in 1987. Repair recommendations were out of the scope of the work and were not provided.

Building and Materials

The steel-frame building housing the indoor ice skating rink was constructed in 1938. The building includes a main rink area and adjacent mechanical and office areas. The exterior walls of the building consist of 200 mm (8 in.) concrete masonry blocks with single-pane steel-framed windows. A previous investigation of the building indicated walls and windows were not airtight, and windows were single glazed with old, deteriorated, and broken glass. There were visible gaps at the wall-to-roof connection at the rake detail. The walls were single wythe concrete masonry and were step cracked in some areas. This information indicated the building had a relatively high infiltration rate. Building infiltration rates generally range from 0.2 to 2 air changes per hour (ACH), according to Chapter 23 of the *1993 ASHRAE Handbook—Fundamentals*. Since the information provided indicated a relatively leaky building, an infiltration rate of 1 ACH was assumed for analyses.

No dehumidification or air-handling system was incorporated into the design of the building. Fog routinely formed above the ice rink in the summer, and condensation was pervasive on the steel structural members of the roof. Pools of water formed on the ice in the summer months due to condensate dripping from the ceiling. This condition reduced skating quality and contributed to unsafe conditions. The ice provided a continual source of water vapor to the building air.

Evidence of fog in the building in the summertime, the condensate in the summertime, and the lack of dehumidification equipment indicated the building relative humidity was greater than 80% and probably close to 100%. Building relative humidities were assumed to be 80% in the winter and 99% in the summer for analyses. The building was heated to 13°C (55°F) only during occupied periods. Therefore, the temperature of the rink in the winter was assumed to be 13°C (55°F) or lower. The temperature of the rink in the summer was not reported in available information and was assumed to be 21°C (70°F) or lower.

The rink area has an arched roof that consists of steel girders spanning the entire width of the rink and steel purlins. The original roof deck consisted of 50 mm (2 in.) tongue-and-groove wood decking supporting a built-up roof membrane.

A 50 mm (2 in.) layer of insulation was installed underneath the wood decking. According to an insulation manufacturer's representative interviewed over the telephone, the insulation produced at that time was most probably sugar cane as currently specified by *ASTM C208, Standard Specification for Cellulosic Fiber Insulating Board*. This specification covers boards made from wood or cane. The thermal conductivity of this material is listed as 0.048 W/m·K (0.33 Btu·in./h·ft^2·°F) in the *1981 ASHRAE Handbook—Fundamentals*, Table 3D, "Abbreviated Reference of Previously Listed Insulating Materials," page 23.20. The permeance was assumed to be 0.3 mg/Pa·s·m^2 (5 perms) based on a conversation with an insulation manufacturer's representative and ASTM C208. Reportedly, the insulation boards were installed under pre-assembled deck panels before installation over the steel purlins, which resulted in a layer of insulation between the wood decking and steel purlins.

The 50 mm (2 in.) wood decking was assumed to have the thermal conductivity of pine, which is 0.15 W/m·K (1.06 Btu·in./h·ft^2·°F), as listed in the *1993 ASHRAE Handbook—Fundamentals*, Table 4, "Typical Thermal Properties of Common Building and Insulating Materials—Design Values," page 22.9. The permeability was assumed to be 4.2 ng/Pa·s·m (2.9 perm·in.), based on the *1993 ASHRAE Handbook—Fundamentals*, Table 9, "Typical Water Vapor Permeance and Permeability Values of Common Building and Insulating Materials," page 22.14.

When analyzing moist wood decking and insulation, permeances and thermal conductivities were estimated to be twice that of dry materials. Built-up roofing was assumed to have a thermal conductance of 17 W/m^2·K (3 Btu/h·ft^2·°F) from Table 4 and a permeance of 0.0 from Table 9, *1993 ASHRAE Handbook—Fundamentals*.

Scope of Evaluation

A steady-state water vapor diffusion analysis was performed for the roof of the enclosed ice rink to determine the surfaces of condensation and an estimated quantity of condensate at those surfaces. The analysis was performed for design summer and winter climatic conditions and average summer and winter climatic conditions.

Results of Analyses

A steady-state water vapor diffusion analysis was performed in accordance with Annex A1 of ASTM C 755-85. Average and design winter and summer temperature conditions were assumed for the analysis.

TABLE 3

Results of Steady-State Vapor Diffusion Analyses to Determine the Condensation Potential of the Roof With Dry Materials

Case	Indoor Condition			Outdoor Condition			Condensation		
	Temperature		Relative Humidity%	Temperature		Relative Humidity,%	Surfaces(s) with Condensation	Condensation Rate*	
	°C	°F		°C	°F			g/day/m^2	grains/day/ft^2
Winter Design	13	55	80	−13	9	60	top of insul./bot. wood deck top of deck/bot. of roofing	19.5 5.2	28.0 7.5
Average November	13	55	80	7	45	60	top of insul./bot. wood deck top of deck/bot. of roofing	1.4 0.8	2.0 1.1
Average December	13	55	80	1	34	60	top of insul./bot. wood deck top of deck/bot. of roofing	8.6 2.6	12.3 3.7
Average January	13	55	80	−1	30	60	top of insul./bot. wood deck top of deck/bot. of roofing	10.8 3.2	15.4 4.6
Average February	13	55	80	−1	31	60	top of insul./bot. wood deck top of deck/bot. of roofing	10.1 3.1	14.6 4.4
Average March	13	55	80	3	38	60	top of insul./bot. wood deck top of deck/bot. of roofing	6.2 2.0	8.8 2.9
Average April	13	55	80	9	49	60	None	–	–
Summer Design	21	70	99	29	85	60	None	–	–
Average July	18	65	99	23	74	65	None	–	–

* Approximately 7000 grains is equivalent to 1 pound.

TABLE 4
Results of Steady-State Vapor Diffusion Analyses to Determine the Condensation Potential of the Roof With Moist Materials

Case	Indoor Condition			Outdoor Condition			Condensation		
	Temperature		Relative Humidity%	Temperature		Relative Humidity,%	Surfaces(s) with Condensation	Condensation Rate*	
	°C	°F		°C	°F			g/day/m²	grains/ day/ft²
Winter Design	13	55	80	−13	9	60	top of insul./bot. wood deck top of deck/bot. of roofing	37.1 10.1	53.1 14.6
Average November	13	55	80	7	45	60	top of insul./bot. wood deck top of deck/bot. of roofing	2.3 1.4	3.3 2.0
Average December	13	55	80	1	34	60	top of insul./bot. wood deck top of deck/bot. of roofing	16.0 5.1	22.4 7.3
Average January	13	55	80	−1	30	60	top of insul./bot. wood deck top of deck/bot. of roofing	20.1 6.2	28.3 8.8
Average February	13	55	80	−1	31	60	top of insul./bot. wood deck top of deck/bot. of roofing	19.1 5.8	27.3 8.4
Average March	13	55	80	3	38	60	top of insul./bot. wood deck top of deck/bot. of roofing	11.4 3.8	16.3 5.5
Average April	13	55	80	9	49	60	None	–	–
Summer Design	21	70	99	29	85	60	None	–	–
Average July	18	65	99	23	74	65	None	–	–

* Approximately 7000 grains is equivalent to 1 pound.

Winter. The results of the steady-state water vapor diffusion analysis are presented in Tables 3 and 4. Results showed that significant amounts of water moved from the indoors through the insulation and wood deck and condensed in these materials during average winter weather conditions and winter design conditions. Since 1 gram of water is approximately equal to one cubic centimeter, approximately 97 cubic centimeters of water accumulate within or on each square meter (10.76 ft^2) of the insulation and wood decking during each week in January. Condensation rates were nearly twice as high when the material properties reflected the moisture in the materials. Condensation rates were also doubled for the winter design condition compared to the average January condition.

The calculated condensation in the insulation and wood decking for the months of November through March was 0.003 m^3 per m^2 (0.27 quarts per ft^2) of ceiling per year when the materials were analyzed as wet. For a 2970 m^2 (32,000 ft^2) ceiling, the condensation rate was 8.3 m^3 (2200 gal) per year. For the 54 years from 1938 to 1987, prior to when the membrane was installed, this condensation rate was predicted to be 0.17 m^3 per m^2 (15 quarts per ft^2) or 443 m^3 (117,000 gal) for the total ceiling. The moisture from the high relative humidity of the ice rink was trapped in the building by the low permeability of the built-up roofing. The heating system did not remove moisture from the building, and no dehumidification system was installed.

Spring. The results for average April are also presented in Tables 3 and 4. Although no condensation was predicted to occur during average April conditions, these conditions did not allow the insulation and wood deck to dry. The built-up roof prevented the materials from drying to the outdoors. Calculations indicated the vapor pressures for saturated insulation and wood decking were approximately equal to the vapor pressures in the building air. Therefore, the materials would not dry to the interior.

Summer. The results for average July and design summer, also in Tables 3 and 4, show that no condensation occurred during these conditions. The building air relative humidity was at or near 100% as evidenced by fog near the rink. The built-up roofing prevented the wood decking and insulation from drying to the outside. The potential for drying to the indoor air was limited due to its high relative humidity.

Sublimation of the ice to water vapor will continually increase the relative humidity of the building air until it reaches 100%, and then it will form condensate on the ice and any surface cooler than the indoor air. Infiltration of warm, humid air from outdoors will increase the relative humidity of the building air whenever the outdoor air has higher total humidity (moisture content) than the indoor air. If the building air is at 100% relative humidity, then the same conditions will cause condensate on any surfaces cooler than the indoor air. If the building air is assumed to be 21°C (70°F) and 100% relative humidity in the summer, infiltration of outdoor air will cause condensate on any surface cooler than 21°C (70°F) at outdoor air temperatures of 29°C, 27°C, 24°C, and 21°C (85°F, 80°F, 75°F, and 70°F) if the relative humidities are greater than 61%, 72%, 85%, and 100%, respectively. Lower building air temperatures will cause greater condensation, which will start to occur at lower outdoor air relative humidities.

Once again, calculation assumptions may not replicate field conditions. The analytical method was a steady-state first-order method used to show the potential for condensation. The method does not consider the dynamic effects of daily temperature changes, solar effects, and material absorption. It is further assumed that insulation and wood decking joints and roof punctures do not provide a path for moisture to penetrate. Therefore, the condensation rates are approximate and are better suited as approximate average rates for comparison purposes rather than actual volumes of water.

Findings

Average winter conditions indicated moisture would migrate from the building air to the insulation and wood decking and condense within them. Average spring and fall conditions indicated that the water vapor pressures in the building air and the moist materials were similar, thereby preventing the drying of the insulation and wood decking. Average summer conditions indicated high indoor air relative humidities that limited drying of the insulation and wood decking. These conditions over an extended number of years resulted in the accumulation of moisture in the insulation and wood decking. The high moisture content in the wood decking led to fungi attack and wood decay.

SUMMARY AND CONCLUSIONS

Evaluations were performed for an enclosed swimming pool and an enclosed ice rink with moisture problems. The analytical method was a steady-state first-order method used to show the potential for condensation. High relative humidities within buildings and the lack of effective vapor retarders led to undesirable condensation in both cases.

For the enclosed swimming pool, the reported leaks at the skylights in the pool area were attributed to condensation in the roof assembly. The brown stains at the exterior walls were also attributed to this condensation. As water condensed on the ventilated deck boards, it either leaked to the interior at the skylight openings or ran down over the surfaces of the OSB and discharged at the eaves. The condensation in the roof assembly was caused by lack of an effective vapor retarder on the interior surfaces of the roof assembly. The efflorescence observed on the exterior masonry was also attributed to lack of an adequate vapor retarder.

In the enclosed ice rink, moisture migrated from the building air to the insulation and wood decking and condensed during winter months. Relative humidity and temperature conditions of the indoor and outdoor air during other months prevented these materials from drying. These conditions over an extended number of years resulted in the accumulation of moisture in the insulation and wood decking and subsequent deterioration of the wood decking.