IDENTIFYING WATER AND MOISTURE INFILTRATION PATHS IN BUILDING ENVELOPES

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ABSTRACT
In the past ten years, fungal contamination of buildings has been linked to many complaints related to indoor air quality. Three elements promote microbial growth in an indoor environment: a) a microbial source, b) nutrients, and 3) water. Controlling the presence of water is generally the most effective means of limiting fungal colonization. The pervasiveness of microbes in our environment and the presence of many nutrient substrates limit the possibilities of rapid and effective intervention at these levels. In order to determine leakage sources and to perform an effective field investigation, the role of building components in preventing moisture intrusion and the mechanisms of moisture migration must be understood. Specialized techniques such as thermography and spray tests can be used to conduct the analysis and the assessment of the integrity of a building enclosure.

INDEX TERMS
Bioaerosol, Building envelope, Water leakage, Moisture, Microbial contamination

INTRODUCTION
Studies tend to demonstrate the existence of relationship between mold exposure and the development of some symptoms, particularly respiratory symptoms (Goyer, Lavoie, Lazure *et al,* 2001). Several of these studies have also noted the presence of high humidity. Among the various elements that contribute to microbial growth in an indoor environment, three are of particular interest: a) a microbial source, b) nutrients, and c) water (ACGIH, 1999). Controlling water accumulation is generally the most effective means of limiting colonization. The pervasiveness of microbes in our environment and the presence of many nutrient substrates such as cellulose, adhesives and other carbon containing materials limit the possibilities of rapid and effective intervention at these levels.

A preliminary walkthrough survey of the building should be initiated as soon as a microbial contamination of the building is suspected. All information related to the activities that take place inside the building, the nature of the processes, the operation of the heating, ventilation and air conditioning (HVAC) system, the plumbing system, the building materials and the exterior landscape should be documented. The building occupants as well as the technical personnel assigned to equipment operation and maintenance must be involved in this evaluation. Any past water infiltrations, sewer backups, floods, dust accumulation, as well as the cleaning techniques and products used for such events should be listed.

In general, the humidity in a building comes from: 1) the normal activities of the occupants and from the processes, 2) water infiltration in liquid or vapor form through cracks in the building envelope, 3) moisture that has collected in the construction materials, 4) the gradual release, during winter, of the humidity that was absorbed in the furniture and materials during

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the summer period, and 5) the migration of the moisture from the ground through the walls and the basement floor slab (ASHRAE, 2001(b), SCHL, 1999, Latta,1975).

MIGRATION OF WATER THROUGH THE BUILDING ENVELOPE

Exterior cladding

Water and water vapor can result in a reduction of the thermal resistance of the insulating materials and accelerate deterioration of building materials by chemical, physical and biological action (ASHRAE, 2001(a), Hutcheon and Handegord, 1989). In general, the resulting degradation can be observed by 1) the presence of molds on surfaces and in cavities, 2) degradation of wood materials, 3) spalling of masonry and concrete by freeze-thaw cycles, 4) hydrolysis of plastic materials, 5) corrosion of metal components, 6) damage caused by the expansion of materials (e.g., warping of wood floors), 7) a change in surface finishes (flaking of paint on wood siding and efflorescence on masonry), and 8) bulging and cracking of stucco due to condensation of humid air escaping from the envelope or originating from inadequate removal of rain and snow (ASHRAE, 2001(a), Anis, 2001, Hutcheon and Handegord, 1989).

Since water can travel long distances before appearing on an interior surface, the inspection of the exterior envelope should not be limited to the zone near where the water is appearing. The exterior wall components must be inspected, preferably while it is raining, because several infiltrations occur at this time. It must also be kept in mind that the cavities in the envelope can act as reservoirs, which can result in a delay between contact of the water with the cladding and its appearance on the interior (Nicastro, 1991).

From the exterior, water can migrate through the envelope under the effect of forces due to 1) gravity, 2) capillarity, 3) a difference in air pressure, 4) the kinetic energy of raindrops, and 5) surface tension (ASHRAE, 2001(a), Anis, 2001, CNRC, 1997, Nicastro, 1991). The effect of gravity is to carry the water towards the bottom of the cladding, allowing it to enter through the orifices. This type of infiltration occurs mainly when the materials are not superimposed at the horizontal joints or if the overlapping is reversed. Capillary suction allows water to move in porous and permeable materials as well as through small orifices such as cracks, joints and connections. When the air pressure on the sides of the envelope is unequal, air moves towards the lower air pressure. Surface tension allows the water to adhere to the lower face of horizontal surfaces and to move into interstitial spaces by means of the above forces.

To limit the risks of water infiltration, the following waterproofing principles are generally applied during building design and construction: 1) the building is equipped with a water collection system (gutters, flashing), 2) the roof can drain easily (sufficient slope, presence of a roof drain) and 3) the two levels of protection to control rainwater infiltration through the exterior walls are applied (CNRC, 1997, Nicastro, 1991). The first level consists of ensuring that the amount of water that can come in contact with the exterior wall is minimized mainly by 1) the presence of protective components such as eaves, cornices and drip edges under the window sills, 2) choosing the cladding based on its permeability, the attention paid to the details of the joints and connections, the limited number and size of openings in the cladding, and 3) controlling the effect of forces exerted on the wall. The second level consists of intercepting the water that has come through the first protection and of discharging it outdoors. In a wall built using the rain screen principle, protection is achieved by the presence of an air space with or without a waterproof membrane on the internal wall of the cavity. Any water that enters the cavity is subsequently carried towards the bottom of the wall, to then be drained by the flashing or the weepholes.

Various factors may promote infiltration through the exterior cladding (ASTM, 1998, Nicastro, 1997, Latta, 1975):

- improper installation of seals during window manufacture or their deterioration during usage
- the use of sealant products that are not weather resistant or are incompatible with the support on which they are applied or the lack of a proper support when sealant is installed
- the presence of cracks in the exterior cladding (masonry veneer, stucco, wood)
- crumbling of the mortar in masonry structures
- water accumulation at the window weepholes due to a reversed slope in the sill
- no drip edge at the window ledges and door sills
- nonexistent or improperly installed flashing around the windows for recovering and draining any water that could appear due to inadequate sealant between the cladding and the window
- nonexistent or improperly installed sealant around the doors, windows, sill and trim

Certain buildings require the use of expansion joints to allow the materials to expand. The force applied when materials move may result in the loss of adhesion or separation of the sealant and allow water to enter (ASTM, 1998, Nicastro, 1997).

Foundations
Foundation inspection may detect the presence of cracks. These cracks can have various causes, mainly deficient design, an incorrectly proportioned concrete, the lack of reinforcement, inadequate backfilling, excessive hydrostatic pressure, frost, aging and differential settlement produced by the drying of the soil (Bergeron, 2000, SCHL, 1998). Better surface-water drainage conditions can be achieved by increasing the ground slope near the foundations and by moving the downspouts farther away. A blocked or overloaded foundation drain located on the building's perimeter may also result in water at floor level. Connection of the downspouts to the building drain is not indicated due to the significant hydraulic load that it imposes on the drainage system and the possible blockage that might occur due to the presence of sediments in the water. In some cases, infiltration may result from the deterioration of the dampproof coating covering the exterior face of the foundations (Bergeron, 2000, ASHRAE, 2001(b)).

Roof
The presence on roof elements of damp surfaces, traces of water, corrosion, frost and molds may be related to water leaks (Baker, 1980). Noted among the possible causes are the lack of a ceiling vapor barrier or damage to it, insufficient ventilation of the roof space, insufficient insulation, perforations in the roof sheathing, leaks of humid air from an exhaust fan, and the lack of insulation on the roof drain and vent piping (SCHL 1998, Baker, 1980).Visual inspection of the roof may reveal damage to the flashing whose purpose is to ensure waterproofness of parapets or openings for chimneys, vents, ventilation outlets, mechanical system piping and skylights. Water accumulation on the roof, due to inadequate drainage (insufficient slope; settlement of the structure; damage; blockage or lack of a drain), must be avoided because it promotes the premature aging of some types of roofing.

Signs of roof deterioration vary with the type of roofing. In the case of a multilayer roofing (consisting of felt paper and asphalt in alternating layers, all covered with a layer of asphalt and gravel), the most common problems are (Bergeron, 2000, Baker, 1980):

- perforations resulting from wear or impact

- blisters between the layers caused by trapped water vapor or air
- bubbles in the asphalt caused by expansion of the asphalt due to solar radiation
- bare membranes due to too thin a layer of crushed stone or poor adherence to the asphalt
- surface folds due to the sliding of the felts, or adherence problems caused by the softening of the asphalt under the effect of sun
- cracks caused by the hardening of the asphalt (oxidation of the asphalt by the sun results in hardening that creates contraction forces), crushing of the blisters, structural movement or the contraction of materials under frost action.

MOISTURE MIGRATION THROUGH THE BUILDING ENVELOPE

Water vapor can travel across the building envelope by two mechanisms, namely 1) air movement, and 2) diffusion caused by a difference in vapor pressure. It is accepted that air movement is the main mode of vapor transfer (ASHRAE, 2001(a), Nicastro, 1991). When moisture-laden air crosses the envelope from a warm area to a cold area, hidden condensation may occur. This situation occurs when the surface temperature is equal to or less than the dew point of the air-water mixture. If the water is not eliminated, it may cause deterioration of the materials and promote the development of molds.

Air movement across the envelope is caused by three major sources of air pressure: wind pressure, stack pressure, and pressure induced by mechanical air-moving systems (Anis, 2001, ASHRAE, 2001(c)). The magnitude of the air leakage depends on the difference of pressure across the envelope and the leakage characteristics (shape and size) of the openings (Hutcheon and Handegord, 1989). When the wind impinges on a building, the positive pressure exerted on the windward side causes air infiltration. At the opposite, under the negative pressure created on the leeward sides exfiltration of air occur. Stack pressure results in the difference in weight of the column of air inside the building compared to the column of air outside. The weight of the column of air depends on its height and the density of the air. For instance, in winter, the outdoor air being more dense than the indoor air, the absolute pressure decreases more rapidly with height which lead to a pressure differential across the envelope that causes air to flow (Hutcheon and Handegord, 1989). When the indoor air is warmer than outdoors, the building is depressurized at its base and the top is pressurized relative to outdoors. In cooling climates, the opposite situation occurs and exfiltration takes place at the base of the building while infiltration is observed at the top.(Anis, 2001, ASHRAE, 2001(c)), Hutcheon and Handegord, 1989). Improper balancing of HVAC systems (exhaust and supply) can also generate a pressure difference across the building envelope. Excessive depressurization can therefore increase the rate of entry of rain and moisture particularly during the cooling period in hot humid climates. In heating climates, pressurization of building can drive moisture-laden air towards the outside where it is likely to condense.

When water vapor concentrations at two points differ and in the absence of air movement, water vapor flows from the point of high concentration towards the point of low concentration. Diffusion across a material depends on the difference between the vapor pressures, the permeability and the length of the material (ASHRAE, 20019(c), Latta, 1975). In winter, since the vapor pressure is generally higher inside a building than outside, the result is a flow of water vapor towards the outdoors. The reverse phenomenon takes place in summer when the outdoor vapor pressure is higher. In both situation, condensation occurs when the vapor pressure is greater than the maximum allowable vapor pressure (saturation vapor pressure) at this temperature.

To minimize air movement and vapor diffusion across the building envelope an air barrier system has to be properly designed and installed. In heating climates, a vapor barrier is placed on the warm surface of the insulation in order to limit the exfiltration of the moisture towards the exterior and therefore prevent condensation of the air on contact with the cold surfaces. The air barrier which has a higher permeability than the vapor barrier is installed towards the outside of the envelope to allow the moisture that has infiltrated into the wall cavity to dry out. In cooling climates, exterior building surfaces should have a higher vapor resistance than interior surfaces and low-permeability material such as vinyl wall covering should be omitted (ASHRAE, 2001(b)).

DETERMINATION OF LEAKAGE SITES AND WETNESS OF MATERIALS

During a walkthrough survey, areas that may promote bioaerosol proliferation must be identified. In general, sources of stagnant water are sites for bacterial growth, while damped dusty surfaces are sites for mold growth (Goyer, Lavoie, Lazure *et al.,* 2001). Buckling of wood-based panels, dampness of carpets, plaster buckling, drywall deterioration are evidences of moisture related effects. The inspection must also include the HVAC system where water accumulation or leakages are frequent near cooling coil, humidifier and air intake (Lavoie and Lazure, 1994).

Dust deposition in the vicinity of joints or cracks is generally indicative of air movement. Air leaks can be detected using a smoke tube and occur most of the time at the following locations: around windows and doors, around piping and air ducts, through electric outlets (light fixtures), through cracks in wall sheathing or ceilings and along moldings, at the juncture of the structure and masonry walls or the chimney.

When visual inspection does not locate sources of leaks, a spray test can be performed on the exterior cladding (ASTM, 1998). Two in situ methods are proposed by the American Society for Testing and Materials (ASTM E-1105) and the Architectural Aluminum Manufacturers Association (AAMA 501.2). Although their respective methodologies are different, these methods essentially consist of spraying the exterior surface with water and of observing whether there are leaks.

Infrared thermography is also used in some situations. It is a non-destructive technique that can be used both inside and outside a building. Using a camera that captures the infrared radiation emitted by a body, thermal images are obtained that show the variations in temperature of a surface. The thermal irregularities that are revealed originate from variations in thermal conduction, air flow and from temperature inversion in the exterior sheathing, the roof, as well as the interior walls (CNRC, 1984). Anomalies in the building envelope such as the lack or movement of insulation, damp insulation, the presence of a thermal bridge and air leaks can thus be located.

The use of a moisture meter can be very practical during an inspection to detect non-visible accumulations of water (ACGIH, 1999). This instrument is used to determine the water content of wood, which is expressed as a percentage and corresponds to the weight of water contained in the wood in relation to the weight of oven-dry wood. It can also be used qualitatively for other types of porous materials such as concrete, gypsum and insulating materials. However, the user must establish the water content beforehand, using a dry sample of the material to be tested. The percentage displayed by the moisture meter is therefore the reference value for this material and not the material's actual water content. When the instrument is being used, contact of the electrodes with a metal surface (metal stud, aluminized vapor barrier) may result in a significant error. A rigid borescope can be used to confirm the presence of water mainly in wall cavities and ventilation ducts as well as to detect signs of microbial growth or the accumulation of nutrient substrates in these areas.

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