OAA Mould Control Practice Guide

Executive Summary

Mould growth in buildings has received increasing interest and concern in the press and building industry recently. Climbing costs of insurance claims, primarily in the United States, has resulted in excessive costs for insurance premiums and the OAA Indemnity Plan has limited coverage to mould-related damage. This OAA Practice Guide explains what mould and fungi are, why they are a concern, how to design and build to control mould growth, and provides resources and information about how to diagnose and remediate mouldy buildings.

Most moulds do not cause health problems, and they are a natural part of our environment. However, dampness in buildings has been associated with health problems, and some moulds are known to generate allergic responses and cause asthma. Hence, although moulds do not justify a hysterical response, their growth should be avoided and mould should be removed, along with the source of moisture, when observed.

Mould control is not about selecting materials or applying biocides. Mould spores exist everywhere. Hence, mould control is primarily about controlling moisture to levels and durations appropriate for the material used. The general strategy is to construct and operate buildings in such a way that materials do not get wet enough to support mould growth, or to ensure that those materials that will get wet dry quickly and do not provide sufficient food value.

Enclosures must be designed for rain and air leakage control as well as to allow drying of incidental moisture. HVAC systems must be designed to manage humidity and condensation within the system and the space they serve, by ventilation during cold weather and proper dehumidification during warm weather. Where moisture control is not possible (e.g., pools, bathrooms, cladding) choose materials with few nutrients.

Damage from floods, accidents, and maintenance activities can be minimised if such events are planned for. Vigilance is also required during construction to avoid excess wetting, premature closing in, and insufficient drying. Finally, operation and maintenance must be conducted in such a manner as to avoid moisture problems.

Most mould problems can be dealt with in a straightforward manner. Testing is rarely required or useful. Stop the mould from growing, remove it, and make sure it does not grow back by removing moisture sources, nutrients, or both. If the mould infestation is large or occupants are reporting health effects, one should act more quickly and firmly than if it is a small growth and the occupants are healthy. Mould remediation should follow the available guidelines. Identification followed by removal or control of the moisture source that caused the problem must be part of any remediation.

Mould control should be considered in all phases of building design, construction, maintenance, and operation. In most cases where moisture is controlled, mould growth will not be a problem. Good moisture control strategies are described in the OAA Rain Penetration Control Guide, CMHC Best Practise Guides, and other moisture control handbooks.

Introduction

In industrialised countries most people spend more than 90% of their lives inside. During this time the nature of the indoor environment directly affects the health, quality of life, and productivity of the occupants.

Some buildings however have problems providing a healthy or even appropriate indoor environment. The US Environmental Protection Agency (EPA) reports that about 30% of new or renovated buildings have serious indoor air quality problems (IAQ) (Roodman and Lenssen, 1995). In fact, recent estimates place the direct health care costs of poor indoor air quality problems (IAQ) in the US at $30 billion, with sick leave and productivity losses adding another almost $100 billion annually (Fisk and Rosenfeld, 1997).

A major indoor air quality concern is the growing number of studies, including landmark Canadian work, that link allergies, immuno-depression, and illness to the amount and type of mould (i.e. fungal growth)or dampness in a building (e.g., see Health and Welfare Canada 1987, Scanada 1995, Dales et al 1991, Dales and Miller 1999).

Largely because of health concerns, cases of mould in buildings have become headline news. The Insurance Information Institute reported that mould-related repairs and litigation cost the insurance business US$1.2 billion in the US during 2001. There are also about 10 000 mould-related lawsuits pending in the US (Turner, 2002), of which about 20% allege design and construction defects. The incidence of asthma in children, sometimes triggered and exacerbated by mould, has grown dramatically in the last 25 years (Health Canada, 1998).

To provide balance to these sobering statistics, it can also be said most mould causes no health problems, little scientific evidence directly links mould (as distinct from bad ventilation or dampness) to health problems, and avoiding mould growth is relatively straightforward.

This guide explains what mould and fungi are, why they are a concern, and how to design construct, operate and maintain buildings to control mould growth. It will also provide guidance for when a mould infestation requires action and good practice for remediation. Although most of the document is general, the focus is architecturally-designed buildings in Ontario. The topic of mould control is vast, and essentially builds on the large body of work in controlling moisture. This guide cannot comprehensively cover all that is required, but it aims to provide an overview and background that will allow a skilled practitioner to avoid damaging mould growth. Although the guide's scope is broad it does not cover the special needs of hyper-sensitive, highly allergic, or immuno-compromised occupants. A higher standard may be required for these special situations

What are Fungi, Mould, and Mildew

Moulds have been growing in damp buildings since we have begun erecting them, and certainly shared caves with the first humans. However, the health impacts of so-called "toxic mould" have only recently become a major news story and raised awareness amongst both the general public and the design professions. While moulds can cause illness and allergic responses in humans moulds are also a part of our natural environment, produce useful antibiotics, good cheese, and port. Most mould growth is harmless and is no cause for alarm. Nevertheless, mouldy buildings are not good buildings and the building industry must understand more about mould and its impact.

Close-up of mould growing on wood

Fungi are part of neither the plant nor animal kingdoms, but have a kingdom of their own. Over 60 000 fungi species have been identified (there are an estimated total of 1.5 million), although less than 400 species have been proven to cause disease in humans or animals (Levetin, 1995). Fungi can be subdivided into two groups: moulds and yeasts. Moulds are fungi that grow in filamentous form whereas yeast are characterized by single cells that reproduce by budding. Mildew and mould are terms used somewhat imprecisely to mean fungal growth that is undesirable much like “weed” is used to describe plants that are undesirable. Mould is often used to describe fungi that grow on surfaces, mildew to describe fungi that grow on fabric, and mushrooms is the term used to describe the fruiting bodies of certain types of fungi.

Mushrooms can be seen growing on the wood substrate, fed by water leaking through a standing seam roof (out of focus, above)

The long multi-cellular threadlike filamentous structures that form mould are called hyphae, and can be seen with limited magnification. A mass of hyphae is called a mycelium: this is the dark and slimy mass that can be observed with the unaided eye. Each of the individual hyphae strands can penetrate beyond the surface of a material into its open pore structure. This makes mould removal difficult for porous materials.

Mould fungi reproduce by releasing clouds of spores. The spores lie dormant on substrates until conditions (temperature, moisture, and nutrients) favouring germination occur. Most mould spores are very hardy, and can lie dormant through years of very dry and cold conditions. Some spores have even been reported to have survived on the exterior of spacecraft.

Mould spores are very small, ranging from only 1.5 micrometers (*Phialophora*, sometimes found growing in humidifiers and filters) to 14.5 micrometers (for the common *Aspergillus* species) (Kowalski, 2000). This diameter is less than 1/10 of the diameter of human hair, and this small size allows spores to float on light currents of air. Hence, spores are easily transported by air distributions systems, on occupant clothing, through open windows and doors, etc.

Requirements for Mould Growth

Fungi have evolved over many billions of years to efficiently decompose plants and other organic matter. Different sets of fungal species occupy different ecological niches. While some fungi grow best at low relative humidity and/or low temperature, other species grow best under high moisture and above room temperature conditions. A series of different mould species will typically grow on a substrate as the conditions change with time. Most of the moulds that both grow in buildings and may be dangerous to human health thrive under warm and very moist conditions.

Mould growth begins when favourable conditions allow spores to germinate. Once begun, growth can proceed at conditions less favourable than those required for initial germination. Hence, an intense wetting event may be required to start mould growth after which it can proceed at cooler or drier conditions.

Mould growth requires:

1. Infestation, i.e., mould spores to germinate (these are everywhere in the air)

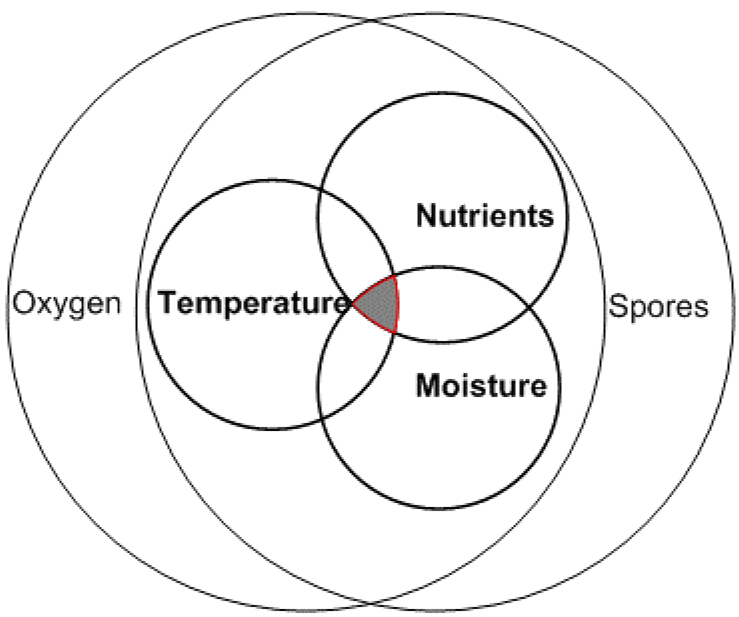
2. Nutrients (mostly cellulose and starch, but also dirt and dust),

3. Temperature (typically in the range of 5 to 50 °C)

4. Moisture (nominally surface RH>75 to 80%, but serious growth requires higher levels), and

5. Oxygen (freely available above the waterline in all buildings)

Each of these five requirements will be investigated below.



Five conditions must be met for mould growth to occur: regardless of design spores and oxygen are always available, but we can control the supply of temperature, nutrients, and moisture

Infestation

Infestation of a building must be assumed. Mould spores exist in the outdoor in significant concentrations, especially in summer and in areas with vegetation, as well as in materials delivered to construction sites. Because mould spores are very hardy, numerous, and light enough to essentially float in the air, mould spores can be expected to be available in essentially every indoor environment, within all enclosures, and on all building materials.

The concentration of mould spores in the air within unhealthy buildings is generally more than in the exterior air but not always. (In wet conditions, mould spores often do not become airborne, and even large areas of vigorous mould grow may not cause high spore counts in the air). The type of moulds in the indoor environment that cause health and comfort problems are usually very different than exterior species and this is one of the few reasons why species identification and counts may be useful in a mould investigation.

Nutrients

Nutrients for fungi are also usually available in buildings. Many building products are organic – wood and paper, many glues and paints, etc. – and so act as a ready food source. However, mould can even grow on glazed tile since small amounts of captured airborne dust, dirt and even soap provides nutrients. For example, it is difficult to avoid mould growth on the grout between shower stall tiles without aggressive maintenance because of the constant supply of moisture.

Mould growth on gypsum wallboard behind vinyl wallpaper (a vapour barrier) of an exterior wall in a hot humid climate hotel

Most mould food is based on carbon and nitrogen with small amounts of micronutrients. The food most moulds prefer is sugar and starch. Those moulds of particular interest to buildings are able to break down the more complex cellulose and lignin sources found in wood and wood products. Cellulose has the advantage that it can be broken down into sugar. Nitrogen is often part of the natural plant materials fungi have evolved to decompose, but other sources of nitrogen include proteins, especially those from human and animal dander. Starch is a naturally simpler form of cellulose and is easier for moulds to eat. Starch is used in some products such as gypsum wall board and adhesives.

In general, the more processed the plant material, the easier it is for the mould to grow. Each stage of increasing the surface area of the food, by chopping lumber into chips (eg., oriented strandboard), by reducing it to fibre (eg. fibreboard), or even further to particles (eg., particle board) and to pulp (eg., acoustic ceilings, paper facings) increases the ease of mould attack.

The structure of the material also plays a role. If the product is open-pored, mould spores and hyphae can easily gain access, and mould growth can develop at many surfaces readily supplied with atmospheric oxygen. However, open-pored materials also tend to dry quickly, thereby depriving mould of the moisture required for growth.

The highly processed and large surface area of paper facing on gypsum board and large-pored cellulose in ceiling tiles therefore provides an almost ideal source of food, while the original source for these products, solid wood, is not nearly as attractive.

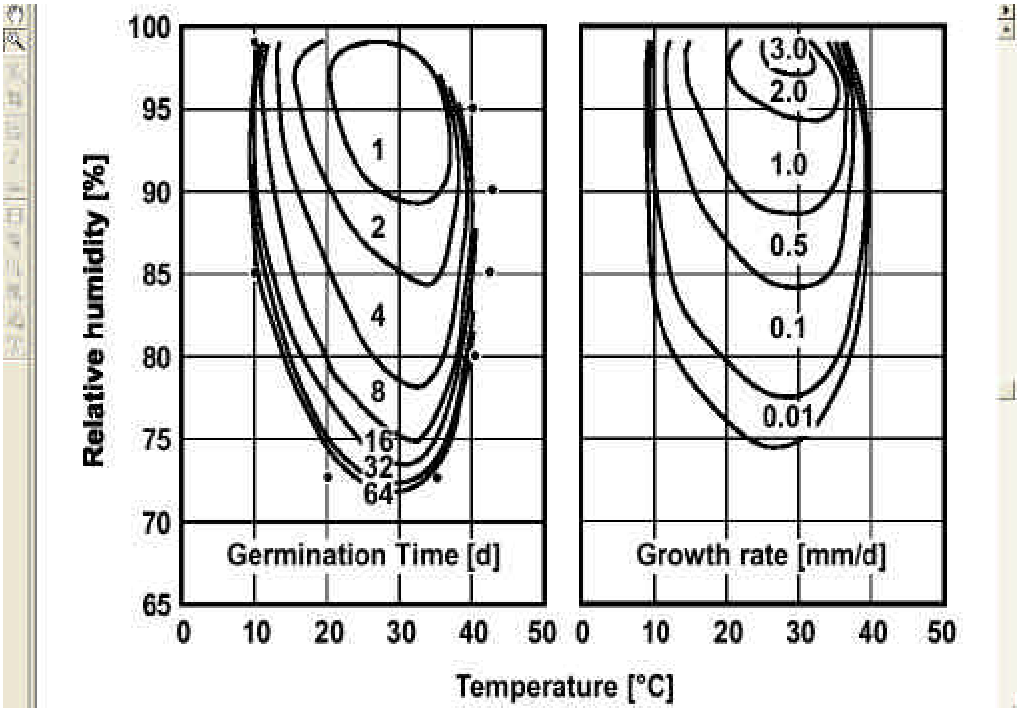
Temperature

Temperature is important for the growth of most organisms, including mould. Ideal conditions for mould growth are species dependent, but tend to be in the range of 20 to 35 °C. Most moulds will grow much more slowly outside this range, and little growth occurs below 5 °C or above 50 °C. Mould spores can survive, but mould cannot germinate or grow, well outside of this range – from below freezing to over 60 Celsius. Hence, mould growth can resume when conditions becomes favourable again.

Moisture

Moisture is necessary for all living organisms. Fungi digest their food outside their bodies – they manufacture and excrete enzymes that break down complex food sources. This approach to digestion requires a certain level of moisture on the surface of the material being consumed. The moisture can be provided by the humidity in the air, be built into the material during construction, or be provided by rain, surface, or groundwater. In some cases, mould growth itself generates moisture to help the process proceed.

Fungi typically require a *surface* relative humidity of at least 80% (IEA, 1991), sometimes termed a water activity level of 0.80. Some moulds can grow with less moisture, but these species are less important to building problems, and their growth is very slow, even on nutrient rich surfaces. Although mould can grow on nutrient cultures in the laboratory at lower RH, serious mould growth tends to require considerably higher surface RH levels and room air temperatures.



Temperature-Time-Moisture relationship for *Aspergillus restrictus* on a high nutrient substrate (Krus et al 2001)

Surface relative humidity is quite different than the relative humidity in a room. Since the RH of air increases with decreasing temperature, surfaces colder than room air will have higher relative humidity. These cold surfaces can be caused by thermal bridges and air leakage in cold weather or air conditioning equipment, thermal mass, or soil in warm weather. Hence, the air within a building in winter may be "only" 50%RH, but the RH in cold corners, behind furniture, or in closets may be well over 80%RH (see also enclosure design later in this guide)

Short periods of high RH or wetness do not cause germination, as can be seen in the plot for *Aspergillus restrictus*. For example, 8 days at 80%RH and 20 °C are required for this particular mold to germinate on a nutrient rich substrate. At these same conditions, 250 days will be required for one inch of growth. If a surface had a spore every square inch, it would be essentially covered at the end of this period.

It has been shown experimentally that repeated intermittent high RH (as may be experienced in a bathroom or kitchen) can result in fungal growth if the surface stores some moisture and does not dry completely between events (Adan, 1994). Hence, it can be seen that the ability for a surface to dry quickly may be as important as avoiding wetting.

Many porous building materials can store moisture. This means that wetting may occur over a period of only an hour, but the surface RH may remain high for days until the material dries out. Wet materials have close to 100% RH regardless of the air RH (that is why they are wet). Hence, fresh drywall compound, green wood and concrete, rain wetted concrete block, etc. all can be expected to be built with essentially 100% surface relative humidity.

Given time and proper conditions, these materials will dry to below levels required for mould growth.

Non-porous materials have their limitations too. They are unable to store any moisture within them, so even a small amount of condensation results in surface water for mould. This explains why water forms on the bathroom mirror during a shower but not on the porous and absorbent towel next to it.

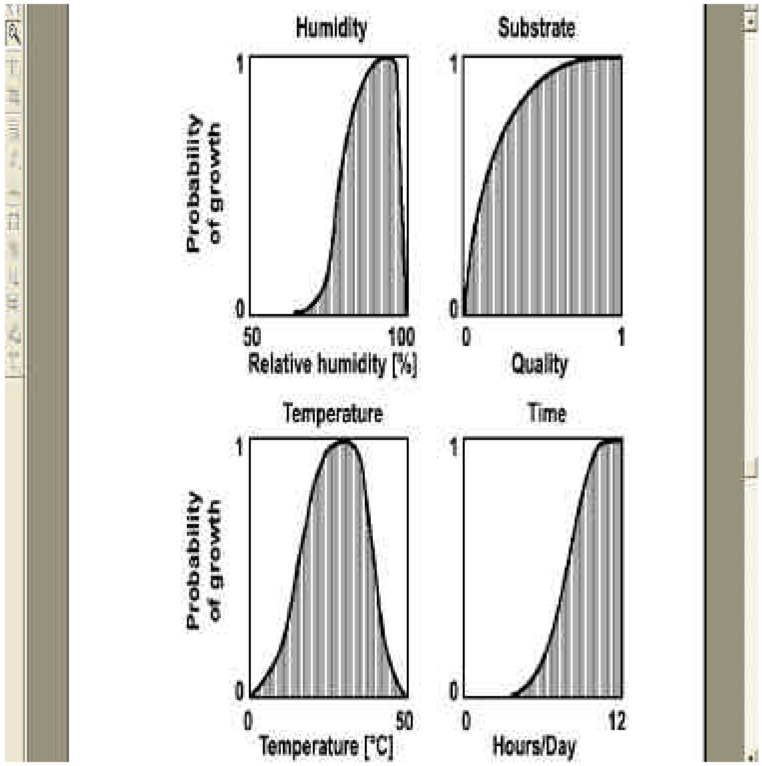
Oxygen

Oxygen is required for all fungal growth. Hence, moulds will not grow underwater, but they can grow if starved of oxygen for only a few hours at a time. In all practical cases, the required level of oxygen is available in buildings – sealing wall and roof spaces will not restrict oxygen transfer enough to affect mould growth. Mould spores in flooded basements will not begin to germinate until after the water recedes.

Other factors

Surface alkalinity and radiation also play a role in the viability of mould growth. Most fungi require the pH of the substrate to remain within the bounds of about 5 to 8 (i.e., neutral to slightly acidic). This sensitivity to alkalinity is the reason that lime washes (“whitewash”), with a high pH of 10 to 13, were used in the past to control fungal growth. Some modern anti-fungal coatings use stabilized lime with a high pH as their primary ingredient to control mould growth

Unlike plants, moulds do not require sunlight (since they do not use photosynthesis) and in fact their growth is limited by sunlight. Exposure to ultraviolet radiation (UV) may slow or kill fungi, but this depends on the intensity. Carefully designed UV light systems are used in some HVAC systems are used to kill mould spores. Bright sunshine is also effective. For exterior cladding the UV intensity is often high enough on cladding to stop growth. Exposure to direct sunlight typically reduces fungal growth both because the light warms (and hence dries) the surface and the high UV intensity.



Relationship of temperature, moisture, substrate (nutrient), and time-of-wetness on the probability of mould growth (Krus et al 2001)

Why Control Mould

Moulds in buildings are undesirable for four primary reasons:

1. they cause decay of materials, including structural members,
2. they cause objectionable staining,
3. they generate offensive odours, and
4. they can have negative health impacts.

Decay

Decay fungi that attack wood and wood products with sufficient vigour and speed require relatively high moisture (equilibrium RH of 95% or more) and nutrient levels. All measures that control surface mould growth will also control decay. Typical decay fungi also do not appear to have as many health effects as those that grow at lower moisture levels. However, decay of structural members can become an immediate structural safety problem.

Decay fungi attacked the perimeter wood beam where rain water leaked in around the patio door

Staining and Odours

Staining and odours are the most common result of mould growth in buildings, and it is clear that these are features of most moulds. In fact, these are likely the most common mould problem. The staining may remain even after mould is removed. In such cases a light sanding, bleaching, or refinishing may be required to restore the appearance.

Mould odours are generated by small mould particles and volatile organic compounds (VOCs).

Health Effects

Although staining, odours and decay are the most common and best understood mould problems, the health affects have generated the most publicity and are the most complex and poorly understood. In general mould is claimed to cause head aches, coughs, eye irritation, fatigue, runny noses, sore throats, chest tightness and more.

It must be emphasized that most moulds and most mould growth in buildings are not “toxic”. In fact, we can eat mouldy cheese and use mould mycotoxins (penicillin and cyclosporine) as antibiotics to save lives. In the words of Dr Joe Lstiburek, a recognised building science and mould expert, if all or most mould growth were dangerous to health, farming would be banned, cutting lawns would require a respirator, and compost bins would be declared toxic zones (Lstiburek, et al, 2002).

The health affects of mould are not completely understood, although a few of the potentially thousands of interactions are. Moulds are suspected of health effects because they give off spores (which are small organic particles that irritate the respiratory system), volatile organic compounds (large organic molecules that enter the air as vapours), and mycotoxins (produced by the moulds as poison for some living thing). The range of response that fungi generate in humans can be classified as allergenic, toxigenic, or infectious. Yeast infections such as athletes' foot are not a building-related mould problem. Some moulds may grow on immuno-compromised people, such as transplant patients. These types of infections require specialised interventions.

Mould spores can float in air and irritate the respiratory tract because of their small size. Moulds can generate millions of spores, and often produce the most spores as a survival measure when their environment or nutrient source is threatened. These spores (and many other small airborne particles such as pollen) can result in allergic reactions and irritate the respiratory tract, even if they are already dead.

Allergic reactions are essentially the result of our bodies' over-eager response to a supposed health threat when none exists. Allergens are proteins that sensitize the immune system. Subsequent exposure to the same allergen can cause the body to release histamines which result in swelling, itching, and other allergic symptoms. In some cases permanent damage may result. More than 60 fungi species can cause chronic allergies (Goodish, 2001). Some common species of mould (*Penicillium* and *Aspergillus*) are also believed to cause asthma (Shen and Han, 1998).

Mycotoxins can cause neurological damage and immune systems responses but not all fungal growths release mycotoxins and the environmental and substrate conditions required to release mycotoxins are not known. The health risks of some mycotoxins such as aflatoxin (a proven powerful carcinogen) and satratoxin (an immunosuppressant) have been studied, but not all mycotoxins are very dangerous, and few have any effect when inhaled as opposed to ingested with food (Armstrong and Liaw, 2002).

Volatile organic compounds (VOC) released by moulds irritate the mucus membranes of people and generate some of the pungent odours characteristic of many moulds. The level and duration of VOC exposure required to cause health damage is not well known, but is unlikely to be reached by mould production alone. Mould-produced VOCs are generally believed to be irritants only (many common building materials release far more).

Although the health impacts are not completely understood, there is no doubt that some moulds, including some of those that occur within decaying buildings (e.g., *Stahybotras Chartoroum, Aspergillus*) will cause health problems in most people at sufficient dosage for sufficient time. In most practical cases this does not occur.

We do know that mould exposure can make a person hypersensitive to subsequent mould exposure, but we do not know how much exposure, or the nature of the exposure required. We certainly do not fully understand the interactions of mould and previous health history, synergistic environmental conditions and other stressors. We do know that immuno-compromised individuals such as the ill, the young and the elderly are more at risk.

Four factors affect the health impact of building mould – the size of the mould colony, the type of mould, the sensitivity of occupants to mould, and the nature of the building's air distribution. In general, the greater the size of the mould colony, the greater the severity and frequency of health effects will be. The type of mould is another critical factor, but it is difficult to definitively differentiate "toxic" moulds from "healthy" moulds by species information alone. Response to mould exposure is quite variable. Some people become hypersensitive by excessive or repeated exposures, while others appear unaffected in the midst of a building full of ill co-workers. The manner in which air is distributed (HVAC, stack effect, wind, etc.) from the mouldy surface to the occupied space will change the likelihood of exposure to mould.

In short, we know that breathing large amounts of mould and its products is not a good idea, and that the more we breath, the more mould growth involved, and the worse the mould species, the higher the chances of experiencing health problems.

Despite these many unknowns, most mould problems can be dealt with in a straightforward manner. The approach should be to stop the mould from growing, remove it, and make sure it does not grow back. If the mould infestation is large or occupants are reporting health effects, you must act more quickly and firmly than if it is a small growth and occupants are healthy. The best strategy is to construct and operate buildings in such a way that materials do not get wet enough to support mould growth, or that those that will get wet dry quickly and do not easily support mould growth. The rest of this guide deals with these issues.

How to Control Mould

Controlling mould is simple in theory. Do not water or feed it.

Since buildings are infested with mould spores, provide nutrients to the mould in the form of building materials and dust/dirt, and have interiors and enclosure layers that are maintained at temperatures conducive to mould growth, the obvious and most practical means of controlling mould growth is to restrict the moisture available. **The industry has reached the important consensus that mould control is merely an extension of moisture control**. In many cases the level of moisture control required to control mould is no more stringent than that required to ensure good performance and durability.

In locations that can be expected to be moist (such as exterior cladding, foundations in contact with soil, and shower stalls), the use of materials that provide little food may be necessary, and have in fact been traditional choices. Using paper-faced gypsum in shower stalls for example is certainly not traditional, is likely to generate mould on the surface and is not recommended.

Good Practices to Avoid Mould

Almost all serious mould problems are due to a major lack of bulk water control, eg., plumbing leaks, leaky basements, the use of wet construction materials, bad flashing, poor ventilation, undrained condensate pans, etc. Since liquid water is the most likely to wet significant areas for significant lengths of time, the control of rainwater, condensation, and ground water are very important for the avoidance of significant mould problems (Straube, 2002). Prolonged high humidity is the second most common cause, and hence standard good moisture control practice should be followed. See OAA's Rain Control Practise Guide and CMHC's Best Practise Guide series for detailed guidance.

Decisions made and actions taken during design, construction and operation of a building may all have an affect on the potential for and consequences of mould growth. Architects are involved to varying degrees in each of these stages of a building's life – each phase is considered below.

During Design

The proper choices of materials, assemblies, and systems during design are the first major step toward avoiding mould. The following sections cover design under the categories of Enclosure, Interior Partitions, Plumbing and HVAC.

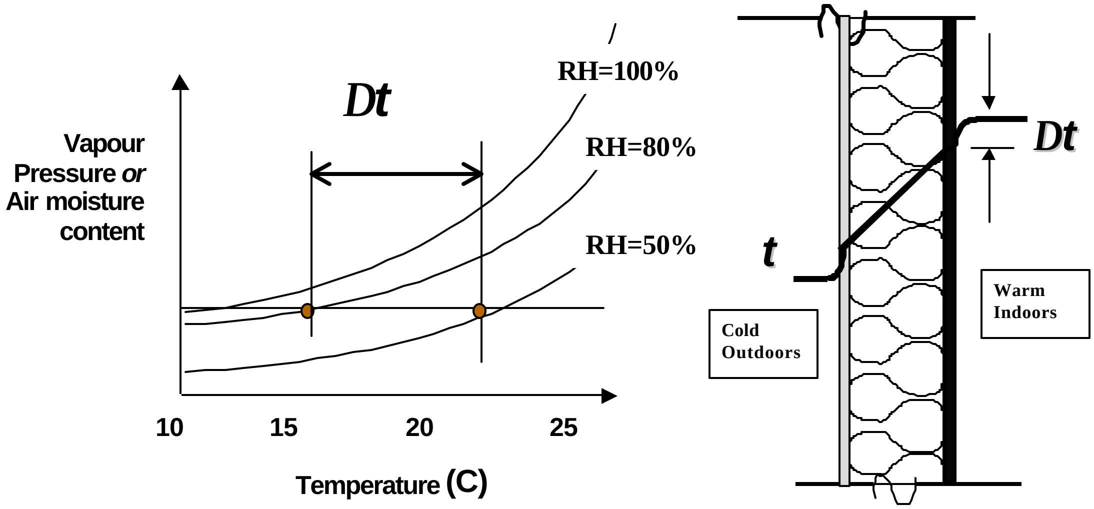
Enclosure

The building enclosure is often implicated in mould problems, primarily because it is exposed to a range of moisture sources, including rain and condensation (due to temperature variations). Although the outer portions of enclosures are often exposed to wetting, mould is seldom a problem since they tend to be constructed of relatively moisture-tolerant materials and are cold for a large part of the year. The mould that may grow in these areas is also usually separated from the interior air by an inboard air barrier system. In contrast the inner portions of the enclosure are exposed to less wetting but are more prone to mould growth since these are kept warm all year are often made of moisture sensitive materials and are better connected to the interior environment.

Condensation occurs when warm moist air contacts a cold surface. This can easily occur within insulated enclosures (interstitial condensation) during cold weather when warm humid interior air leaks outward through flaws in the air barrier system. It can also happen when interior air contacts a cold surface (surface condensation)

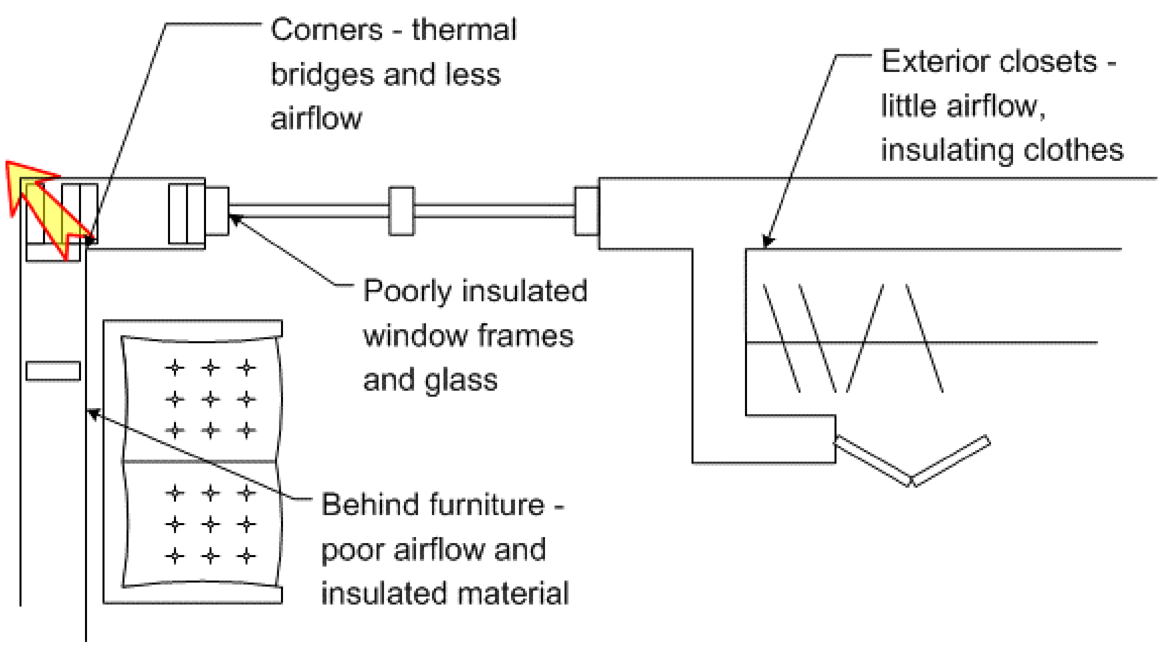
Both interstitial and surface condensation can occur in warm humid weather. Although the Ontario climate is cold for longer than it is warm and humid, mould grows much more quickly when it is warm. Hence warm weather condensation can be a real concern.

Condensation and high humidities occur at interior enclosure surfaces when their temperature drops below that of the surrounding air. As mentioned earlier, these cold surfaces are often caused by thermal bridges and air leakage in cold weather, or air conditioning equipment, plumbing, thermal mass, or soil in warm weather.



Cooling air near a surface will cause an increase in RH

The most common locations of cold surfaces and hence high cold weather surface humidity are in corners (less airflow, more thermal bridging) floor or ceiling-to-wall intersections (for the same reason), behind furniture (warm air cannot flow to the surface and the furniture provides some insulation), and any other location that encourages heat flow through the enclosure or retards heat flow to the surface.



Any location that encourages heat flow through the enclosure or retards heat flow to the surface can cause cold interior surfaces on which high humidity and condensation can form during cold weather

Air barrier systems are an important part of preventing condensation, but they also help to exclude mould spores that may be in the enclosure form spreading to the indoor environment (Straube, 2002). Stack effect (caused by the buoyancy of hot air rising) can drive air out the top floors of buildings. The taller the building the higher the pressure. This pressure can be controlled in tall buildings by sealing the floors and all penetrations and placing an airtight boundary around the core and stairwells (typically in the form of air sealed drywall and doors in the elevator foyer).

Enclosure Checklist

- Design the building enclosure to control moisture, e.g., rain penetration, interstitial and surface condensation, built-in moisture, and air leakage condensation. Moisture control in the building enclosure is itself a major topic that requires detailed attention.

- Rain control is often the most significant source of moisture. The OAA has recently prepared a Rain Control Practice Guide and CMHC has several excellent best practice guides with details and strategies to control rainwater.

- Below grade spaces such as crawlspaces and basements must be given special consideration. Exterior drainage layers and perimeter drains are almost always necessary. Drying of the wall to the interior (since the exterior is always wet) should be provided. Venting crawlspaces is usually not recommended since warm moist summer air will condense on soil-cooled surfaces (Moffat and Sikorski, 1991).

- Grade, driveways, garage floors, balconies, porches and stair landings should all be sloped away from the building to remove surface, rain, and meltwater.

- Air leakage can not only cause condensation, it subsequently acts to distribute the mould growth throughout the building. An air barrier system must be provided and shown on drawings complete with all seals and connections.

- Control excessive thermal bridging that can cool interior surfaces close to the dewpoint of interior air during winter. Light-gauge steel studs, concrete floor slabs that penetrate the insulation, and other structural penetrations are the most common problems. A small amount of exterior insulation is the solution.

- For parts of a building or building enclosure that can be expected to be warm (over 5 °C) and moist, materials with low or no food value should be used combined with frequent cleaning. There are no truly mould proof materials, as anyone who has found mould on their bathroom tiles can attest. Although paper-faced gypsum should be replaced with more mould resistant paperless glass-faced treated gypsum, it is often much easier and more prudent to avoid getting the materials wet in the first place.

Rain leaking through the skylight in this bathroom caused mould growth on the wood trim

These 3 month old crawlspace joists were kept cool (18 °C) by the soil resulting in high humidity and condensation when warm humid summer air from outdoors entered through vents

Interior Partitions and Finishes

Thermal mass can cause the temperature of a surface to lag behind that of the air. As a result, hot humid summer air may contact a cool surface and condense. This regularly occurs on uninsulated toilet tanks where it rarely causes problems. However, placing carpet over uninsulated concrete slabs on grade can result in the same problem since the carpet insulates the slab (keeping it cool) but allows water vapour free access to the slab. Since carpets store significant quantities of dirt, dander and other organics, mould growth can quickly flourish. Avoiding carpet in such situations is the best solution, although insulating under the entire slab (to reduce the thermal mass and increase its temperature) or mechanical dehumidification are other possible solutions.

Water fountains are often chilled and have plumbing. Hence, mould can grow in the hidden spaces behind water fountains. Such spaces should be avoided (by containing supply and drain lines as well as power connections in an integral easy to access stainless steel enclosure) or constructed of concrete or masonry. Drywall enclosures in this case present a high risk.

In some cases, an unheated or cooled space may be located on one side of a partition and a heated or uncooled space on the other. This can cause high relative humidities and condensation in partition walls. An example of this situation is the wall that separates a pool from an air conditioned classroom, office or gym. These partitions should be designed as exterior enclosure walls, that is, to control heat, air, and moisture.

Air leakage condensation from an adjoining pool caused wetting and consequent staining and mould growth on the ceiling tiles of this stairwell next to an interior wall of this school

Plumbing and HVAC

The HVAC system of many large buildings is complex, contains many coils, fans, dampers and actuators. It is also implicated in many mould problems. The architect should work closely with the mechanical engineer and contractor to ensure that appropriate measures are taken to control mould growth in this complex system.

HVAC systems can be both an ideal location for mould growth and ideal distribution system to broadcast spores, allergens, and mycotoxins through the building. Hence, ensuring that the HVAC system does not contain mould takes on additional urgency. Fibrous sound absorbing duct linings collect dust from the air and the condensation which occurs during summer air conditioning allows mould growth to form on this ideal substrate. Condensate pans or clogged condensate drains are often the source of moisture accumulations. Traps of sufficient height should be used for condensate drains to avoid negative air pressures sucking water upward into the pan.

Mould growth on ceiling of poorly ventilated hotel bathroom

Dual sloped pans are required to positively drain away condensate that flows off of cooling coils

That the AC in HVAC stands for air conditioning, not cooling is not widely understood. HVAC systems should be explicitly designed to control humidity as well as temperature, but typically are not. In most cases, air conditioning systems are designed for the cooling load, and humidity control is expected to be an implicit result. This approach is the reason for many comfort and indoor air quality problems with modern air conditioning systems. Because of improvements in the thermal performance of enclosures the cooling load in modern buildings with a normal amount of glazing and/or high density occupation is often primarily latent (i.e., dehumidification) not sensible (i.e., cooling). This is especially true during part load conditions such as rainy summer days when the outdoor temperature is moderate and the humidity high. Failure to control humidity results in clammy, uncomfortable buildings and increases the possibility of mould growth.

In response to the growing awareness of the importance of humidity control and the generally poor present practise, the American Society of Heating Refrigeration and Air-conditioning Engineers (ASHRAE) has recently published an excellent and useful guide book for humidity control in buildings (Harriman et al, 2002).

Cold weather air leakage through a poor air barrier system, exacerbated by poor control of interior humidity levels, caused condensation and mould growth on the OSB sheathing in this home

The relative humidity within ducts should not be allowed to exceed 80%RH if mould growth is to be controlled. In the vicinity of cooling coils, where high humidity cannot be avoided, condensate drain pans, maintenance access doors, and cleanable non-porous surfaces should be used while dust entry is controlled by proper *upstream* filtration. Ultra-violet irradiation lamps immediately downstream of the cooling coil has sometimes been used to effectively control bacterial and mould growth at these critical locations.

The winter time humidity of spaces must be controlled to avoid condensation on windows and within insulated enclosure spaces. In the Ontario climate, winter interior relative humidities of 30 to 35% should be the target. Special use buildings which, for some reason, require high winter humidities (i.e., over 40%) will often require special enclosure details (e.g. insulated sheathing, special air tightening, high performance windows) to avoid condensation and its attendant problems.

For high density occupations, such as small apartments, school classrooms, and portables, and high moisture production occupancies (kitchens, baths, classrooms, etc.) dedicated exhaust ventilation will almost invariably be required to control cold weather humidity. If the required ventilation imposes a large energy penalty a heat recovery ventilator should be considered. It is, for example, practically impossible to control the interior relative humidity of a 100 m^2 portable classroom with 25 children to safe levels without active means of ventilation or dehumidification. Exhaust fans rated for continuous operation with sufficient capacity to overcome duct resistance should be specified. Fans should also be quiet enough that occupants are not tempted to turn them off.

Some HVAC systems still apply positive pressurizations (i.e., the pressure is acting to drive air outward) to prevent or avoid cold inward drafts. Forcing air out through the building enclosure invites large and damaging amounts of interstitial condensation and is therefore not recommended. Drafts and air leakage should not be controlled by pressurization – a proper air barrier should always be provided. The air barrier system has other benefits, as discussed in the enclosure sections.

HVAC Checklist

- Mould control should be discussed with the HVAC consultant and contractor and explicit moisture control requirements should be given in the project specifications.

- Exhaust ventilation should be provided to remove moisture during cold weather in spaces with moderate to high rates of moisture production per unit area (classrooms, kitchens, baths, small apartments, etc.)

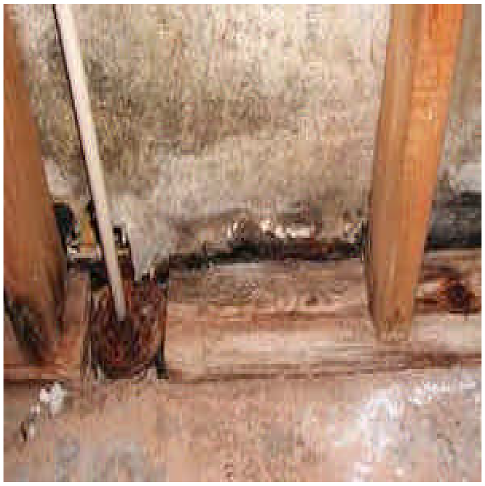
- Design the air conditioning system to control humidity in the space and in the ductwork, especially during part load cooling conditions (e.g., warm, rainy days).

- All cooling coils should have condensate drain pans located under them with bottoms sloped in *both* directions to a drain large enough to avoid clogging from dirt (e.g., min. 3/4” diameter).

- Do not use open porous insulation inside ductwork to control sound levels. Such insulation is an ideal growth media for mould. Although the inorganic fibers do not support mould growth they do collect dust and allow mould growth if humidity is not controlled. Such insulation is also almost impossible to clean.

- Place filters upstream of cooling coils – this keeps the coils clean and avoids water blowing down from the coil and supporting mould growth on the filter. Control the blow through of condensate from coils by limiting airflow velocities and designing coils appropriately. Research has shown that anti-mould treatments on filters have no effect once dirt is deposited [ASHRAE Journal]

- Cool potable water and chilled water lines can allow summertime condensation to form and then drip onto ceiling tiles or within drywall partitions. Such lines should be insulated with closed-cell insulation or at least routed through parts of a building with materials able to withstand occasional wetting (e.g., concrete chaseways).



Evaporation of water from drain trap allowed mould growth on the back of this drywall basement partition.

During Construction

Many, if not most, mould problems occur during or immediately after construction. Since architects are often involved in site visits and sign off when materials can be installed, they play a major role, and accept liability, in controlling mould growth during the construction phase.

Lack of humidity control during the long construction period of this custom home resulted in staining and mushroom growth on the oak beams

Most buildings, and hence many building materials, experience direct rain entry during construction before they are closed in. Even without rain, many structural materials such as wood (often 20 to 30% water by weight), concrete (which must dry 20 to 40 liters of water per square meter for a 200 mm thick wall or floor), and masonry (snow trapped in CMU cores during construction adds to the moisture in the material and mortar) provide moisture. Finally, the finishing process involving drywall compounds, carpet and tile glue, paints, and washing builds moisture into the building materials. All of this substantial amount of moisture must be allowed to dry out.

Construction Checklist

- Measure the moisture content of substrates before allowing finishing. Follow manufacturer's recommendations for substrate moisture content before applying finishes.

- Control the relative humidity within spaces by ventilation or, if needed, mechanical dehumidification.

- Do not use construction heaters that generate moisture (e.g., unvented propane and kerosene heaters) in moisture sensitive areas. Venting propane and kerosene heaters directly outdoors is an alternative to electric heaters.

- Plan for appropriate construction sequencing to avoid moisture sensitive material installation before the enclosure is complete. For example, the use of paper-faced gypsum board as fire separations and shaft lining before the building is rendered rainproof is a common problem.

- Do not trap construction moisture in assemblies by the indiscriminate use of low-permeance vapour barriers such as plastic film or aluminum foil.

Maintenance and Operation

Buildings that are not properly maintained have a much higher risk of experiencing mould problems. Well-designed and constructed buildings will only require simple cleaning to ensure continued good service.

More complex buildings require more complex and scheduled maintenance. Maintenance instructions for the building and equipment should be developed for each project and reviewed for compliance with good mould control practice. For example, filters must be replaced, cooling coils cleaned, and condensation pans inspected for blockage.

Maintenance Checklist

- Beware of wetting from cleaning activities – excessive wash water can wet drywall, sub flooring, and even the ceiling below.

- Develop maintenance strategies and guides during the design stage

Heating and cooling fins can easily become blocked with dirt and subsequently grow mould – regular cleaning is required

Accidents and Floods

During the life of most buildings a plumbing failure, a flood, roof leak or ice dam can cause a large amount of water to enter a building. Finished basement space is especially vulnerable since excess amounts of water from any accident will flow downward through the building.

In almost all cases, the responsible parties (owners, occupants, insurance company, etc.) must react quickly, within 48 to 72 hours, to remove all bulk water with pumps and wet/dry vacuum cleaners, followed by dehumidification drying. Comprehensive moisture measurements of the materials within walls, floors and ceilings (behind finishes) should be used to decide when drying has proceeded far enough.

Accident and Flood Checklist

- Do not locate plumbing in insulated wall assemblies. If the piping must be in exterior walls, place all of the insulation outside of the chaseway.
- Water heaters have pressure relief valves that occasionally open and relieve pressure by discharging water. Hence, locate water heaters on drained concrete slabs or on a “disaster pan” (an inexpensive plastic or custom sheet metal pan plumbed to a drain).
- The flexible rubber hosing servicing washing machines and dishwashers often fails and should be replaced with the reinforced metal braided type, and/or be located on disaster pans.
- Basements are likely to experience a flood and should have drains. If drywall finish is used, it should be kept up off the floor a minimum of 19 mm (¾”).

- Crawlspaces, especially those with floor levels below grade, may flood or collect plumbing leaks, and rarely provide indications of these accidents until too late. Design crawlspaces with water impermeable ground covers sloped to drains, raise the ground level above the surrounding grade and/or design as a complete basement system.

Poorly built or designed crawlspaces can collect rainwater and support mould growth

Mould Remediation

Architects may become involved in the assessment and remediation of mould problems. In such cases they should consider seeking specialist advice, especially if the problem is large, if health effects are indicated, or the occupants are potentially sensitive.

If someone, whether builder, engineer, occupant, janitor, or owner suspects that a building has a mould infestation, the first step is to find the mould. The simple presence of a musty smell or the observation of certain health symptoms is not sufficient to diagnose a building as having a mould problem.

Testing for mould has limited value. Most tests provide a measure in terms of Colony Forming Units per cubic meter of air. More advanced tests define the species, and may identify the amount of total as well as viable spores. Almost any test will show some mould, and most tests will also show some known toxigenic or allergenic mould species. This is the case for all buildings, healthy or infested. The ratio of the amount of mould inside to that outside *may* provide some indication that there is a mould problem, but will offer almost no information to guide further action. Sampling may be useful for medical or legal reasons when the identity of the specific species may become necessary.

The most widely recognised remediation guidelines have been prepared by the New York City Department of Health and Mental Hygiene *Guidelines on Assessment and Remediation of Fungi in Indoor Environments* (2002). This document summarizes the goal of remediation as:

> "to remove or clean contaminated materials in such a way that prevents the emission of fungi and dust contaminated with fungi from leaving a work area and entering an

occupied or non-abatement area, while protecting the health of the workers performing the abatement".

In most cases the response to mould concerns should be:

1. find the mould and contain it so that spores no longer are distributed through the building. Specialists in building mould problems (this does not mean all building scientists, mycologists, or industrial hygienists) can be useful, but are not always necessary.

2. identify the source of the moisture. In all but the most obvious cases, this may require a building science specialist (including architects and engineers with the requisite knowledge) -- an industrial hygienist or mycologist (mould specialist) would be of limited value.

3. develop a strategy or means to control the moisture supply. This may require a design professional such an HVAC, plumbing, or enclosure specialist.

4. remove the mould and mouldy materials before they are too dry (to avoid spores and dead mould material from breaking up and floating away), followed by finish drying of the building, reinstatement of damaged materials and final spotless clean-up. Professional remediation specialists should be consulted for large or sensitive projects.

The degree of intervention, the effort required for containment, and the level of personal protection required for workers will depend on the size of the mould problem, and the health response of the building occupants to it. The New York City Guidelines provide specific advice which depends on the extent of the extent and location of the problem. Other useful documents to consider are the US Environmental Protection Agency's *Mold Remediation in Schools and Commercial Buildings* (2001), and Building Science Corporation's *Mold Remediation in Occupied Homes* (2002). All three of these documents can be downloaded from the Web.

Remediation of small isolated areas (less than 10 m^2) can generally be carried out by building maintenance staff if no health effects have been observed. For large infestations, or situations in which health effects have been observed, professional specialists should usually be involved.

Remediation Checklist

- Plan the remediation for large projects, i.e., select clean up methods, drying equipment, containment methods, personal protective gear, etc.

- Removing mould before the substrate is completely dry makes some sense since the mould is less likely to release spores and small mould body parts if moist.

- Biocides, such as chlorine, are not recommended except in special situations, since dead mould can cause many of the same reactions, and the biocides also have health effects on humans.

- Ensure that the cleaning does not wet the building materials in such a way that new mould growth is encouraged.

- The HVAC system should be shut down and/or isolated (sealed grilles, etc.) to prevent the spread of spores and dust.

- All materials that are removed should be sealed and bagged so as to prevent the spread of spores and allergenic mould material through the building.

- The entire area must be thoroughly cleaned and HEPA vacuumed to remove all dust and mould parts. Mould colonies, once established, can be remarkably durable. For this reason, what may seem an extreme amount of diligence and care is required when cleaning up after a mould infestation.

- Clients and occupants must be kept informed of progress and planned action. This is also the best approach to avoiding fear and mass hysteria.

- Return to remediation sites several times over several months to ensure that the moisture problem has been resolved and that mould growth does not return.

Conclusions

Mould growth can be controlled in buildings by proper moisture control. Moisture control is a major topic of its own for which many guides exist.

Remediation should follow accepted guidelines. For large or sensitive projects, experienced professionals should be retained, whereas for small area (less than about 10 m^2) normal maintenance staff, properly informed, can do the work.

References

Adan, O., *On the Fungal Defacement of Interior Finishes*, Ph.D Thesis, Eindhoven University of Technology, Eindhoven, Netherlands, 1994.

Armstrong, S., and Liaw, J., “The Fundamentals of Fungi”, *ASHRAE Journal*, Vol. 44, No. 2, pp. 18-24, 2002

Burge, H.A., Su, J., and Spengler, J., “Moisture, Organisms, and Health Effects”, Moisture Control in Buildings, ed. Heinz Trechsel, American Society for Testing and Materials, Philadelphia, PA., pp.84-90, 1994.

Burge, H. A. *Bioaerosols*, CRC Press, Lewis Publishers, Boca Raton, Florida, 1995.

Dales, R., Zwanenber, H., Burnett, R., and Franklin, C., "Respiratroy health effects of home "dampness" and moulds among Canadian children", *Am. J. Epidemiol.* Vol 134, pp. 196-203, 1991.

Dales, R., and Miller, D., "Residential fungal contamination and health: microbial cohabitants as covariates", *Environ. Health Perspect.* Vol 107 Supplement 3, pp. 480-483, 1999.

Environmental Protection Agency. *A Brief Guide to Mould, Moisture and Your Home.* EPA 02-K-02-003, Washington, D.C., 2002. Available on-line at: www.epa.gov/iaq/moulds/mouldguide.html

Environmental Protection Agency. *A Mold Remdiation in Schools and Commercial Buildings.* EPA 402-K-01-0031, Washington, D.C., March 2001. Available on-line at: www.epa.gov/iaq/molds/graphics/moldremediation.pdf

Fisk W. and Rosenfeld A., "Improved Productivity and Health from Better Indoor Environments", *Center for Building Science Newsletter*, Lawrence-Berkeley Labs, Summer, 1997.

Goodish, T. *Indoor Environmental Quality*. Lewis Publishers, Boca-Raton, FL, 2001.

Harriman, L. Brundrett, G. Kittler, R., *Humidity Control Design Guide.* American Society of Heating Refrigeration and Air-conditioning Engineers, Atlanta, 2002.

Health & Welfare Canada. *Significance of Fungi in Indoor Air: Report of a Working Group.* Ottawa, 1987.

Health Canada. *The Burden of Asthma and other Chronic Resiratory Diseases in Canada*, Health Protection Branch, Facts and Figures p 87, 1998.

International Energy Agency. *Report Annex 14, Task 2:Condensation and Energy: Guidelines and Practise*, ed. H. Hens, 1991.

Krus, M., Sedlbauer, K., Zillig, W., Kuenzel, H., "A New Model for Mould Prediction and its Application on a Test Roof", *Proc. Of Current Problems of Building Physics in the Rural Building*, Cracow, Poland, Nov. 2001.

Levitin, E., "Fungi", *Bioaerosols.* Harriet Burge, ed. Center for Indoor Air Research. Lewis Publishers. CRC Press, Boca Raton, Florida, 1995.

Lstiburek, J. *Mould: Causes, Health Effects, and Clean-up.* Building Science Corporation, Westford, MA, 2002. Available on the web at www.buildingscience.com

Moffatt, S, and Sikorski, B., *Investigation of Crawl Space Ventilation and Moisture Control Strategies for BC Houses*, Report by Sheltair Scientific for CMHC, June, 1991, Ottawa.

Molhave, Lars, "Volatile Organic Compounds, Indoor Air Quality and Health", *Proc of Indoor Air '90*, Vol. 5, pp. 15-30.

New York City Department of Health, Bureau of Environmental and Occupational Disease Epidemiology. *Guidelines on Assessment and Remediation of Fungi in Indoor Environments.* New York, New York, January 2002. Available on the Web at www.nyc.gov/html/doh/epi/mouldrpt1.html

Ontario Architects Association. *Rain Control Practice Guide*, Toronto, June 2002.

Roodman, D.M., and Lenssen, N., A. *Building Revolution: How Ecology and Health Concerns are Transforming Construction*. World Watch Institute, Washington, D.C., 1995.

Scanada Consultants. *Mould in Finished Basements*. Report for Canada Mortgage and Housing Corporation, Ottawa, 1995.

Shen, H.D., and Han, S.H., “Characterization of Allergens of Penicillium and Aspergillus Species”, *J. Microbiol. Immunol. Infect.* Vol 31, No. 3, pp. 141-145, 1998.

Straube, J.F., "Moisture in Buildings", *ASHRAE Journal*, pp. 15-19, January 2002.

Straube, J.F., “Air Barriers Role In Preserving IAQ”, *IAQ Applications*, ASHRAE, Spring 2002, pp. 6-8.

Straube, J.F., "The Influence of Low-permeance Vapor Barriers on Roof and Wall Performance", *Proc. of Performance of Whole Buildings 8*, Dec. 2001.

Turner, F., “Moisture and Mold”, *ASHRAE Journal*, Vol. 44, No. 2, p. 4, 2002.

Yost, N., Lstiburek, J., and Brennan T., “Mold Remediation in Occupied Homes”, Building Science Corporation, Westford, MA, 2002. Available on the web at www.buildingscience.com