Moldy Houses—Building Science Lessons from the Wallaceburg Project

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ABSTRACT

Thirty-nine houses with high levels of biologically active contaminants in Wallaceburg, Canada, and twenty houses with low levels of biologically active contaminants, were subjected to field inspections and testing, monitoring of indoor environmental conditions, and simulation to predict the condensation formation potential in winter. Occupant health was evaluated through questionnaires and blood sampling from an index child (closest to age ten) for analyses of T-lymphocyte and B-lymphocyte structure. We found that low air leakage and natural ventilation were not associated with higher measures of mold growth. Analyses found that moisture sources in the houses were a more significant factor in mold and dust mite antigen levels than relative humidity. Visible mold area was not a good predictor of ergosterol concentrations, indicating that hidden mold growth may be a factor. This paper addresses the influence of house and construction characteristics on the levels of mold growth and the building science lessons provided by this project.

INTRODUCTION

Most people spend the majority of their time indoors, with most of that time in their homes. With the high exposure time, the presence of any indoor air contaminant is of major concern. There is a considerable body of evidence that indoor biological agents such as mold (fungi), dust mites, and bacterial endotoxins are associated with adverse health effects, as well as the degradation of the building and its contents and unpleasant appearance and odors. Some species of fungi produce potent mycotoxins and allergens. Clinically recognized diseases caused by fungi include cancer, infection, hypersensitivity pneumonitis, and allergic bronchopilmanary aspergillosis. Apart from these clinically recognized diseases, the reported presence of visible mold in houses has been consistently associated with increased symptoms, if not objective measures, of health (Yeung et al. 1995; Murray and Ferguson 1983; Owen et al. 1990; Wickman et al. 1991; Flannigan et al. 1991; Tobin et al. 1987).

It is important to understand what house construction and operating factors lead to or control mold growth. This was a major focus of the work described in this paper.

In general, all that mold requires to proliferate is a suitable substrate to grow on, moisture, a source of nutrients, and the temperature and humidity appropriate for the specific species. Dust mites have similar requirements. Gram negative bacteria, the source of endotoxins, also require a water source. Most absorbent surfaces are appropriate substrates for mold growth, and virtually all organic material, even the small quantities in house dust, can provide nutrients for both molds and dust mites. The temperature that people require for their own comfort is ideal for most species of molds and dust mites. With this situation, the primary variable affecting the mass of mold in homes is the presence of moisture at surfaces that mold can grow on and the relative humidity (RH) of the microclimate.

Most mold species with established health impacts require an initial presence of free moisture to become established and need a relative humidity above 60% in their local microclimate to keep them from drying out. Many require a frequent source of free moisture to thrive. Dust mite populations are also strongly associated with relative humidity in their microclimate. If relative humidity is maintained below 50% RH, their populations are restricted.

It is logical that controlling general humidity levels in a house should have an impact on the levels of mold growth and dust mite populations, but the relationship of such general parameters to the microclimates where mold and mites live is very complex. First, the relative humidity of air in a house is

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affected by a host of interrelated factors including weather conditions, indoor temperature, the size and location of air leakage paths, internal moisture sources, external moisture sources, ventilation provided, moisture storage effects, and phase change effects. Furthermore, the relative humidity in a microclimate depends on local temperature (which can be very different from the general space temperature), local air movement, and the presence of a local moisture source either directly or by condensation from a chilled surface. Many of these factors are strongly influenced by house construction and operation.

Determining the factors that lead to the proliferation of mold and mites in houses and finding methods of controlling them could have an important impact on public health. Two Canadian governmental agencies have sponsored a series of studies examining the health effects of indoor biological contamination and determining the housing characteristics that lead to it. A major component of this work is the Wallaceburg field study.

OVERVIEW OF THE WALLACEBURG FIELD STUDY

Questionnaire surveys were conducted in 30 Canadian cities. All showed correlations between reported moisture and mold problems and reported respiratory health symptoms. In an effort to provide more detailed and quantitative data on relationships between housing, microbiological contaminant levels, and the health of school-age children, a two-phase research project centered in the town of Wallaceburg in southern Ontario was initiated. Wallaceburg has a climate that is warm by Canadian standards, with 3700 degree days below 18°C, a winter design temperature of −16°C (2½% of January), and an annual precipitation of 825 mm.

Phase I was carried out in 1993 and 1994 and addressed about 400 houses. Houses were recruited from a census of elementary school children. Levels of biological contamination in the homes of these "index children" were assessed by air and dust sampling and analysis for biological contaminant. Health impacts were assessed by way of questionnaires administered to the occupants and overnight recording of the frequency of coughs in the index child's bedroom. House characteristics were assessed by way of a survey carried out by the project field staff. The results of the Phase I study showed a very large variation in the levels of some types of biologically active material in the sample houses and even a large variation by location within a house.

Phase II of the study was designed to address some of the unanswered questions about what housing factors lead to the production, or lack of production, of biologically active material: whether or not high exposure is reflected in measurable immunological response and were there exposure conditions that could confound or synergize a moisture/mold/health causality. Thirty-nine houses with high levels of biologically active contaminants and twenty houses with low levels of biologically active contaminants were recruited from the Phase I sample houses. These houses were subjected to detailed field inspections, testing to determine house operating parameters, monitoring of indoor environmental conditions, and simulations to determine moisture source strength and predict the condensation formation potential in winter conditions. Subjective measures of health were gained through questionnaires and brief physical exams of all occupants. Objective measures of health were explored by the collection of samples of blood and nasal secretions from the index child in each house and analysis of the T-lymphocyte and B-lymphocyte structure.

The author was responsible for carrying out the Phase II study. Phase I was carried out by others. This article is based primarily on the house characteristics data collected in Phase II and the measurement of biologically active contaminants carried out in Phase I. There are several articles in the process of development, review, or publication by other research colleagues addressing specific aspects of the data analysis. Notably, Dales et al. (1998) carried out a detailed analysis of the Wallaceburg health data including the measured lymphocyte population and the measured flow cytomery of index children living in houses with high biological contamination levels and low biological contamination levels. They found evidence of an objective biological response to home fungal contamination after controlling for the age of the child, dust mite antigens, and the presence of furred and feathered pets or a humidifier.

This article addresses the relationships between the house operating parameters and the levels of biological contamination found.

SUMMARY OF METHODS

The following summarizes methods used. A more detailed description of the test methods is provided by Lawton et al. (1998).

Sample Selection

The sample for the Phase I study was a consecutive sample of approximately 400 homes recruited from a census of elementary schoolchildren. During the winter of 1993-1994, the levels of biological contamination were assessed by air and dust sampling.

The Phase II sample was selected by scoring the Phase I homes according to the degree of fungal contamination. One point was given for each of the following:

1. a detectable level of bedroom ergosterol (a component of the fungal cell),
2. a detectable level of living area ergosterol,
3. greater than 105 colony forming units/g (CFU/g) of total fungi in dust isolated on glycerol-containing media, and
4. an excess of soil-borne relative to phylloplane fungi, measured as the ratio of

(Aspergillus + Penicillium + Eurotium)/
(Cladosporium + Alternaria + Epicoccum)> 10.

An initial recruitment list of the 50 lowest ranked (low biologicals) and 50 highest ranked (high biologicals) houses was developed. The desired 20 low biological houses were recruited from this list, but only 24 of the desired 40 high biological houses agreed to participate. The remaining 15 high biological houses were recruited from a second list that had lower contamination rankings or were missing data on one or more of the ranking data categories.

Measurement of Biological Contaminants (Phase I)

During the winter of 1993-1994, dust samples for viable fungi were collected in the main living area. Nutrient media containing Martin's rose bengal agar with and without 25% glycerol were used to isolate both hydrophilic and mildly xerophilic fungi. Dust, from the bedding of an index child (closest to age ten), was analyzed by ELISA for Der p 1 and Der f 1, two common dust mite antigens. Air samples from the same bedroom were collected over a 14 to 20 hour period at flows between 1.7 L/min and 2.0 L/min. These airflows were analyzed for ergosterol, a component of the fungal cell, to provide a quantitative measure of total fungi. Bacterial endotoxins were analyzed by Limulus amoebocyte lysate (LAL) assay (Lindsay et al. 1989).

Housing History and Operation Data

Information on housing history and operation was obtained by direct inspection and an occupant questionnaire administered during site visits made during February and March of 1995. The questionnaire included questions on the history of the house, including remembered instances of wetting or mold growth and the frequency of occupant activities generating internal moisture. Inspection data included the basic house dimensions, construction details of the building envelope, and the presence of factors that could affect moisture sources and air change. For every mold growth site identified, either by the occupant or by the inspector, data were recorded on the location, the area of mold growth, the probable source of moisture, the nature of the growth surfaces, the surface temperatures, the indoor air temperature and humidity, and the outdoor air temperature at the time of the site visit.

Medical Data

Medical data collection included a nurse-administered questionnaire collecting information about the index child and the home environment. Venous blood samples were drawn from the index child for analysis of T-lymphocyte and B-lymphocyte structure using a fluorescence activated cell sorter (FACS). For the index child, respiratory function was assessed by parental recording of peak flows for a period of approximately one week using a peak flow meter.

Building Test Data

Quantitative field testing procedures applied to each house included the following:

- airtightness testing according to CGSB149.10 M86 (CGSB 1986), incorporating new procedures proposed by the CGSB committee for testing of occupied houses;
- air-change testing using the tracer gas decay method in accordance with ASTM E741 using sulfur hexafloride (SF_6);
- wet-bulb and dry-bulb temperatures and relative humidity (RH) in the living room, the index child's bedroom, and at mold growth sites using a power phychrometer;
- CO_2 concentration, temperature, and relative humidity were continuously monitored in an index child's bedroom for a period of approximately one week;
- chimney spillage tests in accordance with CAN/CGSB 51.71-94 (seventh draft) (CGSB 1994); and
- average concentration of volatile organic compounds (VOCs) determined using passive dosimeters deployed in the living room for approximately one week. Analysis was by GC/FID.

Simulation of Moisture and Condensation Performance

A calculated internal moisture source strength was determined using an hourly mass balance equation using the air change predicted by AIM-2 (Walker and Wilson 1990), which predicts air change in buildings based on the building dimensions, air leakage test results, estimated distribution of leakage area, outdoor temperature, exposure, and wind speed and direction. The equation used was

$$S = \mathrm{ACH} \cdot V \cdot 1.2 \cdot (W_i - W_o)$$

where

S = internal moisture source strength (kg/h) in hour;

ACH = AIM-2 simulated air change rate for the house for the hour, using collected wind and temperature data in Windsor, Ontario, the closest station for which hourly data was available;

V = heated volume of the house (m^3);

1.2 = density of air (kg/m^3);

W_i = moisture ratio of indoor air calculated from monitored temperature and relative humidity for the hour (kg_{H20}/kg_{air});

W_o = moisture ratio of outdoor air calculated from supplied temperature and dew point temperature for the hour (kg_{H20}/kg_{air}).

This calculation provides a measure of the amount of moisture that had to be added to the indoor air to maintain the monitored humidity assuming the simulated air change rate and given weather conditions. The reported calculated internal moisture source strength is the average for all hours that moni-

toring data were collected, which was typically one week, so that adsorption and desorption effects of short-term humidity fluctuations were minimized.

As a comparison, occupant-estimated moisture source strength was also determined for each house. This was done during the occupant interview in which the daily frequency of moisture-generating activities was determined for a typical day in the household. The assumed moisture production was taken from published estimates from CMHC. Value uses were:

- 0.2 kg/h per adult occupant present in each hour,
- 0.15 kg/h per child present in each hour,
- 0.3 kg per meal prepared,
- 0.2 kg per load of laundry washed,
- 1.0 kg per load of laundry dried indoors or with unvented dryer, and
- 0.45 kg per shower taken.

The total estimated moisture production in the typical day was converted to a kg/h value and reported as occupant-estimated moisture source strength.

A computer program simulation tool was used to evaluate condensation potential. It uses the algorithms AIM-2 (Walker and Wilson 1990) and FPLRH2 (TenWolde 1994) to predict humidity levels and the duration of condensation events based on the AIM-2 estimated air change rate, moisture sources, thermal resistance of the building elements being modeled, and the outdoor temperatures. This simulation tool was used to predict the number and duration of condensation periods on windows during a typical heating season using the following assumptions.

- It was assumed that the leakage area determined by the test was evenly distributed over the envelope surface area.
- Nineteen eighty-eight and 1989 hourly weather data from Windsor, Ontario, were used.
- The calculated internal moisture source strength determined for each house was assumed to be constant over the heating season.
- The moisture storage coefficient was set to zero.
- The interior air film was excluded from the calculation of the window thermal resistance.
- A "period likely to promote mold growth" was defined as a 24-hour period during which RH at the surface being modeled was greater than 70% following a period of 100% RH.

The output reported as total hours of condensation, duration of longest condensation period, and the number of periods likely to promote mold growth were considered summary variables of condensation potential.

Data Analysis Methods

Phase I data on biological contaminant levels were characterized as being highly skewed with many zero values. To accommodate this, data were converted to inverse rank variables (the lowest value was assigned a rank of 1 and the highest rank matched the sample size—59 for our sample). Ties were assigned the mean value of the ranks for the tied set.

Data analyses included contrasting mean data from the high biological and low biological sample sets and determining univariate correlations between the variables considering all houses. In the contrast approach, statistical significance was determined by means of a two tailed T-test. Statistical significance of apparent correlations was evaluated by using a Fisher transformation of the correlation coefficient (z = fisher[r] × (n−3)^0.5 > 1.96 to reject null hypothesis at α = 0.05, or >1.64 to reject null hypothesis at α = 0.1).

RESULTS

The two sample populations studied in Phase II were selected based on the Phase 1 test results for biologically active materials. Table 1 presents a comparison of the biological test measurements for the high and low biological sample groups. Table 2 compares the mean values of found housing, occupancy, and operation characteristics for the two sample groups. Table 3 provides univariate correlations between variables considering all houses. Table 4 presents a summary of the ascribed sources of water leading to mold growth, excluding the report from one house that had an extremely large area of mold growth (on basement walls that were insulated with glass fiber batts but had no interior finishes).

Key findings can be summarized as follows.

Differences in House Characteristics of the Two Sample Sets

- While the median age of the houses in both sample groups was 32, there was a difference in the age distribution (Figure 1). The high biological sample set had a high percentage of houses constructed in the seventies. The low biological house sample set had a higher proportion of houses constructed in the fifties or after 1986.
- The mean size of the houses in the high biological sample set was slightly lower and the size distribution was skewed (Figure 2), with high proportions of houses with a heated volume of less than 500 m^3. The average number of occupants was slightly higher, so that the average density of occupants per cubic meter was about 17% higher.
- A higher percentage of the high biological houses had wood stoves and fireplaces. We found statistically significant correlations between the presence of wood-burning equipment and ergosterol levels ($p<0.05$) and dust mite antigen levels ($p<0.10$) when analyzing the full data set. These correlations were present, but weaker, when using only the high biological sample set.

TABLE 1
Contrast Between Phase I Biological Test Results of High and Low Biological Houses

		High Biological			Low Biological			
Variable	**Category or Units**	**n**	**% or Mean**	**Std. Dev.**	**n**	**% or Mean**	**Std. Dev.**	
Phase I Biological Testing Results (Selection Criteria)								
Ph I Bedroom Endotoxins		39	0.021	0.047	20	0.0063	0.013	
	Rank	39	33.1	16.5	20	24.9	17.1	
Ph I Bedroom Ergosterols	% Detectable	39	87		20	0		
	Rank		38.7	13.6		13	0	
Ph I Dust Mite Antigen F	Log Mean ug/g	39	3.2	0.85	20	2.8	0.41	p<.01
	Rank		32.2	18.2		25.7	14.3	
Ph I Dust Mite Antigen P	Log Mean ug/g	39	2.9	0.91	20	2.6	0.99	p<.01
	Rank		32.2	17.3		24	16.5	
G Index		39	9.61	22.2	20	1.62	1.67	1
CFU (gly)	Log Mean CFUs/g	39	1410	3160	20	55	32.4	p<.01
	Rank		35.7	17.6		18.9	8.86	
CFU (non gly)	Log Mean CFUs/g	39	4.6	0.5	20	5.3	0.9	p<.01

TABLE 2
Means, Standard Deviations, and T-Test Between High and Low Biological Houses

		High Biological			Low Biological			T-test
Variable	**Category or Units**	**n**	**% or Mean**	**std. dev.**	**n**	**% or Mean**	**std. dev.**	**p-value**
House Characteristics								
Deemed Age	Yrs	38	32	18	20	32	20	0.813
Heated Volume	m^3	39	464	141	20	517	143	0.272
Below Grade Wall Area	m^2	39	42	26	20	46	27	0.590
Primary Heating Fuel	% gas	39	82		20	95		
	% oil		5			0		
	% elect		13			5		
Forced Air Distribution	% yes	39	77		20	90		
Air Conditioning	% with Central Air Cond.	39	56		20	85		
	% with Room Air Cond.		21			5		
Special Air Cleaners	% none	39	75		20	65		
	% electronic		20			35		
	% special filters		5					
Woodstove	% yes	39	18		20	0		
Fireplace	% yes	39	38		20	25		
Occupancy and Moisture Source Factors								
Number of Occupants	No. of People	39	4.46	0.79	20	4.26	0.72	0.320
Occupant Density	People/1000 m^3	39	10.40	2.95	20	8.90	3.35	0.136

TABLE 2 (Continued)
Means, Standard Deviations, and T-Test Between High and Low Biological Houses

		High Biological			Low Biological			T-test
Variable	**Category or Units**	**n**	**% or Mean**	**std. dev.**	**n**	**% or Mean**	**std. dev.**	**p-value**
Interior Clothes Drying	% yes	39	21		20	30		
Operating Humidifier	% yes	39	38		20	30		
Open Sump	% yes	39	33		20	55		
Inspection Findings								
Window Moisture Damage	% yes	39	77		20	50		
Basement Wall Moisture Damage	% yes	35	34		18	17		
On Grade Floor Moisture Damage	% yes	39	36		20	15		
Attic Moisture Damage	% yes	21	19		13	15		
Ceiling Moisture Damage (with no Attic Moisture Damage)	% yes	39	5		20	0		
Reported Mold Area	m^2	39	1.173	3.04	20	0.414	0.964	0.283
House Testing and Monitoring Data								
Equivalent Leakage Area	m^2	38	0.175	0.112	20	0.143	0.074	0.237
Tracer Gas Test (1 h)	Air Change/hour	39	0.95	0.927	20	0.510	0.293	0.040
Mean ACR Monitored Temp	°C	36	21.0	1.69	19	20.6	1.53	0.380
Mean ACR Monitored R.H.	%R.H.	37	34.5	9.5	20	37.9	10.3	0.214
ACR Monitored CO_2 Concentration	ppm	39	814	241	20	893	391	0.344
CO2 NightAvg minus LowPtAvg	ppm	38	419	257	20	534	343	0.156
TVOC Concentration	mg/m^3	39	0.313	0.249	20	0.243	0.172	0.267
Simulation Data								
AIM-2 est. AC for Monitoring Period	Air Change/hour	38	1.03	0.71	20	0.66	0.37	0.034
Calculated Moisture Source Strength	kg/h	35	0.85	0.50	20	0.51	0.54	0.023
Moist. Source est. from occ. Activities	kg/h	39	0.68	0.14	20	0.67	0.16	0.746
Ratio Calc./Est.		35	1.28	0.72	20	0.91	1.31	0.190
No. of Periods with Condensation		38	51.3	68.0	20	23.3	59.8	0.126
Longest Condensation Period	h	38	21.9	38.5	20	12.1	16.4	0.284
Total Hours of Condensation	h	38	277	627	20	144	463	0.407
No. of Periods Likely to Promote Mold Growth		38	6.92	8.06	20	4.00	9.48	0.222

Effectiveness of Natural Ventilation

- In all but three houses, ventilation was limited to occupant-controlled fans. Therefore, the vast majority of the houses rely on natural ventilation to dilute and remove contaminants generated in the space.
- The high biological houses had, on average, higher tested air leakage areas and measured and predicted air change rates.
- The expected inverse correlation was found between measured and predicted air changes and concentrations of internally generated contaminants such as CO_2 and VOCs ($p<0.05$), but the ranked measures of endotoxin, ergosterol dust mite antigen, and colony forming units on glycerol base all showed a positive correlation with predicted air change ($p<0.05$ for endotoxins and CFUs $p<0.10$ for dust mite F).
- The average concentrations of CO_2 at night (22:00 h to 6:00 h) were higher than in the day (10:00 h to 18:00 h) by about 45% (984 vs. 680). Twenty-three of the 58

TABLE 3
Significant Univariate Correlation Coefficients

		Age	Occ. Density	Heated Volume	ELA	Tracer Gas Test Est. Air Change	Mean RH	Mean CO_2	Air Change Rate -Week	Moisture Source	Wood Burners	Ergosterols	Mite F	Mite P
	Units	**yrs**	**#/m³**	**m³**	**m²**	**ACH**	**%R.H.**	**ppm**	**ACH**	**kg/h**		**rank**	**rank**	**rank**
Occ. Density	#/m³													
Heated Volume	m³	**–0.278**	**–0.814**											
Equivalent Leakage Area	m²	**0.623**												
Tracer Gas Test est. Air Change	ACH	**0.351**	**0.267**		**0.585**									
Mean RH	%R.H.		0.245											
Mean CO_2	ppm	**–0.320**			**–0.424**	**–0.343**	**0.301**							
Air Change Rate	ACH	**0.703**	0.267		**0.799**	**0.630**	**–0.357**	**–0.417**						
Moisture Source	kg/h	**0.450**			**0.481**				**0.511**					
Wood Burners				**0.380**										
Mold Area	m²													
Endotoxin	rank					**0.275**			**0.283**					
Ergosterols	rank					0.214			0.227		**0.287**			
Mite F	rank										0.254	**0.262**		
Mite P	rank		**0.363**	**–0.312**			**0.462**		0.222	**0.463**			**0.622**	
CFU Glys	rank	0.248							**0.367**	**0.436**		**0.268**	**0.299**	**0.403**
VOCs	mg/m³	**–0.352**			**–0.303**				**–0.400**					
Longest Condensation Period on Windows	hrs													**0.260**
Total Condensing Hours on Windows	hrs													0.231

Bolded values formatted as 0.333 reject null hypothesis at 0.05 level of significance.
Nonbolded values formatted as 0.222 reject null hypothesis at 0.10 level of significance.
Blank values were not significant.

TABLE 4
Inspector Ascribed Source of Water to Mold Growth Site

Source of Water	No. of Reports	% of Mold Growth Area
Condensation on Envelope	95	36.2
Other	53	34.0
Wicking from Ground	12	16.2
Exterior Precipitation	5	5.8
Plumbing Accident	8	5.4
Condensation on Pipes/Ducts	13	2.4
Total	187	100.0

houses with CO_2 data had night period average concentrations over 1000 ppm. In four of these houses, it was over 1500 ppm, and in one it was over 3000 ppm. Both day and night CO_2 levels showed a strong ($p<0.05$) inverse correlation with the natural air change predicted by AIM-2 for the week-long monitoring period.

Moisture Source Issues

- The calculated moisture source strength varied from 0.11 kg/h to 2.60 kg/h. The high biological houses had higher average calculated moisture source strength than the lower biological houses ($p=0.023$). The average relative humidity recorded in the week-long monitoring period for each house was, on average, slightly lower in the high biological houses but the difference was not statistically significant. The calculated moisture source strength showed significant univariate correlations with ranked levels of dust mite antigens ($p<0.10$) and colony forming units ($p<0.05$). The correlation with ergosterol was positive but not statistically significant
- The mean or the ratio of calculated vs. occupant estimated moisture source strength was 1.143. The mean of the difference between the calculated and occupant-estimated moisture source strength in the 35 high biological houses was 0.177 and for the 20 low biological houses it was −0.156. The difference is statistically significant ($p=0.030$). It is likely that the high biological house group likely had more sources of moisture that were not directly related to occupancy.
- Calculated moisture source strength showed a positive correlation with the age of the house ($p<0.05$). It did not show significant correlations with the number of occupants or occupant density, CO_2 levels (a measure of air change per occupant), or average relative humidity.

Mold Growth Factors and Condensation Potential

- A visible area of mold growth found by inspection was not a good predictor of whether houses had high measured levels of biologically active contaminants. The high biological houses had a higher incidence of discovered water damage and mold growth area, but mold growth was also found in the low biological houses. The difference in mold growth area of the two sample sets was not statistically significant.
- As shown in Table 4, less than 40% of the found mold growth area was attributed by inspectors to condensation on the envelope. Most of the found mold area was

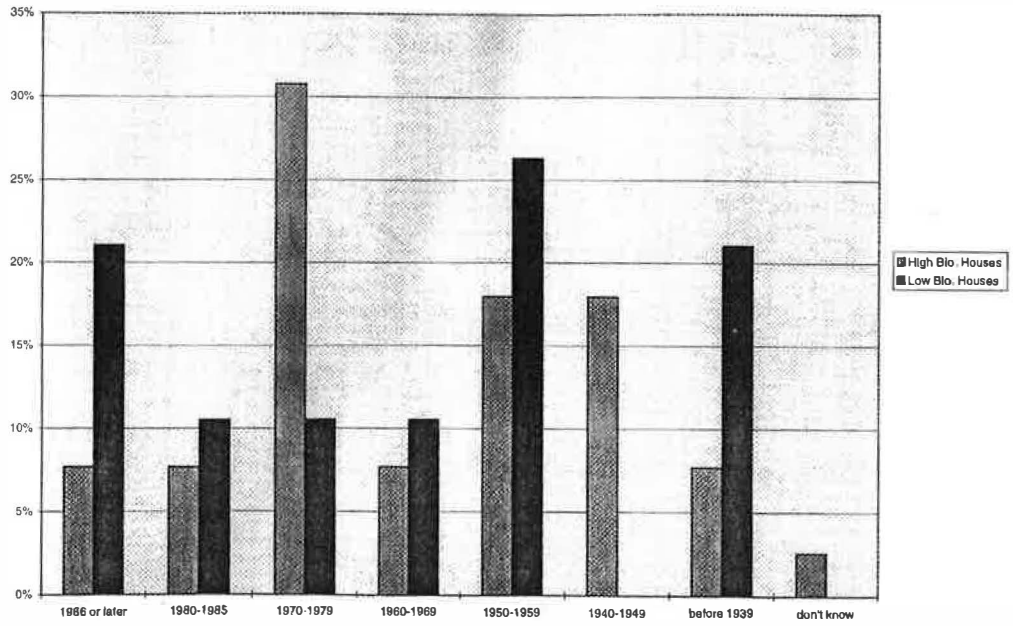

Figure 1 Age distribution of sample set.

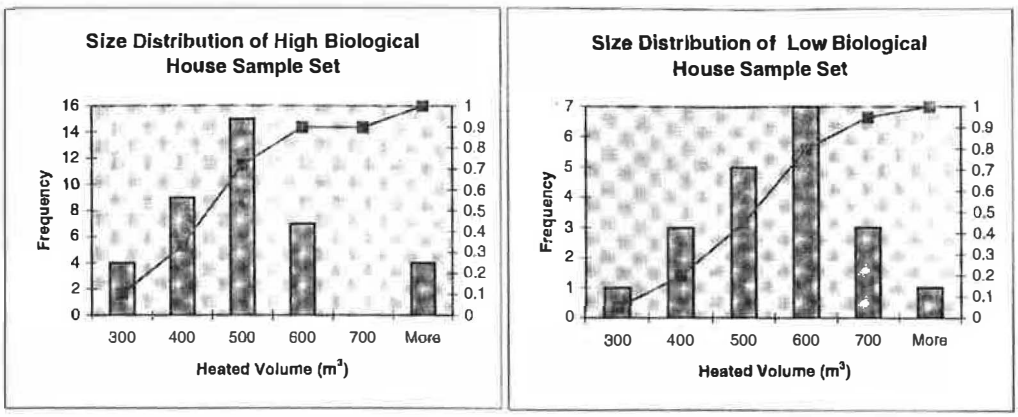

Figure 2 Comparison of size distribution of sample sets.

associated with direct sources of moisture or areas of high generation (such as surfaces in bathrooms that were not part of the building envelope).

- Screening the data to use only the mold growth site reports completed where the outdoor temperature at the time of the site visit were below −10°C and the indoor temperature at the mold growth site was available provided a sample of 73 reports. In these, only 39% (accounting for 22% of the mold area in the reduced sample) had indoor air temperatures at the site that were more than 1°C below the temperature recorded in the living room.
- The measures of condensation potential, obtained by simulation, were much higher for high biological houses than for the low biological set, but with the high variability and small sample the difference was not statistically significant. There was a significant correlation of total condensation hours and longest condensation period with the antigen of one species of dust mite ($p<0.1$ and $p<0.05$, respectively). The correlations with measures of mold (ergosterol and CFUs) were positive but not statistically significant.

DISCUSSION

Relationship of Natural Ventilation to Mold Growth

Only three of the tested houses had ventilation systems other than occupant-controlled fans. Therefore, most of the houses rely on natural ventilation driven by stack forces and wind through leakage areas in the building envelope (walls, windows, and roof) to dilute and remove contaminants generated in the space. Conventional logic dictates that tighter buildings have lower air changes, which result in higher levels of internally generated contaminants including humidity, which, in turn, leads to increased condensation and microbiological contamination. Many people in the building industry believe that increasing airtightness of the building envelope increases the potential for exposure to molds and dust mites, and, conversely, retaining a certain level of envelope leakage generally avoids mold problems. The findings of this study refute these beliefs. The high biological houses had, if anything, higher air leakage levels than the low biological houses. We did find the expected inverse correlation between air leakage and concentrations of common internally generated contaminants such as CO_2 and VOCs, but the correlation with relative humidity was not statistically significant. There were positive correlations with measures of biological contamination including ranked measures of ergosterol, colony forming units on glycerol base, dust mite antigen, and endotoxin. This suggests that natural ventilation, even in leaky houses, does not control biological contamination and leaky houses may even be more likely to have high levels of biological contamination.

Importance of Moisture Sources

Whether calculated internal moisture source strength is a direct measure of the actual moisture sources, strength in a house can be questioned. The calculation is based on the predictive accuracy of the AIM-2 simulation. A strong correlation between the calculated internal moisture source strength and both the simulated air change rate over the monitoring period and the equivalent leakage area from which air change is derived is expected, but the found correlations (0.51 for air change and 0.48 for ELA) were very high. This can be related to the observation that humidity levels measured in the houses were much more consistent across the sample group than ELAs or simulated air change rates. The calculated internal moisture source strength had to show a high positive correlation with air change rate with this pattern.

One can put forward theories to explain this apparent relationship. Relative humidity is a measure of the balance between moisture sources and removal mechanisms and this tends to be stable. The relationship between air change and relative humidity will not be linear because reducing the relative humidity or vapor pressure will increase sources relying on evaporation (e.g., diffusion and capillary transfer through basements walls and floors). Leaky buildings may also draw

in a significant quantity of humid air directly from the soil rather than the exterior. We did not find a correlation between the moisture source strength and the ground contact area, but the size of leakage paths is likely more important than the area of ground contact.

Analysis of air change results suggested that AIM-2 may underestimate air change at low driving forces so the moisture source strength calculation used may overemphasize the relationship to air change, but one can accept the calculated internal moisture source strength as an combination variable relating building leakage area, climate, exposure, and humidity. One can accept the found association of the calculated internal moisture source strength and the measures of biological contaminants as an indicator of the relevance of moisture sources in the house.

There are several indicators that many of the extra moisture sources in high biological houses were not generated by occupant activities. Calculated internal moisture source strength did show the expected correlation with the number of occupants, occupant density, CO_2 levels (a measure of air change per occupant), or average relative humidity. The difference between calculated internal moisture source strength and the moisture source strength estimated from the reported occupancy and occupant activities was positive in the high biological houses and negative in the low biological houses. While the differences were relatively low, it is possible that moisture sources not related to occupant activities are more likely to lead to mold growth.

As shown in Table 4, over 60% of the observed mold growth was attributable to sources of moisture other than condensation on the envelope. Condensation on the building envelope was the largest of the defined categories, but it was followed closely by the other category (which included mold on the interior walls and ceilings of bathrooms, refrigerator drain pans, and sumps). The next largest categorized moisture source was wicking from the ground. In terms of interior locations (excluding attics) where mold was found, bathrooms (39% of mold area) and basements (30%) were the most common locations. Mold on attic sheathing accounted for a significant portion of discovered mold area, but its significance should be discounted somewhat (but not eliminated) since it occurred outside the envelope. In the heating season, when all measurements for this project were undertaken, stack effect would cause air to flow from the interior to the attics. When the interior is cooler than outside, this pattern could be reversed.

Condensation and Potential for Hidden Mold Growth Sites

With respect to the visible interior mold growth attributable to condensation on the building envelope, it is not surprising that mold associated with windows accounted for over 50% of the number of reports. Windows have much poorer thermal performance characteristics than virtually all other building envelope elements and they are readily visible. However, in terms of the area of mold growth found, windows accounted for only 29% of reported mold growth area. Mold growth on foundation walls and on grade floors accounted for most of the reported mold growth area (54%).

While the majority of found mold growth was attributed to moisture sources other than condensation on the envelope, it is likely that the importance of condensation is understated by these data. There was almost assuredly hidden mold growth not detected in the inspections and much of this could be condensation related. It could be argued that visible surfaces are the least likely to support condensation-related mold growth because exposure to indoor heat would normally keep their temperature above the dew point of indoor air. We suspect that many houses had mold growth sites that would not be visible without destructive test openings.

A prime focus of the Wallaceburg study was to determine if there were relationships between house construction and operating characteristics, condensation on interior surfaces, biological contamination levels, and health factors. Many of the factors affecting house performance are interrelated and vary with time. This greatly complicates statistical analysis based on measurements that are not concurrent. One way of addressing this is to create summary variables relating the various factors and comparing them to the independently measured health and contamination variables. This was the purpose of using the computer program simulator to predict the extent and duration of condensation on the windows in each house. The input assumptions were selected to force condensation at some time during the heating season in typical houses (a realistic assumption). The output in terms of the total hours of condensation, the length of the longest condensation period, and the number of periods with condensation or high surface humidity greater than 24 hours could then be considered summary variables of the condensation potential. The means of these measures of condensation potential for high biological houses were about double those for the low biological set, but with the high variability and small sample, the difference was not statistically significant.

BUILDING SCIENCE LESSONS TO BE GAINED FROM ANALYSES

Up to this point, this article presented and discussed the direct findings of the research work. The following section explores some of the implications of the findings. In doing this, we have to go beyond statements of fact and draw on the insight, interpretation, and, to some extent, opinions of the author.

Airtightness (and lower natural ventilation) does not mean higher biological contamination.

Many people in the building industry believe that increasing airtightness of the building envelope increases the potential for exposure to molds and dust mites, and, conversely. retaining a certain level of envelope leakage generally avoids mold problems. The findings of this study tend to refute these

beliefs. Leakier houses may be more likely to have high levels of mold and other biological contaminates.

There are several possible explanations.

- Perhaps houses with higher air leakage also had more water leakage because the same paths leaked air and water, or perhaps air leakage was an indicator of lower assembly quality, which also resulted in poor waterproofing details.
- Perhaps the air exiting from above-grade portions of the houses was replaced with near saturated air entering through the soil from below grade. This would be consistent with the found correlation between air leakage and the calculated internal moisture source strength.
- Perhaps houses with higher air leakage had more hidden mold growth caused by condensation within the envelope assemblies. This could help explain why the area of mold growth found during the inspection did not correlate well with the measured level of mold in dust samples.

The findings about the relationship between measures of mold growth and airtightness and the observation that some of the leakier houses also had high bedroom CO_2 concentrations at night show that one cannot rely on natural ventilation to control indoor contaminates. There is no safe level of airtightness that results in healthy indoor environments. Consistent control of indoor contaminants requires mechanical ventilation.

Control of moisture sources is at least as important as ventilation in controlling biological contamination.

It was not possible with the sample group of houses in this project to draw direct conclusions about the effectiveness of mechanical ventilation in controlling biological contamination. Indirect evidence, however, leads to the conjecture that general mechanical ventilation may not be as effective as one would hope. This conjecture is supported by several findings.

- Measures of mold growth had an inverse correlation with air leakage area and natural ventilation.
- The high biological houses did not have significantly higher humidity levels.
- There was a strong correlation of the calculated moisture source strength with measures of mold.
- More than 60% of the found mold growth area was attributable to sources of moisture other than condensation.

This observation is not meant to downplay the value of controlled ventilation. On the contrary, the author believes that the provision of a controlled ventilation system is important for control of all indoor contaminants including biological ones. However, ventilation is not a magic bullet. General ventilation, which can control most contaminates and humidity to generally accepted levels, does not necessarily control mold growth, which can proliferate where there is a local source of water or a surface with a temperature below the dew point of the indoor air at normal house humidity levels. The evidence indicates that such local problems played a significant role in the houses addressed in this study.

The most troublesome moisture sources in the high biological houses were from sources other than occupant activities.

The evidence also indicates that houses that have to deal with high moisture sources had more mold even though average humidity levels may not have been significantly higher. On average, the houses selected for high biological contamination had higher calculated moisture source strengths, but the moisture sources estimated from occupant activities were not significantly different. This leads to the conjecture that the really troublesome sources of moisture leading to mold growth are not vapor generated by occupants. This seems to make sense. Vapor generation in the living spaces requires a condensation mechanism to provide the free water needed to allow mold to thrive and this can often be averted by air change (whether provided by natural or mechanical driving forces). Liquid-phase water entering by leakage or capillary action can provide a frequent source of moisture into specific microclimates, which may not be visible or easily dried by air change.

Condensation, especially on windows, was a significant source of water supporting mold growth.

It came as no surprise that windows were the most common location of visible mold growth. They are usually the building envelope component with the lowest thermal resistance and surface temperature and they are readily visible. Mold attributable to condensation on windows was common even in the low biological sample group. Luckily, modern window standards such as CSA A440 M90 (CSA 1990) and AAMA 101 (AAMA 1993) provide the ability to specify windows by their condensation resistance performance.

Much of the mold growth in houses is not readily visible.

One of the most disturbing findings of the research was that the area of mold growth found by knowledgeable inspectors was not a good indicator of the amount of mold in dust samples. Accepting that the measurements of mold in dust was a good indicator of mold growth in the house, this means that the mold was growing in locations not found during nondestructive visual inspection. This is logical. Surfaces that are visible are generally exposed to the heat of the interior environment. This will keep surface temperatures higher than the dew point and speed drying of moisture. Surfaces that are concealed behind others but not fully isolated from indoor humidity are more likely to be condensing surfaces. Other CMHC sponsored research looking at mold growth in the walls of finished basements (SCL 1996) found that in 400 houses with finished basements surveyed, over half showed signs of moisture in the basement. In a sample of these, mold was found in the finished walls of over 75%, and in all of these, toxiogenic species were present.

Building mold resistant houses is more difficult than building energy efficient houses.

A mold resistant house would include features that eliminate unnecessary sources of moisture, a ventilation system that removes moisture and other contaminants from all rooms in the house, and an envelope that resists condensation.

Condensation will form on any surface with a temperature that is below the dew point of the air with which it comes in contact. Mold will grow virtually anywhere there is a reasonably constant source of water or high humidity in the local microclimate, but it prefers substrates that can absorb and retain water and/or provide nutrients. This study focused on winter conditions for which Health Canada recommends humidity levels of 30%RH to 55%RH, unless constrained by condensation. The dew point of air at 20°C, 35% RH, is 2°C. At 55%, the dew point is 11°C.

A condensation-free envelope requires that all interior surfaces be kept above this temperature and that the moisture carried in the indoor air be prevented from reaching surfaces that will get colder than this temperature (those farther out in the wall or other envelope assembly).

The insulation incorporated in most modern Canadian wood-framed walls and roofs is usually adequate to eliminate surface condensation except where the construction has major thermal bridges through the insulation (such as framing in corners and duct penetrations through the wall), where the surface is isolated from indoor heat (as in closets on exterior walls or where padded furniture is placed against exterior walls) or where there can be high vapor generation (as in bathrooms). Insulation details are very important for eliminating condensation and mold growth, but luckily the trend in modern construction is to improve insulation levels and reduce thermal bridges for energy efficiency reasons, and this will reduce the potential for surface condensation.

Windows are one obvious thermal weak point, but again, the trend toward improved thermal performance and the ability to specify condensation resistance under modern standards should lead to a reduction of mold growth.

The difficult aspect of building mold-resistant houses is the effort and detail it takes to keep indoor air from reaching cold surfaces. It has long been recognized by cold climate building researchers that control of moisture flows through the insulated building envelopes is one of the major challenges we face in house construction. Finding ways of doing so reliably is a major focus of building research agencies and code writing bodies. Air leakage is the dominant mechanism for moisture transport through envelope assemblies. Since air leakage is primarily through joints in building materials, controlling the leakage of air to areas with cold surfaces requires great attention to detail in design and construction. Furthermore, changes made to the house over its life can compromise its performance and may lead to mold growth; therefore, the attention to detail must continue to be applied by the home's occupants and renovation contractors.

An air leakage site that has an insignificant effect on energy costs can lead to significant moisture collection and resultant mold growth and the effect can be aggravated by high levels of insulation. Building a house with high insulation levels but little control of air leakage and avoiding ventilation because it costs energy and money is inviting mold problems.

Characteristics of a Mold Resistant House

Designing and constructing a house for mold resistance would incorporate the following concepts.

- There should be a well-drained foundation with basement floors and walls that are protected from hydrostatic pressure and capillary transfer of moisture.
- The sump pit, if required, should be sealed from the inside space.
- All walls and ceiling, including the basement, should be evenly provided with a continuous air barrier system to keep indoor air from moving out to cold surfaces (a location inside the insulation is preferable) and a vapor resistant layer on the warm side of the insulation. Attention should be paid to eliminating thermal bridges, but the most important thing, and the most difficult, is the resistance to air leakage
- Windows should be selected for condensation resistance and water leakage resistance. They should be mounted in a manner that maintains airtightness with the wall air barrier system and encourages circulation of indoor air over the inside surfaces (no deep window wells). The material used for sills should be nonabsorbent
- A ventilation system that serves all rooms in the building should be provided.
- There should be air circulation within rooms, either by the heating system or with other fans.
- Exhaust should be supplied to high vapor production rooms, and it should be used.

REFERENCES

AAMA. 1993. *ANSI/AAMA101-93, Voluntary specifications for aluminum and PVC prime windows and glass doors.* American Architectural Manufacturers Association.

CGSB. 1986. *CAN/CGSB149.10 M86, Determination of overall envelope airtightness of buildings by the fan depressurization method.* Canadian General Standards Board.

CGSB. 1994. *CAN/CGSB 51.71-94 Seventh draft, Second version, Spillage test—A method to determine the potential for pressure induced spillage from vented, fuel fired space heating appliances, water heaters and fireplaces.* Canadian General Standards Board.

CSA. 1990. *CAN/CSA A440-M90 Windows, A national standard of Canada.* Canadian Standards Association.

Chan Yeung, M., A. Becker, J. Lam, H. Dimich-Ward, A. Ferguson, P. Warren, E. Simons, I. Broder, and J. Manfreda. 1995. House dust mite allergen levels in two cities in Canada: Affects of season, humidity, city and home characteristics. *Clinical and Experimental Allergy*, 25(3):240-246. March.

Dales, R., D. Miller, J. White, C. Dulberg, and A.I. Lazarovits. 1998. Influence of residential fungal contamination on peripheral blood lymphocyte populations in children. *Archives of Environmental Health*, 53(3): 190-195.

Murray, A.B., and A.C. Ferguson. 1983. Dust-free bedrooms in the treatment of asthmatic children with house dust or house dust mite allergy: A controlled trial. *Pediatrics*, 71(3):418-422. March.

Owen, S., M. Morganstern, J. Hepworth, and A. Woodcock. 1990. Control of house dust mite antigen in bedding. *Lancet*, 335(8686): 396-397. February 17.

Flannigan, B., E.M. McCabe, and F. McGarry. 1991. Allergic and toxigenic micro-organisms in houses. *Journal of Applied Bacteriology*, 70: 618-738.

Lawton, M.D., R.E. Dales, and J. White. 1998. The influence of house characteristics in a Canadian community on microbiological contamination. *Indoor Air*, pp. 2-11

Lindsay, G.K., P.F. Roslansky, and T. Novitsky. 1989. Single step, chromogenic limulus amebocyte lysate assay for endotoxin. *J Clinic. Microbiol,* 27:947-951.

SCL. 1996. Molds in finished basements. CMHC Research Report. Scanada Consultants Limited.

TenWolde, A. 1994. Ventilation, humidity, and condensation in manufactured houses during winter. *ASHRAE Transactions* 100(1): 103-115.

Tobin, R.S., E. Bavoneuslei, A. Gilman, T. Kuiper-Goodman, J.D. Miller, and M. Giddings. 1987. Significance of fungi in indoor air: report from a working group. *Canadian Journal of Public Health* (suppl) 8: 51-530.

Walker, I.S., and D.J. Wilson. 1990. The Alberta air infiltration model AIM-2. University of Alberta.

Wickman, M., S.L. Nordvall, G. Pershagen, J. Sundell, and B. Schwartz. 1991. House dust mite sensitization in children and residential characteristics in a temperate region. *Journal of Allergy & Clinical Immunology*, 88(1):90-95. July.