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Emissions of Indoor Pollutants from Building Materials — State of the Art Review

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Indoor air contaminants from building materials are often the major source of complaints. The demand for materials with low-emission characteristics is on the rise, along with the need for more sensitive and reliable emission studies. Air quality and product testing standards need to be revised and updated to take into account not only health effects, but also comfort considerations, especially for hypersensitive occupants. Modern building materials, including sealants and adhesives emit a rainbow of contaminants at ambient temperatures. The bake-out and demand controlled ventilation techniques are some attempts in reducing emissions after the materials have been installed.

This paper discusses the state of knowledge of building materials emissions and describes techniques to reduce the emission rates.

Introduction

People spend the majority of their time indoors, either in their home or their workplace. There has been growing concern and uncertainty with the quality of the indoor environment in many countries, including Canada, due to common adverse effects on comfort and health. This uncertainty has resulted from a number of factors: changing design and operation of buildings to reduce energy consumption, tightening of the building envelope to reduce uncontrolled air leakage which contributes to the moisture deterioration of the building fabric, and new materials and related emissions.

There have been considerable cases of complaints about the quality of indoor air. The complaints comprise of irritation of mucous membranes, feeling of stale and stuffy air, headaches, and malaise. A recent survey has shown that 65 percent of buildings operate in a Sick Building Syndrome (SBS) condition, and are estimated to have caused several billion dollars in lost annual productivity, excluding the medical expenses [1]. ASHRAE defines acceptable indoor air quality as being 'air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction' [2].

One way to solve this problem is to dilute the contaminants with large amounts of fresh outdoor air. However the idea that the "Solution to Pollution is Dilution" is an expensive proposition. It has been estimated that more than one third of the energy consumed in North America is used in buildings for heating, cooling, lighting, and ventilation. For example, more than 25 quads of energy are used to heat, cool, light, and ventilate buildings in the USA every year. This energy costs the users more than $166 billion [3]. This solution also contributes to global warming.

At the same time, it has been a big frustration for engineers and building owners who design and operate the buildings. Believing they have complied with the standards and have provided the required fresh air, they feel there is no reason for complaints, and/or the complaints are psychosomatic. However, designers forget that in the development of the existing standards, the human is considered to be the only source of the pollution, and the recommended required fresh air is based on this assumption.

It is assumed implicitly that the building materials and mechanical systems are clean. The meaning of this assumption is that if the people were not there, the quality of indoor air should be as good as outdoor air. This is hardly ever the reality; the building materials and building itself can be a source of pollution.

Buildings are being constructed with increasing amounts of glues, adhesives, and other materials which are known to emit chemical gases into the building air, Table 1, [4]. Work supplies, maintenance materials, consumer products and cleaning agents also emit Volatile Organic Compounds (VOC) and are strongly suspected of contributing to the so called "Sick Building Syndrome" [5]. Engineers, designers and/or manufacturers who select, design and/or manufacture these products are legally responsible for negligence and product defect [6]. They need access to emission data for protecting themselves and the public.

A much better way to solve this problem is to use materials and products with low emissions of substances that cause health or comfort problems, or to condition the material or building itself before use; as in the bake-out procedure. This is especially important for sources that are close to occupants, such as office furniture, furnishings, office supplies, and personal care products. Another approach is the use of Demand Controlled Ventilation (DCV) system technology. The DCV principle of operation is a ventilation system in which the flow rate of fresh air is controlled by airborne contaminants.

The order of this paper is as follows: the present state of knowledge of building material emissions is discussed briefly

Table 1

Typical emission rates for sources of vapour-phase organics in residences [4]

Label	Source*	Condition	Emission factor**	Assumed amount	Emission rate (mg/h)
	Material Sources				
A	Silicone caulk	<10 hours	13mg/m²-h	0.2m²	3
A'	Silicon caulk	10-100 hours	<2mg/m²-h	0.2m²	<0.4
B	Floor adhesive	<10 hours	220mg/m²-h	10m²	2200
B'	Floor adhesive	10-100 hours	<5mg/m²-h	10m²	<50
C	Floor wax	<10 hours	80mg/m²-h	50m²	4000
C'	Floor wax	10-100 hours	<5mg/m²-h	50m²	<250
D	Wood stain	<10 hours	10mg/m²-h	10m²	100
D'	Wood stain	10-100 hours	<0.1mg/m²-h	10m²	<1
E	Polyurethane wood finish	<10 hours	9mg/m²-h	10m²	90
E'	Polyurethane wood finish	10-100 hours	<0.1mg/m²-h	10m²	<1
F	Floor varnish or lacquer		1mg/m²-h	50m²	50
G	Particleboard	2 years old	0.2mg/m²-h	100m²	20
G'	Particleboard(HCHO)	new	2mg/m²-h	100m²	200
H	Plywood panelling(HCHO)	new	1mg/m²-h	100m²	100
I	Chipboard		0.13mg/m²-h	100m²	10
J	Gypsum board		0.02mg/m²-h	100m²	3
K	Wallpaper		0.1mg/m²-h	100m²	10
L	Moth cake (Para)	23°C	14,000mg/m²-h	0.02m²	280
	Combustion Sources				
M	Unvented gas burner		85-144mg/m²-h	1 burner	100
N	Unvented gas space heater (HCHO)	radiant	0.001mg/kJ	20,000kJ/h	20
O	Unvented Kerosene space heater	convective/ radiant	0.007mg/kJ	6100kJ/h	45
P	Unvented kerosene heater	radiant/ radiant	0.064mg/kJ	9400kJ/h	600
Q	Cigarette smoking	one smoker	10mg/cig.	2 cig./h	20
	Activity Sources				
R	Hair spray	6-sec. use	3 mg/use	1 use/h	3000
R'	Hair spray	6-sec. use	3 mg/use	1 use/day	120
S	Disinfectant spray	6-sec. use	5 mg/use	1 use/h	5000
S'	Disinfectant spray	6-sec. use	5 mg/use	1 use/day	210

Notes

* Emissions data shown are typical only for the specific brands, models or units that have been tested; the data do not represent all products of the source type listed. Product-to-product variability can be very high.

** Typical values selected by author based on data in a database on the source of indoor air pollutant emissions.

Para = paradichlorobenzene HCHO = formaldehyde and techniques to reduce the emission rates are given; and then, an assessment of existing technologies and current knowledge about DCV systems is given.

Emissions from Building Materials

The selection of building materials is an important parameter in the design of ventilation systems. Many discomfort or health-related complaints are claimed to be due to new and freshly renovated buildings [7]. For example, workers which perform renovations or construct new buildings often complain of eye and throat irritation (probably resulting from high concentrations of formaldehyde). Organic vapours in new and freshly renovated buildings are on average more than an order of magnitude higher than those found in older houses. The sealing of wooden parqueted floors with coatings and adhesives under the parquet have frequently led to complaints because of odour annoyances [8]. Solvents are also major indoor air pollutants. Solvent emissions mainly originate from the use of solvent-containing products, such as varnishes, paints, and adhesives. Solvent-containing paints and varnishes are used indoors for renovation as well as in the construction of new buildings. When released into the atmosphere, solvents further cause environmental problems, particularly the formation of photo-oxidants [9]. It seems that even used materials from a 7-year old building still emit low and constant concentrations of pollutants.[10]

Construction activity, material type, and change in ventilation conditions all affect the levels of organic vapour concentrations found in indoor air.[11] The effect of renovations and construction work on Total Volatile Organic Compounds (TVOC) values in indoor air can be seen in the following table:

Table 2

Changes in TVOC levels in an office buildings [11]

MONTH	DAY	INDOOR/ OUTDOOR	COMMENT
0	1	2.40	no activity
	2	5.70	partitioning
	3	13.80	partitioning
6	1	1.53	no activity
	2	8.87	painting
	3	10.50	painting
18	1	5.72	no activity
	2	8.57	renovations
	3	19.20	renovations

The ratio of indoor to outdoor TVOC levels rises steadily as construction activity is being done. The ratio returns to the original level after 6 months of no construction activity, however increases as soon as painting commences. A similar trend occurred after 18 months, when adhesives, paints, and solvents were being used.[11] Levels can reach as high as 30.7 mg/m^3 in freshly renovated buildings.[12]

New dwellings are built more airtight than in the past, and are often heavily insulated against heat loss. A recent study showed that houses built today are approximately 30 percent "tighter" than homes built less than a decade ago [13]. The types of insulations used result in different air contaminants found, with levels reaching as high as 0.1 mg/m^3 of styrene (from polystyrene foam) and of formaldehyde (from ureaformaldehyde foam).[14]

Water barriers may also lead to discomfort. The most frequently used hydrophobing agents (resins) in the Netherlands consist of oligomeric or polymeric alkylalkoxy-silanes. The processes resulting in emission of the organic are diffusion through the pores of the wall and through the cavity space and evaporation at the surface of the wall. At higher temperatures, the rates of both processes are increased. During the winter season, temperature differences between indoor and outdoor are maximal and a substantial part of the organic is emitted indoor. Also, a high wind pressure on the wall and strong heating by solar radiation can create such a condition. The penetration of the organic through the walls results in pollution levels causing acute health effects. High concentrations of the measured compounds are known to be irritating for mucous glands, and after adsorption can cause alterations of the central nervous system; resulting in dwellers being evacuated for a lengthy period of time.[15] Typical air contaminants from water barriers used in Switzerland are epoxides, acetone (measured: 7.8 mg/m^3), and siloxanes (0.2 mg/m^3).[12]

Renovations done on floors may also create discomfort problems. Carpet glues may emit 4-phenylcyclohexane (4-PC) (levels measured: 7.3 mg/m^3), while the softening agent in the carpet may release triethylphosphate (levels measured: 0.1 mg/m^3).[12] Public awareness about off-gassing of the carpet came in early 1988, when employees at the Washington headquarters of the USA Environmental Protection Agency complained of odour and SBS symptoms after new carpeting was installed in part of their building.

Ventilation conditions have a great impact on the levels of organic vapour concentration over time. A study in an environmental chamber shows that increasing ventilation from 0.1 to 0.2 air changes per hour results in a corresponding decrease in 4-PC concentration from 80 ppb down to less than 5 ppb. [16] We should remember that the odour threshold for 4-PC is 3 ppb; perhaps less than 1 ppb for sensitive individuals.

Parqueted floors are usually renovated with a two-component polyurethane coating. After priming, the coating is applied twice. To avoid dust particles on the liquid surface, the coating is mostly done with closed windows and doors, which results in a relatively high loading of solvent vapours. Plus, there exist solvent emissions due to the adhesive under the parquet. The odour threshold is in the range of 0.1 to 1 mg/m^3, so it could still be smelled after 9 months.[8] Table 3 shows the results of a study which measured 6 main solvent components of the PUR coating [8].

The emissions from 4 types of very common building materials; waterborne painted wallpaper on gypsum wall, rubber floor covering, nylon carpet with rubber mat, and acid-curing painted particle board is shown in Table 4.[7] As can be seen, all 4 materials emitted an odour, and all 4 contained irritants. It is important to note that it is recommended to either substitute certain compounds with other odourless and harmless organic compounds, or to remove them during the manufacturing process to produce healthy building materials.[7] These tests were also coupled with individual perceptions.

Comparison between the symptoms recorded before and after exposure to the material is shown in Figure 1.[17] For all 4 materials, the occupants complained more about discomfort after they were exposed.

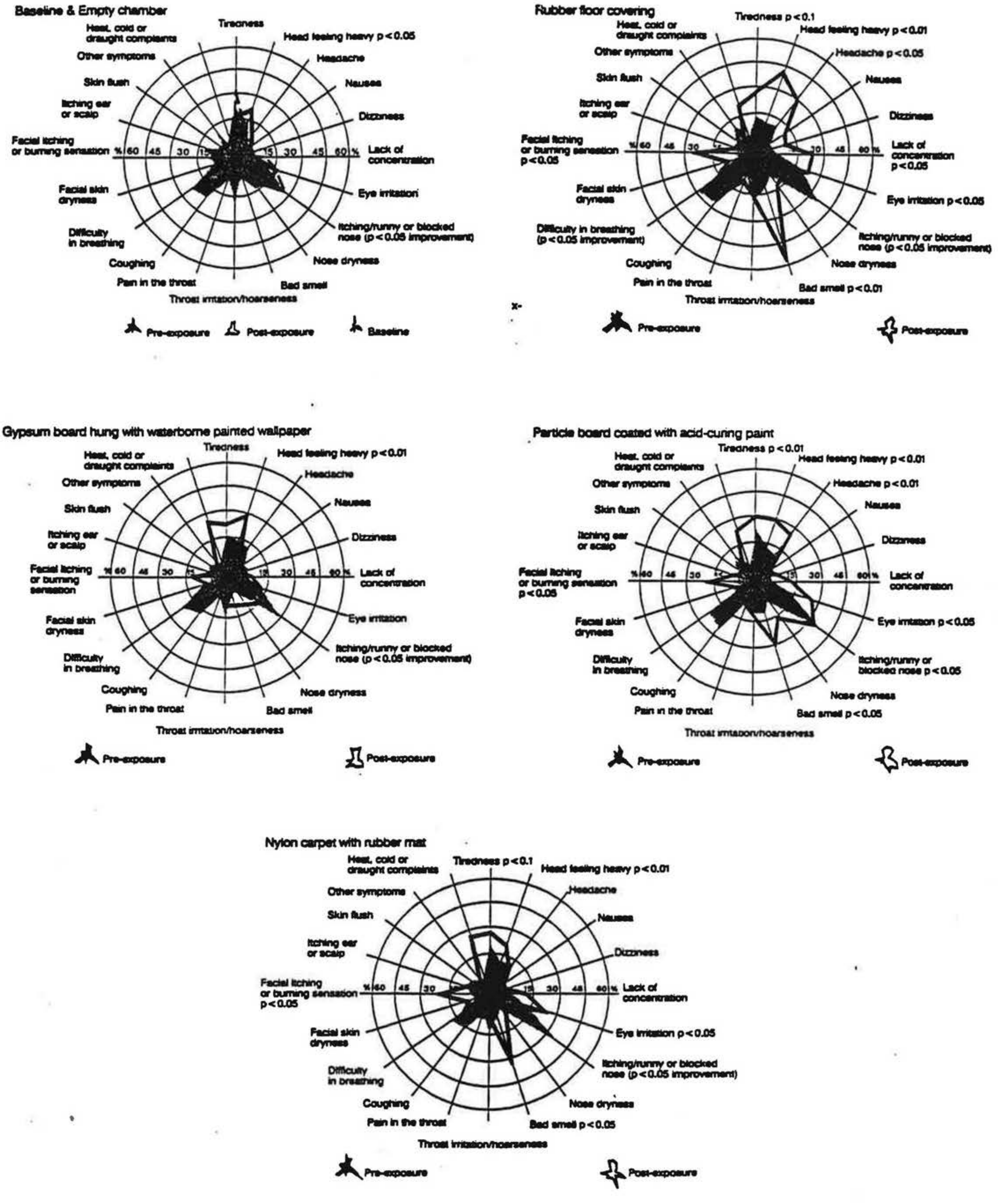

Figure 1. Comparison between symptoms recorded in questionnaires before exposure and deterioration of symptoms after exposure in climate chambers to several building materials. [17]

Table 3
Indoor Air Concentrations of Solvent compounds After Parquet Sealing
(concentrations of mg/m³) [18]

Time after painting (d)	before	0.04	5	10	18	46	124	214	495
Temperature(°C)	19	20	23	19	22	22	25	21	23
ethyl acetate	0.036	170	1.44	0.65	0.43	0.25	0.092	0.026	0.036
i-butyl acetate	<0.014	1620	20.6	7.5	4.5	1.1	0.60	0.06	0.02
n-butyl acetate	0.020	2040	45	17	11.4	2.9	1.9	0.22	0.094
n-butanol	0.31	288	2.8	1.2	0.87	0.40	1.02	0.24	0.30
toluene	0.023	28.0	0.93	0.30	0.24	0.066	0.071	0.045	0.032
xylene	0.045	140	4.8	1.14	0.56	0.098	0.117	0.045	0.045

Figure 2 shows the formaldehyde emission of an acid-hardened parquet sealing. The parquet was based on a urea formaldehyde-bonded particleboard, coated with a 4 mm layer of oak, using a polyvinyl acetate adhesive.[8] The formaldehyde emission diminishes rapidly until it levels off after about 20 days.[8]

Table 4
Concentrations (mg/m³) and emission factors (mg/m2) of VOC and formaldehyde emitted from 4 building materials (1-4) and empty chamber [7]

Material/VOC	Conc.	Emission Factor	Odor	Irritant	Action
1.Waterborne painted wallpaper on gypsum wall:					
Acetone	62	13			
Hexanal	24	5			
Toluene	50	11			
1.2-Propandiol	676	145			
2-Butoxyethanol	129	28			
Limonene	65	14	yes		
Texanol	158	34			
Unideentified	115	25			
Total VOC	1,230	264			
Formaldehyde	86	18		yes	
2. Rubber floor covering:					
Acetone	8	1.7			
Acetophenone	62	13	yes		yes
Undecane	32	7			
Toluene	9	1.9			
Styrene	191	41	yes		yes
α-Methylstyrene	404	87	yes		yes
Indene	69	15	yes		yes
1,3-Diisopropylbenzene	195	42	yes		yes
1,4-Diisopropylbenzene	102	22	yes	yes	yes
4-Vinyl-1-cyclohexene	15	3	yes	yes	yes
Isododecene	108	23			
Unidentified	779	167			
Total VOC	1,923	412			
Formaldehyde	11	2.4			
3. Nylon carpet with rubber mat:					
Undecane	57	12			
Acetone	141	30			
Hexanal	16	3.4	yes		
Toluene	515	110			
1,3 Diisopropylbenzene	112	24			
1,4-Diisopropylbenzene	42	9	yes	yes	yes
Limonene	57	12	yes		
Isododecene	43	9			
Un identified	297	64			
Total VOC	1,406	301			
Formaldehyde	26	5.6			

Selection of Building Materials

One way of reducing contaminants emission in indoor air is through source control. Emphasis is placed on controlling the sources of pollutants rather than on dilution. Many indoor air quality problems can be prevented during building design. While the importance of proper design of ventilation systems has long been recognized, selection of materials and products is now receiving increased attention.[18]

Building materials are chosen for non-toxicity or lack of emission of particulates and gaseous pollutants. A preliminary screening of the building materials may consist on the basis of chemical composition. Natural materials, or those having the lowest content of non-inert substances or least emission of volatile or gaseous components, are selected. Some examples are:

-redwood and non-odorous caulking (instead of pine and cedar),

-solid birch and non-toxic sealants (instead of plywood particleboard),

-ceramic and quarry tiles and cement without additives (instead of synthetic floor coverings),

-plaster walls with gypsum and lime coat without plasticizer or bonding agents (instead of latex or oil-based paints), and

-work-station dividers of finished sheet rock, gypsum (instead of conventional partitioning).[8,19,20]

The use of an air purifier with filters for removal of particulates and gaseous chemical contaminants in the living spaces can lead to less complaints. Both analytical data and qualitative effects on the health of the occupants indicate that exceptional air quality can be achieved.[19]

Table 4 (continued)

Material/VOC	Conc.	Emission Factor	Odor	Irritant	Action
4. Acid-curing painted particle board:					
Acetone	31	6.6			
Toluene	19	4.1			
Butanol	846	181	yes		yes
Unidentified	214	46			
Total VOC	1,109	238			
Formaldehyde	743 (min)	159		yes	yes

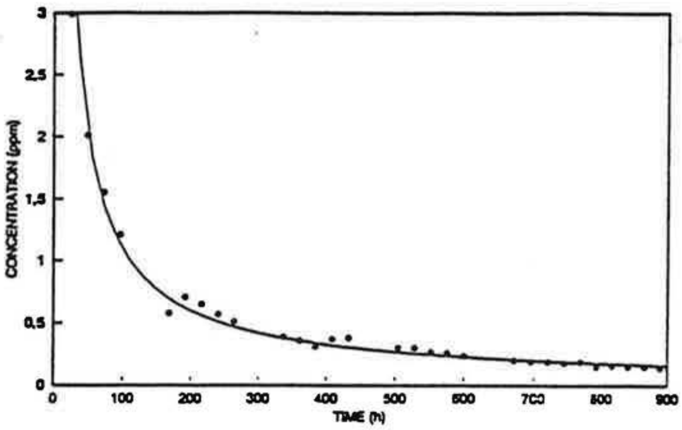

Figure 2. Formaldehyde emission versus time of parquet sealed with an acid-hardened coating.

The Federal Environmental Agency (Berlin) decided, in 1980, to award the "Environment Label" — a symbol created for products of particular environmental compatibility — to the product group of "low-pollutant paints and varnishes." This was to promote the sale of paints and varnishes with a low solvent and pollutant content. The Environment Label helped to increase the share of low-pollutant products in the house paints and varnishes market from 1 % to approximately 20 % between 1980 and 1989.[9]

Low-pollutant paints and varnishes are offered for nearly all applications, such as:

-gloss paints for indoor and outdoor use,

-coating materials for window frames, radiators and floors,

-translucent varnishes for the coating of wood indoors and outdoors, and

-transparent varnishes for wood (furniture, panels, parquet flooring).

The majority of these products are water-based paints, e.g. acrylic resin paints, but also include high-solid paints and varnishes with a low solvent content.[9]

Prior to the award of the Environment Label, certain requirements must be met:

-the product may not contain any components which exhibit chronic effects, such as carcinogenicity and mutagenicity;

-the content of VOC is limited to 0.5 - 15 % weight (depending on the application); and

-the product may not contain any heavy metals, such as cadmium, lead, and chromium.[9]

Low pollutant paints and varnishes which meet the requirements of the "Environment Label" cause markedly lower solvent levels in indoor air as compared to conventional high-solvent coating materials. Independent product testing has shown that low-pollutant paints and varnishes are of the same quality as conventional products.[9]

New Regulation for New and Renovated Buildings

Several cases of IAQ problems in office buildings in the U.S. have been widely publicized. To help avoid such problems in its new and renovated buildings, the EPA has begun to emission-test several products and is considering the following evaluation approach:

-require emission rate testing data from manufacturers or suppliers;

-require that the manufacturer or supplier provide Material Safety Data Sheets for chemicals used in the manufacture of each product;

-require from manufacturers or suppliers an emissions rate testing report that documents: emission factors for the five major organic compounds emitted and for any specified compounds; emission factors at three "ages" of the product; chamber testing conditions; and product storage and handling procedures used;

-reject, or evaluate conditioning of, materials or products that are likely to increase organic vapour concentrations by 0.5 mg/m^3 or more;

-evaluate the likely benefits of product conditioning before use, and ventilation strategies for the building; and

-conduct quality assurance checks on selected data supplied by manufacturers or suppliers.[18]

In the state of Washington, suppliers are required to submit data on emissions with their bids, and the successful bidder will have to submit quality control data on products that are actually supplied. The State has set the acceptability criteria as summarized below:

-emission rates that will result in building air concentrations less than 60 µg/m^3 of formaldehyde, 500 µg/m^3 of total VOC, and 50 µg/m^3 of total particles;

-emissions of carcinogens and reproductive toxins must be identified, quantified, and eliminated or reduced as much as technologically feasible;

-large chamber testing (covering a 6 week period) of emissions is required.

Several large building projects in the U.S. are using the following approach to specifying materials and products in their building design requirements:

-materials shall be designed, manufactured, handled, installed, and maintained in a manner that will produce the least harmful effects on occupants of thebuilding;

-manufacturers shall avoid unnecessary use of chemicals that are toxic or irritating in the manufacture, treatment, or handling of their products;

-manufacturers shall implement measures to reduce installed-product emissions of chemicals that are toxic or irritating; and

-suppliers or installers shall submit the following before authorization to proceed will be issued by the architect: a list of all chemicals used in the manufacture of the product; a description of any procedures used by the manufacturer to minimize the emissions of VOC from its products; a description of all emission testing performed; and a listing of all chemicals in the product that are considered carcinogens.

These requirements are included in the general conditions of the design specifications, and therefore apply to all materials used in the building. Following is an example of a specific material for which the general conditions are amplified:

-insulation:

-where possible, coat thermal and fireproofing insulation materials with a smooth and impermeable membrane to reduce the adsorption of VOC and water vapour.[18]

Bake-Out

Once the building has already been constructed, the only way to lower contaminant emissions is to increase the ventilation whereby more outdoor (fresh) air is supplied, hence diluting the air contaminants. However, ventilation only reduces the actual concentration of the organic, it does not speed up the depletion of the organic.[15] To solve this, it has been suggested that the air temperature needs to be increased along with the increase in ventilation.

In an effort to reduce the presence and concentration of contaminants in buildings, it has been suggested that warming a building for a period of time will enhance the vaporization of VOC, thus reducing their concentration and reducing the likelihood of SBS being experienced by the occupants of the building.[21]

A "bake-out" is a process of simultaneously or alternately applying heat and ventilating to increase the emissions of volatile organic compounds from building materials; to remove them from indoor air.[22] This could reduce the solvents and, in a sense, artificially age the materials and furnishings.[23,24]

Table 5

VOC concentrations (mgm^{-3}) in an office cubicle before, during and after bake-out at 32°C to 39°C for 24 h with ventilation of 1.59 ACH [22]

COMPOUND	BEFORE	DURING	AFTER
Formaldehyde	34	67	28
Methylcyclopentane	16.5	T	6.0
Benzene	T	T	T
Heptane	1.7	42.2	1.9
Methylcyclohexane	T	12.1	BD
Toleune	71.7	236	22.7
Octane	T	4.9	T
Ethylbenzene	T	4.2	T
m,p-Xylene	5.4	97.0	19.7
o-Xylene	BD	24.8	T
Ethylmethylbenzene	BD	47.6	T
1,2,3-Trimethylbenzene	BD	31.4	T
Decane	49.7	191	53.7
1,3,5-Trimethylbenzene	BD	10.1	T
Dodecane	35.4	110	21.0
TOTAL	214.4	878.3	153.0

T-Trace; BD-below detection

It was found that a 13°C temperature increase will result in a 200% increase in vapour pressure for VOC, Table 5. Thus, theoretically, heating a building should drive off VOC quickly. However, the building environment is complex and dynamic, and the effectiveness of the bake-out will be a function not only of the emission rate but also of the ventilation or removal rate within the enclosed space.[22]

Both financial and practical considerations limit the time available for a bake-out. Financially, it is desirable for a bake-out to be conducted as quickly as possible. The cost of conducting a bake-out is approximated at $2.50 to $5.00/m². This is an indirect cost which does not include the rent for the delayed occupancy time. The often inevitable delays in construction and interior finishing restrict available time. However, from an engineering perspective, one would wish to bake out the building as long as possible to obtain the maximum reduction of VOC emissions. Also, since the heat capacity of a building can be large and the rate of heat transfer by air is limited, long periods are desirable. Nominally, a bake-out is conducted for 4 to 5 days, of which 24 hours are at 32 to 39°C.

Because the time available is usually limited, high air temperatures are desirable to maximize the effect of a bake-out. There are limits to air temperatures which can be achieved since heating units are sized for particular climates, both to minimize the capital costs of the building equipment and to maximize the efficiency of the heating unit. Portable heaters may need to be installed if HVAC capacity to heat is too low. An additional constraint is the concern for possible material damage to the building due to excessive heat. For example, freshly applied paint could dry too quickly, causing cracking or peeling. Employees need to be informed so that they may be instructed to remove anything which could be damaged by high temperatures (e.g., plants, chocolates, etc).[22,23].

Some ventilation must be maintained during the bake-out to flush out the VOC emitted at the high temperatures. If this is not done, the possibility exists that the VOC emitted from some of the materials will be absorbed by other materials, creating secondary sources. Air circulation is increased by opening interior doors. Outdoor and exhaust air dampers need to be equalized. Ventilation rates suggested varied between 0.5 - 1.6 each. [22,24].

Some cases do not always show such dramatic results, Table 6. Most studies show that the pre and post bake-out results for VOC were very scattered, producing few trends. On average, individual VOC concentrations were decreased by only 20-30%. TVOC reductions ranged from 0 to 95 %. Several compounds were present at higher concentrations after the bake-out as compared to before. This was consistently observed with toluene. 1,4 Dioxane and formaldehyde were consistently lower after the bake-out [21]. The results from this limited study do not support the hypothesis that baking out a building helps to reduce the concentration of all VOC in the building. It is not clear why several of the other compounds were not affected in this way, or the observed opposite effect noted for some, with higher concentrations after the bake-out.[21,24]

Unlike many other VOC, formaldehyde is not always present in materials as a trace constituent, contaminant, or residue. Instead, many products containing formaldehyde have formaldehyde as a major constituent. Thus, formaldehyde would not be depleted from such materials in a bake-out for only a few days. In addition, many of the materials containing

Table 6
Selected Volatile Organic Compound Measurements [21]
($\mu g/m^3$)

	Before Bake-Out						After Bake-Out (Percent change - Before Conc.)					
Compound	Lobby	1st Flr	2nd Flr	3rd Flr	4th Flr	Roof (Outdoor)	Lobby	1st Flr	2nd Flr	3rd Flr	4th Flr	Roof
Benzene	2.8	2.7	2.9	ND	1.7	2.4	5.1(84)	2.2(-21)	3.8(32)	2.3(NA)	2.3(34)	1.3
Toluene	38	53	143	7.1	31	13	490(1200)	230(350)	150(8)	56(690)	120(310)	38
O.Med Xylene	28	35	52	ND	25	13	334(1100)	82(140)	24.(-52)	52(NA)	41(65)	19
Ethyl Benzene	6.9	7.8	12	ND	4.8	ND	104(1400)	29(270)	6.1(-50)	13(NA)	8.7(82)	5.2
1,4 Doiexene	14	7.9	14	ND	18	14	7.9(-45)	6.5(-18)	9.0(-38)	MD(NA)	ND(NA)	6.8
Formaldehyde	25	26	23	22	23	9.8	14(-45)	15(-43)	14(-42)	11(-50)	16-(-32)	5.7
Methylene Chloride	13	56	ND	111	120	240	26(100)	42(-26)	ND NA	7.7(-93)	9.4(-92)	5.6
1.1.1.-Trichloroethene	7.6	60	17	ND	5.4	ND	8.2(7)	16(-73)	7.6(-55)	4.6(NA)	5.0(-7)	ND
Perchloroethylene	3.7	4.7	ND	ND	ND	ND	3.6(-4)	2.3(-51)	ND(NA)	ND(NA)	ND(NA)	ND
Total Non-methane Hydrocarbone	280	360	490	180	760	630	750(171)	480(34)	300(-39)	440(138)	190(-75)	240

NA: Not applicable ND: Not detected µg/m-: micrograms per cubic metre of air

formaldehyde are fairly thick and are often covered by other materials which limit transport. At the temperatures normally achieved during bake-outs, the diffusion coefficient is only increased by an order of 10%. Therefore, the major effect of a bake-out is restricted to VOC found near the surface of materials. The effect would be expected to be small for VOC such as formaldehyde, which are distributed in large amounts throughout many of the materials that contain them. This is not meant to imply that because they are not likely to be effective for formaldehyde, bake-outs are not potentially beneficial since formaldehyde is only one of many VOC found in indoor air.[23]

However, it was found that when occupants did return to their offices after the bake-out, no complaints regarding indoor air quality had been lodged (as opposed to their many complaints before the bake-out).[23]

Obviously, additional information concerning the effects a building bake-out has on pollutant concentrations in necessary. This limited group of studies does not disprove the hypothesis that this technique is a viable method of reducing or eliminating complaints of indoor air quality. However, additional studies are warranted to determine the effectiveness of the method, and to provide guidance on bake-out protocols. Not much information is available to suggest the optimal duration, temperature, and ventilation rate of a bake-out, or its practicality [21, 24].

California state legislators are considering a bill to require bake-outs of all new public buildings—or as they stated "detoxification" of new buildings. It requires extra ventilation during the initial period, an increase in the number of hours of HVAC operation, and to operate the system at the lowest possible temperature.

Demand Controlled Ventilation

Another means of reducing energy consumption while controlling building material emissions is through Demand Controlled Ventilation (DCV). Instead of operating the outdoor air ventilation to design specifications, why not ventilate with fresh air only when it is truly necessary. The ASHRAE ventilation standard includes a control option called the "Indoor Air Quality Procedure" [2]. This option allows us to ventilate with reduced outdoor air rates as long as we keep the contaminants level below the recommended maximum limits.

If we were to place sensors in representative locations throughout our occupied zone, we would be able to detect the various contaminants being produced. Once the level detected reaches a pre-determined limit, a signal is sent to the ventilation system to increase the amount of outdoor air supplied to that particular zone. The increased outdoor air then acts to dilute the concentration of contaminants in the zone.

Recently, an international effort under the auspices of the International Energy Agency (IEA) has developed an efficient ventilation system by a demand control based on analysis of the ventilation effectiveness and proposed ventilation rates for different cases in residential, office and school buildings [25]. Some of the results of this international project was presented at the 12th AIVC conference [26]. Much research has been done with CO_2 demand-controlled ventilation; in the form of case studies [27-30], controlled test condition [31] and field measurement [32]. However, additional research is needed before building designers or energy analysts efficiently start implementing this variable ventilation system using contaminant concentration. More sophisticated and state-of-the-art control equipment is now available [33].

There is one high-rise building in downtown Montreal which is installing such a system in their building now being constructed. It will monitor over 5 contaminants: formaldehyde, CO2, CO, VOC and dust, at 12 locations in the building. The initial expense of such a system is very high ($250,000 for this particular building), but the payback period is quite quick. Because we only use the outdoor air when we really need it, we save all that energy during the time when there is no outdoor air being introduced.

For a DCV system to be effective, the building envelope must be tight. The ventilation system must be very well-maintained. And, the air distribution system must be properly balanced. If the ventilation effectiveness is low, the sensors would not detect representative and true values. One has to be certain that all of the air that is supplied is really distributed evenly throughout the zone. It is obvious that if the air never descends to the occupied zone but short-circuits straight into the return, no matter when the DCV system is turned on, the contaminant will never be diluted. So, the air flow patterns are an important criteria for the DCV to work[34].

The sensors need to be placed at representative locations, in the work zone itself. Placing them in the return ducts would only send a diluted average to the system control. The sensor control would work as follows: if the parameter being measured is less than the pre-set lower limit, no outdoor air is introduced into the space. Once the measured level is equivalent to the lower limit, the outdoor air dampers start to open, up to a maximum opening when the contaminant reaches the upper limit.

A DCV system must not hinder any thermal comfort parameters. So, it may be necessary to couple the sensors with temperature sensors. The worst case scenario would then prevail. As soon as any contaminant or thermal comfort parameter would reach a pre-set limit, the ventilation system would act accordingly.

The energy savings attributed to the use of a DCV versus the conventional systems are important. A study carried out by the authors, compares the indoor environment created by two different types of ventilation control systems in an elevenstorey office building. The two ventilation systems tested consisted of: a conventional system controlled by outdoor temperature, and a demand-controlled system regulated by indoor carbon dioxide concentration. The parameters measured were dry-bulb temperature, relative humidity, formaldehyde, VOC, CO_2, and energy consumption. Questionnaires were also distributed to the occupants [32].

Measurements indicated that the concentration of contaminants levels remained well below the recommended limit. The air temperature and relative humidity measurements showed that these parameters did not always remain within ASHRAE thermal comfort limits. A large difference in energy consumption was found between the normal and CO_2-control ventilation systems. An energy saving of 12% was calculated by using the CO_2-control system. The payback period was estimated at being 0.4 years. In other work, measured energy savings have been recorded as high as 40 %, while simulated energy consumption savings have gone as high as 60 %. The payback periods have been calculated to range from 2 to 5 years [25].

Conclusion

Emission rate testing of certain materials and products has become a significant step in the design of some new and renovated office buildings. Such efforts, if coupled with appropriate attention to ventilation system design and operation, aesthetic and ergonomic factors, and building maintenance, are almost certain to reduce the types of occupant complaints that characterize "sick buildings". However, our current ability to design buildings with materials and products that protect indoor air quality is hampered by the lack of:

-data on emissions; and

-clear, predictable relationships between exposure to emitted substances and health or comfort effects.[17]

Very little is known about many of the air contaminants already identified, and it is hard to predict what contaminants will be generated by the future building materials, furniture materials, and office process equipment. There is a need to know the generation rates, the acceptable comfort level and health levels of each of those air contaminants both when present alone, and when combined with other air contaminants, or other physical, physiological or psychological sources of stress.

The Bake-Out process can be used to reduce the amount of airborne TVOC, and the Demand Controlled Ventilation system can control the amount of contaminants in the air while saving energy.

References

1. Axelard R. (1989): *Economic Implication of Indoor Air Quality and its Regulation and Control*, Report of NATO Committee for the Challenges of Modern Society, February 13-17, Enrice, Italy.
2. ASHRAE Standards (1989): *Ventilation for Acceptable Indoor Air Quality*, American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc. Atlanta.
3. Anderson R. and Mehos M. (1988): "Evaluation of Indoor Air Pollutant Control Techniques Using Scale Experiments", *Proc. of the ASHRAE IAQ 88, Engineering Solutions to Indoor Air Problems*, pp. 193-208, Atlanta, Georgia.
4. Tucker W.G. (1988): "Air Pollution from Surface Materials: Factors Influencing Emissions, and Predictive Models", *Healthy Buildings '88, State of the Art Reviews, Stockholm*, Vol. 1, pp. 149-157.
5. *Conclusions and Recommendations for Healthier Buildings*, (1991). Edited by Birgitta Berglund and Thomas Lindvall, Swedish Council for Building Research.
6. Marston, D.L. (1985): *Law for Professional Engineers*, Second Edition, McGraw-Hill Ryerson.
7. Wolkoff, P. et al: (1991) "A Study of Human Reactions to Emissions from Building Materials in Climate Chambers. Part I: Clinical Data, Performance and Comfort", *INDOOR AIR, International Journal of Indoor Air Quality and Climate*, Vol.1, No.4, pp. 377-388.
8. Schriever, E. and Marutzky, R.: (1990)"VOC Emissions of Coated Parqueted Floors", *Proceedings of The Fifth International Conference On Indoor Air Quality And Climate, Toronto*, July 29 - August 3, Volume 3, pp. 551-555.
9. Plehn, W.: (1990),"Solvent Emission From Paints", *Proceedings of The Fifth International conference On Indoor Air Quality And Climate, Toronto*, July 29 - August 3, Volume 3, pp. 563-568.
10. Berglund, B. et al, (1987): "Volatile Organic Compounds From Building Materials In A Simulated Chamber Study", *Proceedings of The Fourth International Conference on Indoor Air Quality and Climate, Berlin*, 17-21 August 1987, Volume 1, pp. 16-21.
11. Baldwin, M.E. and Farant, J.P.: (1990) "Study of Selected Volatile Organic Compounds in Office Buildings at Different Stages of Occupancy", *Proc. of the Fifth International Conference on Indoor Air Quality and Climate, Toronto*, July 29-August 3, Volume 2, pp. 675-670.

12. Rothweiler, H. et al: (1990),"Volatile Organic Compounds and Very Volatile Organic Compounds in New and Freshly Renovated Buildings", *Proceedings of The Fifth International Conference On Indoor Air Quality And Climate, Toronto*, July 29 - August 3, Volume 2, pp. 747-752.

13. Hamlin T., Forman J. and Lubun M.: (1990), "*Ventilation and Airtightness in New Detached Canadian Housing*", Canada Mortgage and Housing Corporation, Ottawa, Ontario, Canada.

14. Van der Wal, J.F., et al: (1990),"The Indoor Air Quality in Renovated Dutch Homes", *Proceedings of The Fifth International Conference On Indoor Air Quality And Climate, Toronto*, July 29 - August 3, Volume 2, pp. 441-446.

15. Bloeman, H.J.Th., et al: (1990),"Indoor Air Pollution After the Application of Moisture Repellents", *Proceedings of The Fifth International Conference On Indoor Air Quality And Climate, Toronto*, July 29 - August 3, Volume 3, pp. 569 - 574.

16. Tucker, W.G.: (1988): "Emissions of Air Pollutants from Indoor Materials An Emerging Design Consideration" *Proceedings of The Fifth Canadian Building and Construction Congress, Montreal*, pp. 101-109.

17. Johnsen, C.R., et al: (1990), "Controlled Human Reactions to Building Materials in Climatic Chambers. Part I: Performance and Comfort", *Proceedings of The FifthInternational Conference On Indoor Air Quality And Climate, Toronto*, July 29 - August 3, Volume 1, pp. 269-274.

18. Tucker, W.G.: (1990),"Building With Low-Emitting Materials and Products: Where do We Stand?", *Proceedings of The Fifth International Conference On Indoor Air Quality And Climate, Toronto*, July 29 - August 3, 1990, Volume 3, pp. 251-256.

19. Salares, V., et al: (1990),"Design, Construction and Ventilation of a Low Pollution Home", *Proceedings of The Fifth International Conference On Indoor Air Quality And Climate, Toronto*, July 29 - August 3, Ottawa, Volume 3, pp. 245-250.

20. Turner, W.A., et al: (1990),"Design of a Healthy Modern Office Building", *Proceedings of The Fifth International Conference On Indoor Air Quality and Climate, Toronto*, July 29 - August 3, Ottawa, Volume 3, pp. 269-274.

21. Hicks, J., et al: (1990) "Building Bake-Out During Commissioning: Effects on VOC Concentrations", *Proceedings of The Fifth International Conference On Indoor Air Quality And Climate, Toronto*, July 29 - August 3, Volume 3, pp. 413-418.

22. Girman, J., et al: (1989), "Bake-Out of an Office Building": A Case Study. *Environmental International*, Vol. 15, pp. 449-453.

23. "Field Test: Building Bake-out to Reduce VOC", Indoor Air Quality Update, *Practical Research Briefs, Premier Issue*, May 1988, pp. 3-4.

24. Girman, J.R., et al: (1990), "Building Bake-Out Studies", *Proceedings of The Fifth International Conference On Indoor Air Quality And Climate, Toronto*, July 29 - August 3, Volume 3, pp. 349-354.

25. "*Demand Controlled Ventilating System: State of the Art Review*", Edited by Willigert Raatschen. 1990, International Energy Agency, Swedish Council for Building Research, Stockholm, Sweden.

26. *The 12th AIVC Conference Proceedings, Air Movement and Ventilation Control Within Buildings*, Ottawa, 24-27 September 1991.

27. Sodergren D. and Puntilla A.: (1983) "*A CO_2 Controlled Ventilation System - Pilot Study*", Swedish Council for Building Research, Document D7.

28. Warren B.F.: (1982), "Energy Saving in Buildings by Control of Ventilation as a Function of Indoor Carbon Dioxide Concentration", *Building Services Engineering Research and Technology*, Vol. 3, No.1.

29. Janssen J.E., et al: (1982), Ventilation for Control of Indoor Air Quality: a case Study, *Environment International*, Vol. 8.

30. Berglund B., et al: (1982) "*The Influence of Ventilation on Indoor/Outdoor air Contaminants in an Office Buildings*", The National Institute of Environmental Medicine.

31. Schnakenberg G.H., et al: (1984) "Use of CO_2 Measurements in Monitoring Air Quality in Dead-End Drifts", *The 3rd International Mine Ventilation Congress*, Paper No. 22.

32. Haghighat, F. and Donnini D.: (1992) " IAQ and Energy-Management by Demand Controlled Ventilation", *Environmental Technology*, Vol. 13, No. 4, pp. 351-360.

33. Raatschen, W.: (1991), "*Demand Controlled Ventilating Systems: Sensor Market Survey*", Energy Conservation in Buildings and Community Systems Programme, Annex 18, Swedish Council for Building Research, Stockholm.

34. Haghighat, F., et al: (1991) "ACFD Analysis of Ventilation Effectiveness in a Partitioned Room". *Indoor Air*, the International Journal of Indoor Air Quality andClimate Vol. 1, No. 4, pp. 606-615.