Lessons Learned from Product Testing, Source Evaluation, and Air Sampling from a Five-Building Sustainable Office Complex

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Summary: *A five-building, 140,000 m^2 (1.5 million ft^2) sustainable office building complex was constructed for the State of California in 2002-03. The majority of the interior finishing materials were tested for volatile organic compound (VOC) emissions by their manufacturers prior to selection and installation. Building ventilation rates and indoor concentrations of chemicals were measured multiple times, from pre-occupancy to several months after occupancy. This paper discusses the variability in measured ventilation rates and concentrations of measured chemicals, the time course of emissions of some chemicals, and the relative contributions of the building materials versus the occupants and their activities.*

Keywords: *indoor air quality, green/sustainable building, low-emitting building materials*
Category: *Measurements and IAQ Monitoring*

1 Introduction

In 1999, the State of California initiated the design of the largest office-building complex ever built by the State Government. The State Legislature mandated that this project be sustainable. As a result, numerous pioneering practices and specifications were developed [1,2]. In order to enhance the indoor air quality of this new office building complex, manufacturers of major interior finishes were asked to submit emissions data based on a new specification known as *Section 01350* [3,4] that was written for this project. Emission limits were specified for the interior finishing building materials, based on their modeled impact on indoor concentrations. All 5 buildings were built with interior finishing materials that were tested for chemical emissions. Besides selection of building materials, a number of other requirements, such as early continuous ventilation and installation of building materials according to their emissions characteristics were also specified.

Limited air monitoring in the new office building complex was conducted before occupancy in four buildings, and more extensive post-occupancy monitoring occurred in all five buildings. The goal of the research reported here was to monitor the air quality and measure ventilation rates of all five buildings over a period of at least one year after occupancy in order to learn more about the decay or rise of building-related and occupant-related indoor air chemicals.

This paper focuses on the lessons learned from this extensive study.

2 Methods

Air samples were collected at all heating, ventilating, and air conditioning (HVAC) system return air streams, one outdoor location, and several indoor locations at or near cubicles. Exact locations depended on the arrangement of the floor to be sampled, possible VOC sources present, and other considerations. When possible, all locations sampled previously by the design/build teams, were also sampled for this study.

Air samples for Volatile Organic Compounds (VOCs) and aldehydes were collected on: (a) Tenax® tubes for VOCs; and (b) XpoSure® DNPH cartridges for aldehydes. Tenax® tubes were analyzed by Thermal Desorption Gas Chromatography/Mass Spectrometry and the DNPH cartridges were analyzed by High Performance Liquid Chromatography (HPLC). During the 20-month study, four buildings were sampled four times each and one building five times, for a total of 21 site visits.

A list of 110 target chemicals was developed based on: (a) Section 01350 target chemicals (b) most abundant chemicals; and (c) chemicals reported in previous studies of building materials [5,6].

Building ventilation systems were set at their design minimum airflow through each building's energy management system the afternoon prior to air sampling and operated at this setting until after the air sampling was completed the following day. Building and local ventilation rates were measured with a tracer gas (sulfur hexafluoride). Tracer gas measurements were taken continuously on a sequential basis at each supply and return air stream of all HVACs. In addition, syringe samples of the tracer gas were manually collected at steady state conditions and three times during the tracer gas decay at the same locations that the VOC and aldehyde air samples were taken.

By measuring chemical concentrations and ventilation rates simultaneously, emission factors (i.e., mass emitted per hour per floor area) can be calculated for each measured chemical [7,8]. This allows comparison of the emissions on different occasions and analysis of the trends in the emissions of various substances. Since some substances or groups of substances are associated with specific sources or source types, it was possible to obtain a better understanding of the pattern of emissions related to building materials as well as to contributions from occupants and their activities.

3 Results, Discussion, and Lessons Learned

During the 20-month study, 21 site visits were made. There were 285 sampling sites. 7 to 15 sites were sampled simultaneously per visit per building. Approximately 830 samples were collected and analyzed. As a result, an enormous data set was generated.

This paper focuses on the lessons learned from this study with related supporting data. Readers interested in the detailed results are referred to the final report [9].

1. Requiring Emissions Testing Helps Achieve Better Indoor Air Quality. All interior building materials were tested prior to their selection and installation. The concentration goals set forth by this project were met for the most part in the majority of the locations. Table 1 shows a list of selected chemicals and the percent of locations where the concentration targets were met. Acetaldehyde and formaldehyde targets were not met in numerous locations of more than one building. These results are consistent with previously published results on building material emission profiles [5,6]. The measured concentrations for these chemicals also are comparable to those measured by the USEPA's BASE study of 100 existing buildings (this analysis is ongoing and the comparison of the results of our study to the BASE study will be included in [9]). Therefore, careful selection of building materials during a building's design is likely to reduce elevated concentrations of VOCs drastically during the initial months of newly constructed building.

Table 1. Degree of Success in Meeting Air Concentrations Goals For Selected Chemicals

	% of Locations Meeting Concentration Criteria (Sample Size)				
	171 (43)	**172 (45)**	**173 (45)**	**174 (42)**	**225**
Acetaldehyde	53	91	67	95	83 (58)
Caprolactam	100	100	100	100	100 (50)
Formaldehyde	100	49	100	100	95 (58)
Naphthalene	100	100	100	98	100 (50)
Nonanal	100	98	100	100	94 (50)

2. Actual Local Ventilation Rates in Large Buildings May Vary Significantly from Design Minimum Rates. An arbitrary value of 20% between measured and design air change rates (ACH) was used in this study to account for field measurement errors. Table 2 shows the number of occurrences when measured local ACHs were 20% or more below design. As can be seen from Table 2, in two of the five buildings, about 50% of the measured ventilation rates were below design values by more than 20%. In contrast, the remaining three buildings had higher than design overall average ventilation rates and only a few percent of the measured ventilation rates were below design by more than 20%. The two buildings with the highest percentage of under ventilated areas were also the largest of the five. The measurements made in the study show that building ventilation performance was not always as expected. It is also evident that more under-ventilated areas may exist in larger buildings than might be expected by designers and operators.

Table 2. Measured Local Ventilation Rates Below Design

Building #		Number of Local ACH 20% Or More Below Design (Sample Size) Post-Occupancy					
		#1	#2	#3	#4	#5	Total % (N)
171		2 (12)	4 (14)	12 (14)			45 (40)
172		0 (14)	1 (14)	0 (14)			2.4 (42)
173		0 (14)	0 (14)	0 (14)			0 (42)
174		0 (2)	1 (13)	0 (14)			3.4 (29)
225	2 thru 6	3 (4)	4 (4)	2 (10)	0 (10)	10 (10)	50 (38)
	1	2 (2)	2 (2)	3 (3)	0 (3)	3 (3)	77 (13)

3. There are a number of uncertainties and variations associated with building ventilation systems, and ventilation and chemical measurements that can lead to erroneous conclusions. A great deal of caution is necessary when doing air sampling in order to assess the quality of the indoor air and establish whether a building is "safe" to occupy. These variations include the following:

   a. Analytical procedure variations within the same laboratory and across laboratories result in a range of variations when duplicate or side-by-side sampling is conducted: In the discussion below, we define the Relative Percent Difference (RPD) between a measured sample value v1 and a co-located sample value v2 as follows:

$$\text{RPD} = \frac{Absolute(v1 - v2) \times 100\%}{Average(v1, v2)}$$

Where:
v1 = sample measured value
v2=side-by-side or duplicate sample measured value

The higher the RPD the further apart two co-located measurements are. Side-by-side sampling by two independent sampling teams was conducted during two of the five sampling scenarios at one building. For seven selected common target chemicals [acetaldehyde, caprolactam, decamethylcyclopentasiloxane (d-5), d-limonene, formaldehyde, naphthalene, and nonanal] reported RPDs varied by as little as 25% to as much as 160%. Our team collected duplicate Tenax® tubes at all sites. Two duplicate DNPH cartridges also were collected per building per sampling scenario. RPDs for duplicate samples taken during the same two sampling scenarios when side-by-side sampling occurred, ranged from as little as <1% to as much as 140%. Therefore, analytical procedure variations need to be accounted for especially in low-emitting building material certification programs or when air sampling in buildings is conducted to determine whether target concentrations have been met.

   b. Building ventilation rates can vary on different days. As stated above, the ventilation systems during all sampling scenarios were set to provide the minimum design airflow rates. However, measured ventilation rates for the same locations were not consistent between consecutive sampling scenarios occurring a few months apart. Table 3 shows the local ventilation rates for selected locations over the course of the study. Ratios of ACH between consecutive air sampling scenarios varied by as much as a factor of 2.5. Therefore, reliance on a building's ventilation system to replicate air change rates measured previously under same settings of the outdoor air controls may lead to erroneous results.

   c. For meaningful interpretation of concentration comparisons, concentrations need to be normalized by ventilation rates measured at the same time concentrations measurements were taken. As was mentioned earlier, emission factors can be compared across buildings or across different sampling scenarios of the same building when concentrations and local air change rates are measured simultaneously. Table 3 illustrates the variation in emission factors for caprolactam and formaldehyde over the course of the study for two buildings. The measured air concentrations and air change rate information are also listed. As can be seen from this Table, comparisons of measured concentrations of the same location sampled over different dates would be misleading if based on this metric alone without consideration in the differences of measured ventilation rates. Therefore, comparisons among buildings or among different sampling scenarios of the same building based on measured concentrations alone can lead to erroneous conclusions.

Table 3. Emission Factors, Concentrations, and Air Change Rates For Selected Building Locations and Chemicals.

		Local ACH, Emission Factor (EF), and Concentration (Conc)					
		Pre	Post-Occupancy				
		Building 225 (floor 4, location 1)					
		6/28/02	10/29/02	6/5/03	10/23/03	3/10/04	5/19/04
ACH (hr^{-1})		1.1	0.7	0.7	0.9	1.5	0.6
Caprolactam	Conc $\mu g/m^3$	17	6.1	3.2	4.2	2.8	ND
Caprolactam	EF $\mu g/m^2 \cdot hr$	65	17	8.9	14	17	ND
Formaldehyde	Conc $\mu g/m^3$	43	11	21	31	26	25
Formaldehyde	EF $\mu g/m^2 \cdot hr$	160	25	48	91	140	53
		Building 172 (floor 4, location 1)					
		10/10/03	2/11/04	3/30/04	6/804		
ACH (hr^{-1})		1.4	1.0	1.3	0.7		
Caprolactam	Conc $\mu g/m^3$	8.4	3.6	10	11		
Caprolactam	EF $\mu g/m^2 \cdot hr$	46	14	54	34		
Formaldehyde	Conc $\mu g/m^3$	28	47	42	50		
Formaldehyde	EF $\mu g/m^2 \cdot hr$	130	174	210	130		

d. <u>Emissions testing of building material samples by their manufacturer does not necessarily guarantee that materials of similar chemical profile would be delivered and installed in a building</u>. The office furniture systems for the entire complex were tested to the State's IAQ emissions specifications [1,8,10]. One manufacturer provided systems for Buildings 172 and 225, and another provided systems for the other three buildings. Median formaldehyde emission factors in Building 172 were the highest of all buildings followed by Building 225 (see Table 4). The median of all post-occupancy emission factors in Building 172 was 4 times higher than the median emission factors for Buildings 171 and 174. Based on testing of the complete workstation and its components by the office furniture systems manufacturer who supplied the workstations to Buildings 172 and 225, the presumed source of moderate emissions in these buildings appears to have been the acoustical boards within the panels.

Although the same manufacturer provided these boards to the two office systems furniture manufacturers, it appears that one office systems manufacturer had done a more effective airing out of the acoustical boards prior to assembly in the panels. Airing out of the panels was one of the State's contract requirements.

Table 4. Emission Factors for Formaldehyde for All Buildings.

Building #	Median Emission Factor						
	Pre	Post-Occupancy					
		#1	#2	#3	#4	#5	Median
171		30	30	30			30
172	94	94	120	130			120
173		47	25	43			43
174		43	30	29			30
225	160	29	52	74	100	53	53

4. <u>Reliance on short-term building air measurements taken on a single scenario will only capture chemicals present that day and at the time of testing and may not be representative of the occupants' exposure for the majority of the time</u>. Table 3 shows the source strength variation for caprolactam and formaldehyde over the course of our study. Table 5 shows the source strength variation for acetaldehyde, benzaldehdye, d-5, and d-limonene, naphthalene, and nonanal. It is clear that source strengths vary depending on activities within the building and the influence of outdoor air (such as that containing ozone resulting in formaldehyde and acetaldehyde formation when common indoor pollutants are present indoors). Therefore, caution should be exercised when interpreting results of short-term building air measurements.

Table 5. Emission Factors for Selected Chemicals and Buildings

	Median Emission Factors for Buildings 225 and 172 for Selected Chemicals					
	Pre	Post-Occupancy				
	Building 225					
	6/28/02	10/29/02	6/5/03	10/23/03	3/10/04	5/19/04
ACH (h^{-1})	1.3	0.8	0.8	0.9	1.5	0.6
Acetaldehyde	32	6.8	9.9	15	28	19
Benzaldehyde		5.5	1.3	0.8	3.4	2
d-5	0	62	25	48	130	58
d-limonene	10	49	10	27	46	11
Naphthalene	0	0.4	0	0	0	0
Nonanal	35	0	3.8	0	0	5
	Building 172 (floors 1 thru 6)					
	10/10/03	2/11/04	3/30/04	6/804		
ACH (h^{-1})	0.9	0.9	1.1	0.7		
Acetaldehyde	9.4	18	16	13		
Benzaldehyde	2	1.2	12	1.6		
d-5	0	76	150	60		
d-limonene	0	24	22	3.1		
Naphthalene	0	0	3.8	0		
Nonanal	23	3.4	28	0		

5. Few chemicals can be clearly linked to specific sources. In our study we identified eight building- and occupant-related chemicals. These are: (a) building-related chemicals: acetaldehyde, caprolactam, formaldehyde, naphthalene, and nonanal; and (b) occupant-related chemicals: benzaldehyde, d-5 and d-limonene. We anticipated that the building-related chemicals would decay with time, whereas, occupant related compounds would increase as occupants moved in. In the case of d-5, a chemical used in perfumes and dry cleaning, the data indicated a 60 to 80-fold increase between pre- and post-occupancy measurements (see Table 5). In the case of caprolactam, a chemical found in carpets and other Nylon 6 products, the expected decay in emission factors was observed in Building 225 (see Table 3) – in the other four buildings hallway carpeting was replaced shortly after occupancy and therefore an increase in emission factors was observed. However, in the case of formaldehyde, fluctuations in emission factors were observed, indicating that either occupant-related activities or indoor chemistry byproducts resulted in high emission factors. Emission factors of acetaldehyde, benzaldehyde, naphthalene, d-limonene, and nonanal also fluctuated throughout the study (see Table 4 for Buildings 225 and 172, others were similar) indicating that with the exception of some signature chemicals, accurate source determination is extremely difficult in occupied buildings.

5 Conclusions

Requiring emissions testing from manufacturers helps achieve better indoor air quality. Studies to characterize indoor air chemical concentrations can be accomplished with sufficient measurements. However, it should be noted that:

1. A comprehensive indoor air quality study is time consuming and expensive. Numerous samples are required at several locations over an extended period of time. Numerous variables need to be considered and controlled in the building, or accounted for in the data analysis.
2. Simultaneous ventilation rate measurements are required to normalize chemical concentration measurements to the area/materials in the buildings.
3. Besides the limited number of chemicals with unique sources, it is extremely difficult to pinpoint the source of the majority of chemicals.
4. Even when ventilation systems are locked in minimum outdoor air supply setting, fluctuations of building ventilation rates occur and local ventilation rates may not necessarily meet design values.
5. Performance of low emitting building materials can be highly variable. They should be confirmed by a third party, with random emissions testing required in certain occasions to ensure that materials delivered are of similar chemical profile as those tested previosuly. .

This paper also points out the benefits of on-going testing of building materials. The results of such testing allow manufacturers to reduce emissions of chemicals from their products with known health and odor problems, to reduce occupant exposures to potentially harmful chemicals, and to reduce manufacturers' own exposure to potential litigation. It is equally important that building material specifiers carefuly select building materials that have been tested in order to ensure the best possible achieval indoor air quality in the built environment.

The paper also identifies cautions and emphasizes the care required when air sampling in buildings is conducted in order to determine whether target concentrations have been met or whether ventilation is adequate to control pollutant concentrations.. Potential problems associated with building material emissions testing include: analytical procedure variations, concentrations not normalized for ventilation rates and ventilated volumes and reliance on short-term building air measurements to characterize daily occupant exposure.

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