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CHARACTERIZATION OF A HEALTHY BUILDING

D.J. Moschandreas
S.M. Relwani
D. Novosel

IIT Research Institute
10 West 35th Street
Chicago, Illinois 60616-3799

Comfort, indoor air, and HVAC system parameters were measured in a three-floor office building. This building is a "healthy" building because over a two-year occupancy period only five environmentally-related complaints were registered. This number of complaints is much smaller than the average number of complaints registered in seven similar office buildings managed by the same company. A typical number of complaints over the same period of occupancy is about 50. Two comfort perception questionnaires were distributed; the first one to about 20 visitors to the building, and a second to about 25 percent of the occupants. Answers to the questionnaires were obtained daily. Ten indoor and four outdoor sites were sampled for CO, CO_2, O_3, nicotine, particulate matter, total volatile organic compounds, and biopollutants. The performance of the HVAC system was determined by ventilation multi-component experiments, ventilation efficiency experiments, and relative exposure index experiments. This paper discusses the experimental design, the instrumentation package, the data base generated, and results of the study. A comprehensive and practical definition of an occupied "healthy" office building is formulated.

INTRODUCTION

One of the intellectual and practical costs of establishing a glossary that anticipates reality is that the included terms lose their novelty, utility, and lead to confusion. Terms used to describe building environments clearly suffer from this predicament. Such terms include Sick Building Syndrome (WHO, 1983) or Building Related Illness (Woods, 1988), Complaint Buildings (Moschandreas, 1989) or Healthy Building (Healthy Building Conference, 1988). Our understanding of these terms is qualitative and not quantitative. The technical community has anticipated reality and after nearly 10 years of investigations it has not clearly defined them.

Quantitative definitions of these terms have not been achieved because building environments are studied in accordance with principles of scientific reductionism which breaks a complex system into simple components and investigates each one of the components individually. The building environment, however, is a holistic phenomenon that involves synergy of indoor air quality, comfort, and energy parameters. In this sense, air conditioning becomes space conditioning that should optimize comfort, air quality, and ventilation. In this paper we report the design, analysis, and results of a holistic approach to define and characterize a healthy building.

Characterization of a healthy building was preferred to a sick or complaint building because the variance of parameters of the former is likely to be smaller than the latter. The most important ingredient for such a characterization study is identification of a healthy building. The building was assumed healthy because over a period of two-year occupancy, only five environmentally-related complaints were registered by building management. This number of complaints is much smaller than the average number of complaints registered in the seven other buildings (of similar size and design) managed by the same company. A typical number of complaints over the same period of occupancy is about 50.

EXPERIMENTAL

Indoor air quality, comfort, and ventilation parameters were measured daily for four weeks and two weekends. This was a characterization design; consequently, its objective was to generate sufficient data that support inferences on the environmental nature of the building. The building is a combination bank and office center of approximately 50,000 square feet. At the time of testing it was occupied by 16 different organizations with a total of 112 employees.

Indoor air quality parameters were measured in 10 indoor locations, three outdoor-roof locations by the HVAC system, and two outdoor locations on ground level. The selected indoor locations represented the range of indoor air quality, from good indoor air (no sources) to potentially elevated ones (by indoor sources). At each location, measurements were taken for 15 continuous minutes. A period of 15 minutes was allotted to move the instrumentation assemble between sampling sites. Repeat measurements at three indoor sites were taken intermittently. Carbon monoxide, carbon dioxide, particulate matter, total volatile organic compounds, ozone, microbial contamination, nicotine, and odor and noise levels were measured. The instruments used for this study are state-of-the-art, commercially-available instruments designed for sampling of indoor air (Moschandreas and Relwani, 1990).

Responses to questionnaires helped measured perception of comfort. A minimum of 20 visitors to the building were asked to respond to the "Visitor's Odor Perception Questionnaire". The objective was to determine whether the building air was perceived as "acceptable" according to the ASHRAE Standard 62-1989. A second questionnaire was distributed to 30 randomly sampled occupants of the building to obtain their perception of comfort. The occupant questionnaire recorded the employees' evaluations of the indoor conditions for their respective primary work area. Of concern were the perception of four comfort parameters (see Table 4), assessment of the indoor air and overall building environment, and the desire to change any of the comfort parameters. The comfort, indoor air, and overall building environment parameters were recorded on a seven-point semantic scale. Bimodal ("yes/no") responses recorded the desire to change any of the comfort parameters. The occupant questionnaire was distributed and collected daily between 3:00 and 5:00 p.m.

Three ventilation parameters were determined: ventilation efficiency, ventilation effectiveness, and relative exposure index. Tracer gas (SF_6) techniques were used to establish these parameters (Moschandreas and Relwani, 1990). The measurements were executed on a two-day cycle over a four-week period.

Comfort parameters were measured daily. Air quality and ventilation parameters were measured on a two-day cycle. On one day field staff measured VOCs and particulate matter along with one ventilation parameter, on the second day the staff measured only air contaminants. Over the month long sampling period, sampling was carried out during two weekends to determine background levels without any occupants in the building. After Quality Control, quality assurance of the data, over 90% of the desired data were captured for analysis.

ANALYSIS AND RESULTS

Air quality data analysis followed a multi-step process. Descriptive statistics were determined for two distinct time periods, the first two weeks, and the second two weeks. Using Bartlett's test for homogeneity of variance, homogeneity of daily contaminant concentrations was established for the indoor and outdoor environments. Analysis of variance (ANOVA) was used to test the null hypothesis of no difference between indoor and outdoor levels for each of the two-week periods. Duncan's New Multiple Range Test (NMRT) was employed to isolate which means are different when the ANOVA rejected the null hypothesis. In addition to these steps, t-test and pair t-tests were used to determine whether certain indoor areas, such as bathrooms or copy rooms, exhibit significantly different air quality from the rest of the building.

The four-step process of data analysis will be illustrated with microbial concentrations measured over two two-week periods. Bartlett's homogeneity test tests whether the null hypothesis of all means (corresponding to each floor) are equal. The null hypothesis could not be rejected. Table 1 shows that indoor microbial levels are between 18% and 15% of corresponding outdoor levels for periods 1 and 2.

Analysis of variance tested the null hypothesis that the means of all groups are equal. Four groups were considered outdoor and indoor each for two sampling periods. ANOVA rejected the null hypothesis at the $p = 0.05$ level. Duncan's NMRT test was used to determine which means are statistically different. A graphical illustration of the NMRT results of microbial contamination, Table 2, shows that the outdoor levels of the two periods are from the same population and that the indoor levels are from the same population, but the difference between outdoor and indoor levels of corresponding periods is statistically different.

A t-test was used to investigate whether the rest rooms are significant sources of indoor microbial contamination. The null hypothesis of no difference between rest room levels and the indoor levels of all other sites could not be rejected. It is surmised that for the test building, the rest rooms are not sources of indoor microbial contamination. Similar analyses were performed for all other contaminants measured in the building. All measured levels are low, see Table 3.

Even though TVOC outdoor levels are statistically different over the two sampling periods, the indoor levels are from the same population. The difference between indoor particulate matter concentrations over the two sampling periods is statistically significant. This difference is driven by the statistically significant difference of outdoor levels. Smoking affects the indoor levels of nicotine.

Based on the analysis, the following conclusion is drawn. Occupant perception of comfort parameters was high and it did not change over the two sampling periods, see Table 4.

Occupant perception of comfort parameters that were rated on the 1 to 7 scale are shown in Table 5. Remarkably, about 45% of the occupants would like to adjust, presumably improve, the temperature of their office. Yet 84.5% of the same occupants had rated temperature as comfortable. A similar portion of occupants would like to adjust the magnitude of indoor air movement but only 19% would wish to adjust the noise level and 28% the humidity and light levels. Fewer than 35% of the visitors perceived any indoor odors best on the hedonic classification. Fewer than 1% of all respondents perceived an unpleasant or worse odor. Both visitors and occupants characterized the odors with conventional odor notes. These perceptions satisfied ASHRAE's 62-1989.

Tracer experiments indicated the degree of mixing of air in occupied space. Results from 12 tracer experiments are shown in Table 6.

DISCUSSION

This characterization study measured simultaneously air quality, comfort, and ventilation parameters of a building that is assumed to be a healthy building. All contaminant concentrations are uniformly low, and independent of outdoor levels. The building appears to smooth out outdoor variations and local sources. Both visitors and occupants perceived a comfortable indoor environment. The visitor's perception satisfies ASHRAE's guidelines of acceptable air. Over 80% of occupants rated various comfort parameters as comfortable. Temperature is perceived as a parameter that should be adjusted even though it is rated comfortable. This nearly dichotomous perception of occupants is assumed to denote the occupant desire to control his/her environment and not a dissatisfaction with temperature comfort.

Clearly, one building does not provide sufficient data for inferences to healthy buildings, yet insights have been gained for further research. The easiest component to be assessed by reductionist principles is perception of the indoor environment. The challenge is to develop associations between the other two components and perception so that a holistic picture can be developed by measuring effectively one part of the desired total. A series of studies should be performed to determine the perception levels that distinguish low and high (above indoor guidelines) levels of indoor pollutants and ventilation parameters. Perception may be the signature parameter for the various types of indoor building environments.

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TABLE 1. MICROBIAL LEVELS (cfu/m³)

	Site - Period (P)			
	Outdoor-P-1	Outdoor-P-2	Indoor-P-1	Indoor-P-2
Mean	626	802	111	120
Standard Dev.	72	299	59	30

TABLE 2. DUNCAN'S NMRT RESULTS FOR MICROBIAL CONTAMINATION (cfu/m³)*

Sample Identification	Outdoor-P-2	Outdoor-P-1	Indoor-P-2	Indoor-P-1
Mean	802	626	120	111

*Means lying above the same horizontal line are not significantly different, those over different lines, or no lines, are with $P = 0.05$.

TABLE 3. SUMMARY OF AIR QUALITY RESULTS (Average ± 1 st. dev.)
Sampling Location - Period of Sampling

Contaminant	Outdoor P-1	Outdoor P-2	Indoor P-1	Indoor P-2
Microbial (cfu/m³)	626 ± 72	802 ± 299	111 ± 59	120 ± 30
TVOC[1] (ppb)	320 ± 119	35 ± 32	62 ± 36	30 ± 36
PM[2] (mg/m³)	0.01 ± 0.02	0.06 ± 0.04	0.02 ± 0.02	0.06 ± 0.02
CO_2 (ppm)	280 ± 16	335 ± 28	522 ± 59	558 ± 62
O_3 (ppb)	40 ± 10	29 ± 19	10 ± 3	12 ± 4
CO (ppm)	1.4 ± 0.2	1.7 ± 0.3	1.6 ± 0.2	1.8 ± 0.2
Nicotine (μg/m³)	NM[4]	NM	15.1 ± 75[3]/ 2.6 ± 11	12.5 ± 5.3/ 2.4 ± 0.6
Noise (dBA)	NM	NM	49 ± 1.2	47 ± 0.5
Odors (ED_{50})	$ED_{50} \leq 15$	$ED_{50} \leq 15$	$ED_{50} \leq 15$	$ED_{50} \leq 15$

[1]TVOC: Total Volatile Organic Compounds
[2]PM: Particulate Matter
[3]Smoking Area/Non-Smoking Area
[4]NM: Not Measured

TABLE 4. OCCUPANT PERCEPTION IN % OF COMFORT PARAMETERS

Comfort Parameters	Comfortable Period-1	Comfortable Period-2	Uncomfortable Period-1	Uncomfortable Period-2
Temperature	84.7 ± 4.2	84.3 ± 6.4	17.6 ± 5.9	15.1 ± 2.9
Humidity	89.4 ± 5.2	86.7 ± 10.4	10.0 ± 6.1	10.6 ± 7.8
Air Movement	82.9 ± 4.5	76.8 ± 7.5	23.0 ± 7.4	16.4 ± 4.4
Noise	93.6 ± 5.3	91.2 ± 7.5	7.6 ± 10.8	7.2 ± 11.2

TABLE 5. OCCUPANT PERCEPTION OF INDOOR AIR QUALITY

	Period 1	Period 2
Air Freshness (stuffy to fresh)	4.4 ± 0.2	4.5 ± 0.4
Smoke Content (smoky to clear)	4.9 ± 0.2	4.7 ± 0.2
Indoor Odor (bad odors to no odors)	5.0 ± 0.2	4.9 ± 0.2
Physical Appearance (worst to best)	4.8 ± 0.2	4.7 ± 0.1
Comfort and Air Quality (worst to best)	4.4 ± 0.2	4.5 ± 0.2

Scale: 1 = worst; 7 = best; 4 = midpoint

TABLE 6. VENTILATION EXPERIMENTS

Parameter	Period 1	Period 2
Air Exchange Rate (ACH)	0.61	0.64
Ventilation Effectiveness (#)	1.00	1.00
Ventilation Efficiency (%)	99	100
Relative Exposure Index (#)	0.73	0.92