VOLATILE ORGANIC COMPOUNDS (VOCS) EMISSIONS FROM SOURCES IN A PARTITIONED OFFICE ENVIRONMENT AND THEIR IMPACT ON IAQ

IT Berrios*, JS Zhang, B Guo, J Smith and Z Zhang

Department of Mechanical and Aerospace Engineering, Syracuse University, Syracuse, NY 13244, USA

ABSTRACT
Mid and full-scale stainless steel chambers were used to characterize emission sources in a partitioned office environment, including personal computers, printers, copiers, office workstation components (desk, cabinet, partition panels), chairs and carpet. Major compounds emitted from these sources include: 1,3-dichlorobenzene, ethylbenzene, m-xylene, p-xylene, pentadecane, phenol, styrene and toluene. Results show the emission rates for computers were 10 to 120 times higher when they were on than off. The computers with CRT monitors emitted slightly more than those with TFT monitors. The emission rates for the copiers and printers can be negligible during the off and idle periods compared to the on period. The emissions from the furniture components decreased slowly over time, following a power-law decay curve. Simulations indicated that operation of the copier, printer and computer would contribute most to the total VOC concentrations and several individual VOCs including ethylbenzene, pentadecane, styrene and toluene in a typical office environment.

INDEX TERMS
VOC, office workstation, emissions, office equipment, Indoor Air Quality (IAQ)

INTRODUCTION
VOCs represent a major type of indoor pollutants. Many potential sources of VOCs exist in an office environment including construction materials, furniture, polluted outdoor air, and office equipment. Emissions from construction materials have been measured in many previous studies (e.g., Zhang et al. 1999, Hodgson 1999, Tucker 2000), but data are relatively limited for computers, printers, computers and workstation systems.

Chemical emission rates of Personal Computers (PC) and other electronic appliances were reported by Funaki et al. (2003), finding that the formaldehyde emissions were 9 times higher when the PC was on than when it was off. Nakagawa et al. (2003) compared the PCs with Thin Film Transistor (TFT) monitors and Cathode Ray Tube (CRT) monitors, finding that the CRT monitors had slightly higher emission rates of formaldehyde and acetaldehyde than the TFT monitors. Nineteen monitors were tested by Wensing et al. (2002) for phenol, toluene and TVOC emissions, finding that the VOC emission rates of monitors decreased as a result of ageing. A large chamber emission test method for office equipment was developed by Leovic et al. (1998), and evaluated by testing four photocopiers in different labs. Emission rates from commercial office workstations have been reported by Mason and Black (1995) and Zhang et al. (1997). Personal computers and printers may be considered as "active" sources because they also emit heat as well as pollutants. Their emissions also depend on the [i]operation modes as well as the materials used; their effects on the microenvironment are more complicated than "passive" sources such as building materials and furnishings.

This study is focused on sources that are close to the occupants in a partitioned office environment. The objectives were to identify the VOCs emitted, measure the emission rates over time, and estimate the relative impacts of the tested sources on the VOC concentrations.

EXPERIMENTAL METHODS
Facilities
Tests were conducted in a mid or a full-scale stainless steel chamber. The mid-scale chamber has dimensions of 5.5ft x 6ft x 5.5ft high and an interior volume of 181.5 ft^3. Two full-scale chambers were used depending on the tests and availability. One has dimensions of 6.5ft x 12ft x 10ft high (780 ft^3), and the other 16ft x 12ft x 10ft high (1920ft^3). All chambers have environmental controls that maintain the standard test conditions used, i.e., 23°C, 50% RH and constant air change rates (0 to 1 ach) depending on the specific test, as verified by the tracer gas decay

* Corresponding author email: itberrio@syr.edu

test (ASTM D6670).

Test Procedures

The general procedures described in ASTM D6670 were followed, while the specific test procedure differed, depending on the type of sources tested. Before each test, the chambers were cleaned and flushed for at least 12 air changes (i.e., 12 hours at 1 ach). Background samples were taken, showing that the average TVOC and Sum of VOC (summation of the VOCs with identifiable peaks) concentrations of every test were lower than 30 μg/m^3 and 10 μg/m^3, respectively. For the "active" sources, two different methods were used. The computer tests included two periods, each of twelve hours; the first was when the computers were "on" and the second was when the computers were "off". For the copier and printers, the experimental method included three periods, two of twelve hours and a third of four hours; the first was when they were "off", the second was when they were "idle" (i.e., power on but not operating) and the third period includes the operating and post-operating period. For "passive" sources (workstation components and carpet), each test was 120 hours, with samples being taken every 24 hours.

Sampling and Analysis Method

For the identification and quantification of the VOCs, the air samples collected by sorbent tubes were analyzed using a thermal desorber-GC/MS system according to ASTMD6196. VOCs were identified using the NIST MS library and an in-house database of the GC retention times for the compounds confirmed previously. After the air samples were analyzed, the amount of VOCs determined by the GC/MS was divided by sampling volume for respective tube sample to calculate the VOC concentrations.

For each test, the VOCs with highest concentrations were selected to determine their emission rates over time. To calculate the average emission rate, the mass balance equation was used for the "active" sources assuming perfect mixing conditions in the chamber and neglecting the sink effect and any minor mass loss due to the chamber leakage and sampling. For the "passive" sources the power-law decay model was used to represent the emission rate data (Zhang et al. 1999, and Magee et al. 1999): $EF(t) = at^{-b}$, where EF(t) is the emission factor (μg/h/m^2 or μg/h/unit) at time t, and a and b are empirical constants from regression analysis.

RESULTS AND DISCUSSIONS

Identification of Emitted VOCs

For "active" sources, some components were found in every computer test such as m-xylene, p-xylene, pentadecane, phenol, toluene, and unidentifiable VOC while others were found in only one or two of them (Table 1). Toluene was the only common VOC found in every printer test. Printer 2 was the one with highest emission rates but approximately 50% of the total emission factor was from d-limonene. Different computers and printers may have very different compounds emitted. Printers tested emitted less number of VOCs, but more TVOC than the computers tested. For "passive" sources, d-limonene was the most common VOC identified and was present in 60% of the tests.

Emission Factors as a Function of Time

Emission factors were calculated based on the measured concentrations during the tests. For the computer tests, the emission factors increased during the first hours in the "on" period and then approached their relatively stable values. During the "off" period, the emission factors can be negligible (Figure 1). For the printers and copiers, the emission factors increased quickly during the copying and printing period, respectively, and kept at relatively high level during the post-printing and post-copying periods. The "off" and "idle" periods can be negligible comparing with the printing and copying periods. The overall trend is similar to the computer tests (Figure 1). For the "passive" sources, the higher emission factors can be found in the first 24 hours, after that they decreased quickly approaching their quasi-steady state (Figure 2). The emission factors for the passive sources can generally be well represented by the power law model (Figure 2).

Comparison of Emission Factors of the Different Sources

The five most common VOCs were selected to compare their emission factors among different sources. In addition the TVOC and the summation of the VOCs emission factors were compared too. The most common VOCs were d-limonene, pentadecane, styrene, toluene and m,p-xylenes, which were found in almost every test (Table 1). The sources with higher emission factors were the printers and copiers. The second printer had the highest emission rate. Passive sources in general had lower emission factors with the chairs having the highest among the test products.

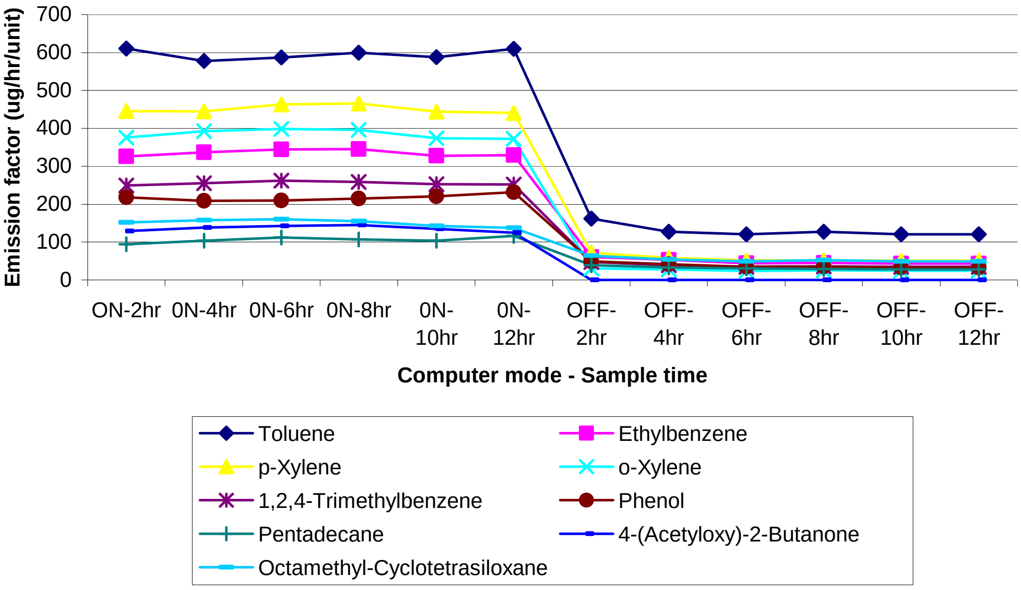


Figure 1. *Individual VOC emission factors for computer test #2 (an example for "active" sources)*

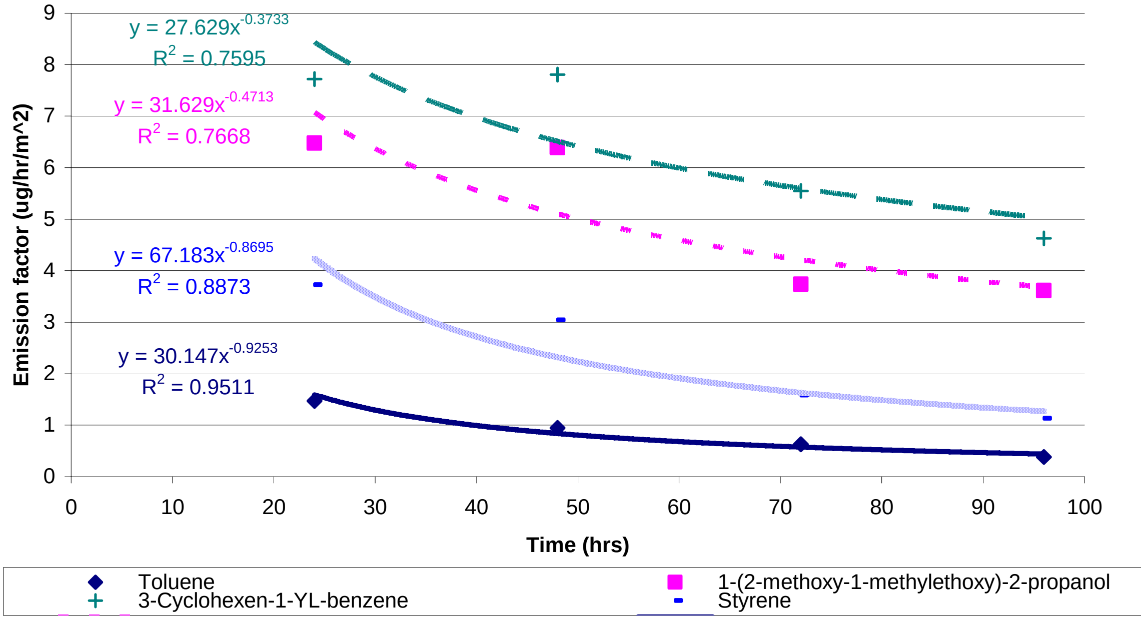


Figure 2. *IVOCs Emission factor for carpet test (an example for "passive" sources)*

Table 1.*VOCs identification for passive and active sources*

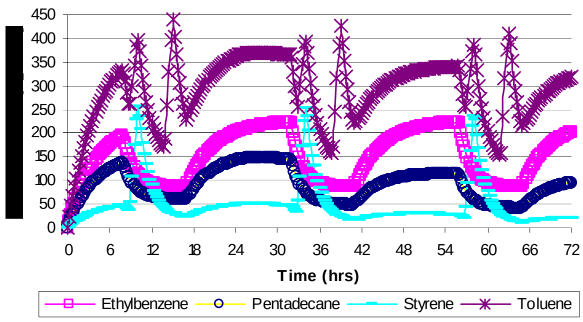
Category	VOC Name	Passive Sources[1] (ug/hr/m^2)					Active Sources (ug/hr/unit)						
							Computers[2]			Printers[3]			Copier[4]
		carpet	drawer	panels	table	chairs	1	2	3	1	2	3	1
ARH	1,2,4-Trimethylbenzene					11.72							
ARH	Butylated Hydroxy Toluene					183.28							
ARH	Ethylbenzene							334	30.6				
ARH	m-xylene, p-xylene						11.8	450	103	520		83.9	1381
ARH	o-xylene							381		1128			1192

ARH	Pentadecane	4.34	6.75	1.68			31.5	109	31.1				
ARH	Styrene	3.72					29.9		119		1132		
ARH	Toluene	1.47	2.78	2.37			16.8	599	175	207	996	509	1336
ALH	Nonane,3,7-Dimethyl-			7.51									
ALH	Tetradecane	3.74											
ALH	Undecane, 3-methyl			10.8									
HLC	1,3-DichloroBenzene		38.9	2.18									
ALC	1-Octanol, 2-butyl	5.14		6									
ALD	Benzaldehyde						10.7						720
ALD	Nonanal			6.55		6.94							
TER	D-limonene		26.4*		117		83.5		21.5			58.8	
TER	α-Pinene				5.28		15.2						
O	Oxirane, (butoxymethyl)											1370	
O	N-Butylether												1673
O	Phenol						10.8	222	159				
O	Unidentifiable 1						90.1	184	102				
O	Sum_{3VOCs}**										19237		
O	Sum VOC	73.1	74.2	95.3	138	994	511	3135	1172	2883	32158	2417	7593
O	TVOC	134	73	135	86.7	811.76	501	5517	1665	2536	43488	2684	9632

Categories: ARH=Aromatic hydrocarbons, ALH=Aliphatic hydrocarbons, HLC=Halocarbons, ALC=Alcohols, ALD=Aldehyde, TER=Terpenes, O=Others. *The emissions from this compound did not follow a specific pattern. **Sum_{3VOCs}=3 VOCs could not be separated by the GC/MS to calculate the concentration, including d-limonene, propane,1-(1,1-dimethylethoxy)-2-methyl and an unidentifiable VOC. [1]Emission factor at 24 hrs, using power law decay model, [2]Computer emission factor values are the average at time equals to 8, 10 and 12 hours during the on period, [3]Printer emission factor values are the average values during the printing and post-printing period, [4]Copier emission factor values are during the copying period.

Impact Of Emissions On An Office Environment

Emission data from the tests were used to simulate the impact of the sources on the VOC concentrations in an office environment. First, all the data was added to the database of a simulation program, MEDB-IAQ (Zhang et al. 1999). Simulations were then conducted, modeling a typical workstation system consisting of partitions, work surfaces, shelves, and flipper and pedestal file cabinets. In addition, a computer, a printer, a copier and a carpet were included in the simulations. A 10ft x 13ft x 9ft high room was used with a ventilation rate of 0.66 ach during the working hours (8:00-17:00) and 0.25 ach during the non working hours (0:00-8:00 and 17:00-24:00). Ventilation rate during the working hours was based on the ASHRAE standard 62 (2004) (i.e. 5 cfm/person plus 0.06 cfm/ft^2). The printer was active from 8:00 to 9:00 every morning and the copier was active from 13:00 to 14:00 during the afternoons. It is apparent that operations of the printer and copier significantly elevated the VOC concentrations (Figure 3). In addition, the concentration of the TVOC and the IVOCs are decreasing very slowly from day to day due to the decay sources. Table 2 shows that the operation of copier, printer and computer had significantly more contributions to the toluene concentration than the furniture components. The same results were observed for Sum VOCs, TVOC and IVOCs from the active sources.



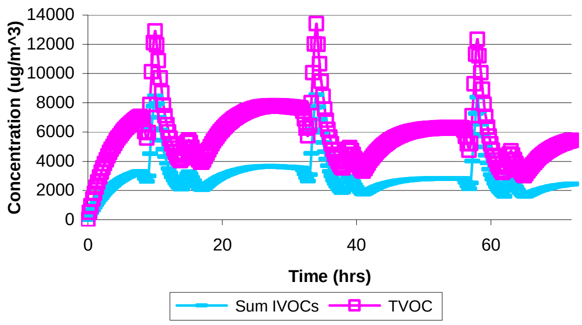


Figure 3. *Impacts of emissions of tested sources on VOC concentrations in a typical office environment*

Table 2. *Relative contributions of individual sources to the total of toluene concentration in the room*

Component	Computer 2	Printer 2	Copier	Drawer + Cabinets	Table	Carpet	Chair	Panels	Room
Amount	1	1	1	2.36m^2	2.23m^2	12.08m^2	1	12 m^2	33.13 m^3
Conc-Toluene (μg/m^3)	16.274	60.146	80.653	0.396	0	1.073	0	1.715	160.25
$C_{Tol\text{-}comp}/C_{Tol\text{-}room}$	0.102	0.375	0.503	0.002	0	0.007	0	0.011	1.000

CONCLUSIONS

1. Emissions were 10 to 120 times higher when the computers were “on” than “off”. All three computers emitted m-xylene, p-xylene, pentadecane, phenol, and toluene.
2. Toluene was the only common VOC found in emissions from all three printers tested. The inkjet printer was the one with lower emissions.
3. Styrene was found in the carpet test, two computer tests and one printer test.
4. Pentadecane and toluene were found during the in 3 out of 5 “passive” source tests.
5. Emission rates were highest when the copier and printers were in the operating mode while significant emission also existed immediately after the operating period.
6. Emission factors of the passive sources tested decreased over time following the power-law approximately.
7. The operation of the printer, copier and computer had most significant impact on the overall VOC concentrations in a typical office environment based on the simulations.

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