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Characterization of VOCs, ozone, and PM_{10} emissions from office equipment in an environmental chamber

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Abstract

Indoor air pollution in working places is widely recognized as one of the most serious potential environment risks to human health (WHO, Indoor air quality research: Report on a WHO meeting Stockholm 1984, Euro-reports & Studies 103, WHO, Copenhagen, Denmark 1986, p. 1–64). A stainless steel flow-through environmental chamber was used to characterize the emissions rate of pollutants from office equipment. Different types of office equipment (including fax machines, laser printers, ink-jet printers, scanners, and photocopying machines) were investigated. The concentration of volatile organic compounds (VOCs), total VOC (TVOC), ozone, respirable particles (PM_{10}) and temperature were measured. Characterization the species of VOCs was carried out by gas chromatography—mass selective detector (GC-MSD). The highest emission rates of VOCs compounds were toluene, ethylbenzene, *m*, *p*-xylene, and styrene. Results showed that emissions of ozone and VOC from laser printers were significantly higher than that from ink-jet printers. The emission rates of TVOC varied from 0.2 μg/copy(ink-jet printer) to 7.0 μg/copy(laser-jet).

Keywords: Indoor air quality; Office printers; Environmental chamber; Office printers; Indoor emissions characterization

1. Introduction

People spend approximately 80% of their time in indoor environments such as residences, public buildings, and offices. The indoor levels of air pollutants can be several hundred times higher than that of outdoors. (U.S. EPA's TEAM Studies [1,2]). Office environments have changed rapidly with the advent of electronic technologies; with laser-jet printers and ink-jet printers becoming commonplace. The modern office technology has now become part of daily office practice. Different types of office printers have been used to an ever-increasing degree since its first commercial introduction. The consequence of the extensive use of modern office equipment is that office workers are exposed to an office climate giving rise to health effects such as headache; mucous irritation and dryness in the eyes, nose and throat; and dry and tight facial skin. Researchers, including Wolkoff et al. [3–5], reported that the operation of office equipment not only contribute to increase indoor air pollutant concentrations, but also, in some cases, has been associated with health complaints from exposed workers. The increased levels of ozone, volatile organic compounds (VOCs) and formaldehyde in a chamber evaluation of operating office equipment were observed in many researches. For example, the users of laser printers and copiers need to aware of ozone gas and its potential harmful effects. The recommended maximum level of ozone is 100 $\mu g/m^3$ which is suggested by American Conference of Governmental Industrial Hygienists (ACGIH). The current occupational safety and health administration (OSHA) standard for ozone concentration levels for occupied buildings is set at 200 $\mu g/m^3$ (0.10 ppm). This is a ceiling limit which should not be exceeded for any period of time. And the World Health Organisation guideline for ozone is 150–200 $\mu g/m^3$ for 1 h (WHO [6]). This study is aimed to identify, characterize and evaluate pollution prevention opportunities to reduce air emissions from office equipment. The objective of this study included:

(i) To characterize the IAQ emissions from various types of office printers by using a dynamic environmental chamber
(ii) To determine emission rates of ozone, particulate, TVOC as well as individual VOC from different office printers

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(iii) To develop pollution prevention solutions to reduce indoor air emissions from office equipment. The results can provide an understanding on the emission rates of individual pollutants and create the opportunity to determine whether specific adverse health effects may occur, allow for a prioritization of pollutants based on total quantity emitted or relative toxicity, and provide information on the root cause of emissions.

1.1. *Ozone emission*

Ozone is the by-product of the electrophotographic process, and is generated by the corona wires which place charges onto photoconductive materials. Therefore the ozone emission is determined by the amount of voltage over the corona wires. Ozone trapped inside the toner cartridge can destroy the charge generation and transfer layers, as well as the polymeric coating on the toner drum surface. The chemicals which make up these photoactive layers are all susceptible to ozone. Ozone can cause eye, nose, throat, and lung irritation. It can also cause headaches and a dryness of the eyes, nose, and throat. Various regulatory agencies and standard setting organizations—such as OSHA, ACGIH, the Health and Safety Executive in UK, and Canadian Federal Government—have established limits for the amount of ozone to which employees may be exposed. The most current recommended standard is the ACGIH Threshold Limit Value (TLV), which is based on experimental data (human and animal) and industrial experience.

1.2. *VOCs emission*

VOC emissions from laser printers were higher as a result of emission from toners by the heat generated from the machine during the operation process. Ink-jet printers differ somewhat in how the toner is delivered in that a photoconductive drum is not necessary. In ink-jet printers, the toner is sprayed towards the paper; in bubble jet printers, a bubble of toner is formed and then “bursts” towards the paper. This process is carried out line by line rather than by creating a photoprocessed image of the whole page.

1.2.1. *PM_{10} (particles with diameter less than 10 μm) Emissions*

The toners used in laser printers contain a wide variety of chemicals in addition to fine, black carbon particles or dyes and pigments for color toners. A study (Schnell et al. [7]) found the concentration of black carbon aerosol produced by a photocopier occasionally raised room levels to the 1 $\mu g/m^3$ level. This is equivalent to black carbon levels observed in urban areas under moderate vehicle traffic. The concentration of finely dispersed, charged black carbon aerosol is reduced upon cessation of photocopying. The potential for particulates indoor air emissions is expected to increase over time between maintenance cycles. Typically, about 75% of the toner is transferred to the photoconductive drum. Toner particles that do not adhere to the drum become available for emission to the indoor air. The size of individual particles influences the degree to which they can be inhaled and the types of effects they can cause.

Table 1
Sampling parameter and methods

Pollutants	Method
VOCs	VOCs were collected by a canister (6 l) through Teflon tubings. Gas sample then analyzed with TO-14 method by gas chromatograph (Model HP6890)/mass selective detector(Model HP5973).
Ozone	Continuous monitoring of ozone concentrations using a Thermo Environmental Instruments ozone analyzer model 49.
Particles(PM_{10})	Continuous monitoring of particle concentrations using a DustTrak Aerosol monitor model 8520 with 100 mm cellulose ester filter.
TVOC	Continuous monitoring of TVOC concentrations using a Mini RAE Plus photoionization detector (PGM 76 K)

2. Methodology

The selection of office machines was based on the consumer market, and their emission criteria of ozone, TVOC and VOC. Two laser printers (Printer A and B), two ink-jet printers (Printer C and D), and one all-in-one (colour printer, fax, copier, and scanner) office machine (Printer E) were chosen for screening. The toner recommended by the individual manufacturers was used and a new one was placed for each test. A standard printing file has been used. Table 1 lists the measurement methods for various types of pollutants.

A special chamber was designed for this study. Stainless steel was used as the interior surfaces because of its non-adsorbent and chemically inert nature in order to minimize any potential sink effects. The size of chamber is 1200(H) × 1100(W) × 1800(L) mm. An adequate space was provided for servicing equipment in the chamber, while also allowing for air movement. In order to minimize any chemical reaction, ozone was transferred by Teflon tube and all electrical and plumbing feedthroughs were sealed with inert materials. Relative humidity in the chamber was maintained within $55 \pm 5\%$ and temperature at $23 \pm 2^{\circ}C$. The machine under test was placed in the center of the chamber on the floor. To ensure a well-defined test and comparable results, the test recommendation of the American society for testing and materials (ASTM), 1997 [8] were followed. A recovery efficiency test for carbon monoxide (CO) was conducted in the empty chamber to determine the potential leakage and wall effects at the beginning. Prior to testing, inner surface of the chamber were cleaned by scrubbing with distilled water. In order to have an adequate period for the previous pollutants to be diffused away, the background air was vented out for 2 h prior to each experiment. Background air samples in the empty chamber were measured before each test to ensure that background contamination was within quality assurance (QA) limits. All the experiments under this study were evaluated under no ventilation system in the test chamber. Equipment was placed in the center of the chamber and it was equilibrated in the chamber overnight in idle mode, that is, powered but not printing. The air was then sampled with the equipment idling to obtain data on off-gassing.

3. Measurement of office machine emissions

The tested office equipment was placed in the center of the chamber on the floor and could be turned on and off with a remote button outside the chamber. The sampling equipment for TVOC and PM_{10} were located in the chamber, at the exhaust port of the tested machine and ozone sampling was in the center of the chamber 0.6 m above floor level through Teflon tubings. VOCs sample was also collected through a Teflon tube into a 6 l canister for 30 min with a flow rate of about 0.2 l/m^3 and the sample was analyzed using a cryogenic preconcentrator GC-MSD by US-EPA TO-14 method. Sampling points for the chamber air were selected to be representative of the chamber concentrations. The test was conducted for sufficient duration to ensure adequate mixing. With the use of mixing fan, the chamber air concentration was assumed to be in equilibrium within 15 min. The concentrations of ozone and TVOC in the chamber were monitored during continuous printing at maximum print rate for 60 pages. An integrated reading was taken every minute until 30 min after the machine was turned off. The results were used to indicate the maximum ozone and TVOC concentrations. Temperature reading was taken in the same interval as ozone reading, but stopped when the printing process finished. A duplicate set of VOCs, TVOC, ozone and PM_{10} were collected for analysis.

4. Results and discussion

Average TVOC, ozone, and PM_{10} emissions from various types of office equipment are listed in Table 2. The amount of TVOC produced depends on the type of printer mechanism applied. Laser printers use heat and pressure to fix an image onto the paper surface. The generated heat encouraged the evaporation of VOCs compounds. The emission rates of laser printers were the highest and found to be about 6 times that of ink-jet printers. There is a tendency for laser printers to emit larger amounts of volatiles organic compounds than ink-jet type.

Emissions from office printers result from operation and offgassing from components. For equipment that does not use supplies (e.g., toner, ink, and paper), emissions are primarily from offgassing of residual organics. The source can be either construction materials (e.g., plastic casings) or components (e.g., circuit boards). Equipment that uses supplies has emissions from both offgassing and operation. As shown in Table 3, VOCs were identified and quantified during the operation of office equipment. The emissions of idle mode from all equipment were relative lower comparing with the emissions from operation. The four greatest individual substances found in all equipment were aromatic compounds such as toluene, ethylbenzene, *m*-*p*-xylene, and styrene. These four compounds were normally used as solvent in toner for printers. The greatest relative difference out of toluene, ethylbenzene, *m*-*p*-xylene, and styrene between idle and operation modes was found to be 47% for Ethylbenzene. Ethylbenzene occurs naturally from the production of the binder. According to the toner composition data sheets given by the manufacturers, about 15% of the laser printer toners are made of carbon black, auxilliary pigment and additives. The evaporation rate of the above compounds are all sensitive to temperature. Laser printer toner powders were heated to the temperature of the "fusion" roller of the laser printers examined. The average temperature for laser printers were generally higher than ink-jet type during operation. Elevated temperatures used in fusing can be expected to increase the voltilization of VOCs present in the toner. This explains why the emission of VOCs compounds was much greater for laser printers (Printers A & B). The tendency of TVOC is similar to that of VOCs as shown in Fig. 1. The toners used in laser printers contain a wide variety of chemicals in additional to fine, black carbon particles. A substantial amount of VOCs was from such chemical in toner (Wokloff et al. [4]).

Table 2
Average TVOC, ozone, PM_{10} emission from standard copies (μg/copy) from two laser printers (A,B), two ink-jet printers (C,D) and one all-in-one office machine(E)

Equipment	TVOC (μg/copy)	Ozone (μg/copy)	PM_{10} ($\mu g/m^3$)
A	5.7	1.20	65
B	7.0	1.00	65
C	1.2	0.05	20
D	0.7	0.05	38
E	0.2	0.05	41

Ozone results are tabulated in Table 4. The ozone emission rates were affected by temperature, and electric power (W) (Hansen et al. [9]).

Ozone is generated from corona wires of laser printers. For laser printer, electrically charged corona wires are used to add a uniform primary charge across the surface of the photosensitive drum. These wires are used to apply charges to paper and to electrostatically clean the cartridge drums. During this process, ozone is created. Therefore, the electric effect played an important role in the free-radical chain

Table 3
Average levels of VOCs (unit : ppbv) from Office Equipment A, B, D and E (two laser printers (A,B), two ink-jet printers (C,D) and one all-in-one office machine(E))[a]

Target compound	Idle				Operation			
	A	B	D	E	A	B	D	E
Freon12	0.48	0.52	0.36	0.30	0.61	0.66	0.43	0.45
Methyl chloride	0.53	0.60	0.48	0.52	0.71	0.82	0.55	0.62
Freon114	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
1,3-Butadiene	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Freon11	0.24	0.29	0.23	n.d.	0.25	0.28	0.24	0.27
1,1-Dichloroethene	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Methylene chloride	0.38	0.42	0.57	0.69	0.46	0.58	0.61	0.74
Freon113	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Chloroform	0.96[b]	1.07[b]	0.81	0.74	1.17	1.31	0.94[b]	0.96[b]
Benzene	0.52	0.57	0.42	0.52	0.77	0.84	0.41	0.52
Carbon tetrachloride	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Trichloroethene	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Toluene	14.7[b]	13.8[b]	6.22[b]	7.89[b]	15.3[b]	16.36[b]	6.43[b]	8.17[b]
Tetrachloroethene	n.d.	n.d.	0.23	0.52	n.d.	n.d.	0.21	0.43
Ethylbenzene	1.37[b]	2.07[b]	1.2[b]	1.5[b]	1.99[b]	3.00[b]	1.26[b]	1.63[b]
m, *p*-xylene	1.16[b]	1.22[b]	0.86[b]	0.9[b]	1.56[b]	1.68[b]	0.92[b]	0.87[b]
Styrene	2.71[b]	3.98[b]	1.14[b]	1.23[b]	3.19[b]	5.27[b]	1.43[b]	1.85[b]
o-Xylene	0.86	0.99	0.69	0.58	1.96[b]	2.29[b]	0.68	0.58
1,3,5-Trimethylbenzene	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
1,4-Dichlorobenzene	n.d.	n.d.	0.34	0.34	n.d.	n.d.	0.32	0.35
1,3-Dichlorobenzene	n.d.	n.d.	0.34	0.34	n.d.	n.d.	0.32	0.35
1,2,4-Trimethylbenzene	n.d.	n.d.	n.d.	0.26	n.d.	n.d.	n.d.	0.22
1,2-Dichlorobenzene	n.d.	n.d.	0.21	0.23	n.d.	n.d.	0.21	0.20
1,2,4-Trichlorobenzene	n.d.	n.d.	0.86[b]	0.88[b]	n.d.	n.d.	0.63	0.64
Hexachlorobutadiene	n.d.	n.d.	0.37	0.21	n.d.	n.d.	0.36	0.21

[a]n.d. means not detectable, when the concentration of pollutants was below 0.2 ppbv (detection limits for the pollutants), n.d. was marked. Unit for the compounds : ppbv. Machine E was operated in copy mode.
[b]Five highest peaks.

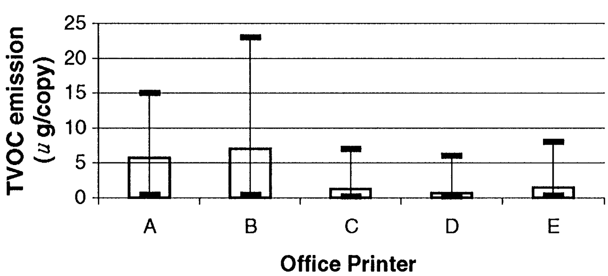

Fig. 1. Minimum, average, and maximum TVOC emission rate for printers A–E.

Table 4
Average ozone emission and conditions in the chamber for five office equipment

Machine	Average temperature chamber in (°C)	Electric power (W)	Equilibrium ozone concentration (ppm)	Average ozone emissions rate (μg/copy)
A	30	374	10	1.2
B	32	408	9	1
C	23	12	5	0.1
D	24	12	6	0.1
E	24	15	6	0.1

reaction during the formation of ozone process in a printing operation. Printed images are produced by charging and discharging process on a drum with generated electrons which depending on the electric voltage and power. During a printing operation, an oxygen molecule, O_2, was broken into two oxygen radicals, O. The energy for this dissociation was provided by the temperature generated and the electrical energy. Both of the average temperature and electric power were recorded to be higher in Printers A and B than that of Printers C and D (Table 4). Such high energy levels encouraged the free-radical chain reaction and hence the formation of ozone. Therefore, the amount of ozone produced really depending on the amount of voltage and charge to the toner drum. The results reported here for ozone can be compared to those done by other researchers (Allen et al. [10]; Selway et al. [11]; Hansen and Andersen [9]). Also, toners in laser printers, composed of plastic and carbon black, may cause residual problems by interfering with the transfer of electrons and charged particles and consequently contributing more ozone production. The residual problem together with the higher electric watt available in a laser printer cause the higher ozone production found in Printers A and B as listed above (Fig. 2). The reason for ink-jet printers

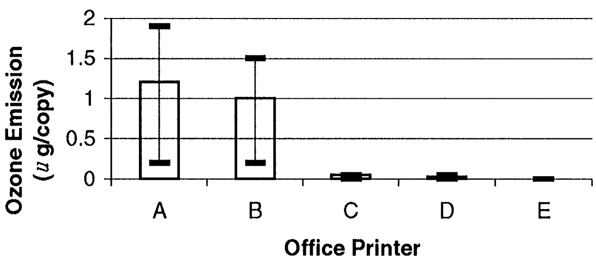

Fig. 2. Minimum, average, and maximum ozone emissions rate for printers A–E.

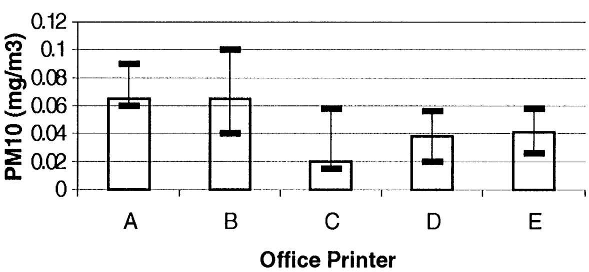

Fig. 3. Minimum, average, and maximum PM_{10} levels of printers A–E.

(Printers C–E) having a lower ozone emission rates is because of the different mechanism applied from laser printer. Ink-jet printers do not use a true photo-imaging process; that is, a photosensitive drum is not used to impart the image. Instead, the image is formed when a nozzle "sprays" the ink toward the paper character by character.

Toner powder in the air exhaust from laser printers can cause dust emission in the indoor environment. Particles problem was caused by the low transfer efficiency of the toner. The size of the toner particles in the carbon black itself is below 10 μm in diameter (Hansen et al. [9]). The measurements of PM_{10} are shown in Fig. 3. In the low ventilation rate of the chamber the average PM_{10} concentrations of Machines A and B were 65 $\mu g/m^3$ which were much higher than that for Machines C, D and E 20, 38, and 41 $\mu g/m^3$, respectively. Eggert et al. [12] measured emissions of particulates from 20 different laser printers and found the average emission rate to be 61 μg/min. However, the maximum particulate levels of Machines A and B exceeded the national ambient air quality standard (NAAQS) which listed to be 75 $\mu g/m^3$.

5. Pollution control opportunities

According to the results shown above, laser printers (Machines A and B) produce higher levels of TVOC, ozone, particulates PM_{10}, and individual VOCs compounds. Large numbers of fresh printings can contribute substantially amount of pollutant concentration. Pollution prevention opportunities for office equipment can be applied to machine design, and toner materials used. As mentioned above that laser printers use heat and pressure to fuse the image to the paper. Elevated temperatures used in fusing can be expected to increase the volatilization of VOCs present in the toner. The fusing process therefore may also provide some opportunities for pollution prevention. Reducing fuser temperature (by changes in pressure) may result in lower VOC emissions. The VOC emissions from ink-jet printers occurred from the volatilization and/or aerosolization of toner and toner solvents. Reformulation of toners using lower-volatility solvents can result in lower emissions. In order to improve the toner transfer efficiency to minimize the amount of toner particles available for emission into the indoor air, changes in toner particle size and a regular maintenance cycle can have a serious impact (Selway et al. [11]). The size of the particles emitted also influence the degree to which they are inhaled and the potential adverse effects. A recent development by Canon using direct contact charging rollers replacing corona wires have shown to be effective to prevent the formation of electrical arcs and ozone. The new design has resulted in lowering ozone emissions (Palmeri [13]). In conventional designs, high voltages are applied to the corona wires to attain the needed charge for a small distance between the toner drum and paper surface. The new direct contact design avoids the use of high voltage and hence reduces the formation of ozone.

6. Conclusions

Individual VOC compounds have been characterized by GC-MSD analyzer. Aromatic compounds (toluene, *m*, *p*-xylene, ethylbenzene, and styrene) found to be the dominant substances in all tested printers due to their low thresholds. Emissions from laser printers (Printers A and B) were higher than that from ink jet printers (Printers C–E), because of the higher temperature generated from fusing process and hence encouraged further evaporation of the organic compounds. Reformulation of toners using lower-volatility solvents/black carbon can result in lower VOC emissions. Also, changes in toner particle size may have an impact on fusing process. It is important to reduce both fuser temperature and pressure to minimize the emission of VOCs.

Ozone generation was only found in laser printers (Printers A and B). The ozone generated by laser printers is a by-product of the electrophotographic process, and was generated when the corona wires placed charges onto photoconductive materials. Installation of a new direct contact electrical charge rollers by many manufactures has resulted that the measured ozone concentration were significantly lower than the international guideline of 150–200 $\mu g/m^3$ for 1 h (WHO [6]).

The root cause of the particles is due to the poor transfer efficiency between the charged toner drum and paper surface. As the photoconductive surface of the drum deteriorates, the toner transfer efficiency decreases increasing the potential for indoor air emissions. A regular maintenance check is necessary to restore the transfer efficiency to its original state and reversing the trend of increasing potential for particulate pollution.

Each of the individual pollutants associated with office equipment has the potential to cause adverse effects if exposures are sufficiently high or if people exposed are sensitive. It is essential to investigate the root cause of emissions in order to reduce the emission, but it is rather difficult to examine all the possible factors which affect the pollutant emission from office equipment since different machines and processes give a wide range of emission levels. Even for the same machine model, the emission levels would be affected by other factors such as age, product history, maintenance cycle, air exchange rate, and product loading. Evaluation of emissions control should not only concentrate on one strategy, but also focus on source control, ventilation, and air cleaning or a combination of these. Identifying specific constituents of concern can direct efforts to reformulate the source material (e.g., toner, photoconductive surface in the case of laser printer) or make alterations in the process that will reduce the emission potential.

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References

[1] U.S. Environmental Protection Agency. Unfinished business: a comparative assessment of environmental problems, EPA-230/2-87-025a-e (NTIS PB88-127030). Office of Policy, Planning and Evaluation, Washington, DC, 1987.

[2] U.S. Environmental Protection Agency. Office equipment: design, indoor air emissions, and pollution prevention opportunities. Air and Energy Engineering Research Laboratory, Research Triangle Park, 1995.

[3] Wolkoff P, Johnsen CR, Franck C, Wilhardt P, Albrechtsen O. A study of human reactions to office machines in a climatic chamber. Journal of Exposure Analysis and Environmental Epidemiology 1992;1(Suppl.):71–96.

[4] Wolkoff P, Wikins CK, Clausen PA, Larsen K. Comparison of volatile organic compounds from office copiers and printers: methods, emission rates, and modeled concentrations. Indoor Air 1993;3:113–23.

[5] Wolkoff P. Photocopiers and indoor air pollution. Atmospheric Environment 1999;33:2129–30.

[6] World Health Organisation (WHO). Air quality guidelines for Europe. WHO Regional Publications, European Series No. 23, Copenhagen, 1987.

[7] Schnell RC, Allen GA, Hansen ADA. Black carbon aerosol output from a photocopier. Presentation at the 85th Annual Meeting & Exhibition Air & Waste Management Association, Kansas City, MO, June 21–26, 1992.

[8] The American Society for Testing and Materials. Standard Guide for Small-Scale Environmental Chamber Determinations of Organic Emissions From Indoor Materials/Products (D 5116 -97), 1997.

[9] Hansen T, Andersen B. Ozone and other air pollutants from photocopying machine. American Industrial Hygiene Association Journal 1986;47:659–65.

[10] Allen RJ, Wadden RA, Ross ED. Characterization of potential indoor sources of ozone. American Industrial Hygiene Association Journal 1978;39:466–71.

[11] Selway MD, Allen RJ, Wadden RA. Ozone production from photocopying machines. American Industrial Hygiene Association Journal 1980;41:455–9.

[12] Eggert TA, Grove SC, Drabaek I. Emission of ozone and dust from laser printers. Presentation of a New Emission Source Test Method, Proceedings of 1990 EPA/AWMA International Symposium on Measurement of Toxic and Related Air Pollutants. Raleigh, NC, EPA-600/9-90-026 (NTIS PB91-120279), 1990.

[13] Palmeri J. Canon. March ed., 1994.