FINAL REPORT:
METHODS FOR CHARACTERIZING EMISSIONS FROM LASER PRINTERS

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ABSTRACT

Since the energy crisis of the early 1970's, buildings have become more energy efficient through such measures as the reduction of outdoor air supplied to the building and the tightening of the building envelope. During this time, complaints about the indoor environmental quality (IEQ) have become common. Research has been conducted on ventilation and microbial contamination, but little has been done to evaluate activities contributing to poor IEQ. In addressing this research need, a study was conducted to develop methods for determining ozone, particulate and volatile organic compound (VOC) emission rates from laser printers, and to provide emission rates for a limited number of printers. A series of test runs were conducted on four different printers in a validated environmental chamber. Older printers, utilizing a corona wire, produced significant levels of ozone. Maintenance of the older printers' ozone filter tended to reduce ozone generation. Newer printers, using a charged roller rather than a corona wire, produced little ozone. Particulate levels were extremely low for all printers. Volatile organic compounds (VOCs) were produced with butanol and xylene being the primary components identified. The significance to the VOC generation rates will depend upon the other sources of VOCs present. The methods and data generated here will help provide building designers with the information needed to adequately size a building's heating, ventilating, and air conditioning system, thereby maintaining acceptable IEQ.

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a	Mean printer regression coefficient
a_i	Printer regression coefficient for i^{th} print run
ACGIH	American Conference of Governmental Industrial Hygienists
ASHRAE	American Society of Refrigerating and Air-Conditioning Engineers
AIHCE	American Industrial Hygiene Conference and Exposition
ASCII	American Standard Code for Information Interchange
b_L	Mean ozone concentration regression coefficient
b_{L_i}	Ozone concentration regression coefficient for i^{th} print run
b_{RH}	Mean relative humidity regression coefficient
b_{RH_i}	Relative humidity regression coefficient for i^{th} print run
C	Concentration
C_o	Inlet concentration
C_{O_3}	Ozone concentration
C_{t_1}	Concentration at time t_1
C_{t_2}	Concentration at time t_2
C_∞	Concentration at time $t = \infty$
G	Generation Rate
$\bar{G}_{part_{decay}}$	Particle generation rate during decay
$G_{mass_{printer}}$	Printer mass particle generation rate
$G_{mass_{run}}$	Print run mass particle generation rate
G_{O_3}	Ozone generation rate

$G_{(O_3)_L}$	Lower 95% confidence interval of G_{O_3}
$G_{(O_3)_H}$	Upper 95% confidence interval of G_{O_3}
$G_{part_{printer}}$	Printer particle generation rate
$\bar{G}_{part_{printing}}$	Particle generation rate during printing
$G_{part_{run}}$	Print run particle generation rate
HEPA	High efficiency particulate air
HSE	Health and Safety Executive
IAQ	Indoor air quality
IEQ	Indoor environmental quality
K	Mixing factor
LOD	Limit of Detection
MCS	Multiple chemical sensitivity
MSDS	Material safety data sheet
N	Air exchange rate
n_i	Number of particles in i^{th} APS size range
NIOSH	National Institute for Occupational Safety and Health
OSHA	Occupational Safety and Health Administration
PEL	Permissible Exposure Limit
Q	Flow rate
r_i	radius of i^{th} APS size range
REL	Recommended Exposure Limit
s_a^2	Variance of a

$s_{a,L}$	Covariance of a and b_L
$s_{a,RH}$	Covariance of a and b_{RH}
$s_{G_{O_3}}$	Standard error of G_{O_3}
$s^2_{G_{O_3}}$	Variance of G_{O_3}
s^2_L	Variance of b_L
$s_{L,RH}$	Covariance of b_L and b_{RH}
s^2_{RH}	Variance of b_{RH}
t	time
t_1	Time 1
t_2	Time 2
t(0.025, n-1)	Student's t statistic with $\alpha = 0.025$ and n-1 degrees of freedom
t(0.975, n-1)	Student's t statistic with $\alpha = 0.975$ and n-1 degrees of freedom
TLV	Threshold Limit Value
TWA	Time weighted average
V	Volume
VDT	Video display terminal
VOC	Volatile organic compounds
x_{SF_6}	Concentration of SF_6
y_{SF_6}	Instrument Response to SF_6
$\Delta H°_f$	Heat of formation
$_L$	Ozone concentration coefficient
$_{RH}$	Relative humidity coefficient

ϵ	Error term
μ	Printer coefficient
ρ	particle density

INTRODUCTION

Since the energy crisis of the early 1970's, buildings have become much more energy efficient. This increase in energy efficiency has been achieved through a combination of measures including the reduction of outdoor air delivered to the occupied spaces and a tightening of the building envelope. As buildings have become more efficient, complaints about the indoor environmental quality (IEQ) have become common.

An abundance of research has been conducted to look at the problems associated with indoor environmental quality (also known as indoor air quality). This research has included such problems as Sick Building Syndrome and Building Related Illness. Ventilation has been extensively researched, as well as the contribution of microorganism contamination to poor IEQ. This research has been conducted by a variety of organizations, including government agencies, universities, private research laboratories, and private industry. A wide variety of conferences and meetings have also been held to discuss IEQ. Among these are the IAQ conferences sponsored by the American Society of Heating Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE), as well as sessions at the American Industrial Hygiene Conference and Exposition (AIHCE).

Maintaining acceptable indoor environmental quality has becoming critical. One estimate places more than 60 percent of the workforce in the western hemisphere in office settings.[1] This percentage is expected to increase in the future.[2]

The ASHRAE Standard 62-1989, Ventilation for Acceptable Indoor Air Quality, provides two methods for determining the ventilation requirements for given occupancy.[3] The first method, the Ventilation Rate Procedure, specifies the volumetric flow rate per person of outdoor air for a particular type of occupancy. This procedure assumes that the supply of outdoor air is of a minimum quality and that any sources of contaminants in the building are controlled at the source. The second method, the Indoor Air Quality Procedure, bases the required outdoor air flow rate on maintaining the concentration of four contaminants, carbon dioxide, chlordane, ozone, and radon, at or below specified levels. To determine the ventilation requirements, emission rates for these contaminants must be known. In addition to these four contaminants, Standard 62-1989 also recognizes that other contaminants may be present in the indoor environment and that they may also need to be controlled. Precise concentration levels for these other contaminants may be difficult to determine. Control, therefore, may need to be done on a subjective basis.

A variety of contaminants may be generated within the occupied spaces of buildings. Some, such as carbon dioxide, are produced by the occupants. Others are generated by the building's furnishings or materials of construction, while still others can be

attributed to the activities taking place within the building. Office equipment such as computers, laser printers, photocopiers, and facsimile machines relate to the activities taking place within the building and have the potential for generating a wide variety of contaminants.[4] The primary goal of this project was to develop a method for characterizing the chemical emissions from common office equipment like printers, photocopiers, and facsimile machines. This project, conducted by researchers in the Engineering Control Technology Branch of the Division of Physical Sciences and Engineering, the National Institute for Occupational Safety and Health, involved the operation of office equipment inside a small environmental chamber and identification of the chemical compounds released.[5] Emission rates of these compounds were then determined for each piece of equipment tested. This work may help in identifying some of the factors associated with IEQ problems, as well as providing direction for implementing effective engineering controls. Because of the proliferation of laser printers used with personal computers, as well as the number of machines readily available for this study, laser printers were chosen as the piece of equipment to evaluate. Therefore, there were two specific goals for this study: to develop and evaluate methods to estimate generation rates for laser printers; and to obtain aerosol, ozone and volatile organic compound generation rates for the tested printers.

LITERATURE REVIEW

Several studies have reported symptoms (dermatitis, rhinitis, pharyngeal constrictor muscle spasms) directly related to office equipment such as laser printers, photocopiers, or video display terminals (VDTs).[1,6,7] Other studies have associated symptoms (headache, fatigue, drowsiness, etc.) with the handling of paper processed by photocopiers.[8] The Danish town hall studies showed that photocopiers and computer terminals were significant risk factors in Sick Building Syndrome.[9,10] Reports have also linked office equipment to multiple chemical sensitivity (MCS). Several cases have linked the onset of MCS to photocopiers,[11,12] while other reports identified office equipment as items which could cause a reaction in persons already suffering from MCS.[13,14] In one instance, a case of siderosilicosis was tied to a long-term exposure to photocopier toner.[15] Several researchers have looked at ozone emissions from office equipment as a contributor to indoor environmental quality problems. One study evaluated ozone generation from typewriters and photocopiers in a sealed room.[16] This study found that several of the evaluated photocopiers produced substantial quantities of ozone, and estimated ozone generation rates for the tested photocopiers. The typewriters did not produce any measurable quantities for ozone. A follow-up to this study evaluated an additional number of photocopiers as well as looked at the effects for servicing on ozone generation.[17] Like the original study, the tested machines produced considerable ozone. Machine maintenance affected ozone generation rates, although this effect did not appear to be long lasting. Several other studies discuss ozone generation in the office setting,[18,19,20] some providing worker ozone exposure data.[19] However, these studies did not provide estimates on generation rates and included little information on laser printers. Several studies discussed volatile organic compound emissions from office equipment.[18,21,22] These studies reviewed the compounds present in the indoor environment or in the equipment. In most of these studies, little was done to determine emission rates from the pieces of equipment studied.

Many IEQ related studies have been conducted utilizing various types of chambers. Contaminants associated with smoking have been evaluated in a number of studies.[23,24,25,26] A substantial number have looked at building contents, most focussing on either building materials such as particle board, or furnishings such as carpet.[27,28,29,30,31,32,33,34,35,36] One study, however, did look at emissions from heated samples of a number of toner powders, processed papers from laser printers, photocopying machines and matrix printers, and carbonless copy forms.[4] This study found a wide variety of volatile organic compounds emitted by the samples.

Laser Printer Operation

The laser printing process is a multi-step operation.[37,38] First, the document or image is sent to the printer's controller by the computer. The controller then processes, or rasterizes, the image and stores the data in memory. Once an entire page has been stored in memory, the raster data is sent to the printer engine. The laser is turned on

and off rapidly by the raster data in a process called modulation. The laser beam is reflected off of a rotating mirror onto a rotating drum covered with a light sensitive material. The areas where the laser strikes the rotating drum are given a static charge. As the drum rotates, it passes a reservoir of charged toner. The toner is attracted to the charged areas on the drum. The drum continues to rotate and passes a sheet of paper. The paper, which also has a static charge, attracts the toner from the drum. The paper now contains the image being printed, although static charge is all that keeps the image on the page. The toner is melted or fused to the paper by a series of rollers which apply heat and pressure to the paper. Temperatures in the fusing process can reach 200°C. The paper cools as it exits from the printer.

Many older laser printers use a corona wire to place a charge on the paper. Corona discharge can produce ozone (O_3). The formation of ozone is an endothermic reaction. The thermodynamics of the reaction are:[39]

$$3\,O_2 \rightarrow 2\,O_3 \qquad \Delta H^\circ_f = 144.8 \text{ kJ/mol } (34.61 \text{ kcal/mol}) \qquad (1)$$

where ΔH°_f is the heat of formation. The formation of ozone by corona discharge is a two reaction process.[39,40] Corona discharge is a silent discharge which accelerates electrons giving them enough kinetic energy to split the double bond in the oxygen molecule (O_2) to yield oxygen atoms (O).

$$O_2 + \text{high energy electron} \rightarrow 2O + \text{low energy electron} \qquad (2)$$

In the second reaction, atomic oxygen reacts quickly with a second oxygen molecule to form ozone.

$$O + O_2 \rightarrow O_3 \qquad (3)$$

Ozone is highly reactive and will react with atomic oxygen to reform oxygen molecules.

$$O_3 + O \rightarrow 2\,O_2 \qquad (4)$$

Ozone may also react with other compounds which may be present. Many newer laser printers are advertised as being virtually ozone free. These newer designs have replaced the corona wire with a charged roller for placing the charge on the paper.

Laser printer toner is made up of small thermoplastic particles impregnated with smaller particles of iron. According to a review of a number of material safety data sheets (MSDS) for toners, most contain iron in the form of iron oxide (CAS No. 1317-61-9) while most of the polymers in the toner are acrylic in nature (i.e. styrene

acrylate copolymer). Many of the MSDSs list more than one polymeric compound as well as a number of other additives, such as pigments.

As mentioned, one earlier study has evaluated emissions from nine toner powders (six from photocopiers, three from laser printers) and eleven types of processed papers from laser printers, photocopying machines, and dot matrix printers. In this study, samples of the toner or paper were heated to 185°C (365°F).[4] A total of 61 volatile organic compounds (VOCs) were identified from the variety of toners from laser printers and photocopiers; 31 VOCs were found from just the laser printer toners. A list of the compounds emitted by the laser printer toners is given in Table 1. This study did not identify the composition of the toners evaluated. A total of 31 VOCs were identified from the paper samples processed by either a laser printer or a photocopier; 18 compounds were identified from just the laser printer processed forms. A list of these compounds is given in Table 2.

Laser printers may also be a source of aerosols, generated from at least two sources within the printer. The first is the toner, which has the potential for becoming airborne during the printing process. The second potential source is the paper. The potential for dust generation by the paper can be shown by opening a laser printer which has been in use for a substantial period of time. There will usually be an accumulation of dust (most likely from the paper) in the paper path. There may be additional sources of aerosols from the printers. However, little research has been conducted on the issue of aerosol emission by laser printers.

Table 1. VOCs emitted from toner powders heated to 185°C (365°F).[4] Printers are identified by code letters (G, H, I) as given in the reference.

Volatile Organic Compound	G	H	I
Benzene		X	
Trimethylsilanol			X
1-Butanol	X		X
Toluene	X	X	X
2-ethoxyethanol			X
C_4-cyclohexane isomers	X		X
1-butyl ether	X	X	X
Ethyl benzene	X	X	X
m- and p-xylene	X	X	X
o-xylene	X	X	X
Styrene	X	X	X
1-butyl acrylate	X		
2-phenylpropane	X	X	X
1-phenylpropane	X	X	X
Ethyl toluene isomers	X	X	X
Methylstyrene isomers		X	X
α-methyl styrene			X
Benzaldehyde		X	X
Diethylbenzene isomers	X	X	
2-ethyl-1-hexanol		X	X
Acetophenone			X
2-ethylhexyl acetate		X	X
2,2'-azo-bis-isobutyronitrile			X
2-ethylhexyl acrylate		X	X
di-(2-methylpropyl)maleate			X
2-methylpropyl cinnamate			X
1,3-diphenylpropane			X
Phenyl benzoate			X
$C_{16}H_{18}$ isomers (including 1,3 and 2,3 diphenylbutanes)		X	
$C_{17}H_{20}$,diphenylpentane		X	
2-hydroxymethyl-2-(phenylchromiumtricarbonyl)-4-phenylbutan-1-ol			X

Table 2. VOCs emitted from paper printed on laser printers.[4] Printers are identified by code letters (G, H, I) as given in the reference.

Volatile Organic Compounds	G	H	I
Benzene	X	X ●	X
1-Butanol	X ●	X	X
Toluene	X ●	X ●	X
Hexanal	X	X	X
1-butyl ether	X ●	X ●	X
Ethyl benzene	X ●	X ●	X
m- and p-xylene	X ●	X ●	X
o-xylene	X ●	X ●	X
Styrene	X ●	X ●	X
2-phenylpropane	X ●	X ●	X
1-phenylpropane	X ●	X ●	X
Ethyl toluene isomers	X ●	X ●	X
Benzaldehyde		X ●	X
Diethylbenzene isomers	X ●	X ●	X
2-ethyl-1-hexanol	●	X ●	X
2-ethylhexyl acetate		X ●	●
2,2'-azo-bis-isobutyronitrile			X
2-ethylhexyl acrylate		X ●	X

X - Identified in the paper.
● - Identified in the toner.

ENVIRONMENTAL CHAMBER DESIGN

As previously mentioned, a number of studies relating to indoor environmental quality have used various types of environmental chambers. One report by the U.S. Environmental Protection Agency discusses the design and operation of small environmental chambers for use in emissions studies.[41] This report classifies a small environmental chamber as being 5 m^3 or smaller. Many other studies have used small environmental chambers, but few focus primarily on the design and operational issues associated with these chamber systems.

Design Criteria

The evaluation of laser printers was conducted in a small environmental chamber. Because of the potential nature of these emissions, many different design and operational criteria were considered. First, the interior surfaces of the chamber need to be smooth, chemically inert, and non-absorbent. Stainless steel or glass are common materials of construction for small chambers. The chamber also needed an access door with seals of a non-absorbent, closed-cell material. Since air passes through the chamber, inlet and outlet ports were needed. Ports were also required for temperature and humidity measurement, as well as for sampling, if the sampling was not to be done on the outlet stream. Outlet stream sampling was preferred, however, since all contaminants were assumed to be well mixed at that point.[41] The methods for collecting samples, as well as the methods for analyzing the samples, must also be considered when designing an environmental chamber. Air flow through the chamber should also be monitored.

Conditioning of the inlet air stream is critical for emission characterization studies. Temperature and humidity of the air stream must be controlled. In addition, the inlet air should be as clean as possible, free from dusts, volatile organic compounds, and other types of contaminant compounds. Not only should the inlet air stream be as contaminant-free as possible, but once the air enters the chamber, it should be as well mixed as possible. The chamber should be evaluated for mixing before any sampling is conducted.

Specific Chamber Design

The chamber used to evaluate the laser printers measured 0.81 m (2.67 ft) by 1.22 m (4 ft) by 0.91 m (3 ft) high with a volume of 906 l (32 ft^3). A diagram of the chamber and temperature control system is given in Figure 1. It was constructed of stainless steel and had a glass and stainless steel door to provide access to the tested printers. The door seal material was foam weatherstripping covered with Teflon® pipe tape. This material minimized off gassing while still maintaining an air-tight seal. Two temperature and humidity measurement ports were provided in the chamber. Ports were also provided for connecting the data and power cables to the printer.

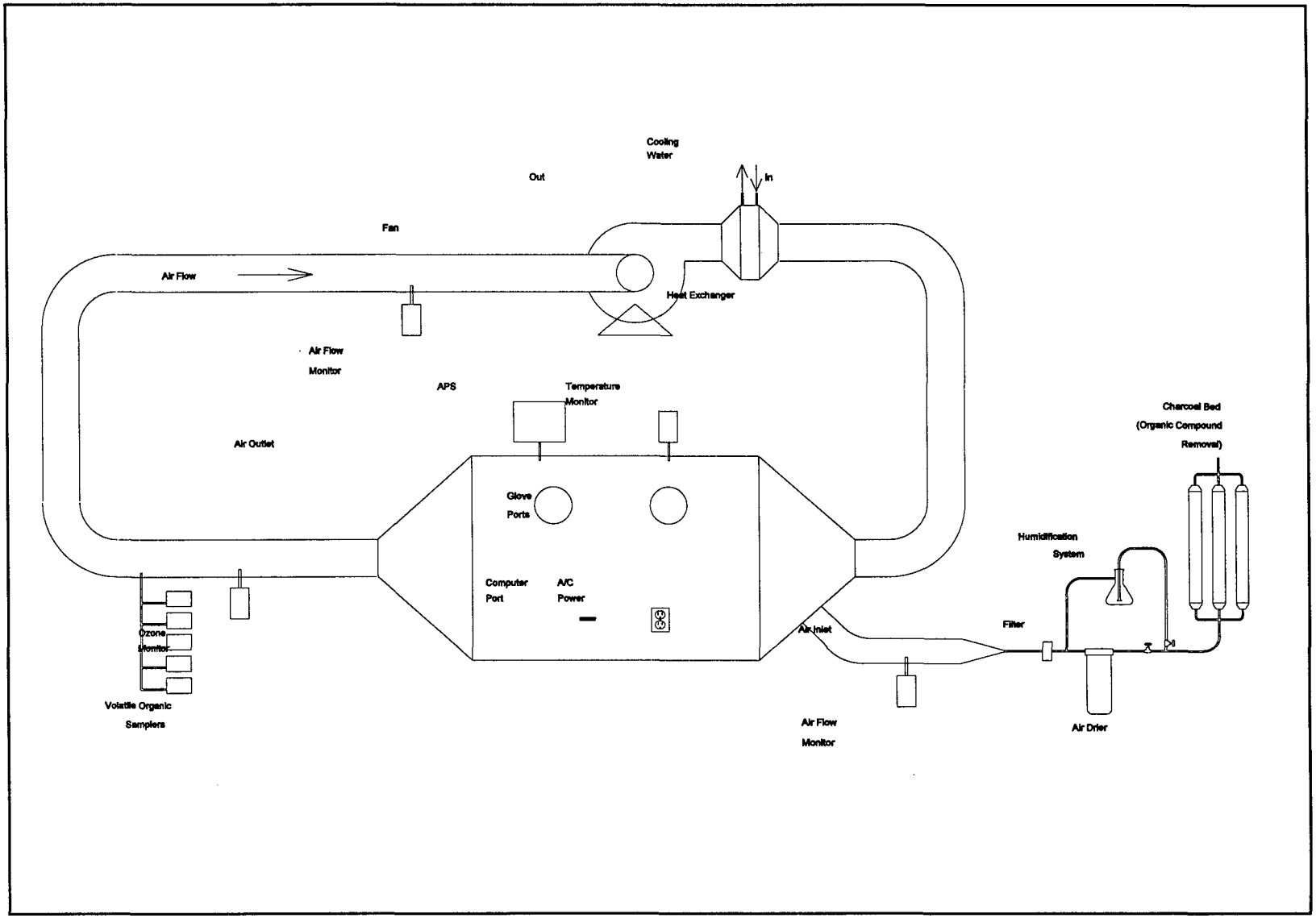

Figure 1. Diagram of printer environmental chamber, test atmosphere generation equipment, and sampling/monitoring equipment.

The environmental chamber was placed and operated in a temperature and humidity controlled room. This room had a dedicated heating and air conditioning system designed to closely control the temperature and humidity. This system consisted of an air handling unit with compressor and reheat, coupled with a humidifier. The air handling unit was controlled by both a humidistat and a thermostat. The humidifier provided a load to the system when cooling was needed. The system was set to 20°C (68°F) and 50% relative humidity. The specifications on this system called for control of temperature to ±0.6°C (1°F) and humidity to ±5%. Additional temperature control for the environmental chamber was needed due to the heat generated by the laser printers. Air was recirculated through the chamber system by a fan, with the air passing through a water cooled heat exchanger to remove the heat generated by the printer. The air recirculation system also helped to ensure mixing in the chamber. The temperature and flow rate of the cooling water to the heat exchanger was manually controlled. Before the testing of a particular printer began, the temperature control system was evaluated for its ability to maintain the chamber at a constant temperature. One potential concern was condensation of water on the heat exchanger. This problem, related to the humidity in the chamber, was eliminated by maintaining the temperature of all chamber surfaces above the dew point (i.e, operating the heat exchanger at a high enough temperature to prevent condensation from forming). The chamber supply air was cleaned by passing it through a bank of charcoal and then a high efficiency particulate air (HEPA) filter.

The supply air flow rate to the chamber system affected the concentration of contaminants in the chamber. Assuming a tracer gas is introduced into the inlet stream of the chamber, the theoretical chamber concentration, as a function of time, is given by the equation[41]

$$C = C_o (1 - e^{-Nt}) \qquad (5)$$

where,
- C = chamber concentration
- C_o = inlet concentration
- N = air exchange rate
- t = time.

The air exchange rate, N, is defined as the air flow rate through the chamber, divided by the chamber volume. The calculation of the air exchange rate assumes perfect mixing in the chamber. The recirculation fan provided the mixing for the chamber system; mixing was evaluated before each printer was tested.

SAMPLING AND ANALYSIS

Sampling for aerosols, volatile organic compounds, and ozone was conducted on the outlet air stream of the environmental chamber. In addition, temperature, humidity, and air flow measurements were also monitored.

Temperature, Humidity, and Air Flow

Temperature and humidity were monitored continuously using a Rustrak® Model POD 29/03 temperature and humidity probe and a Rustrak® Ranger I data logger (Rustrak, East Greenwich, RI). Temperature and relative humidity measurements were made in the general laboratory area as well as in the two locations in the chamber, as indicated in Figure 1. The humidity sensor was calibrated weekly with saturated solutions of lithium chloride and sodium chloride, according to the manufacturer's instructions. Although the temperature sensor of the probe was not adjustable, its measurements were compared to a glass/mercury thermometer when the humidity sensor was calibrated. The data logger stored the temperature and humidity data continuously on separate channels. Following each run, the data logger was downloaded to an IBM compatible computer using the Pronto® software supplied with the Rustrak® Ranger I data logger.

Supply air flow to the chamber was monitored with a Meriam laminar flow element, model 50MH10-INT (Meriam Instruments, Cleveland, OH). The calibration plot for this instrument is given in Appendix A. This plot is based upon a factory calibration. With this device, air flow is determined by measuring the differential pressure across the laminar flow element. The differential pressure is directly proportional to the air flow. The differential pressure was measured using a Neutronics model EDM-I electronic digital micromanometer (Neutronics N. A. Inc., Gainesville, GA).

The recirculation air flow for the chamber system was monitored using a pitot tube and a second Neutronics model EDM-I electronic digital micromanometer. Pitot tube traverses (both 6 and 10 point traverses) were made to determine air flow through the recirculation loop. During sampling, a centerline measurement was made to monitor the air flow. The analog output of each of the two electronic digital micromanometers was sent to separate channels of a Rustrak Ranger I data logger. Following each run, the data were downloaded to an IBM compatible computer.

Ozone

Ozone was monitored using a Dasibi Model 1003-AH ozone monitor (Dasibi Environmental Corp., Glendale, CA). This monitor is a monochromic, ultraviolet (U.V.) spectrophotometer, specific to ozone. It measures ozone concentration directly by the amount of U.V. radiation absorbed by ozone in an optics cell. The limit of detection for this monitor is 0.01 ppm; the response time (rise/fall for 90 percent of final value) is 18 sec. The Model 1003-AH samples at 1.5 to 3.0 l/min.[42] For this study, the instrument was operated at 2.0 l/min. The output of the ozone monitor

was connected to a Rustrak® Ranger data logger for recording and storage. The ozone monitor was factory calibrated prior to the start of this study. Before each sampling run, sample and control frequencies were recorded from the monitor as an indication of its performance. These values degraded with time, and when they reached a specified value, routine maintenance was performed.[42] Information on the calibration of this instrument is given in Appendix A.

Volatile Organic Compounds

Because of the low concentrations expected, thermal desorption methods were used to analyze for volatile organic compounds. The samples were collected and analyzed by Health and Safety Executive (HSE), Methods for the Determination of Hazardous Substances, Volatile Organic Compounds in Air (MDHS 72),[43] with several modifications. With this method, an air sample is drawn by a sampling pump through a sorbent tube, removing the volatile organic compounds from the air stream. The sorbent tubes are then desorbed by heat and the analytes transferred by inert carrier gas to a gas chromatograph for analysis. Gilian Model LFS113 Low Flow Samplers (Gilian Instrument Corp., West Caldwell, NJ) were used to collect the samples. These pumps were calibrated weekly to a flow rate of 100 cc/min, and the flow rates checked before the start of each sampling run. The sampling tubes used were packed with a multi-bed sorbent material. The first two layers were graphitized carbon black materials (Carbopack Y, $\approx$90 mg, and Carbopack B, $\approx$115 mg, respectively); the third layer was a carbon molecular sieve (Carboxen 1003, $\approx$150 mg). Sorbent tubes were desorbed with helium at 300°C for 10 min. The thermal desorber used in the analysis was a Perkin Elmer ATD 400 (Perkin Elmer, Inc, Norwalk, CT), interfaced to a Hewlett Packard 5890 gas chromatograph and a Hewlett Packard 5970 Mass Selective Detector (Hewlett Packard, Co., Bloomington, DE). All analyses were conducted in-house by NIOSH chemists. Five samples were collected for each of the initial runs so that desorption conditions could be determined. For each toner type tested, six samples were collected for each printer run; three for the determination of the generation rate, the other three for determination of the major peaks from the gas chromatograph. For the balance of the runs, three samples were collected for each run. Three samples were also collected for each of the background runs.

An initial screening of the toners used in this study was conducted to determine compounds which may likely be emitted during the printing process. Toner from each printer was loaded into thermal desorption tubes. These samples were desorbed as described above with at desorption temperatures of 150°C and 200°C.

Particulates

Aerosols were measured using a TSI Aerodynamic Particle Sizer (APS) Model 3310 (TSI, Inc., St. Paul, MN). The APS is a time of flight aerosol spectrometer which measures aerodynamic diameter over a range of 0.5 to 32 μm. It samples at a total rate of 5 l/min, 1 l/min is analyzed, 4 l/min is filtered and supplied as sheath air. Time of flight aerosol spectrometers such as the APS are based on the principle that

the magnitude of a particle's lag in an accelerating air flow is directly related to the particle's aerodynamic diameter. The lag is determined by measuring the transit time required for a particle to pass through two laser beams perpendicular to the air flow. A timer measures the time between the two pulses generated by the particle passing through the laser beams. The transit time is related to the aerodynamic diameter through a calibration with spheres of a known density.[44] The APS was calibrated prior to the start of this study, and was checked several times as the study progressed. The APS is controlled by an IBM compatible computer which stores and analyzes the data. Information on the calibration of the APS is given in Appendix A.

CHAMBER VALIDATION

The performance of the environmental chamber systems was evaluated before any printer tests began. The validation procedure was performed to ensure that the results obtained from the tests accurately reflect the emissions from the printers. All validation runs were repeated several times to ensure a valid chamber evaluation.

Temperature

The temperature control system was evaluated to ensure that it can adequately control the internal temperature of the chamber system. A laser printer was operated inside the chamber, while the temperature and flow rate of the water bath supplying the heat exchanger in the chamber system was adjusted to maintain a temperature of approximately 21°C inside the chamber. This evaluation was repeated for each printer evaluated since each printer provides a different heat load.

Relative Humidity

The chamber system was designed to control relative humidity by controlling the humidity of the supply air. The incoming air stream was split, with the air directed to a column packed with a drying agent, or bubbled through distilled water in an enclosed vessel. The design intent was to control the chamber humidity at 45%. The humidity control system was evaluated in the same series of tests as the temperature control system.

Chamber Mixing and Air Flow

Chamber air flow and mixing were evaluated using a sulfur hexafloride (SF_6) tracer gas. A Bruel & Kjaer (B&K) Multi-gas Monitor Type 1302 (Bruel & Kjaer, Naerum, Denmark) measured the tracer gas concentration in the chamber. The B&K is a photoacoustic gas monitor capable of measuring SF_6 concentrations down to the parts per billion level. The specific procedures for evaluating the mixing in the chamber are given in the Experimental Design and Procedures section of this report.

Mixing in the chamber system was determined by evaluating the decay of the SF_6 concentration in the chamber. The accumulation of a compound in a given space is the difference between the generation rate and the removal rate,[45] or

$$V\,dC = G\,dt - \frac{Q\,C}{K}\,dt \qquad (6)$$

where:
- V = volume of chamber,
- C = concentration of tracer gas at time t,
- G = generation rate,
- t = time,
- Q = chamber flow rate, and
- K = mixing factor.

If the volume of the chamber (V), the generation rate (G), the chamber flow rate (Q), and the mixing factor (K) are constant over the period of interest, equation 6 can be rearranged and integrated as follows:

$$\int_{C_{t_1}}^{C_{t_2}} \frac{dC}{G - \frac{QC}{K}} = \frac{1}{V} \int_{t_1}^{t_2} dt \tag{7}$$

where:
- t_1 = time 1
- t_2 = time 2
- C_{t_2} = concentration at time t_2, and
- C_{t_1} = concentration at time t_1.

Solving this integral for C_{t_2} yields:

$$C_{t_2} = \frac{KG}{Q}\left[1 - e^{\left(-\frac{Q}{KV}(t_2 - t_1)\right)}\right] + C_{t_1} e^{\left(-\frac{Q}{KV}(t_2 - t_1)\right)} \tag{8}$$

For the evaluation of the chamber, SF_6 was injected into the chamber system. After the injection, the decay of the SF_6 concentration was monitored. For this situation, the generation rate, G, was 0. Substituting G = 0 in equation 8 gives:

$$C_{t_2} = C_{t_1} e^{\left[-\frac{Q}{KV}(t_2 - t_1)\right]} \tag{9}$$

Solving equation 9 for K, or the mixing factor, gives:

$$K = \frac{-Q(t_2 - t_1)}{V \ln\left(\frac{C_{t_2}}{C_{t_1}}\right)} \tag{10}$$

Ideally, the mixing factor should be equal to 1, indicating perfect mixing. These validation tests were conducted to determine how close the chamber system was to perfect mixing, and were conducted prior to collecting any emission data to evaluate the design of the chamber system. The tests were repeated for each printer to determine how mixing changed with the different printers tested.

Ozone

Because of the reactivity of ozone, the loss of ozone within the chamber system needed to be quantified. This was accomplished by determining the generation or

depletion rate, G, for ozone when no ozone was being produced by the printer. Mixing (K) was assumed to be the same as for the SF_6 tests. In this instance, since ozone was being depleted, G took on a negative value. The loss of ozone was determined for each printer run by evaluating the decay of the ozone concentration following the printing of the last test page of the particular run. The ozone data, contained in a Microsoft® Excel spreadsheet, included time, and ozone concentration readings. Equation 8, rearranged to solve for G, yielded:

$$G = \frac{\frac{Q\,C_{t_2}}{K} - \frac{Q\,C_{t_1}}{K}\,e^{\left(\frac{-Q}{VK}(t_2-t_1)\right)}}{1 - e^{\left(\frac{-Q}{VK}(t_2-t_1)\right)}} \qquad (11)$$

This equation was entered into the spreadsheet for each time interval to calculate an incremental depletion rate. This value is the rate of the conversion of ozone to diatomic oxygen, and will be a function of the square of the ozone concentration, since the ozone is essentially reacting with itself.[46] A regression of the depletion rate and the square of the ozone concentration was performed to determine the depletion rate as a function of ozone concentration. This rate was later used to adjust for the effects of the ozone depletion on the ozone generation rate for each printer run.

Particulates

Validation of the chamber for losses of aerosols was extremely important due to the design of the chamber system. In addition to losses to the walls of the chamber and the ducts, the heat exchanger of the temperature control system could act as a filter and remove some of the aerosols. These losses needed to be documented and quantified.

Like the ozone, each printer run was evaluated for losses of aerosol to the chamber system. And, like the ozone, the concentration decay data were used to estimate the losses. The data from the APS were contained in a spreadsheet, and included time, and particle count readings. Equation 11 was entered into the spreadsheet to determine the incremental depletion rate of aerosols to the chamber system. The mean of this depletion rate was calculated and later used to adjust the particulate generation rate for each printer run.

EXPERIMENTAL DESIGN AND PROCEDURES

Study Design

This study was designed to meet two different goals: to develop and evaluate methods to estimate generation rates for laser printers; and to obtain aerosol, ozone and volatile organic compound generation rates for the tested printers. Toward the first goal, the intent was to develop a method that could provide repeatable and reliable estimates of the generation rates with minimal replication. If a reliable method could be developed, the second goal, estimating generation rates for a series of printers, would be met by the data collected to evaluate the test methods. A total of four printers were evaluated in this study, with two of the printers re-evaluated following the replacement of their ozone filters.

After the chamber system was evaluated to ensure proper operation, the first printer was tested in an initial series of tests. A total of ten tests were conducted on this first printer, using the procedures outlined later in this section. This initial series of tests provided information on the variability of the data so that the number of replications required for future tests could be determined. The generation rates for ozone, aerosols and VOCs were estimated from the collected data, along with the 95% confidence interval about the estimates. From this data, the size of the confidence interval for VOCs and particulates was evaluated for changing sample size to determine the effect of reducing the number of replications. Ozone was not included in this evaluation due to the complex nature of determining the confidence interval. A confidence interval of less than 20% of the mean was considered acceptable for this evaluation. The remaining tests were conducted using the most suitable sample size determined from these initial tests.

Several variables were controlled during the evaluation of the laser printers. The paper used in this study was held constant (Hammermill Copy Plus, No. 00500, Lot No. 0238 2 H7E B3A). Recycled paper was not used. The toner cartridges used in these tests were original equipment manufactured replacements. No recycled cartridges were used. The effect of toner cartridge age (number of pages printer by a cartridge) was evaluated for each printer. The page count for the toner cartridge was recorded for each test run for this purpose. The life of the toner cartridges (the number of test pages that could be printed) was determined from some of the initial printer tests. These tests helped identify how many test pages could be printed before the print quality began to degrade, and estimate the number of test runs that could be carried out on each cartridge.

The experimental procedures for this study were intended to minimize experimental error. Prior to all sampling runs, all equipment was inspected to ensure proper operation. All new toner cartridges were removed from the shipping materials and allowed to air-out for at least 24 hours before they were used in the testing. In

addition, all new toner cartridges were operated for 100 pages before they were used in the testing.

Flow rates for the sampling pumps and direct reading instruments were calibrated periodically and checked before each run. All instruments were allowed to warm-up at least one hour before use. In addition to the flowrates for the pumps and direct reading instruments, the flow rate for the environmental chamber was also measured periodically by pitot tube traverse using a published method.[47] The chamber recirculation flowrate was set to approximately 17 m^3/min. The sampling equipment drew a total of 7.3 l/min (3 sampling pumps totaling 0.3 l/min, the APS at 5.0 l/min, and the ozone monitor at 2.0 l/min). The chamber supply flowrate was set in excess of this amount, at 50 l/min.

Tracer Gas Evaluation Procedures

The tracer gas evaluations were performed to determine the mixing factor for the chamber system. The mixing factor was used in the calculation of the generation rates and gave an indication of the performance of the chamber system. SF_6 was used as the tracer gas, and the B&K monitor was used to measure the concentration inside the chamber. The chamber system was setup to operate in a similar fashion as a normal printer run. The thermal desorption tube pumps were not operated during these tests as their flow rates were small compared to the APS and ozone monitor, and the sampling port was need for injecting the SF_6 into the chamber system. The B&K was connected to a chamber sampling port, with a sampling tube extending to the center of the duct. The B&K was configured for the length of the sampling tube and other environmental conditions. Using a one liter gas syringe, approximately 0.9 l of 22% SF_6 in air was injected into the thermal desorption tube sampling port. This provided an SF_6 concentration of approximately 100 ppm. The B&K was set to begin collecting data. Data collection continued until the concentration in the chamber was reduced to less than 10 ppm, at which time, data collection was halted and the B&K was downloaded to a computer using BK-Link. The data were imported into a spreadsheet and formatted to get two columns of data, time and concentration. Prior to this work, the B&K was calibrated for concentrations up to approximately 70 ppm, as the monitor's response was not found to be linear above approximately 1 ppm. Details of the calibration are given in Appendix A. The calibration curve determined from the calibration data was a second order equation,

$$y_{SF_6} = -0.001185(x_{SF_6})^2 + 0.9551 x_{SF_6} + 0.01181 \qquad (12)$$

where, y_{SF_6} = instrument response to SF_6, and
x_{SF_6} = concentration of SF_6.

Solving equation 12 for concentration, x_{SF_6}, yields

$$x_{SF_6} = 403.00 - \sqrt{162400 - 843.88 y_{SF_6}} \quad (13)$$

Equation 13 was entered into the spreadsheet to determine the actual SF_6 concentration. Equation 10 was then entered into the spreadsheet to determine the mixing factor, K. C_{t_1} and t_1 were the first concentration measurement below 60 ppm and the corresponding time respectively; C_{t_2} and t_2 were the last concentration measurement greater than 10 ppm and the corresponding time respectively. These values of K were subsequently used in the generation rate calculations for aerosols, ozone and volatile organic compounds.

Printer Evaluation Procedures

Similar procedures were followed while evaluating each printer. While the instruments, supply pump and recirculation fan were warming-up, the printer was prepared for evaluation. The printer was placed in the chamber, the power and computer cables were connected to the printer, and the printer was positioned in the center of the chamber. If the toner cartridge was new, 100 pages of the test page were printed before the actual evaluation began. (A toner cartridge was used for more than one test.) A self test of the printer was done both before and after the printer run. This self test prints a test page which includes a page count for the printer, the number of pages printed by the printer in its lifetime. The page count provides a measure of the use and condition of the printer. The page count number was recorded on a printer log which provide a means to track the operation of the printer during the tests. A copy of a printer log sheet is provided in Appendix B. After the self test was performed, the printer was loaded with the test paper, the chamber door was clamped shut, and the chamber was allowed to run idle for at least 30 minutes for an initial flushing. During this period, the cooling water flowrate was adjusted to maintain a temperature of approximately 21°C.

During the 30 minute flush out period, the instruments were readied for sampling. Sample data sheets were filled out for each test run. An example sample data sheet is given in Appendix B. The date, printer type and number, starting page count, and the toner cartridge page count were entered on the data sheet. The data loggers were programmed for the appropriate input types (0-2 VDC analog, temperature, and humidity), data recording time, and clock time. The data logger instrument numbers were entered on the data sheets. The clocks on the data loggers were manually synchronized with the clock on the computer controlling the APS. The APS was controlled by the advanced software, Model 390041, available from the manufacturer (TSI, Inc., St. Paul, MN). The program parameters configured for these tests included the number of samples (set to 250), and the save data options, which included the data file name (unique for each run), and the data to be saved (set to concentration and accumulator data). The sample and control frequencies for the

ozone monitor were verified and entered on the sample data sheet. The micromanometers were zeroed, and the instrument numbers entered on the data sheet, along with the instrument numbers for the temperature and humidity probes. Thermal desorption tubes were connected to each of two three-tube sampling manifolds, one set for background measurement and one set for the print cycle measurement. The inlets to these manifolds remained capped until they were placed on the chamber sampling port. Sampling pumps were connected to the thermal desorption tubes, and pump numbers and tube numbers were entered on the sample data sheet. In addition, pump flow rates and pump calibration dates were also entered on the data sheet.

Once the flush-out period was completed, the samplers were prepared for the background run. A background run was made prior to each print run. A sampling tube manifold was connected to the sampling port, the APS was directed to begin sampling, and the data loggers were set to begin recording. The sampling pumps were started, an event was marked on the data loggers, and the time and APS file number were recorded on the data sheet. The background run lasted 60 minutes, during which time, the cooling water flow rate was monitored to maintain a chamber temperature of approximately 21°C. At the conclusion of the background run, the sampling pumps were turned off, an event marked on the data loggers and the time and APS file number were recorded on the sample data sheet. The thermal desorption tubes were removed from the manifold, disconnected from the sampling pumps, capped, and placed in long-term storage containers. The second sampling manifold was placed on the chamber sampling port. The monitors continued to measure and record data during this short period.

After the second set of sampling tubes was set in place, the printer run was ready to start. The print command was entered into the computer controlling the printer, the sampling pumps were turned on, an event was marked on the data loggers, and the time and APS file number were recorded on the sample data sheet. The cooling water flow rate was increased to remove the additional heat generated by the printing process. The cooling water flow rate was monitored to maintain the chamber temperature at approximately 21°C. The printing operation was monitored to determine when printing stopped. When the last page was printed, (approximately 20 to 30 minutes after sampling started, depending upon the printer) an event was marked on the data logger, and the time and APS file number were recorded on the data sheet. Sampling was stopped when a total of 60 minutes of sampling had been completed. The sampling pumps were turned off, the data logger recording stopped, the APS sampling halted, and the time recorded on the data sheet. The sampling tubes were disconnected from the sampling pumps and the manifold, capped, and then placed in long-term storage containers. The data in the data loggers were downloaded to a computer, with two sets of backup files made to diskettes. Two copies of the APS data files were also made for backup purposes. The chamber door was opened, the printed pages removed and the number of printed pages recorded on the sample data sheet. A self test was then conducted on the printer to determine the

current page count. The reason for the printer stopping was determined (i.e. end of file, printer malfunction, out of paper, output bin full) and recorded on the data sheet along with the current page count. Finally, the thermal desorption tubes were submitted for analysis.

The pages printed during each printer run were full pages of text. Depending upon the speed of the tested printer, 120 to 400 pages of the test page were printed using the MS-DOS PRINT command.[48] The same page (with the exception of the page number) was printed repeatedly for each page in the run. A copy of this test page and details on the font settings for the printer are given in Appendix C. The MS-DOS PRINT command printed an ASCII text file containing 120 to 400 pages of the test page to the printer, forcing the printer to print at the highest rate possible.

RESULTS

The results from the study include not only the generation rate data for each printer, but also data concerning the performance of the chamber. This includes data about the temperature control system, the humidity control system, chamber mixing, and air supply and air recirculation systems.

A total of four different printers were evaluated in this study: a two different generations of 8 page/minute printers, both using a corona wire (Printer 1, newer printer; Printer 2, older printer) one 16 page/minute, network type printer without a corona wire (Printer 3), and a 6 page/minute desktop printer, also without a corona wire (Printer 4). All initial testing was performed using Printer 1. All printers were evaluated for aerosols, volatile organic compounds and ozone. In addition, Printers 1 and 2 were evaluated a second time for ozone and particulates after replacing the ozone filter. Characteristics of the tested printers at the beginning of the test are given in Table 3.

Table 3. Printer characteristics.

Printer	I.D. No.	Test Date	Date in Service	Page Count	Font No./Type/ Pitch/Point	Pg/ Test
Printer 2 A	23312	2/96	9/87	156436	00/Courier/10/12	200
Printer 2 B	23312	4/96	9/87	157861	00/Courier/10/12	200
Printer 1 A	56392	1/96	11/90	113270	00/Courier/10/12	200
Printer 1 B	56392	3/96	11/90	116011	00/Courier/10/12	200
Printer 3	74440	3/96	9/93	151849	39/Courier Bold/10/12	400
Printer 4	80203	4/96	8/95	309	39/Courier Bold/10/12	120

Note: Printers noted with B are the printers noted with A with ozone filters replaced.

Chamber Evaluation

A series of tests were conducted on the chamber system before the actual printer evaluation was begun. The first test was to determine the effectiveness of the temperature and humidity control system for the environmental chamber. For this evaluation, a laser printer was operated in the chamber while monitoring the temperature and humidity. For the smaller capacity printers, the temperature control system was capable of controlling the chamber temperature to 21°C±1°C with the cooling water temperature set to approximately 12°C. Most of this temperature variation was due to the need to adjust the cooling water flow rate when the printer began and finished with a print job. For the larger network-type printer, the temperature control system was not able to control the chamber temperature without reducing the cooling water temperature to approximately 5°C. There was a concern

that this cooling water temperature could result in the condensation of volatile organic compounds at the heat exchanger. Therefore, the laboratory temperature was reduced from 20°C to 16°C, relying on heat transfer through the walls of the chamber system to the laboratory. By reducing the laboratory temperature and setting the cooling water temperature to 11°C, the chamber could be maintained at 21°C±1°C.

The humidity control system, however, was not able to control the humidity in the chamber due to the water vapor generated by the printing process. Although the system was capable of reducing the chamber humidity to less than 10% before printing commenced, relative humidities during printing were measured in excess of 70%. Therefore, the humidity control system (the packed column and the water-filled vessel) was removed and the laboratory humidity adjusted to 40%±5%. The chamber humidity was allowed to increase with the printing operation.

Once the operational capabilities of the temperature and humidity control systems were determined, a series of tests were conducted using SF_6 tracer gas to evaluate the mixing in the chamber. As outlined in the Experimental Procedures section of this report, SF_6 was injected into the chamber while monitoring the chamber SF_6 concentration with the B&K monitor. The data from the B&K was downloaded to a computer and the mixing factor was calculated.

In running these tests, problems were encountered, namely, the mixing factor was found to be less than one. Further investigation found that the duct leading from the chamber to the inlet of the recirculation fan (the area of lowest pressure in the chamber system) was under negative pressure with respect to the laboratory, allowing air to leak into the chamber. This resulted in a higher ventilation flow rate to the chamber. Initially, the recirculation flow rate was approximately 35 m^3/min, and the air supply flow rate was set to 0.0073 m^3/min, the total volumetric flow of the samplers. After changing the supply and recirculation flow rates, flow rates of 0.050 m^3/min for the supply and 17 m^3/min for the recirculation resulted in a positive pressure in the inlet duct to the recirculation fan. With these adjusted flow rates, the static pressure in the duct leading to the inlet of the fan was found to be 0.100 in H_2O. The chamber was subsequently run at these flow rates for both the tracer gas and printer evaluations.

An estimation of the chamber mixing factor was made for each printer tested. For the initial printer tested (Printer 1), the mixing factor estimate was made before printer testing started. For the other printers, the estimate was made after testing for that printer was completed. The results of the mixing factor evaluations are given in Table 4. Table 4 also gives the chamber volume used in the calculations of the generation rate. The chamber volumes were calculated by summing the volumes of the various geometric shapes making up the chamber system and subtracting the volume of the printer.

Table 4. Chamber mixing factors for tested printers.

Printer	Mixing Factor	Chamber Volume (m^3)
Printer 2	1.41	1.25
Printer 1	1.30	1.25
Printer 3	1.22	1.19
Printer 4	1.17	1.27

Printer Evaluation

Particulates

The generation rates for aerosols were determined from the APS data. The APS was configured to save count data from 20 second samples. With the time required to save each of these counts in separate data files, this resulted in counts at approximately 30 second intervals. A macro was written to import these ASCII files into Lotus 1-2-3 to generate a single data file for each printer run. This data file contained accumulator data as well as the count data. In reviewing the data, the count data appeared to be extremely low. Several attempts were made to calculate concentrations from the size distribution data; this was only marginally successful due to the low counts. Concentrations varied widely due to the effects of larger particles. The peaks of the size distributions tended to be less than 1 μm. Because a single larger particle (10-15 μm) would have a significant effect on the mass concentration, the data were analyzed on the basis of total counts to determine the generation rate. Then, based on the size distribution for the entire run (each size range summed over the entire print run), the generation rates were converted from a count basis to a mass basis.

In the spreadsheet containing the count and accumulator data (Lotus 1-2-3), total counts for each 20 sec measurement were calculated. The APS used two different timers to measure the time of flight for particles in two overlapping size ranges. A 2 ns timer is used for sizing particles between 0.5 and 15 μm while a 66.67 ns timer is used for particles between 5 and 30 μm. The total counts were calculated by summing the channels, with the channels in the overlaying region (5 to 15 μm) being weighted. The procedure for calculating the counts for the sizes in the overlap region is given in the documentation of the APS.[49] The total count data and the time the measurements were made were then copied to a new spreadsheet (Excel) for additional analysis. Plots of the particle counts versus time for all the printer runs are given in Appendix D.

From the total count data, generation rates from measurement to measurement were calculated using Equation 11. As previously discussed, losses of aerosols to the

chamber system were quantified for each test run by evaluating the calculated generation rate during the concentration decay period of the printer run (the time between the printing of the final page and the conclusion of sampling). The mean of the generation rate during this period, $\bar{G}_{part_{decay}}$, represents the loss of aerosols to the chamber system. The mean of the generation rate during printing, $\bar{G}_{part_{printing}}$, represents the generation of aerosols from the printer, less the losses to the chamber. Therefore, the generation rate for an individual printer run, $G_{part_{run}}$, can be expressed by

$$G_{part_{run}} = \bar{G}_{part_{printing}} - \bar{G}_{part_{decay}} \quad (14)$$

Note that $\bar{G}_{part_{decay}}$ will be negative. The magnitude of $\bar{G}_{part_{decay}}$ ranged from 11% to 36% of $G_{part_{run}}$. The mean and 95% confidence intervals of $G_{part_{run}}$ were calculated to determine the overall aerosol generation rates, $G_{part_{printer}}$, for each printer. Table 5 gives $G_{part_{printer}}$ and the 95% confidence interval for each of the six printer tests. Values of $\bar{G}_{part_{printing}}$, $\bar{G}_{part_{decay}}$, and $G_{part_{run}}$ for each test run are given in Appendix D.

Table 5. Particle generation rates and confidence intervals.

Printer	Generation Rate ($G_{part_{printer}}$) (Particles/min)	Number of Runs	95% Confidence Interval
Printer 2 A	53,400	6	±9,220
Printer 2 B	123,000	6	±134,000
Printer 1 A	67,200	10	±6,950
Printer 1 B	66,500	6	±37,100
Printer 3	335,000	6	±105,000
Printer 4	134,000	6	±13,800

Note: Printers noted with B are the printers noted with A with ozone filters replaced.

Ideally, the losses to the chamber system would be related to the size distribution of the aerosol, and should be evaluated in such a manner. However, due to the small number of particles measured, this was not possible. In addition, losses due to

inertial impaction and setting in the elbows and straight lengths of the ductwork were evaluated.[50] (No loss estimates were made for the heat exchanger, fan or chamber.) The results of these calculations (Appendix E) show that for 10 μm particles, 95% or more of the aerosol penetrates each of the evaluated sections.

Overall size distributions were also calculated for each printer run. The APS grouped particles by size into 59 different size bands ranging form 0.5 μm to 32 μm. From the distribution data, mass-based generation rates for each test run were estimated as follows:[49]

$$G_{mass_{run}} = G_{part_{run}} \frac{\sum_{i=1}^{59} \frac{4}{3} \pi r_i^3 \rho n_i}{\sum_{i=1}^{59} n_i} \qquad (15)$$

where, $G_{mass_{run}}$ = mass based generation rate for each printer run.
r_i = particle radius of the i^{th} APS size range,
ρ = particle density, assumed to be 1 g/cc, and
n_i = number of particles counted in the i^{th} APS size range.

Means ($G_{mass_{printer}}$) and 95% confidence intervals for the six printer tests were determined, and are given in Table 6. Table 7 gives the generation rates on a per page basis. Values of $G_{mass_{run}}$ for each test run are given in Appendix D.

Table 6. Mass particulate generation rates and confidence intervals.

Printer	Generation Rate ($G_{mass_{printer}}$) (μg/min)	Number of Runs	95% Confidence Interval
Printer 2 A	0.00469	6	±0.00820
Printer 2 B	0.00830	6	±0.00784
Printer 1 A	0.00654	10	±0.000618
Printer 1 B	0.00586	6	±0.00186
Printer 3	0.0297	6	±0.0106
Printer 4	0.0122	6	±0.00333

Note: Printers noted with B are the printers noted with A with ozone filters replaced.

Table 7. Mass particulate per page generation rates and confidence intervals.

Printer	Printing Rate	Generation Rate (μg/page)	95% Confidence Interval
Printer 2 A	6.5	0.000722	±0.00126
Printer 2 B	6.5	0.00128	±0.00121
Printer 1 A	6.5	0.00101	±0.0000951
Printer 1 B	6.5	0.000902	±0.000286
Printer 3	12.5	0.00238	±0.000848
Printer 4	6.5	0.00188	±0.000512

Note: Printers noted with B are the printers noted with A with ozone filters replaced.

Ozone

Generation rates for ozone were estimated from the real-time ozone measurements. The ozone monitor provided readings at 28 second intervals. Plots of the ozone concentration versus time for each test run are given in Appendix D. These data, downloaded from the data logger to an IBM compatible computer, were imported into an Excel spreadsheet. The data were manipulated so that the data set contained a column of time, and a column of measurements. Like the particulate data, ozone generation rates from reading to reading (observed generation rates) were calculated using Equation 11. Because ozone is highly reactive, losses of ozone within the chamber system needed to be quantified. The observed generation rates after printing was complete were evaluated with the ozone concentration. A regression was done with the observed generation rate as the dependent variable, the square of the ozone concentration as the independent variable and the regression line forced though zero. The square of the ozone concentration was used because ozone reacts with itself to decompose. The coefficient from this regression, multiplied by the square of the ozone concentration estimated the loss of ozone to the chamber system. This loss (a negative generation rate) was subtracted from the calculated printer generation rate to estimate the actual ozone generation from the printer.

Ozone generation by the printers was affected by the relative humidity in the chamber. During the printing operation, water vapor is generated by the heating of the paper. Plots of the relative humidity versus time for each test run are given in Appendix D. Therefore, to estimate the ozone generation rates, humidity needed to be considered. A second regression for each printer run was performed to determine the effects of humidity on ozone generation rates. In the second regression, the observed generation rate was the dependent variable, relative humidity and a dummy variable were the independent variables, and the regression line was forced through

zero. The dummy variable was used to determine the coefficient and the standard error for the printer or intercept term.

In reviewing the ozone results from Printers 3 and 4, problems were found with the regression analyses, namely that the R^2 values for the regressions were extremely low, and in many cases were negative. The maximum observed ozone concentrations in the chamber was less than 0.035 ppm for all runs with these printers. These two printers do not use a corona wire to transfer the charge to the paper, and hence, should produce little or no ozone. This was verified in the evaluation of these printers, as the chamber ozone concentrations for these printers were extremely low. Because of the analysis problems encountered with these printers, generation rates for Printers 3 and 4 were determined differently from the other printers. The maximum measured concentration during the printing cycle was assumed to be the final concentration at the end of the printing cycle. The generation rate for the printer was then calculated from Equation 11 with t_1 and C_{t_1} being the time and concentration at the beginning of the printing cycle respectively, t_2 being the time at the end of the printing cycle, and C_{t_2} being the maximum ozone concentration during the printing cycle. This calculation results in a maximum generation rate; the actual generation rate may be less than this calculated value.

For the Printers 1 and 2, the ozone generation rate (G_{O_3}) for each run can be described by a linear equation and is a function of the printer, relative humidity and the square of the ozone concentration, as given by:

$$G_{O_3} = \mu + \beta_{RH}\,(\%RH) - \beta_L\,(C_{O_3})^2 + \epsilon \qquad (16)$$

where: μ = printer (or intercept) coefficient
$_{RH}$ = relative humidity coefficient
%RH = percent relative humidity for the location of the printer
$_L$ = ozone concentration coefficient
C_{O_3} = ozone concentration for the location of the printer
ϵ = error term reflecting measurement of G_{O_3} and factors not included in the model which have a small effect on G_{O_3}.

Estimates for the unknown coefficients for i^{th} printer run are:

a_i for μ, where a_i is the regression coefficient for the printer or intercept (dummy variable),

b_{RH_i} for $_{RH}$, where b_{RH_i} is the regression coefficient for the relative humidity, and

b_{L_i} for $_L$, b_{L_i} is the regression coefficient for the loss of ozone in the chamber system.

Using the data from all of the runs for a particular printer, the generation rate can be estimated by:

$$G_{O_3} = a + b_{RH}(\%RH) - b_L(C_{O_3}^2) \quad (17)$$

where: G_{O_3} = an estimate of the generation for a known value of relative humidity and ozone concentration,
$a = (a_1 + a_2 + \ldots + a_n)/n$,
$b_{RH} = (b_{RH_1} + b_{RH_2} + \ldots + b_{RH_n})/n$,
$b_L = (b_{L_1} + b_{L_2} + \ldots + b_{L_n})/n$, and
n = the number of runs of a particular printer.

The values of a, b_{RH}, and b_L for each of the four tests on Printers 1 and 2 are given in Table 8. Values of a, b_{RH}, and b_L for each test run are given in Appendix D. Appendix D also lists the generation rates for each test run of Printers 3 and 4.

Table 8. Ozone generation rate coefficients for Printers 1 and 2.

Printer	a	b_{RH}	b_L
Printer 2 A	0.198	-0.00273	-0.0837
Printer 2 B	0.0165	-0.000235	-0.741
Printer 1 A	0.0351	-0.000433	-0.827
Printer 1 B	0.0502	-0.000912	-0.482

Note: Printers noted with B are the printers noted with A with ozone filters replaced.

To calculate the 95% confidence interval of the estimated generation rate, the standard error of G_{O_3}, and hence, the variances and covariances of the estimates of the parameters are needed. The variances can be computed as follows:

$$s_a^2 = \frac{[(a_1-a)^2+(a_2-a)^2+\ldots+(a_n-a)^2]}{n(n-1)} \quad (18)$$

$$s_L^2 = \frac{[(b_{L_1} - b_L)^2 + (b_{L_2} - b_L)^2 + \ldots + (b_{L_n} - b_L)^2]}{n(n-1)} \quad (19)$$

$$s^2_{RH} = \frac{[(b_{RH_1} - b_{RH})^2 + (b_{RH_2} - b_{RH})^2 + \ldots + (b_{RH_n} - b_{RH})^2]}{n(n-1)} \quad (20)$$

where: s^2_a = the variance of coefficient a,
s^2_L = the variance of coefficient b_L, and
s^2_{RH} = the variance of coefficient b_{RH}.

The covariances can be estimated by the following:

$$s_{L,RH} = \frac{[(b_{L_1} - b_{L_a})b_{RH_1} + (b_{L_2} - b_L)b_{RH_2} + \ldots + (b_{L_n} - b_L)b_{RH_n}]}{n(n-1)} \quad (21)$$

$$s_{a,RH} = \frac{[(a_1 - a)b_{RH_1} + (a_2 - a)b_{RH_2} + \ldots + (a_n - a)b_{RH_n}]}{n(n-1)} \quad (22)$$

$$s_{a,L} = \frac{[(a_1 - a)b_{L_1} + (a_2 - a)b_{L_2} + \ldots + (a_n - a)b_{L_n}]}{n(n-1)} \quad (23)$$

where: $s_{L,RH}$ = the covariance of b_L and b_{RH},
$s_{a,RH}$ = the covariance of a and b_{RH}, and
$s_{a,L}$ = the covariance of a and b_L.

From the estimates of the variances and covariances, the variance of G_{O_3} ($s^2_{G_{O_3}}$) can be estimated:

$$s^2_{G_{O_3}} = s^2_a + (\%RH)^2 s^2_{RH} + (C_{O_3})^2 s^2_L + 2\left(\%RH\, s_{a,RH} + C_{O_3} s_{a,L} + \%RH\, C_{O_3} s_{L,RH}\right) \quad (24)$$

The standard error of G_{O_3}, $s_{G_{O_3}}$, can be estimated by:

$$s_{G_{O_3}} = \sqrt{s^2_{G_{O_3}}} \quad (25)$$

With an estimate of $s_{G_{O_3}}$, the values for the lower and upper confidence limits can be calculated from:

$$G_{(O_3)_L} = G_{O_3} + t(0.025, n-1)\, s_{G_{O_3}} \quad (26)$$

$$G_{(O_3)_H} = G_{O_3} + t(0.975, n-1)\, s_{G_{O_3}} \quad (27)$$

where: $G_{(O_3)_L}$ = lower 95% confidence limit of G_{O_3},

$G_{(O_3)_H}$ = upper 95% confidence limit of G_{O_3},

t(0.025, n-1) = Student's t statistic with $\alpha = 0.025$ and n-1 degrees of freedom, and

t(0.975, n-1) = Student's t statistic with $\alpha = 0.975$ and n-1 degrees of freedom.

Table 9 gives estimates of the ozone generation rates and 95% confidence limits for each of the six printer evaluations assuming a relative humidity of 50% and an ozone concentration of 0.01 ppm. Table 10 gives the generation rate on a per page basis for the same conditions.

Table 9. Ozone generation and 95% confidence limits for a relative humidity of 50% and an ozone concentration of 0.01 ppm.

Print	Generation Rate (mg/min)	Lower 95% Confidence Limit	Upper 95% Confidence Limit
Printer 2 A	0.0617	0.0446	0.0787
Printer 2 B	0.00489	0.00416	0.00562
Printer 1 A	0.0136	0.00847	0.0188
Printer 1 B	0.0103	0.00944	0.0112
Printer 3*	0.000843	0.000830	0.000857
Printer 4*	0.000864	0.000803	0.000925

Note: Printers noted with B are the printers noted with A with ozone filters replaced.
*Generation rates for these printers are based on the maximum ozone concentration during printing.

Table 10. Ozone generation per page and 95% confidence limits for a relative humidity of 50% and an ozone concentration of 0.01 ppm.

Print	Printing Rate	Generation Rate (mg/page)	Lower 95% Confidence Limit	Upper 95% Confidence Limit
Printer 2 A	6.5	0.00949	0.00686	0.0121
Printer 2 B	6.5	0.000752	0.000640	0.000865
Printer 1 A	6.5	0.00209	0.00130	0.00289
Printer 1 B	6.5	0.00158	0.00145	0.00172
Printer 3*	12.5	0.0000134	0.0000542	0.000120
Printer 4*	6.5	0.000133	0.000124	0.000142

Note: Printers noted with B are the printers noted with A with ozone filters replaced.
*Generation rates for these printers are based on the maximum ozone concentration during printing.

Volatile Organic Compounds

The volatile organic compounds (VOCs) were sampled using thermal desorption tubes and methods. The results were quantified for compounds corresponding to the major peaks on the gas chromatographs, including butanol, toluene, xylenes, and benzene. In addition, total VOCs as toluene were also determined.

In analyzing the samples for Printer 2, an air leak occurred in the trap of the thermal desorber. This resulted in a high air backgrounds for many of these samples. However, the data for these samples were adjusted to account for this malfunction, and the data included in the evaluation of this printer.

Most of the sample results for total VOCs were above the limit of detection. However, several background samples were below the limit of detection (LOD). In these instances, a sample mass of $LOD/\sqrt{2}$ was assumed in order to calculate the background concentrations.[51] For those compounds where the majority of the samples were non-detected, no values were assumed and the concentrations, and hence the generation rates were reported as non-detected.

To determine the VOC generation rates for the different printers, the VOC concentration with respect to time was assumed to follow Equation 8. Figure 2 shows a plot of Equation 8, with two distinct regions: the first where $G > 0$; and the second where $G = 0$. The first region corresponds to the VOC concentrations during printing while the second region is the concentration decay after printing has commenced. The area under these two curves (the average concentration times the sampling time) will equal the VOC concentration, as measured on the thermal

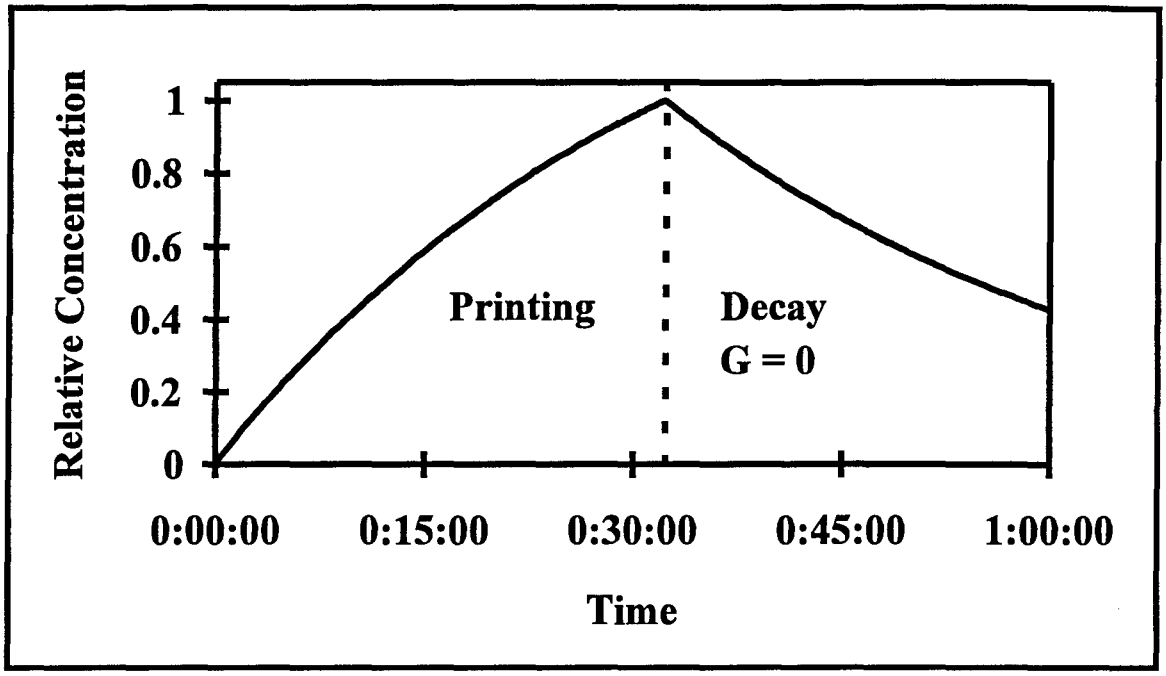

Figure 2. Plot of concentration as a function of time and generation rate (Equation 8), with printing and decay cycles noted.

desorption tubes, times the sampling time, assuming the sampling time corresponds to the time on the plot.

To determine the generation rates for VOCs, Equation 8 was entered into a spreadsheet to calculate concentrations at 15 second intervals. The initial concentration was the concentration measure from the background samples. For those background concentrations which were non-detected, the initial concentration measurement was set to zero. At the time when printing was completed, G was set to zero to complete the print run. This provided an estimate of the VOC concentrations. Means for the samples taken during printing (typically three samples) were calculated and entered into the spreadsheet. Means of the calculated readings were also calculated, and compared to the tube sample means. The generation rate, G in Equation 8 in the spreadsheet was adjusted in an iterative process until the mean calculated concentration was equal to the mean measured concentration. The mean generation rate for each printer was then calculated from the generation rates for each test run for that printer. Table 11 gives the mean VOC generation rates and 95% confidence intervals of total VOCs and other analyzed compounds for the four tested printers. Table 12 gives the generation rates for the VOCs on a per page basis. The generation rates and VOC concentration data for each test run are given in Appendix D.

Table 11. Generation rates (mg/min) for various volatile organic compounds and total volatile organic compounds as toluene.

Printer	Butanol	Toluene	Xylenes	Benzene*	Total VOCs
Printer 2	0.156 ±0.0471	N.D.	0.326 ±0.0688	N.D.	1.55 ±0.318
Printer 1	0.273 ±0.0183	N.D.	0.452 ±0.0813	N.D.	1.67 ±0.163
Printer 3	0.0366 ±0.00911	0.0723 ±0.0107	0.0276 ±0.00395	0.0220 ±0.00532	1.04 ±0.131
Printer 4	0.144 ±0.0276	0.0163 ±0.00666	0.132 ±0.0232	N.D.	1.03 ±0.158

Notes:* -Benzene was quantified for Printer 3 only. Benzene was not identified as a major peak on the gas chromatograph for the other printers. N.D. - Non-detected.

Table 12. Generation rates on a per page basis (mg/page) for various volatile organic compounds and total volatile organic compounds as toluene.

Printer	Printing Rate (pg/min)	Butanol	Toluene	Xylenes	Benzene*	Total VOCs
Printer 2	6.5	0.024 ±0.0072	N.D.	0.050 ±0.011	N.D.	0.24 ±0.049
Printer 1	6.5	0.042 ±0.0028	N.D.	0.070 ±0.013	N.D.	0.26 ±0.025
Printer 3	12.5	0.0029 ±0.00073	0.0058 ±0.00086	0.0022 ±0.00032	0.0018 ±0.00043	0.083 ±0.010
Printer 4	6.5	0.022 ±0.0042	0.0025 ±0.0010	0.020 ±0.0036	N.D.	0.16 ±0.024

Notes:* -Benzene was quantified for Printer 3 only. Benzene was not identified as a major peak on the gas chromatograph for the other printers. N.D. - Non-detected.

DISCUSSION

The methods described in the previous section gave estimated generation rates for ozone, particulates, and volatile organic compounds for each of the tested printers. These generation rates varied widely for some compounds such as ozone, and were very similar for others including total VOCs. These evaluations looked only at the contaminants generated during the printing operation; contaminant generation during other operations such as toner cartridge replacement was not evaluated. Generation rates for individual compounds and individual printers are discussed in more detail in this section.

Particulates

Particulate generation rates for all of the tested printers were low, well below 0.1 μg/min. To place this generation rate into perspective, consider the printer with the highest particulate generation rate, the LaseJet 4Si, in an office supplied with 0.143 m^3/min (5 ft^3/min) of outside air (Q). The mixing factor, K, is assumed to be 3. Setting $t_2 = \infty$ in Equation 8, the equalibrium concentration will be:

$$C_\infty \approx \frac{K\,G}{Q} \qquad (28)$$

The equalibrium particulate concentration for this office space would be 0.625 μg/m^3, an extremely low concentration. The National Ambient Air Quality Standard for particulates (PM_{10}) is 150 μg/m^3.[52] The senario presented here is a worst case since, in most settings, mixing is likely to be better, the air supply flow rate is likely to be higher, and the printer does not run constantly. The calculated value also assumes that the incoming air is free from particulate matter. However, this example does illustrate the practical contribution of these tested printers to the room particulate concentration.

One issue of interest was the effect of changing the toner cartridge on the particulate generation rates. A review of the particulate generation rates for each printer run shows that the generation rates increased after replacing the toner cartridge. In some cases, the generation rate following cartridge replacement was as high as three times the calculated mean generation rate for that particular printer. During some of the initial tests to evaluate the chamber system, this same effect was observed, although to a greater degree. At that time, a "burn-in" procedure was added to the evaluation method. The printer was instructed to print 100 test pages following the replacement of the toner cartridge in an effort to eliminate this new cartridge effect. Although the effect was reduced, it was not eliminated completely. From a practical perspective, however, a generation rate of three or even five times the calculated mean generation rate would not raise the particulate concentration to a level of major concern. This effect does indicate that changing the toner cartridge may be a particulate generating activity in need of further evaluation.

Ozone

The ozone generation rates varied extensively between printers, with the newer printers like Printers 3 and 4 having much lower generation rates than the older Printers 1 and 2. The replacement of the ozone filter on Printer 2 appeared to have a profound effect on ozone generation, while on Printer 1, this effect appear to be reduced. Printers 3 and 4 do not contain a corona wire, and therefore, would not be expected to product significant quantities of ozone. Using the above senario of an office with 0.143 m^3/min (5 ft^3/min) of outside air (Q) and a mixing factor of 3, generation rates from Table 9 will result in the equalibrium concentrations shown in Table 13.

Table 13. Equilibrium ozone concentrations for calculated ozone generation rates for an office with 0.143 m^3/min outside air supply and a mixing factor of 3.

Printer	Calculated Ozone Generation Rate (mg/min)	Equilibrium Ozone Concentration (ppm)
Printer 2 A	0.0617	0.65
Printer 2 B	0.00489	0.051
Printer 1 A	0.0136	0.14
Printer 1 B	0.0103	0.108
Printer 3	0.000843	0.0089
Printer 4	0.000864	0.0091

As Table 13 indicates, for the given scenario, ozone would be a concern with Printers 1 and 2. The current National Institute for Occupational Safety and Health (NIOSH) Recommended Exposure Limit (REL) and the Occupational Safety and Health Administration (OSHA) Permissible Exposure Limit (PEL) for ozone are both 0.1 ppm, as an 8-hr time weighted average (TWA).[53,54] The American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Value (TLV) is 0.1 ppm as a ceiling.[55] Like the scenario in the discussion of the particulate generation rates, the ozone concentrations in Table 13 are conservative, in that the supply to the office is likely to be higher and the mixing is likely to be better. However, these examples serve to show the potential impact that some printers may have on the office environment.

Volatile Organic Compounds

The analysis of the VOC samples identified different compounds for the various printers. Printers 1 and 2 had butanol and xylenes as the major peaks. Printers 3 and 4 had butanol, xylenes and toluene as major peaks. In addition, Printer 3 also had a peak for benzene. Using the same scenario of an office with 0.143 m^3/min (5

ft^3/min) of outside air (Q) and a mixing factor of 3, Table 14 gives equilibrium concentrations for each identified compound and total volatile organic compounds as toluene.

Table 14. Equilibrium concentrations for VOC generation rates for an office with 0.143 m^3/min outside air supply and a mixing factor of 3.

Printer	Butanol (ppm)	Toluene (ppm)	Xylenes (ppm)	Benzene (ppm)	Total VOCs (ppm)
Printer 2	1.08	N.D.	1.58	N.D.	8.68
Printer 1	1.90	N.D.	2.19	N.D.	9.35
Printer 3	0.254	0.405	0.139	0.149	5.82
Printer 4	1.00	0.0913	0.641	N.D.	5.77

The concentrations for butanol, toluene, xylenes are all below the NIOSH RELs, OSHA PELs and ACGIH TLVs.[53,54,55] The concentration for benzene on Printer 3 exceeds the NIOSH REL, but is below both the OSHA PEL and ACGIH TLV.[53,55,56] While this scenario is may not reflect actual printer usage and conditions, it does serve to show how a printer might contribute to the overall VOC concentrations in an office environment.

CONCLUSIONS AND RECOMMENDATIONS

The methods described here were capable of estimating generation rates for VOCs, particulates and ozone. The generation rates for total VOCs tended to be fairly consistent from printer to printer, although there was some variation in the different compounds identified. The generation rates estimated for the tested printers generally were not high, although some identified compounds, such as benzene, may be a concern. The significance of these generation rates should be evaluated along with other VOC generation sources present in the indoor environment.

The particulate generation rates were extremely low for all tested printers, indicating that the printer itself is not a major contributor to particulate levels in the indoor environment. However, this evaluation methods presented here did not look at particulate generation from such operations as toner cartridge replacement, nor was the effect of printer paper evaluated. Some types of paper are dustier than others, and, when used in a laser printer, may affect the particulate generation rate of that printer. In addition, the observed reduction of particulate generation as the toner cartridge was used needs more evaluation. While even the highest generation rates were extremely low, changes to the system affecting generation did take place. These changes should be evaluated to determine the root cause.

Ozone is a compound of concern, particularly with the older printers using a corona wire. These older printers produced quantities of ozone that could potentially increase the concentration in an enclosed space to levels exceeding the NIOSH REL, the OSHA PEL, and the ACGIH TLV. Replacement of the ozone filter appeared to have a dramatic impact on the ozone generation rate, particularly for Printer 2, where the ozone generation rate was reduced by an order of magnitude. The newer printers, using the charged roller as opposed to the corona wire, had very low ozone generation rates. This newer technology appears to be effective at reducing or eliminating ozone generation. The variability of the generation rate for ozone tends to vary more widely than the generation rates for VOCs and particulates. This is due to the complex nature of the calculation of the generation rate for the older laser printers. The effects of ozone concentration and relative humidity on the ozone generation rate contribute to the variability.

There are several areas associated with emissions from laser printers that should be considered for additional research. The most obvious is the need to evaluate additional printers. No attempt was made to choose a representative selection of printers for this study. Evaluation of additional printers may allow some generalization of different classes of printers. Color laser printers should also be included for evaluation. The effects of printer maintenance also need to be evaluated more thoroughly. While some work was done in this study, the issue of maintenance needs to be completely explored. The effects of printer and toner cartridge age should also be addressed. Printer age was not addressed in this study. However, it

would be useful to know how emissions might change with the age of the printer. This study did find an apparent effect of toner cartridge age upon particulate emissions. Because of limited data associated with this issue, it was not fully explored in this study, but should be considered for future work. Also related to particulate emissions is the paper used for printing. This study used only one type of paper, but paper may have an effect on particulate generation rates. The use of recycled papers is also an issue that needs to be addressed in future work.

The laser printer evaluation methods presented here are capable of providing estimates of generation rates for VOCs, particulates and ozone. These generation rates, in turn, can help building designers to properly size air supply systems for the indoor environment. In addition, the methods described here, may also be useful to the printer manufacturers in development of new, low emission equipment.

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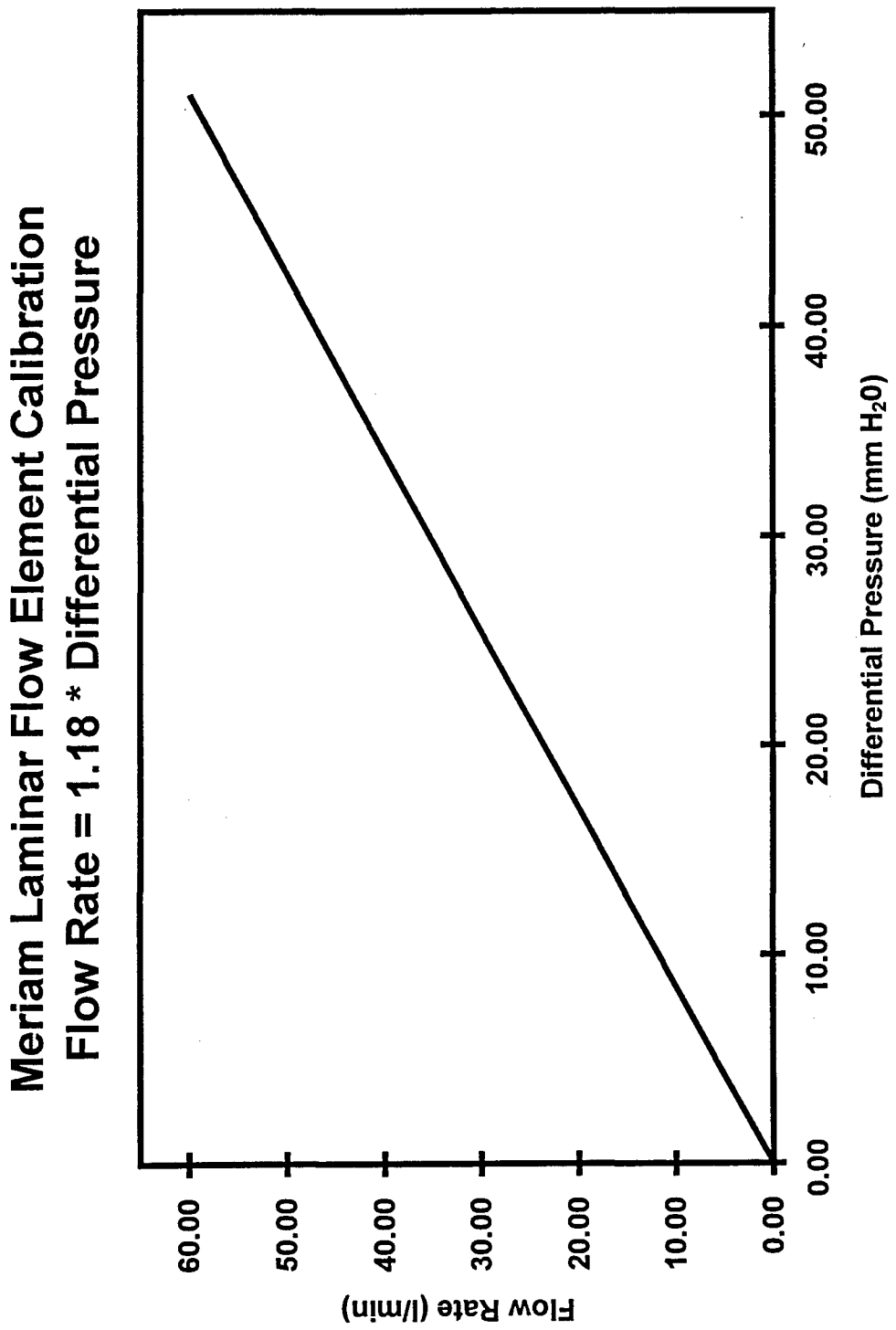
APPENDIX A
Instrument Calibration Documentation


Meriam Laminar Flow Element Calibration
Flow Rate = 1.18 * Differential Pressure
Flow Rate (l/min)
60.00
50.00
40.00
30.00
20.00
10.00
0.00
0.00
10.00
20.00
30.00
40.00
50.00
Differential Pressure (mm H2O)

DASIBI ENVIRONMENTAL CORP.

SERIES 1003 FINAL CHECK SHEET
(1003-AH, 1003-PC, 1003-PS, 1003-RS, 1003-HC)

I. INSTRUMENT DESIGNATION.

A. Customer: NIOSH

B. Production Serial Number: 1 of 1

C. Shipping Serial Number: 6003

D. Work Order Number: 26714

E. Features:

1. 110 VAC 60 Hz ☑ 220 VAC 50 Hz ☐ 240 VAC 50 Hz ☐

2. Range: 0 - 1 ppm ☑ 0 - 0.5 ppm ☐ Other _____

3. Analog Output:

Isolated ☐ Non-isolated ☑

Single ☑ Dual ☐

0-1 V ☑ 0-10 V ☐ 0-100 mV ☐ 04-20 mA ☐ Other _____

4. "RS" Ozone Generator: Single Point ☐ Dual Point ☐ N/A ☑

5. HC Display: N/A ☑

ppm ☐ % wt ☐ g/m³ ☐

6. Photometer Valve: Latching ☑

Diaphragm ☐ 24 VDC ☐ 110V AC ☐

7. "RS" Valve: N/A ☑

24 Vdc Diaphragm ☐

1

Appendix A -- Instrument Calibration Documentation

II. ENVIRONMENTAL CONDITIONS.

A. Temperature: 25 °C

B. Barometric Pressure: 751 mm Hg

III. ELECTRONICS PERFORMANCE.

Inspector: T.Vu Date: 11 13 93

A. Power Supply:

	Measured
5 vdc (± 0.2)	5.03 V
15 vdc (± 0.5)	16.9 V
-15 vdc (± 0.5)	-16.9 V
24 vdc (± 0.6)	24.1 V
220 vdc (± 10 v)	223.3 V
Valve Voltage	32.8 Vdc or _____ VAC
Heater Voltage:	Cold 3.4 Vdc (± 0.5) 3.01 V
	Hot 4.4 Vdc (± 0.1) 4.39 V

B. Ozone Control Board Circuit: N/A ☑

	Measured
5v (± 0.2)	_____ V
15v (± 0.5)	_____ V
-15v (± 0.5)	_____ V
Max Ozone Output:	_____ ppb (@ 999 ozone adjust)
Heater Voltage:	Cold 4.2 Vdc (± 0.5) _____ V
	Hot 2.9 Vdc (± 0.1) _____ V

C. Front Panel Controls:

	Pass	Fail	N/A
Pump Switch	☑	☐	
Mode Switch	☑	☐	
Ozone Switch	☐	☐	☑
Ozone Pump Switch	☐	☐	☑
Auto/Manual	☐	☐	☑
Remote/Local	☐	☐	☑

D. **Ozone Control Verification: N/A** ☑

1003 RS:

SPAN (Set Thumbwheel @ 80) _____ ppb (Displayed)

24 Hour Output Stability (@ 400 ppb): Max ppb _____

Min ppb _____

For Dual Point: Thumbwheel Setting _____

SPAN _____ ppb

Precision _____ ppb

1003 PC:	**Pass**	**Fail**
Manual Mode	☐	☐
Auto Mode	☐	☐

Auto O_3 Adjust Thumbwheel Setting (ppb)	Display (ppb)
_____	_____
_____	_____
_____	_____
_____	_____
_____	_____
_____	_____

IV. PERFORMANCE TEST.

1. Response Time:

90% FS (specification: 18 seconds average)

Pass ☑ Fail ☐

2. Linearity: (specification: ± 1% F.S.) Range: 1 PPM

ppb ☑

Primary Standard	Measured	Non-Linearity %
836	829	0.8 %
430	426	0.9 %
341	338	0.9 %
10	10	_____ %
_____	_____	_____ %

Pass ☑ Fail ☐

3. Noise: (± 1ppb)

   Pass ☑ Fail ☐

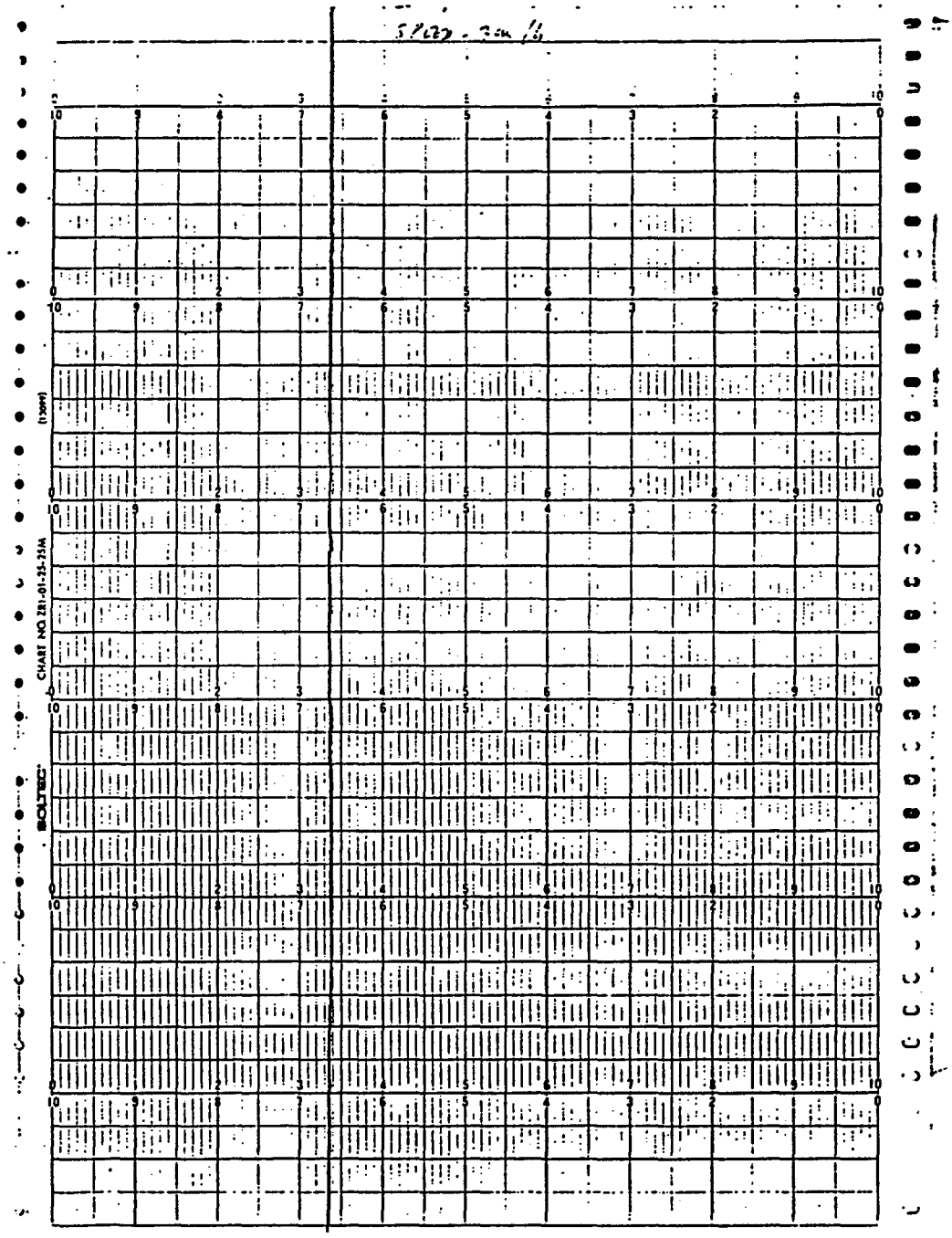
4. Strip Chart Included: ✓

V. SETTINGS.

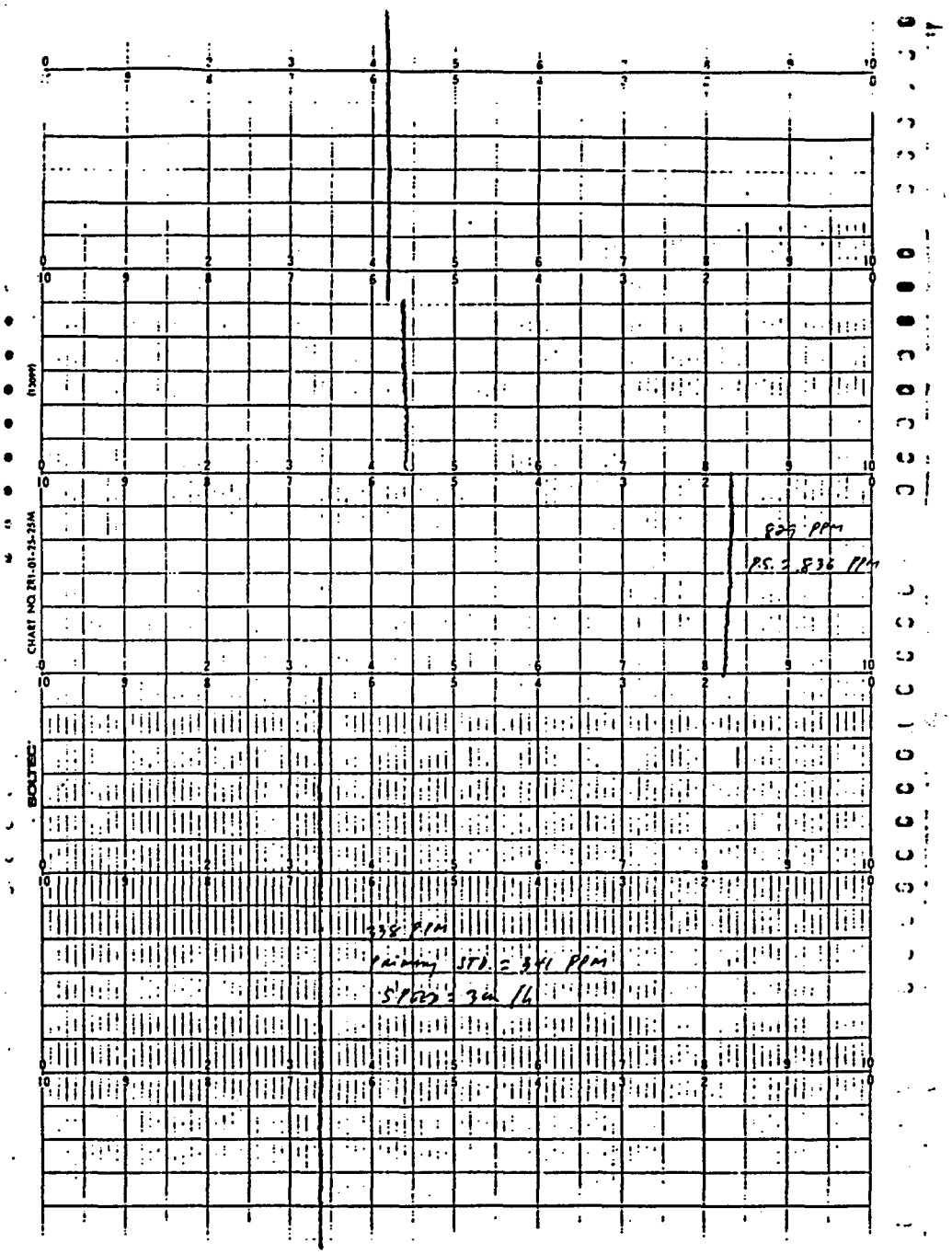
1. Maximum Photometer Flow: 3 lpm (3 lpm)
2. Max. Ozone Generator Flow: N/A lpm (6 lpm)
3. Sample Frequency: 459 khz (450 - 480 khz)
4. Control Frequency: 254 khz (250 - 280 khz)
5. SPAN Number Set: 525
   Note: Dasibi Final Q.C. will set SPAN number to 525 unless otherwise specified.
6. Logic Switches (Jumpers) Set: ✓
7. RIN Tester Installed: ✓

DASIBI ENVIRONMENTAL CORP. 515 W. COLORADO STREET GLENDALE, CALIFORNIA 91204	DOCUMENT NUMBER	QMS-F-QC1003	
	APPROVAL		DATE
	OPERATION DEPT.		
	QA DEPT.		

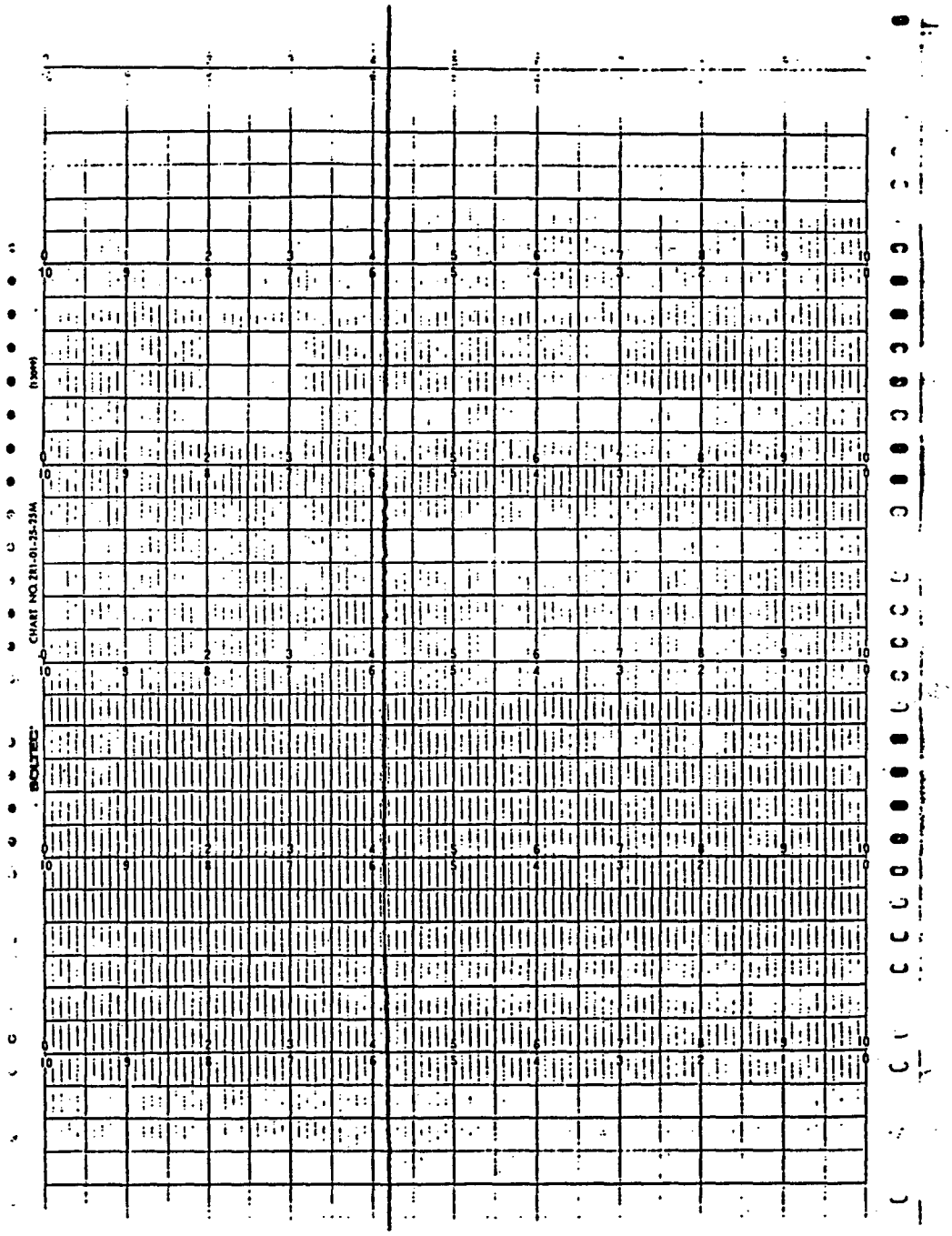
Appendix A -- Instrument Calibration Documentation



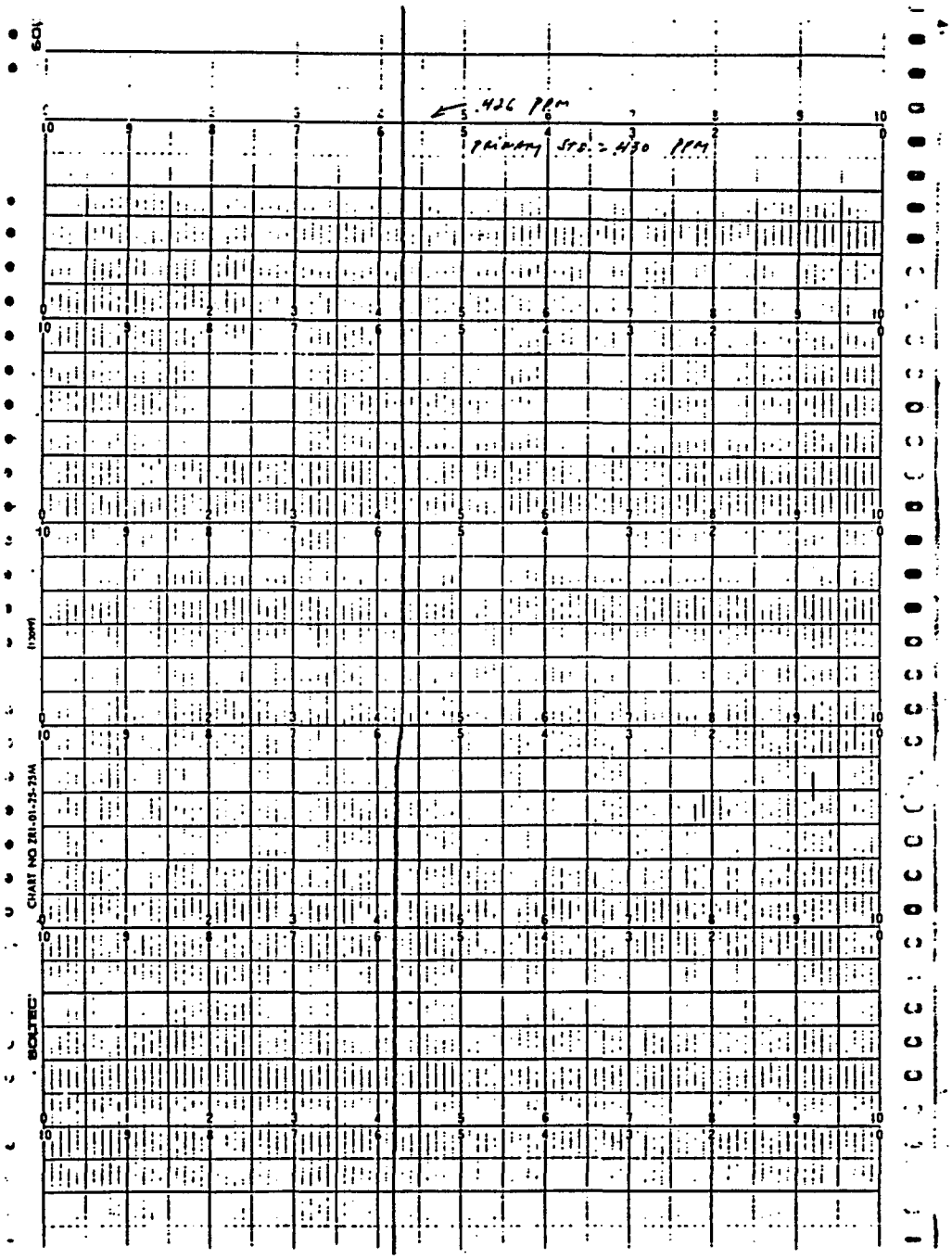
Appendix A -- Instrument Calibration Documentation



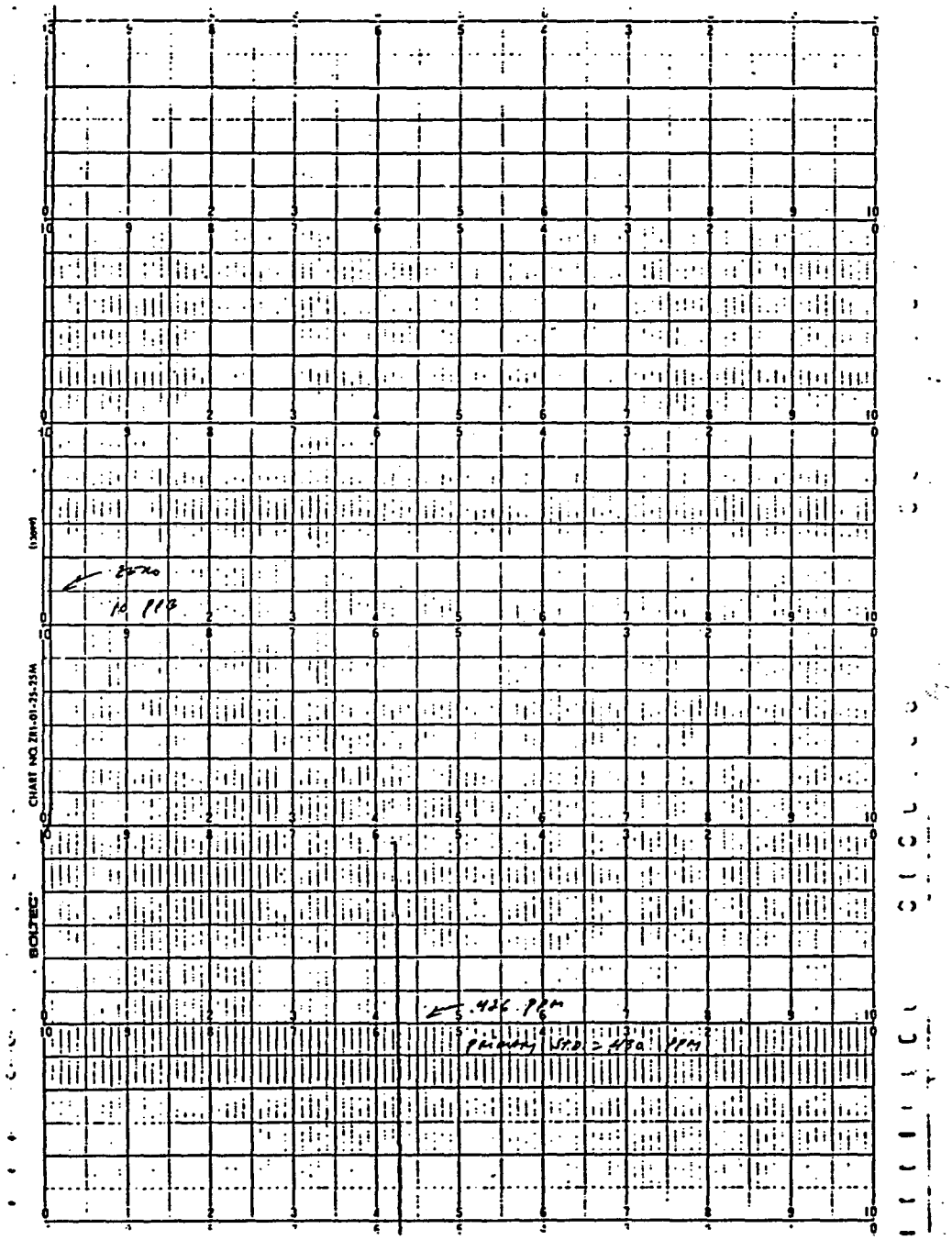
Appendix A -- Instrument Calibration Documentation



Appendix A -- Instrument Calibration Documentation



Appendix A -- Instrument Calibration Documentation



Appendix A -- Instrument Calibration Documentation

TSI AERODYNAMIC SIZER CALIBRATION DATA

01-23-1996 RUN # 1

S/N: 301

PT.	DIA. (μm)	CHAN.	DENSITY	AERO. DIA. (μm)
0	0.343	206.00	1.050	0.353
1	0.503	209.00	1.050	0.517
2	0.705	215.00	1.050	0.724
3	1.031	231.00	1.050	1.058
4	2.013	287.00	1.050	2.065
5	5.010	428.00	1.050	5.136
6	7.040	506.00	1.050	7.216
7	9.870	606.00	1.050	10.116
8	15.000	787.00	1.050	15.372
9	20.490	1000.02	1.050	20.998
10	29.900	1277.19	1.050	30.645

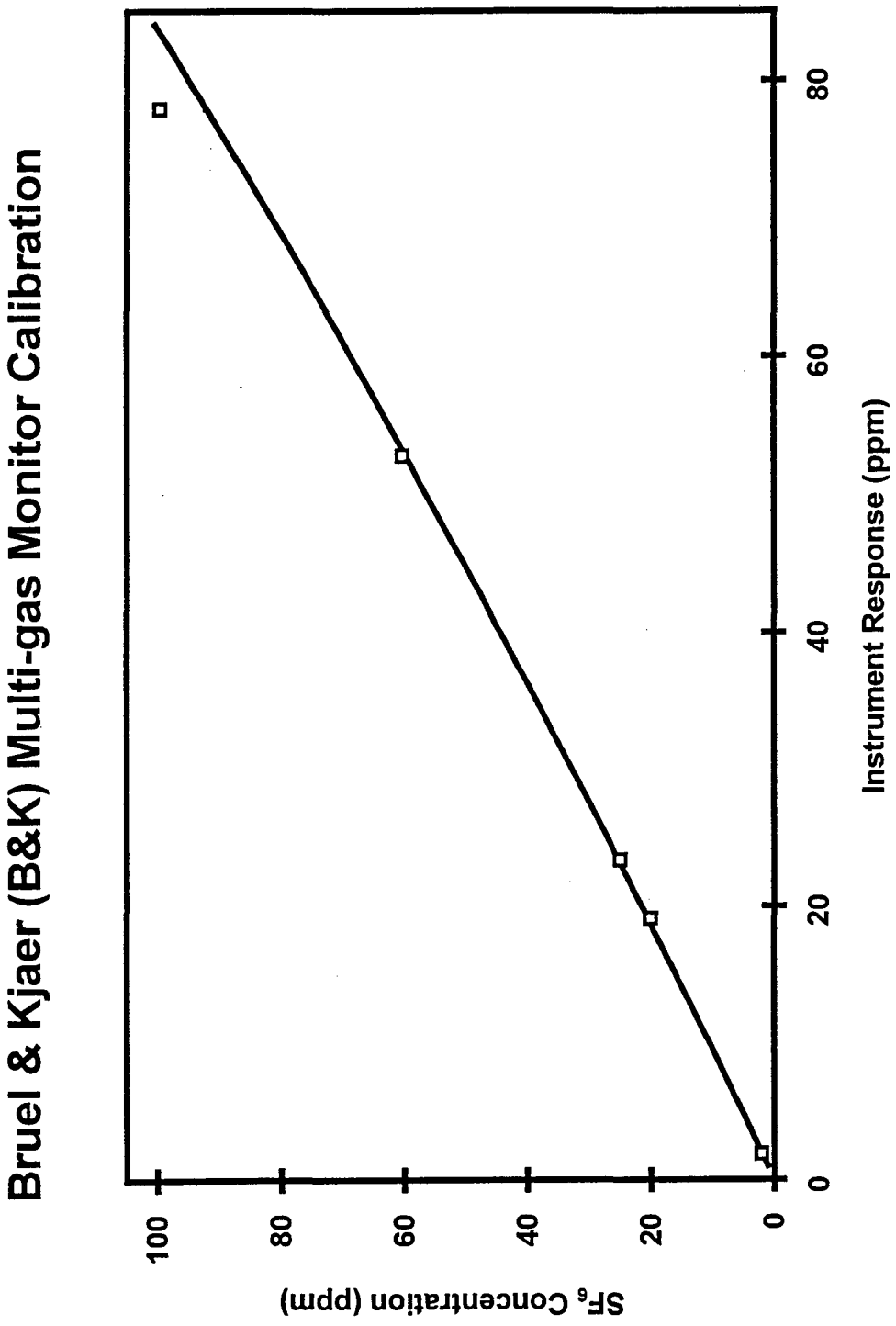
Appendix A -- Instrument Calibration Documentation

APS CALIBRATION DATA

DIA. (μm)	CHANNEL
0.392	206.68
0.422	207.18
0.453	207.74
0.487	208.38
0.523	209.13
0.562	210.01
0.604	211.08
0.649	212.40
0.698	214.02
0.750	216.01
0.806	218.38
0.866	221.15
0.931	224.33
1.000	227.90
1.075	231.88
1.155	236.27
1.241	241.07
1.334	246.28
1.433	251.91
1.540	257.96
1.655	264.43
1.778	271.33
1.911	278.65
2.054	286.40
2.207	294.58
2.371	303.21
2.548	312.30
2.738	321.87
2.943	331.92
3.162	342.48
3.398	353.56
3.652	365.18
3.924	377.35
4.217	390.09
4.532	403.41
4.870	417.32

Appendix A -- Instrument Calibration Documentation

DIA. (μm	CHANNEL
5.233	431.85
5.623	447.03
6.043	462.95
6.494	479.72
6.978	497.42
7.499	516.15
8.058	535.97
8.660	556.90
9.306	578.96
10.000	602.18
10.746	626.64
11.548	652.83
12.409	681.41
13.335	713.03
14.330	748.35
15.399	788.02
16.548	832.37
17.783	931.35
19.110	931.35
20.535	983.69
22.067	1036.45
23.714	1089.22
25.483	1142.00
27.384	1194.78
29.427	1247.56
31.623	1300.34
33.982	1353.12
36.517	1405.91


Bruel & Kjaer (B&K) Multi-gas Monitor Calibration
SF6 Concentration (ppm)
0
20
40
60
80
100
Instrument Response (ppm)
0
20
40
60
80

APPENDIX B
Data Log Sheets

Appendix B -- Data Log Sheets

Printer Log -- Printer HP LaserJet 4Si No. 74440

Page Count	Date	Printer Status			Comments
		Print Start	New Toner	Printer Failure	
151697	3/1/96		X		Start Burn-in
151849	3/1/96	X			End Burn-in. Start PRINT17
152250	3/1/96	X			End PRINT17. Start PRINT18.
152651	3/2/96	X			End PRINT18. Start PRINT19.
153052	3/2/96	X			End PRINT19. Start PRINT20.
153453	3/2/96	X			End PRINT20. Start PRINT21.
153854	3/3/96		X		End PRINT21. Start Burn-in.
153956	3/3/96	X			End Burn-in. Start PRINT22.
154357	3/3/96	X			End PRINT22.

Appendix B -- Data Log Sheets

PRINT20 Date: 3/2/96 Printer: HP LaserJet 4Si #74440

Ozone Monitor Settings

Ozone Monitor File: proz20.log	
Setting	Value
Sample Frequency	49.327
Control Frequency	18.260

APS Settings

APS files print20.001 to print01.211		
	File Name	Time
Background Start	PRINT01.001	16:05:00
Background Stop	PRINT01.105	17:05:00
Printing Started	PRINT01.110	17:07:30
Printing Stopped	PRINT01.165	17:40:35

Tube Samples

Tube No.	Pump	Cal. Date	Start	Stop	Flow Rate	Pump Time
Background						
A05036	1932	2/26/96	16:05:00	17:05:00	100 cc/min	65.15 min
A03722	9051	2/26/96	16:05:00	17:05:00	100 cc/min	59.98 min
A05389	9048	2/26/96	16:05:00	17:05:00	100 cc/min	59.87 min
Printer						
A05120	9052	2/26/96	17:07:30	18:07:30	100 cc/min	59.81 min
A04215	9050	2/26/96	17:07:30	18:07:30	100 cc/min	60.41 min
A04667	9048	2/26/96	17:07:30	18:07:30	100 cc/min	59.95 min

Temperature, Humidity, and Air Flow Monitors

Location	File Name	Data Logger	Probe or Manometer
Room Temperature	20rmtemp.log	42196	785 HM
Room Humidity	20rmhumd.log	42196	785 HM
Chamber Temperature	20uptemp.log	42196	40230
Chamber Humidity	20uphumd.log	42196	40230
Supply Air Flow	20supply.log	29212	29097
Duct Air Flow	20duct.log	29212	0651661

Printer Settings

Parameter	Value or Setting
Start Page Count	153052
Stop Page Count	153453
Page count for Toner Cartridge	1300
Number of Pages Printed	400
Printing Stopped on:	End of File

APPENDIX C
Test Page Information

Appendix C -- Test Page Information

Test Page Settings

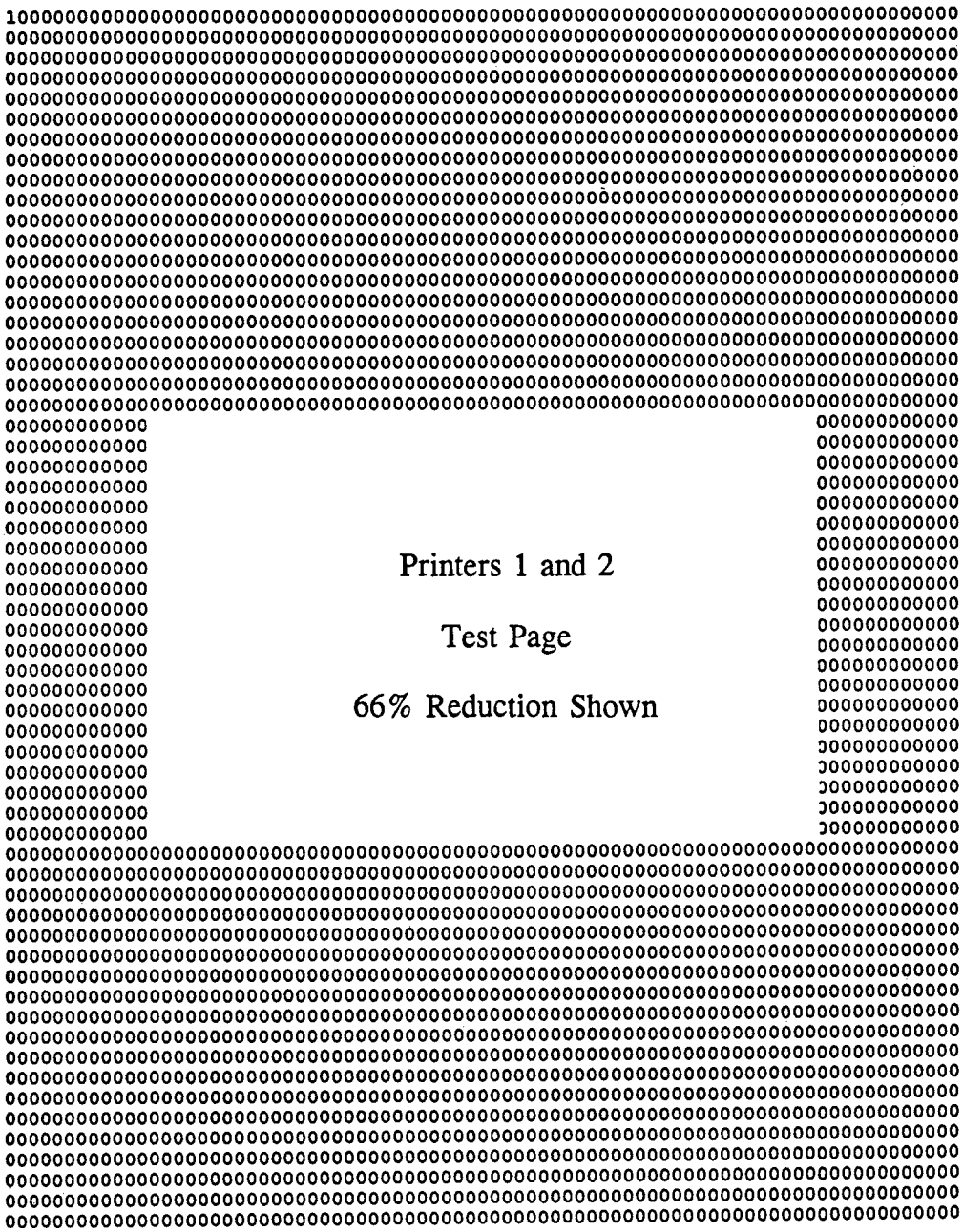
Printers 1 and 2

Source	Internal
Font Number	000
Font Name	Medium Courier
Pitch:	10 point
Lines/page:	60
Characters/line:	79
Top margin:	0.5 in
Bottom margin:	0.5 in
Left margin:	0.25 in
Right margin:	0.375 in
Program:	MS-DOS Print Command

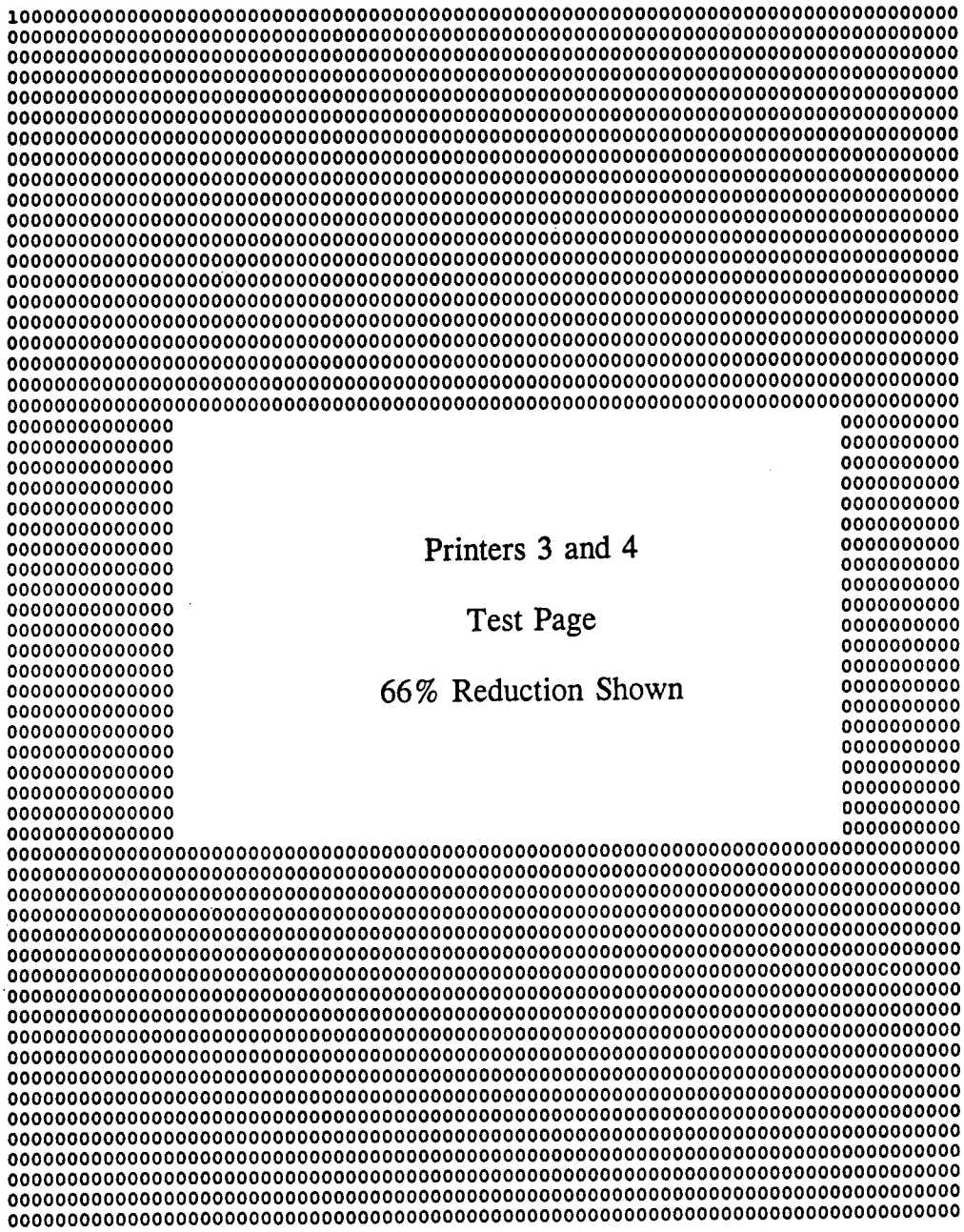
Printers 3 and 4

Source	Internal
Font Number	039
Font Name	Bold Courier
Pitch:	10 point
Lines/page:	60
Characters/line:	79
Top margin:	0.5 in
Bottom margin:	0.5 in
Left margin:	0.25 in
Right margin:	0.375 in
Program:	MS-DOS Print Command

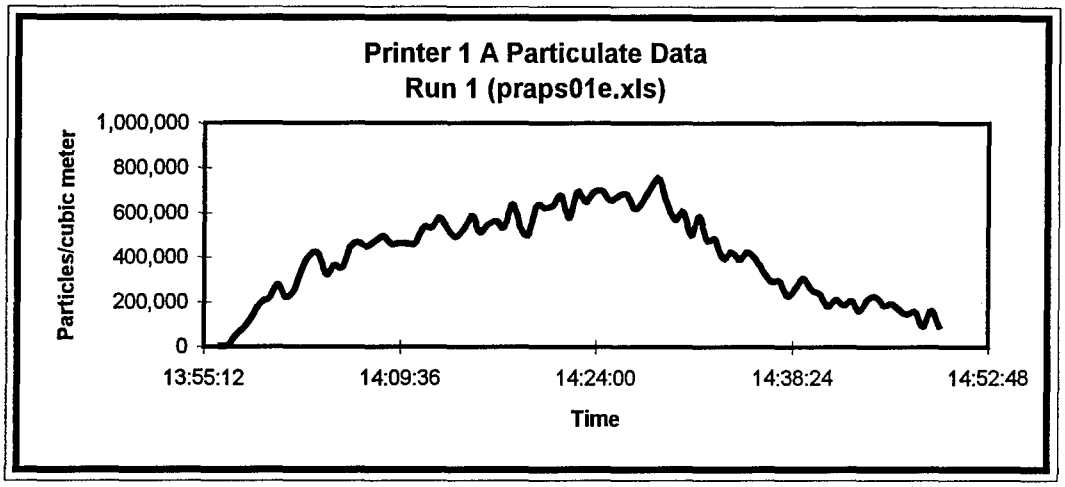
Appendix C -- Test Page Information

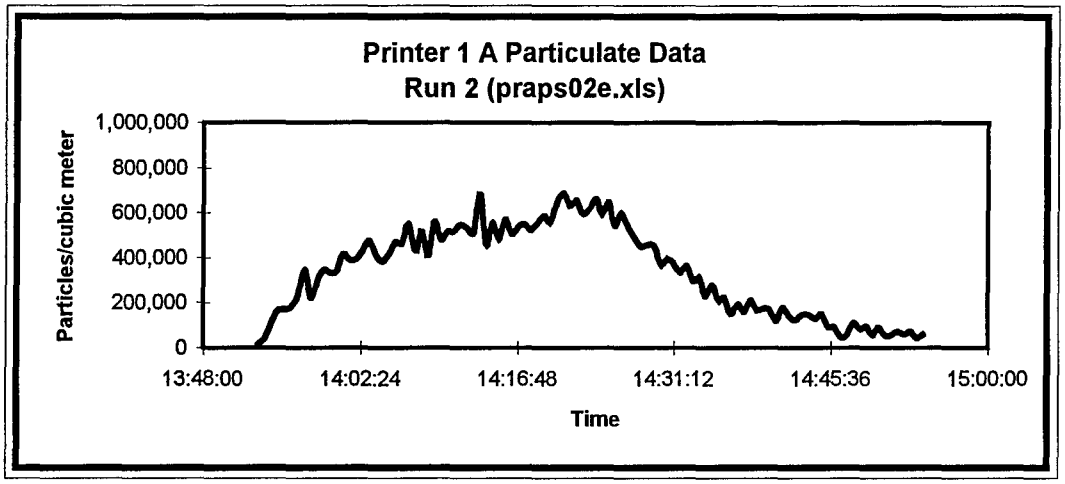


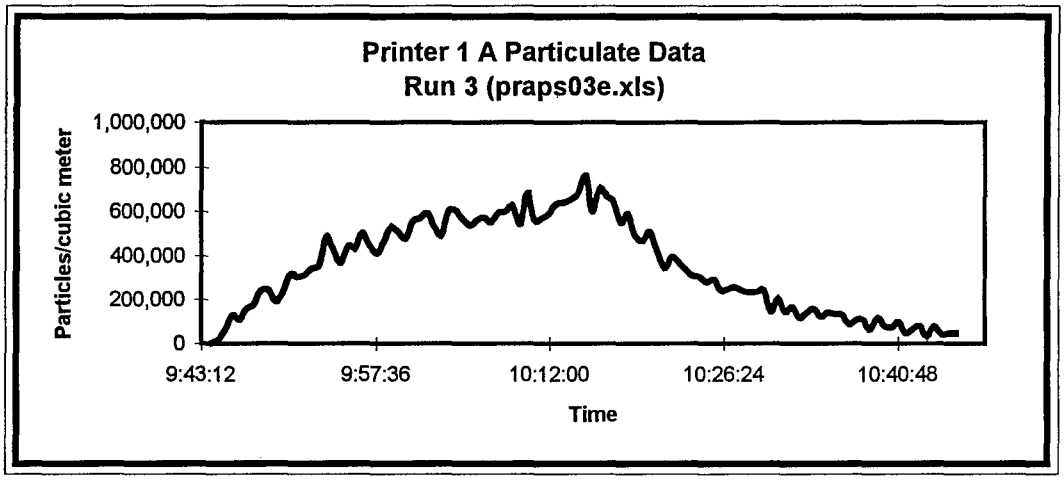
Appendix C -- Test Page Information

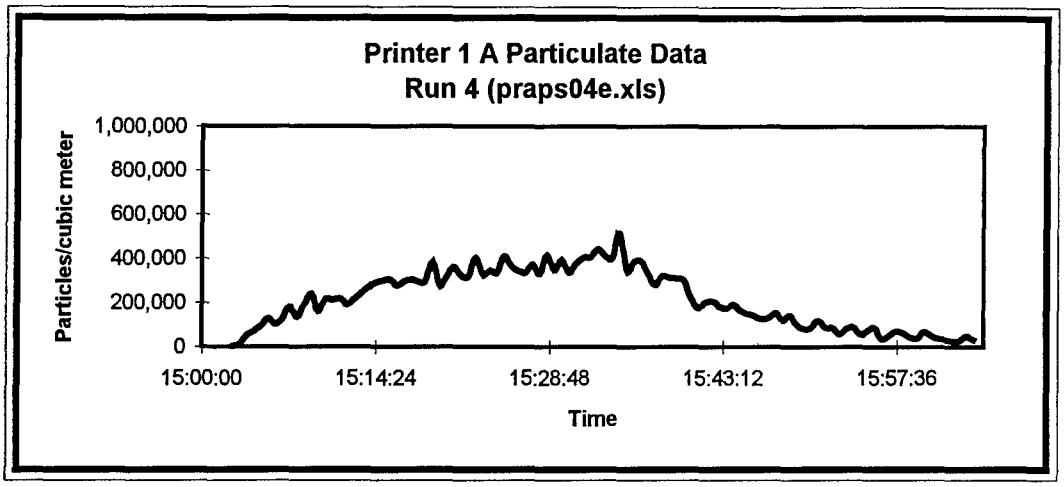


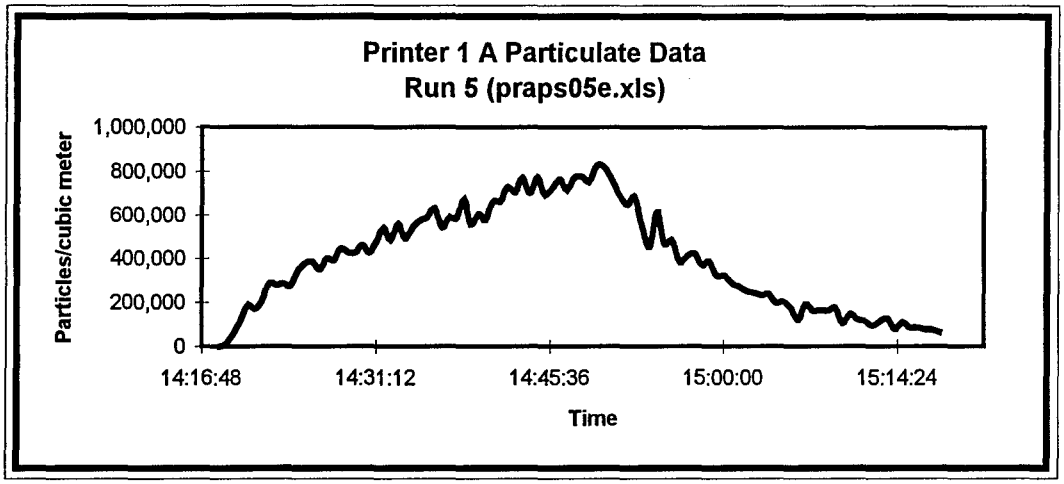
APPENDIX D
Concentration and Generation Rate Data

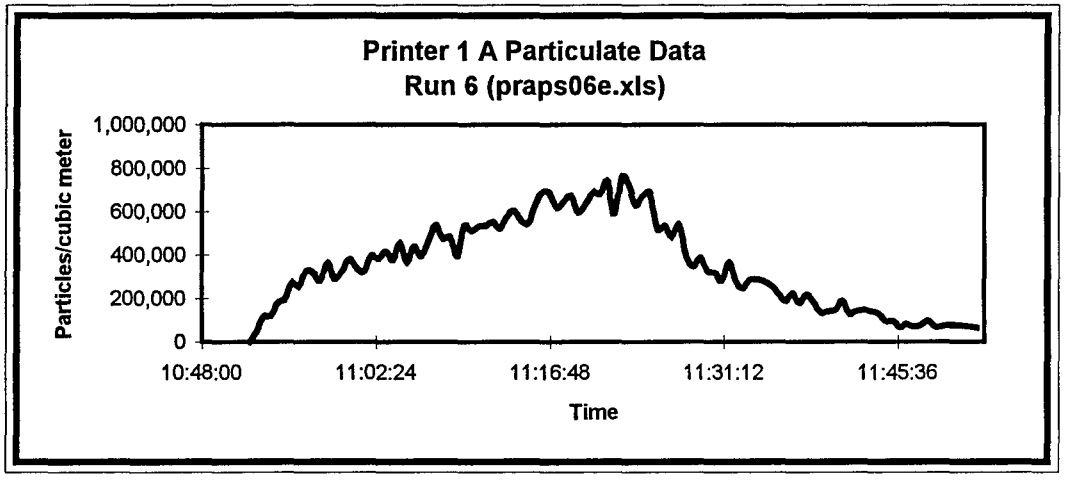

Printer 1 A Particulate Data
Run 1 (praps01e.xls)
Particles/cubic meter
1,000,000
800,000
600,000
400,000
200,000
0
13:55:12
14:09:36
14:24:00
14:38:24
14:52:48
Time


Printer 1 A Particulate Data
Run 2 (praps02e.xls)
Particles/cubic meter
1,000,000
800,000
600,000
400,000
200,000
0
13:48:00
14:02:24
14:16:48
14:31:12
14:45:36
15:00:00
Time


Printer 1 A Particulate Data
Run 3 (praps03e.xls)
Particles/cubic meter
1,000,000
800,000
600,000
400,000
200,000
0
9:43:12
9:57:36
10:12:00
10:26:24
10:40:48
Time


Printer 1 A Particulate Data
Run 4 (praps04e.xls)
Particles/cubic meter
1,000,000
800,000
600,000
400,000
200,000
0
15:00:00
15:14:24
15:28:48
15:43:12
15:57:36
Time


Printer 1 A Particulate Data
Run 5 (praps05e.xls)
Particles/cubic meter
1,000,000
800,000
600,000
400,000
200,000
0
14:16:48
14:31:12
14:45:36
15:00:00
15:14:24
Time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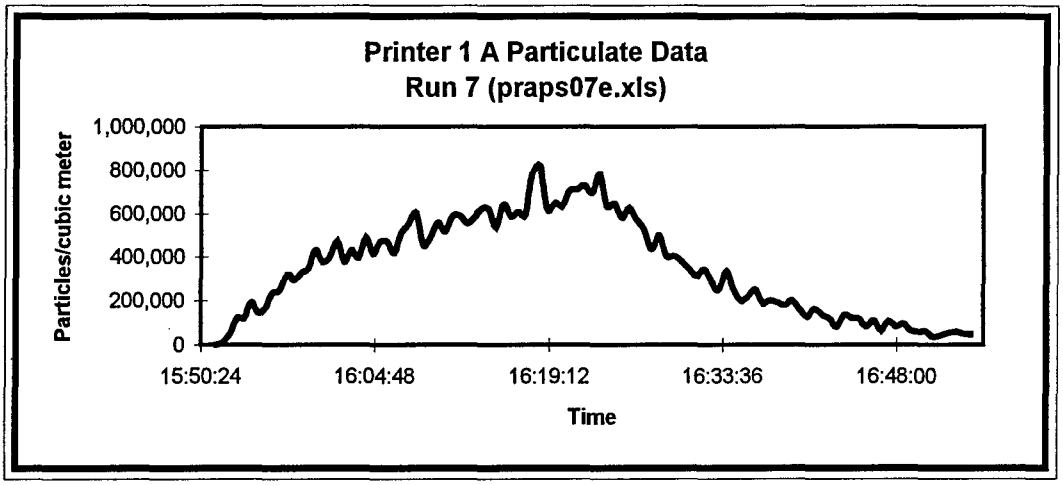
Run 6 (praps06e.xls)
Particles/cubic meter
1,000,000
800,000
600,000
400,000
200,000
0
10:48:00
11:02:24
11:16:48
11:31:12
11:45:36
Time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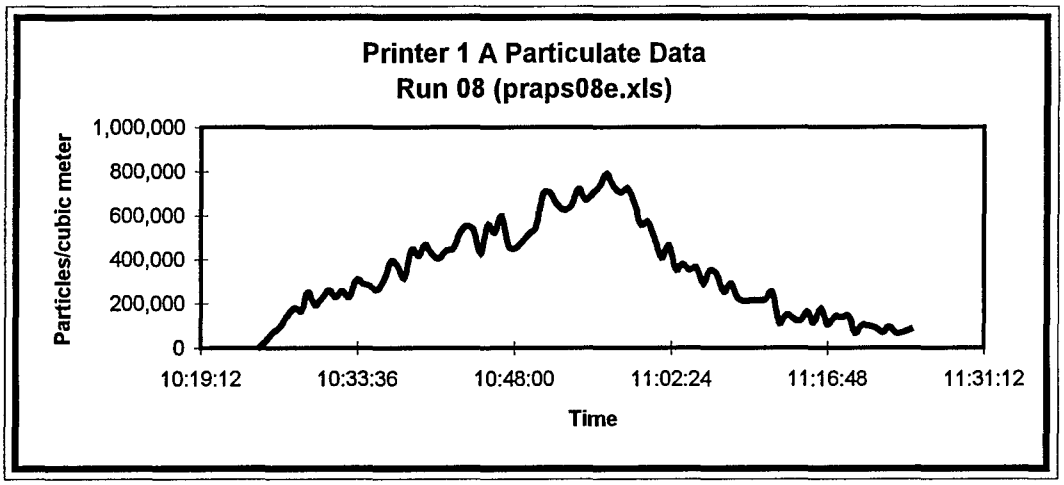
Run 7 (praps07e.xls)
Particles/cubic meter
1,000,000
800,000
600,000
400,000
200,000
0
15:50:24
16:04:48
16:19:12
16:33:36
16:48:00
Time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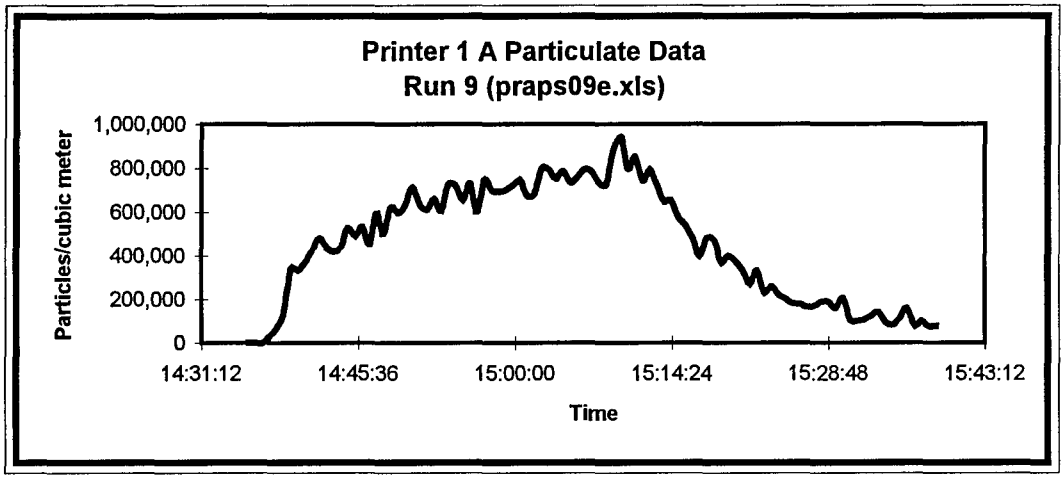
Particles/cubic meter
1,000,000
800,000
600,000
400,000
200,000
0
10:19:12
10:33:36
10:48:00
11:02:24
11:16:48
11:31:12
Time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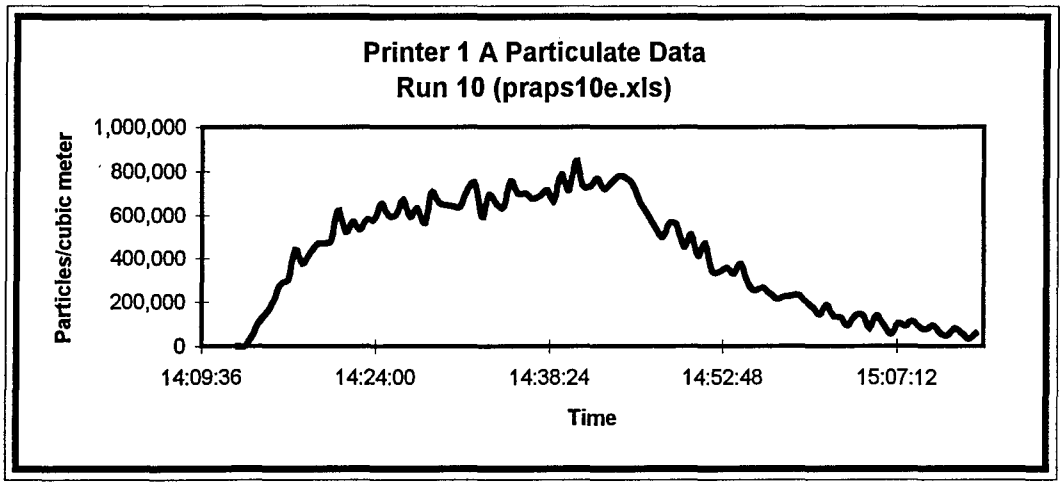
Run 9 (praps09e.xls)
Particles/cubic meter
1,000,000
800,000
600,000
400,000
200,000
0
14:31:12
14:45:36
15:00:00
15:14:24
15:28:48
15:43:12
Time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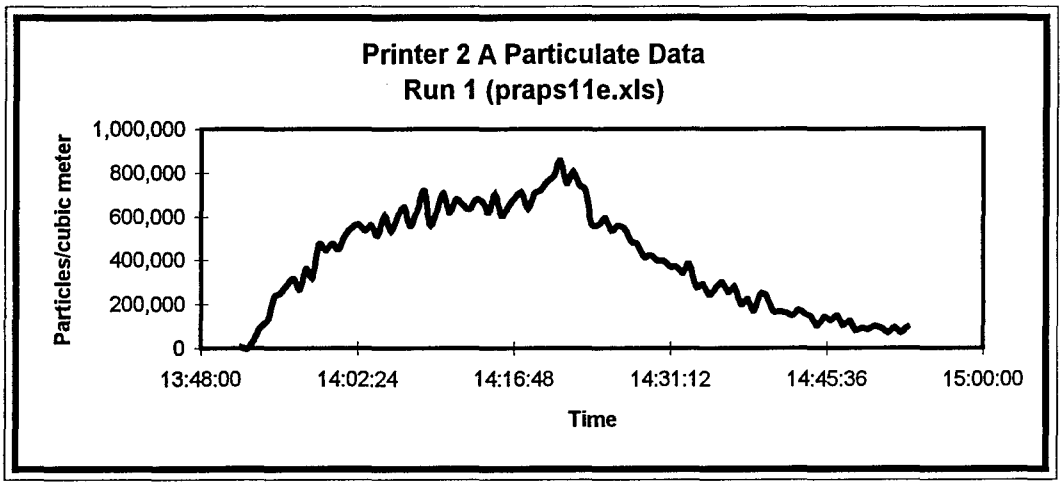
Run 10 (praps10e.xls)
Particles/cubic meter
1,000,000
800,000
600,000
400,000
200,000
0
14:09:36
14:24:00
14:38:24
14:52:48
15:07:12
Time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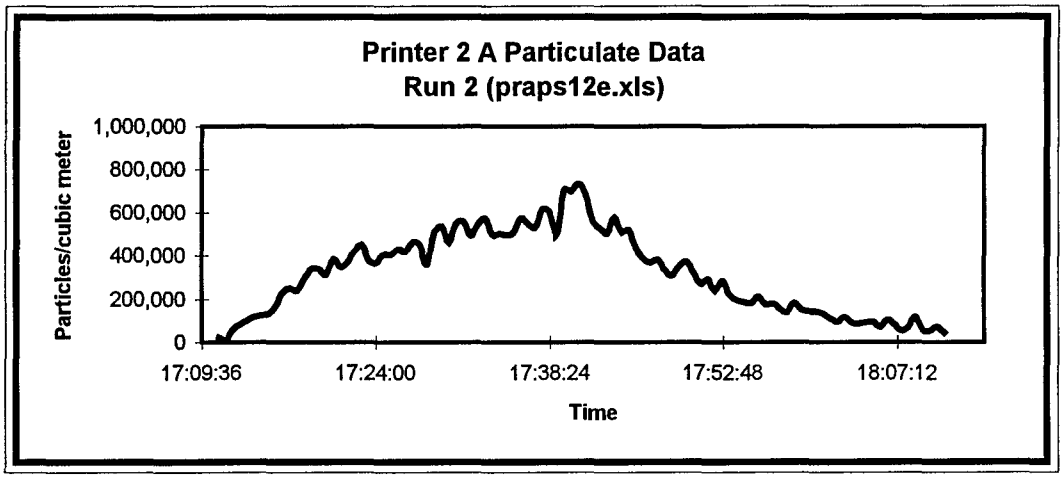
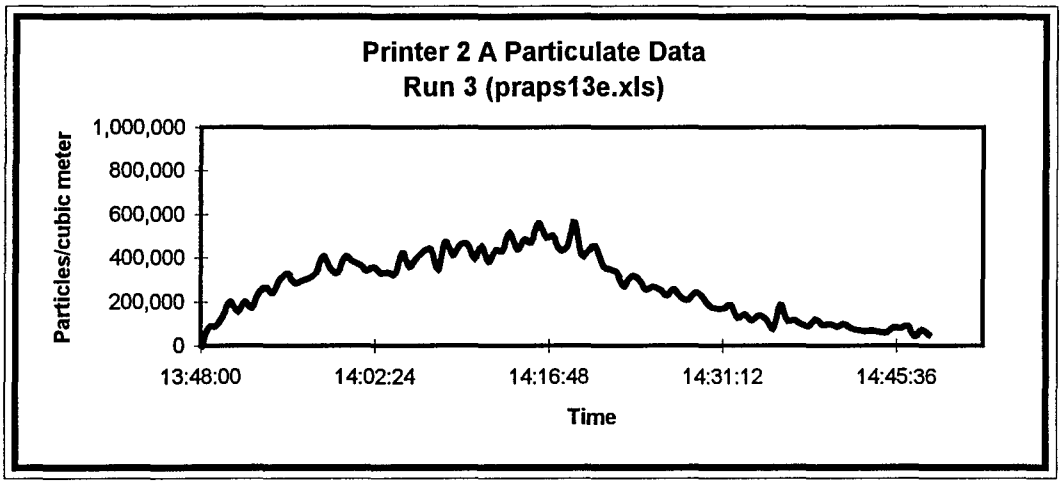
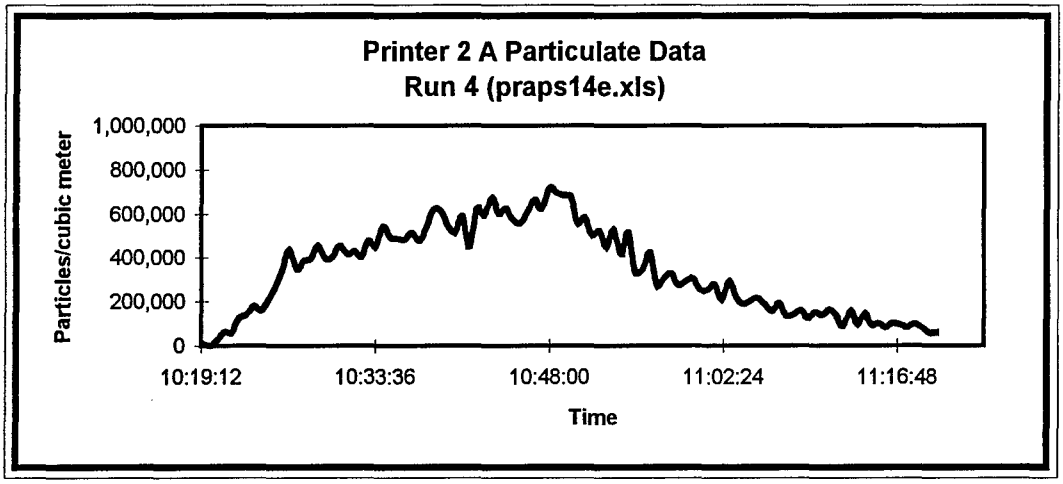
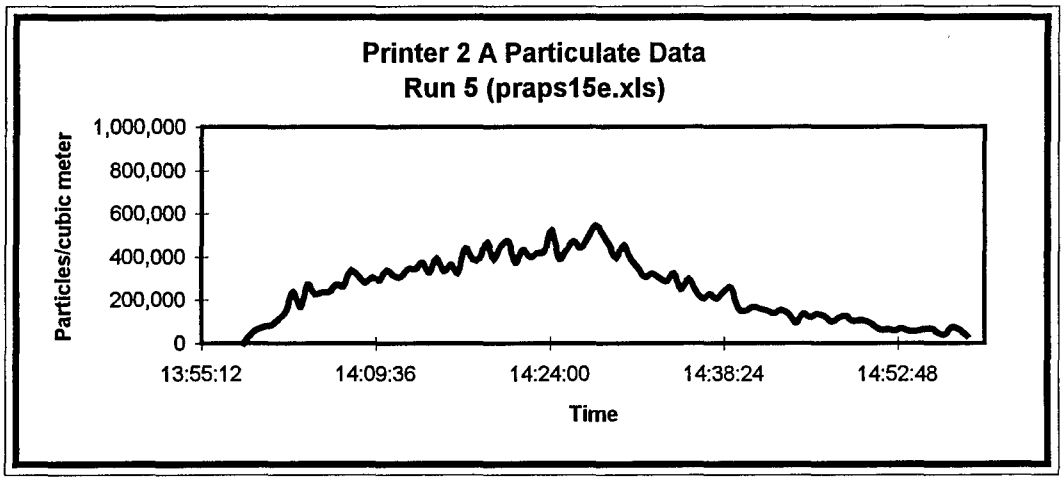
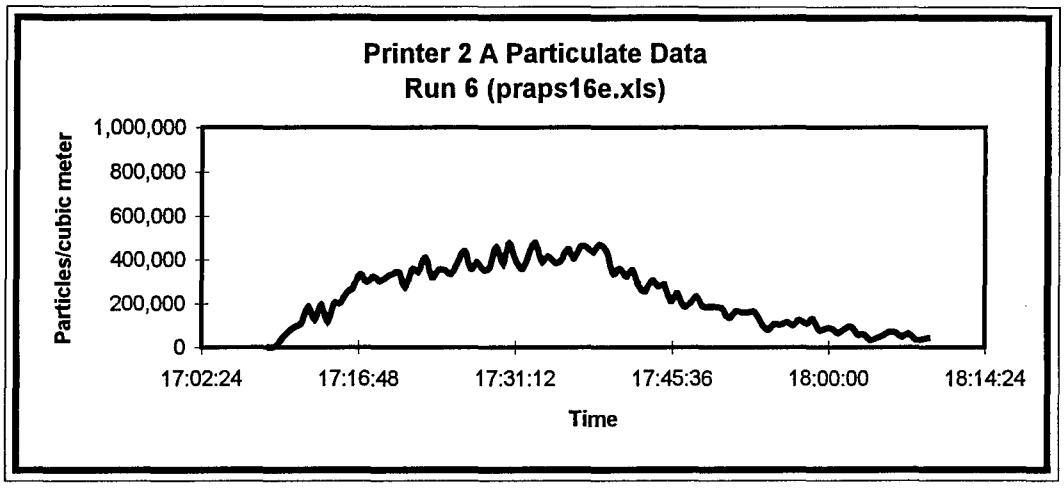
Run 1 (praps11e.xls)
Particles/cubic meter
1,000,000
800,000
600,000
400,000
200,000
0
13:48:00
14:02:24
14:16:48
14:31:12
14:45:36
15:00:00
Time

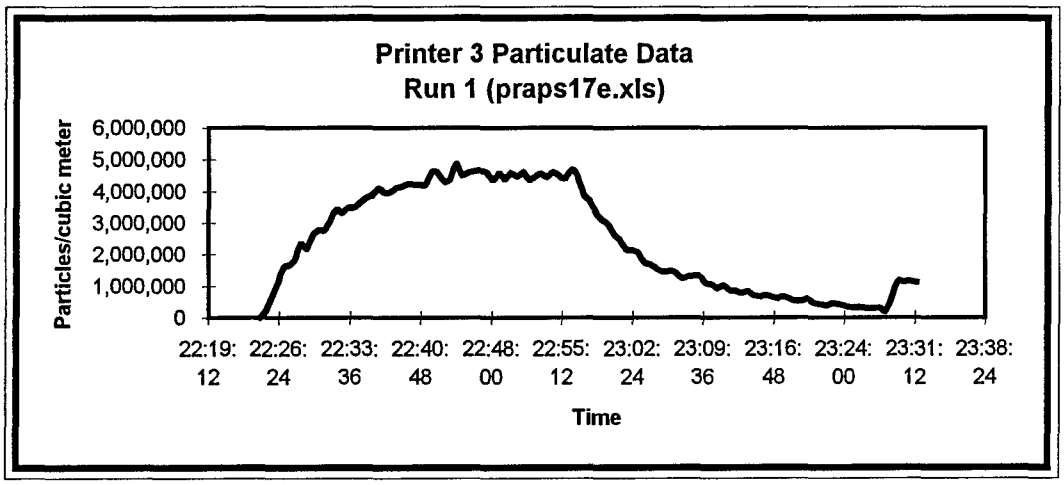

Printer 2 A Particulate Data
Run 2 (praps12e.xls)
Particles/cubic meter
1,000,000
800,000
600,000
400,000
200,000
0
17:09:36
17:24:00
17:38:24
17:52:48
18:07:12
Time

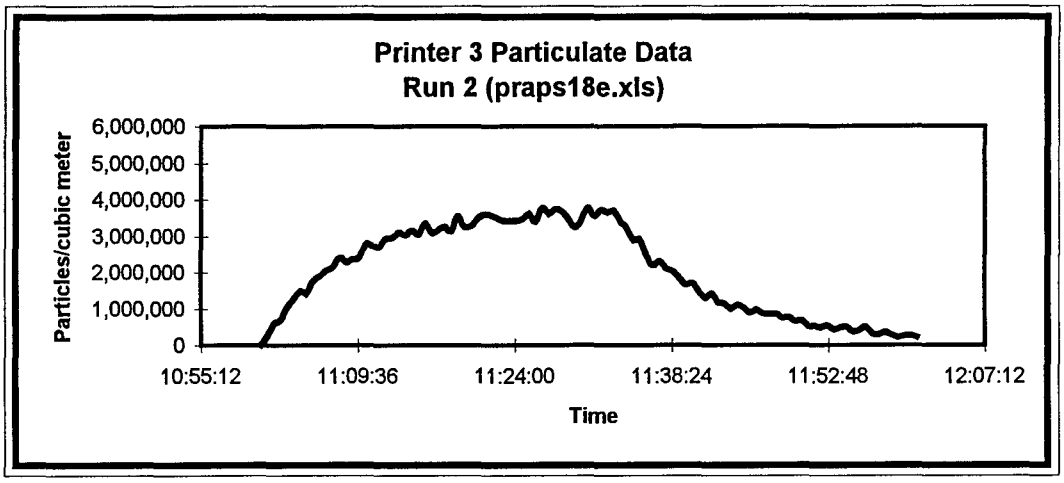

Printer 2 A Particulate Data
Run 3 (praps13e.xls)
Particles/cubic meter
1,000,000
800,000
600,000
400,000
200,000
0
13:48:00
14:02:24
14:16:48
14:31:12
14:45:36
Time

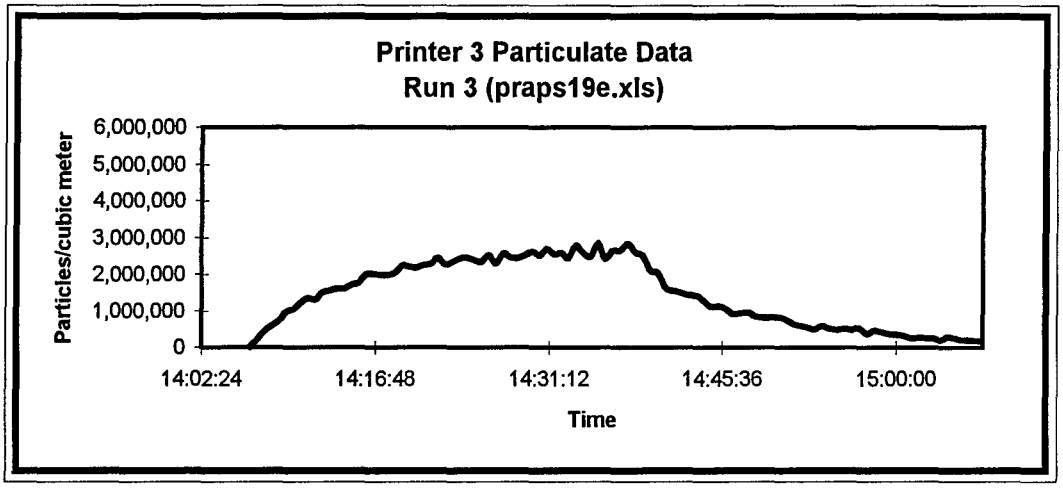

Printer 2 A Particulate Data
Run 4 (praps14e.xls)
Particles/cubic meter
1,000,000
800,000
600,000
400,000
200,000
0
10:19:12
10:33:36
10:48:00
11:02:24
11:16:48
Time

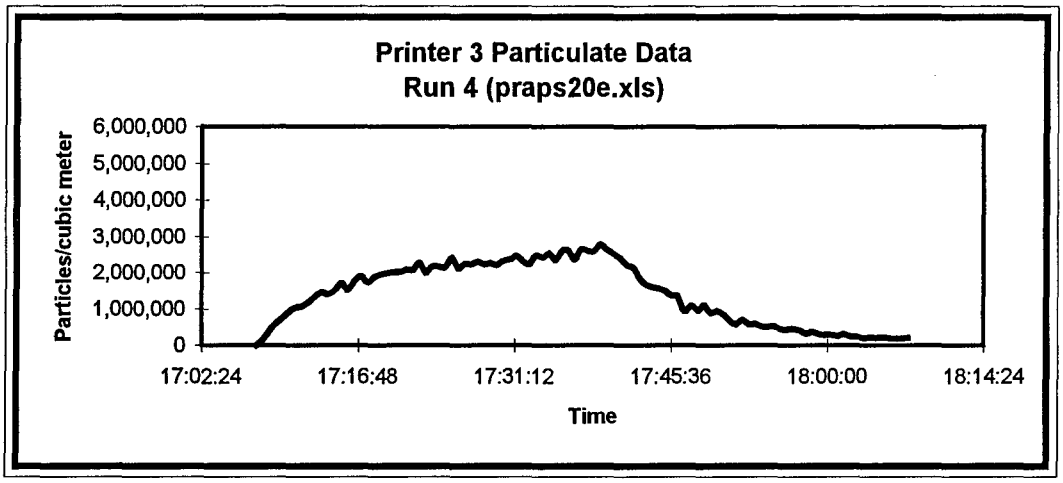

Printer 2 A Particulate Data
Run 5 (praps15e.xls)
Particles/cubic meter
1,000,000
800,000
600,000
400,000
200,000
0
13:55:12
14:09:36
14:24:00
14:38:24
14:52:48
Time

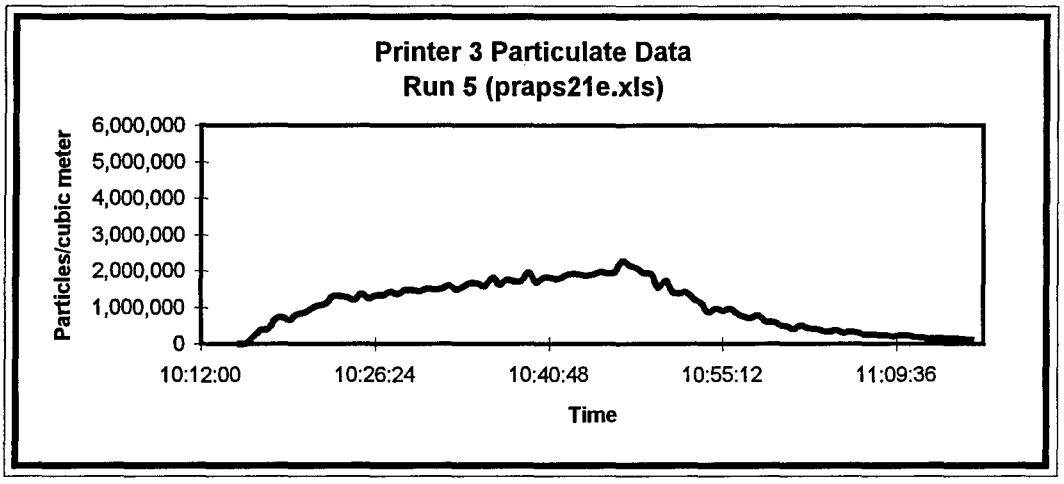

Printer 2 A Particulate Data
Run 6 (praps16e.xls)
Particles/cubic meter
1,000,000
800,000
600,000
400,000
200,000
0
17:02:24
17:16:48
17:31:12
17:45:36
18:00:00
18:14:24
Time

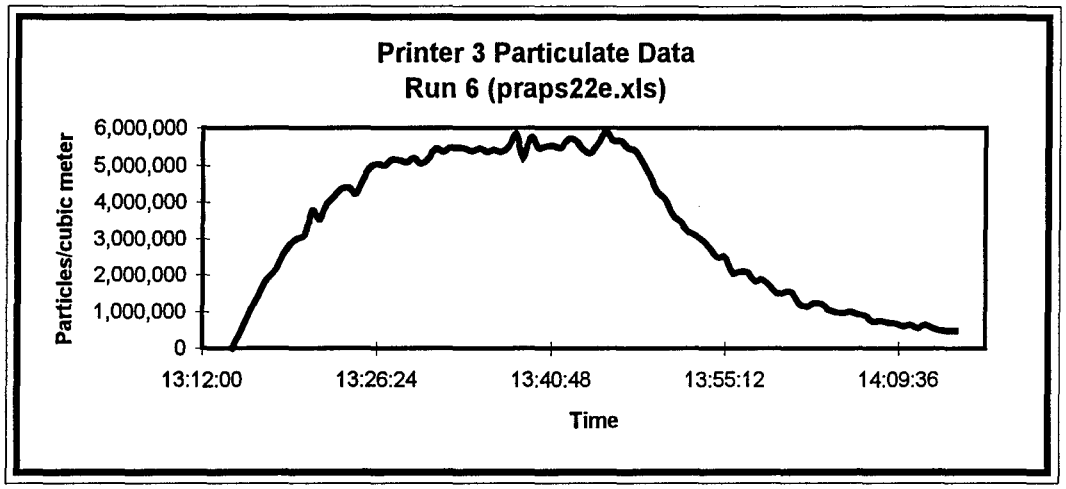

Printer 3 Particulate Data
Run 1 (praps17e.xls)
Particles/cubic meter
6,000,000
5,000,000
4,000,000
3,000,000
2,000,000
1,000,000
0
22:19:12
22:26:24
22:33:36
22:40:48
22:48:00
22:55:12
23:02:24
23:09:36
23:16:48
23:24:00
23:31:12
23:38:24
Time

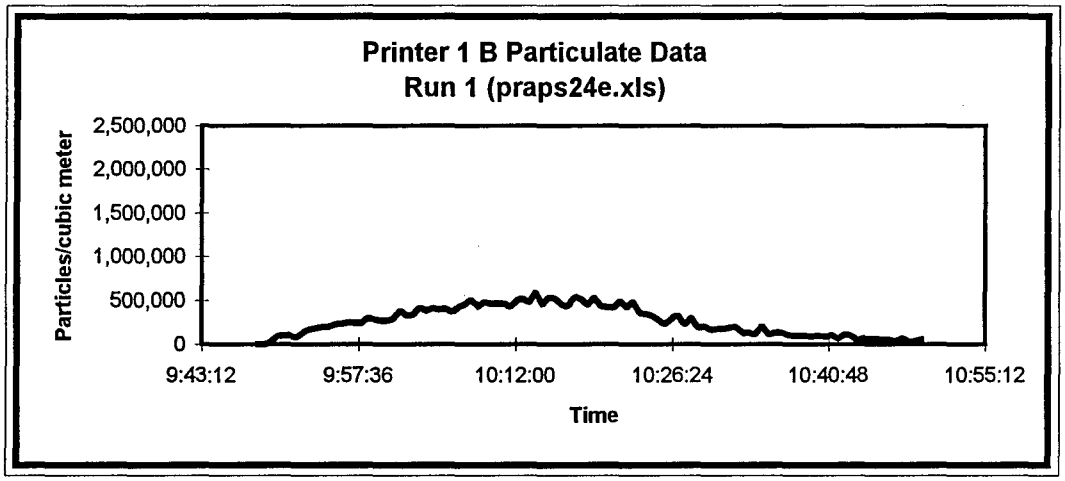

Printer 3 Particulate Data
Run 2 (praps18e.xls)
Particles/cubic meter
6,000,000
5,000,000
4,000,000
3,000,000
2,000,000
1,000,000
0
10:55:12
11:09:36
11:24:00
11:38:24
11:52:48
12:07:12
Time

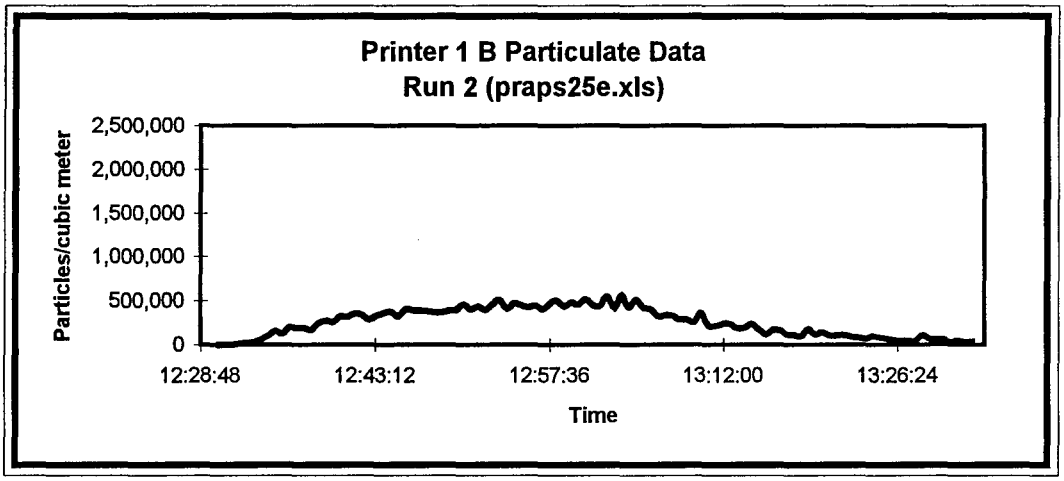

Printer 3 Particulate Data
Run 3 (praps19e.xls)
Particles/cubic meter
6,000,000
5,000,000
4,000,000
3,000,000
2,000,000
1,000,000
0
14:02:24
14:16:48
14:31:12
14:45:36
15:00:00
Time

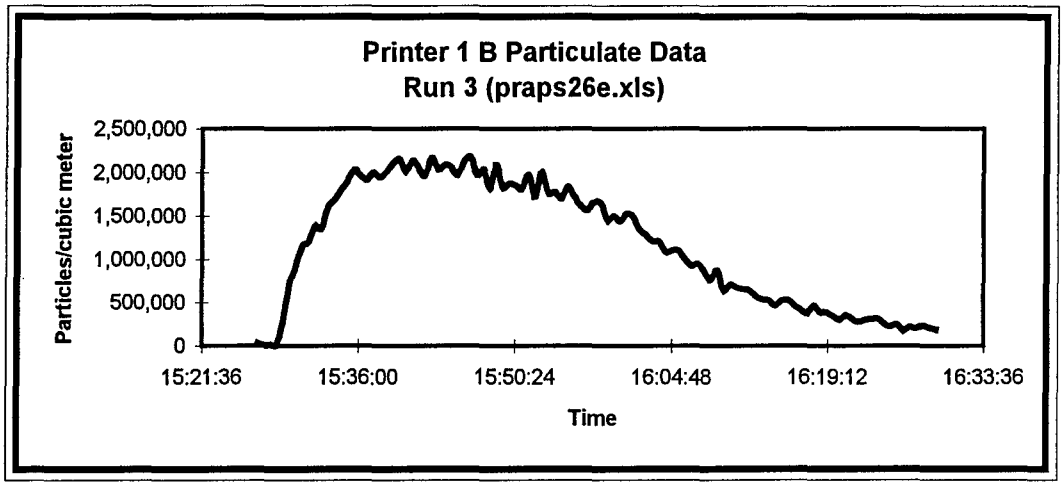

Printer 3 Particulate Data
Run 4 (praps20e.xls)
Particles/cubic meter
6,000,000
5,000,000
4,000,000
3,000,000
2,000,000
1,000,000
0
17:02:24
17:16:48
17:31:12
17:45:36
18:00:00
18:14:24
Time

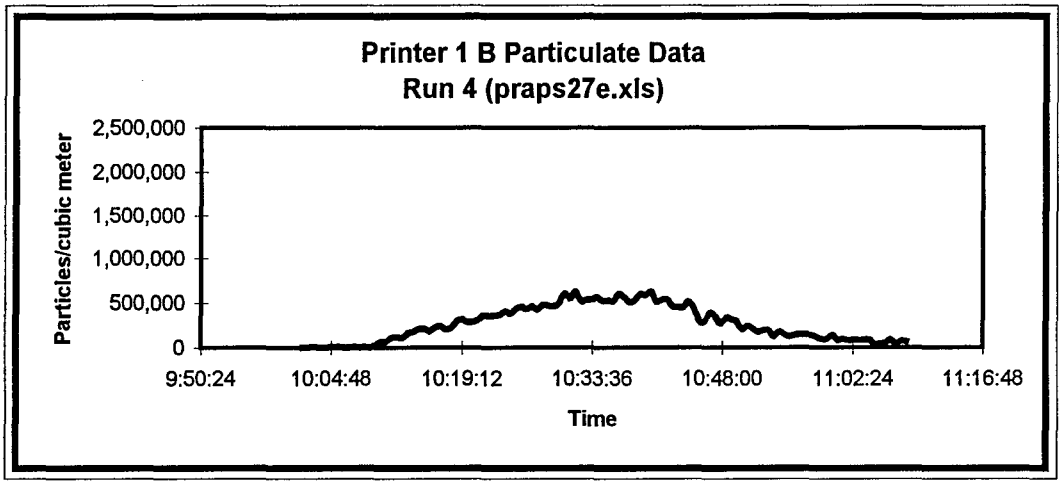

Printer 3 Particulate Data
Run 5 (praps21e.xls)
Particles/cubic meter
6,000,000
5,000,000
4,000,000
3,000,000
2,000,000
1,000,000
0
10:12:00
10:26:24
10:40:48
10:55:12
11:09:36
Time

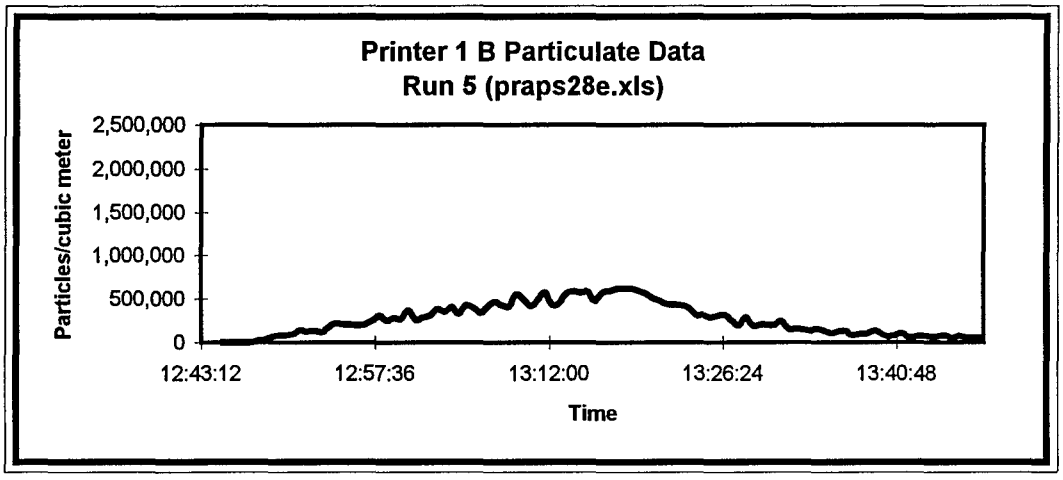

Printer 3 Particulate Data
Run 6 (praps22e.xls)
Particles/cubic meter
6,000,000
5,000,000
4,000,000
3,000,000
2,000,000
1,000,000
0
13:12:00
13:26:24
13:40:48
13:55:12
14:09:36
Time

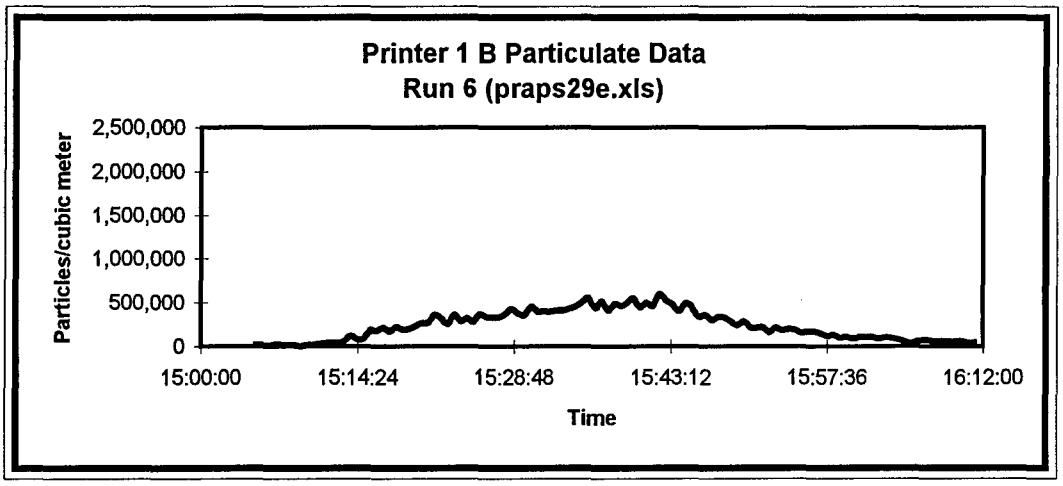

Printer 1 B Particulate Data
Run 1 (praps24e.xls)
Particles/cubic meter
2,500,000
2,000,000
1,500,000
1,000,000
500,000
0
9:43:12
9:57:36
10:12:00
10:26:24
10:40:48
10:55:12
Time

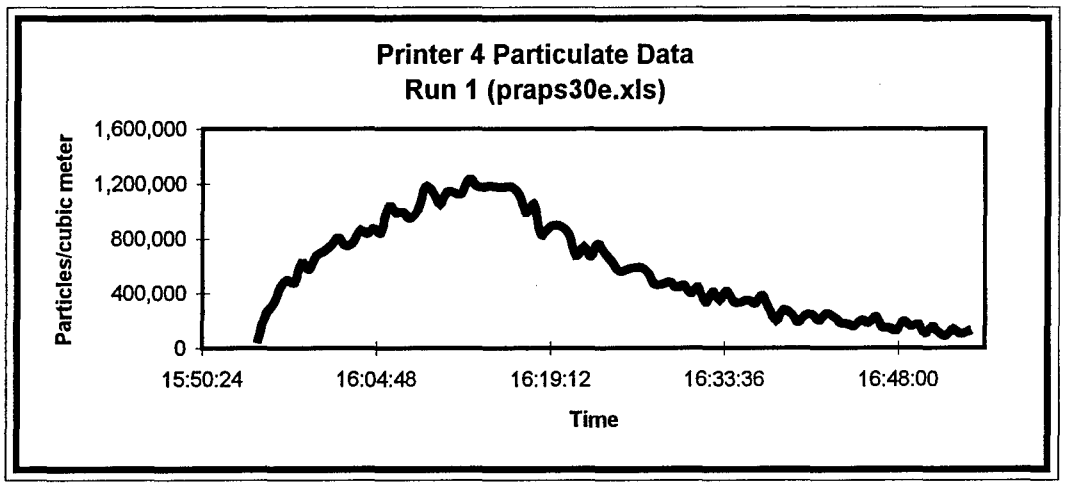

Printer 1 B Particulate Data
Run 2 (praps25e.xls)
Particles/cubic meter
2,500,000
2,000,000
1,500,000
1,000,000
500,000
0
12:28:48
12:43:12
12:57:36
13:12:00
13:26:24
Time

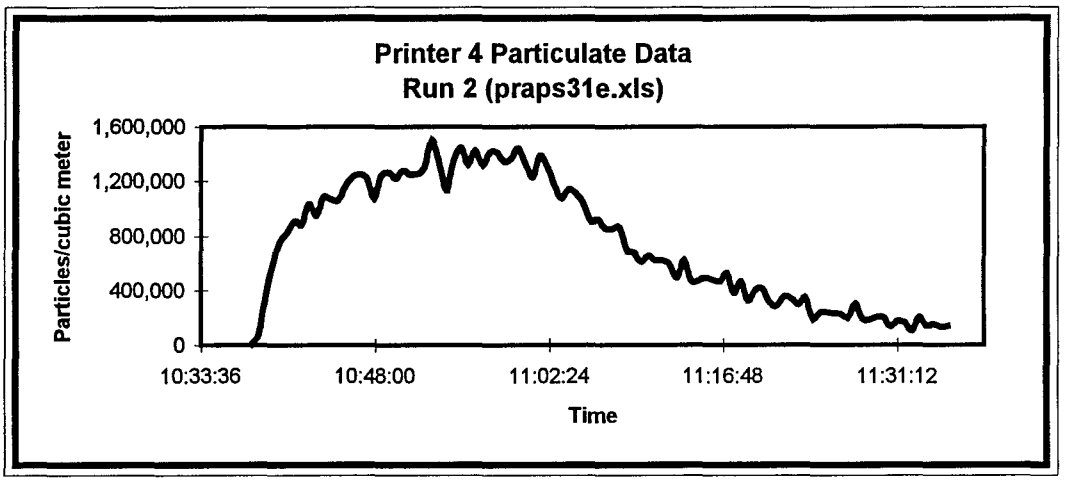

Printer 1 B Particulate Data
Run 3 (praps26e.xls)
Particles/cubic meter
2,500,000
2,000,000
1,500,000
1,000,000
500,000
0
15:21:36
15:36:00
15:50:24
16:04:48
16:19:12
16:33:36
Time

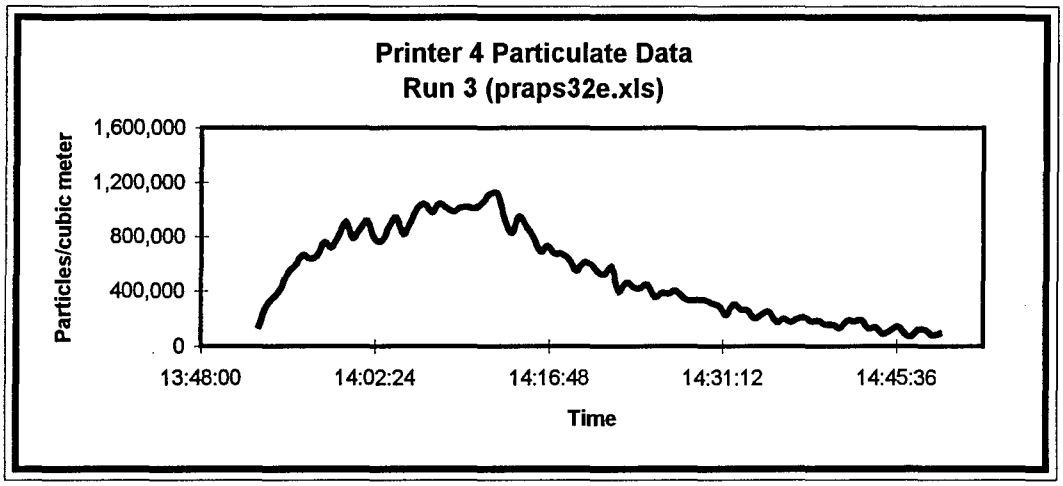

Printer 1 B Particulate Data
Run 4 (praps27e.xls)
Particles/cubic meter
2,500,000
2,000,000
1,500,000
1,000,000
500,000
0
9:50:24
10:04:48
10:19:12
10:33:36
10:48:00
11:02:24
11:16:48
Time

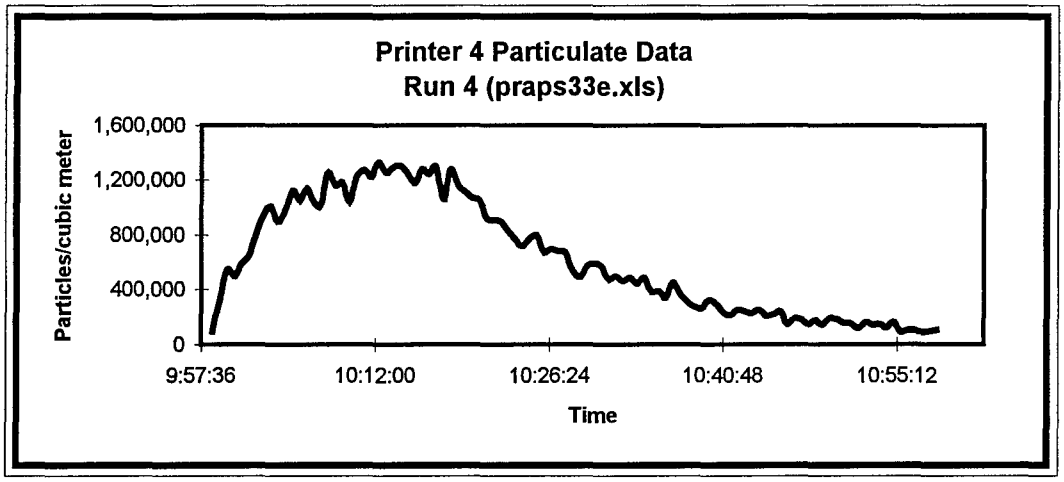

Printer 1 B Particulate Data
Run 5 (praps28e.xls)
Particles/cubic meter
2,500,000
2,000,000
1,500,000
1,000,000
500,000
0
12:43:12
12:57:36
13:12:00
13:26:24
13:40:48
Time

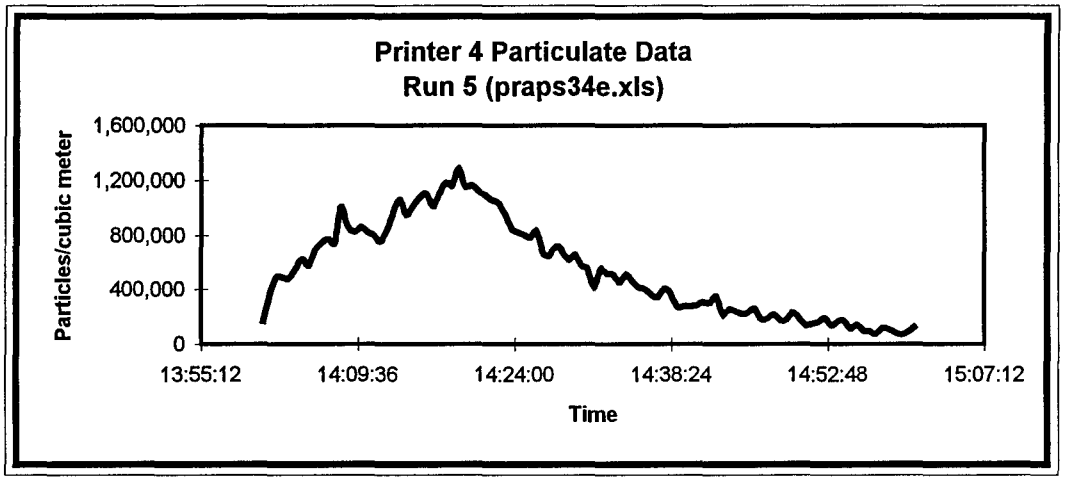

Printer 1 B Particulate Data
Run 6 (praps29e.xls)
Particles/cubic meter
2,500,000
2,000,000
1,500,000
1,000,000
500,000
0
15:00:00
15:14:24
15:28:48
15:43:12
15:57:36
16:12:00
Time


Printer 4 Particulate Data
Run 1 (praps30e.xls)
Particles/cubic meter
1,600,000
1,200,000
800,000
400,000
0
15:50:24
16:04:48
16:19:12
16:33:36
16:48:00
Time

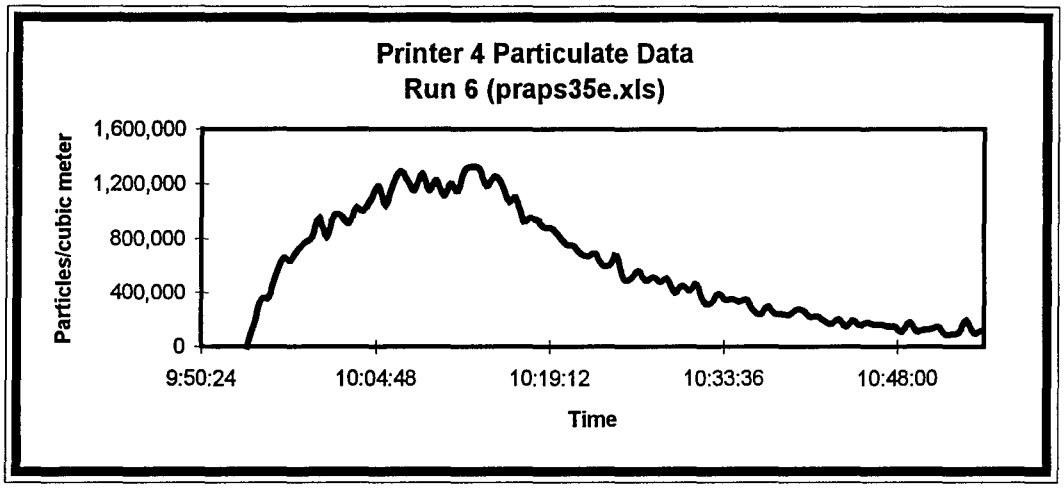

Printer 4 Particulate Data
Run 2 (praps31e.xls)
Particles/cubic meter
1,600,000
1,200,000
800,000
400,000
0
10:33:36
10:48:00
11:02:24
11:16:48
11:31:12
Time

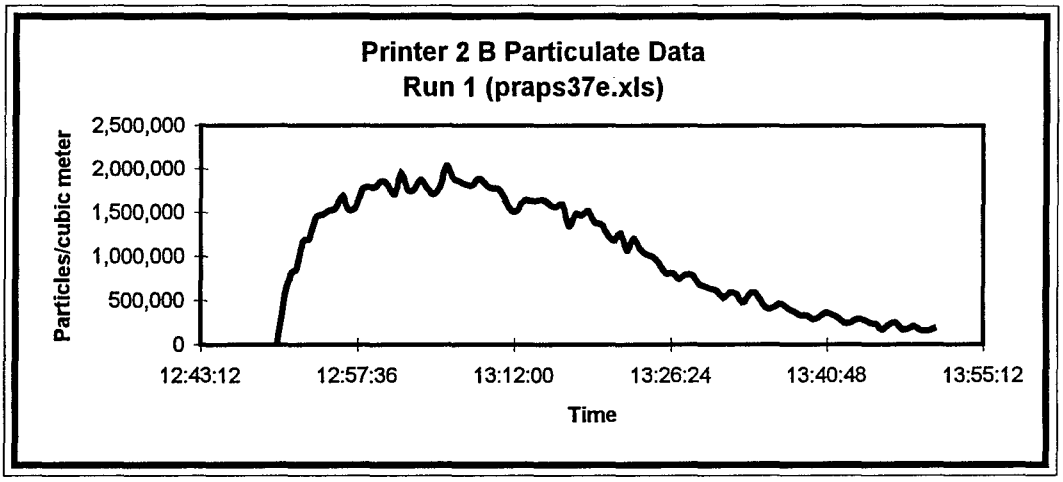

Printer 4 Particulate Data
Run 3 (praps32e.xls)
Particles/cubic meter
1,600,000
1,200,000
800,000
400,000
0
13:48:00
14:02:24
14:16:48
14:31:12
14:45:36
Time

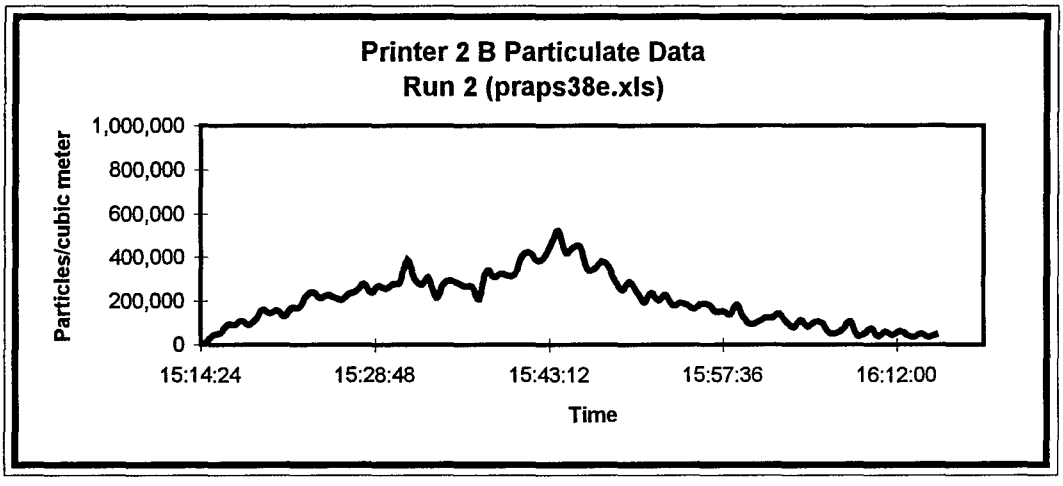

Printer 4 Particulate Data
Run 4 (praps33e.xls)
Particles/cubic meter
1,600,000
1,200,000
800,000
400,000
0
9:57:36
10:12:00
10:26:24
10:40:48
10:55:12
Time

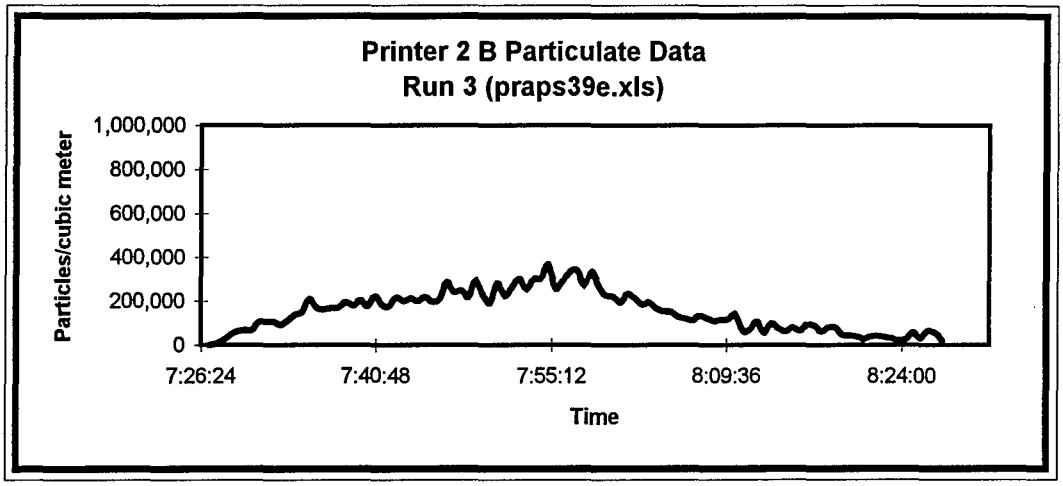

Printer 4 Particulate Data
Run 5 (praps34e.xls)
Particles/cubic meter
1,600,000
1,200,000
800,000
400,000
0
13:55:12
14:09:36
14:24:00
14:38:24
14:52:48
15:07:12
Time

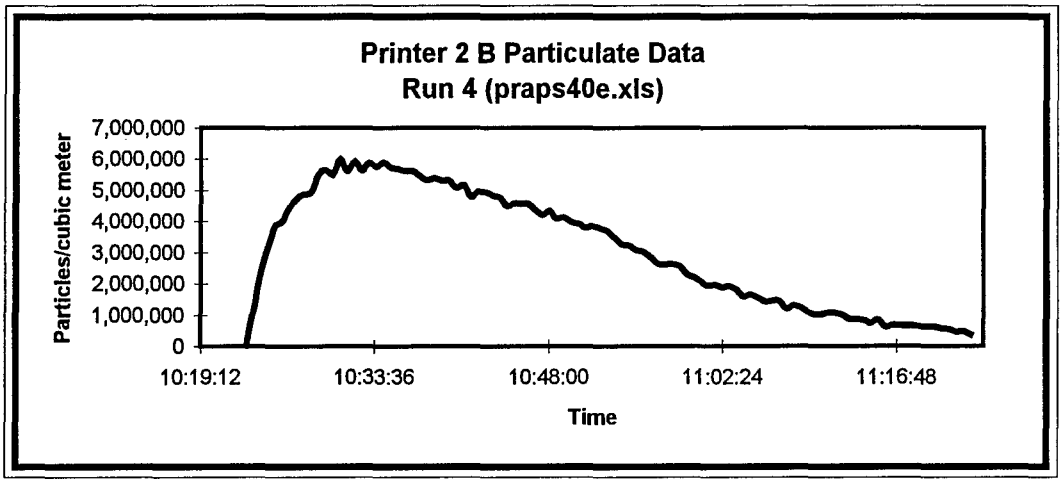
Appendix D -- Concentration and Generation Rate Data

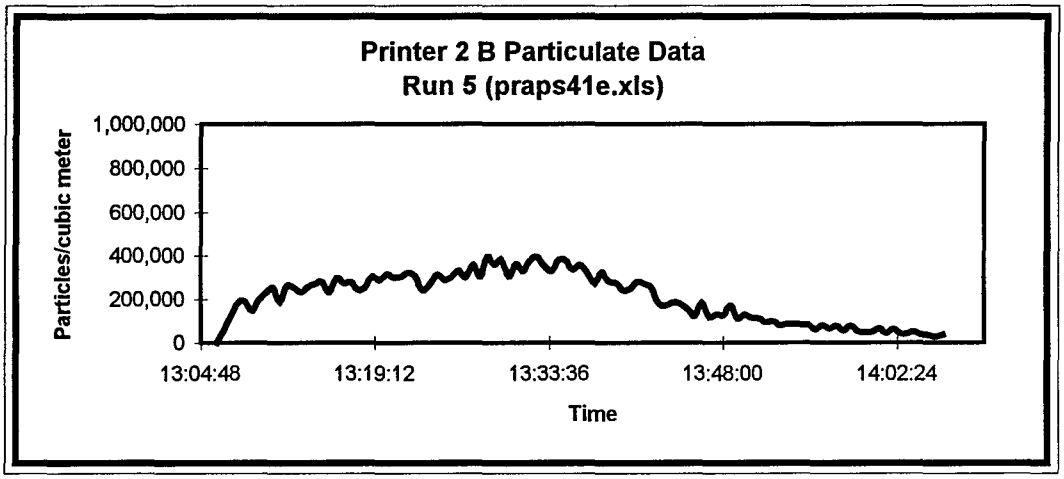


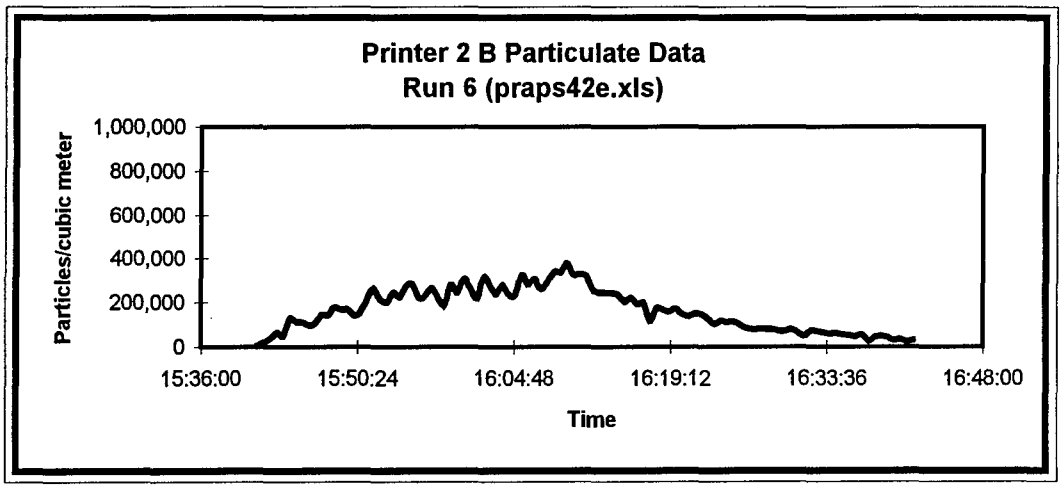





Printer 2 B Particulate Data
Run 3 (praps39e.xls)
Particles/cubic meter
1,000,000
800,000
600,000
400,000
200,000
0
7:26:24
7:40:48
7:55:12
8:09:36
8:24:00
Time


Printer 2 B Particulate Data
Run 4 (praps40e.xls)
Particles/cubic meter
7,000,000
6,000,000
5,000,000
4,000,000
3,000,000
2,000,000
1,000,000
0
10:19:12
10:33:36
10:48:00
11:02:24
11:16:48
Time


Printer 2 B Particulate Data
Run 5 (praps41e.xls)
Particles/cubic meter
1,000,000
800,000
600,000
400,000
200,000
0
13:04:48
13:19:12
13:33:36
13:48:00
14:02:24
Time


Printer 2 B Particulate Data
Run 6 (praps42e.xls)
Particles/cubic meter
1,000,000
800,000
600,000
400,000
200,000
0
15:36:00
15:50:24
16:04:48
16:19:12
16:33:36
16:48:00
Time

Appendix D -- Concentration and Generation Rate Data

Particulate Data Printer 1 A #56392

Run	Printing Generation	Decay Generation	Printer Generation
PRINT01	47728.8869	-27506.671	75235.5578
PRINT02	42417.169	-16865.822	59282.991
PRINT03	47816.8887	-21918.06	69734.9486
PRINT04	28731.2335	-12196.034	40927.2676
PRINT05	51665.4655	-24140.932	75806.398
PRINT06	48425.4776	-23922.537	72348.0141
PRINT07	48055.7716	-18498.531	66554.3027
PRINT08	47558.2562	-12320.103	59878.3587
PRINT09	52394.1469	-24431.32	76825.4664
PRINT10	53580.0254	-21466.585	75046.6108

Particle Generation	
Mean (particles/min)	67163.99
95% CI	6953.284

Particulate Data Printer 2 A #23312

Run	Printing Generation	Decay Generation	Printer Generation
PRINT11	49617.9184	-17396.461	67014.3791
PRINT12	44580.4315	-19303.728	63884.1594
PRINT13	34238.2148	-10010.209	44248.4243
PRINT14	43669.3936	-16045.184	59714.5775
PRINT15	32813.0501	-12447.032	45260.0825
PRINT16	29342.6237	-10696.38	40039.0041

Particle Generation	
Mean (particles/min)	53360.1
95% CI	9218.48

Particulate Data Printer 3 #74440

Run	Printing Generation	Decay Generation	Printer Generation
PRINT17	321012.495	-121421.7	442434.194
PRINT18	252227.792	-100139.12	352366.915
PRINT19	192164.282	-72340.114	264504.396
PRINT20	169940.314	-69435.997	239376.311
PRINT21	127459.967	-55082.626	182542.593
PRINT22	388873.68	-139348.56	528222.236

Particle Generation	
Mean (particles/min)	334907.8
95% CI	105264.9

Appendix D -- Concentration and Generation Rate Data

Particulate Data Printer 1 B #56392

Run	Printing Generation	Decay Generation	Printer Generation
PRINT24	29376.3999	-9978.7688	39355.1687
PRINT25	35177.3322	-15692.762	50870.0947
PRINT26	125207.566	-35548.017	160755.583
PRINT27	35047.2242	-13991.594	49038.8185
PRINT28	35930.0312	-15960.133	51890.1639
PRINT29	32833.1169	-14138.144	46971.2611

Particle Generation	
Mean (particles/min)	66480.18
95% CI	37127.27

Particulate Data Printer 4 #80203

Run	Printing Generation	Decay Generation	Printer Generation
PRINT30	111127.636	-14739.832	125867.468
PRINT31	131959.551	-23170.341	155129.892
PRINT32	96862.386	-15450.77	112313.156
PRINT33	126434.163	-18458.889	144893.052
PRINT34	103362.794	-15864.987	119227.781
PRINT35	128286.743	-18981.509	147268.251

Particle Generation	
Mean (particles/min)	134116.6
95% CI	13839.47

Particulate Data Printer 2 B #23312

Run	Printing Generation	Decay Generation	Printer Generation
PRINT37	134953.505	-28384.937	163338.442
PRINT38	30644.1381	-3908.6142	34552.7522
PRINT39	19435.4536	-4036.5723	23472.0259
PRINT40	377203.539	-71201.391	448404.929
PRINT41	29436.3669	-7578.039	37014.4059
PRINT42	25823.974	-8176.3242	34000.2982

Particle Generation	
Mean (particles/min)	123463.8
95% CI	134157.1

APPENDIX D -- Concentration and Generation Rate Data

Particulate Data (Mass) Printer 1 A #56392

Run	Particle Mass (μg/particle)	Particle Generation (particles/min)	Mass Generation (μg/min)
PRINT01	9.96316E-08	75235.55777	0.00749584
PRINT02	1.06868E-07	59282.99095	0.00633543
PRINT03	1.07523E-07	69734.9486	0.0074981
PRINT04	1.04389E-07	40927.2676	0.00427236
PRINT05	9.0287E-08	75806.39797	0.00684433
PRINT06	8.93082E-08	72348.0141	0.00646127
PRINT07	1.10065E-07	66554.30268	0.00732527
PRINT08	9.54282E-08	59878.35867	0.00571408
PRINT09	9.38312E-08	76825.46643	0.00720862
PRINT10	8.33422E-08	75046.61081	0.00625455

Mean Mass Generation (μg/min)	0.006541
95% CI	0.000618

Particulate Data (Mass) Printer 2 A #23312

Run	Particle Mass (μg/particle)	Particle Generation (particles/min)	Mass Generation (μg/min)
PRINT11	7.65412E-08	67014.3791	0.00512936
PRINT12	1.01964E-07	63884.15942	0.00651391
PRINT13	9.89879E-08	44248.42431	0.00438006
PRINT14	7.55671E-08	59714.57753	0.00451246
PRINT15	8.60075E-08	45260.0825	0.0038927
PRINT16	9.26037E-08	40039.00413	0.00370776

Mean Mass Generation (μg/min)	0.004689
95% CI	0.00082

Particulate Data (Mass) Printer 3 #74440

Run	Particle Mass (μg/particle)	Particle Generation (particles/min)	Mass Generation (μg/min)
PRINT17	9.44559E-08	442434.1943	0.04179054
PRINT18	8.44449E-08	352366.9152	0.0297556
PRINT19	8.39312E-08	264504.3961	0.02220017
PRINT20	8.30395E-08	239376.3107	0.01987769
PRINT21	8.51992E-08	182542.5931	0.01555249
PRINT22	9.28992E-08	528222.2356	0.04907145

Mean Mass Generation (μg/min)	0.029708
95% CI	0.010581

APPENDIX D -- Concentration and Generation Rate Data

Particulate Data (Mass) Printer 1 B #56392

Run	Particle Mass (μg/particle)	Particle Generation (particles/min)	Mass Generation (μg/min)
PRINT24	1.01158E-07	39355.16871	0.00398111
PRINT25	9.65152E-08	50870.09471	0.00490974
PRINT26	6.42941E-08	160755.5831	0.01033564
PRINT27	1.156E-07	49038.81851	0.00566887
PRINT28	1.15786E-07	51890.16386	0.00600813
PRINT29	9.16547E-08	46971.26106	0.00430514

Mean Mass Generation (μg/min)	0.005868
95% CI	0.001857

Particulate Data (Mass) Printer 4 #80203

Run	Particle Mass (μg/particle)	Particle Generation (particles/min)	Mass Generation (μg/min)
PRINT30	1.01409E-07	125867.4676	0.0047633
PRINT31	1.07543E-07	155129.8922	0.01353615
PRINT32	9.21717E-08	112313.1564	0.01429859
PRINT33	1.08301E-07	144893.0522	0.01216361
PRINT34	1.18257E-07	119227.7808	0.01713457
PRINT35	9.64307E-08	147268.2514	0.01149722

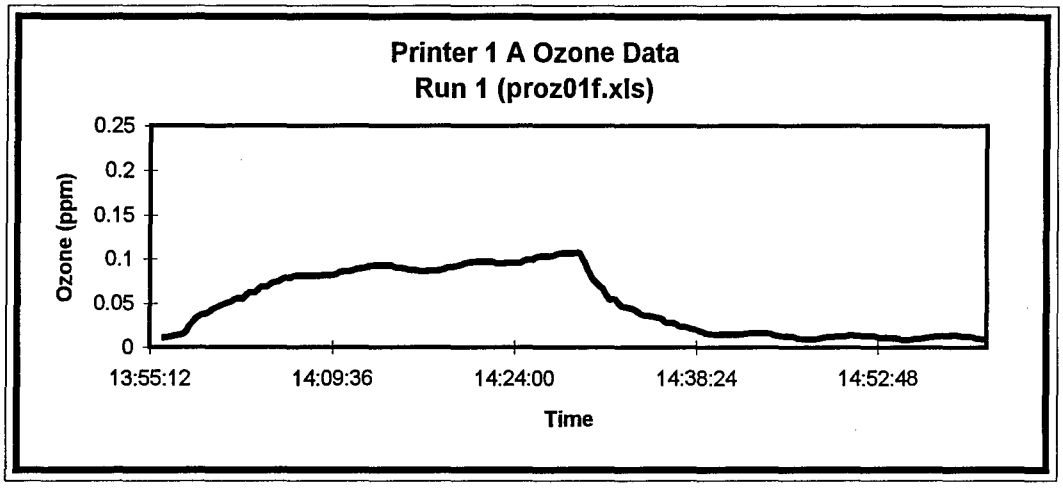
Mean Mass Generation (μg/min)	0.012232
95% CI	0.003325

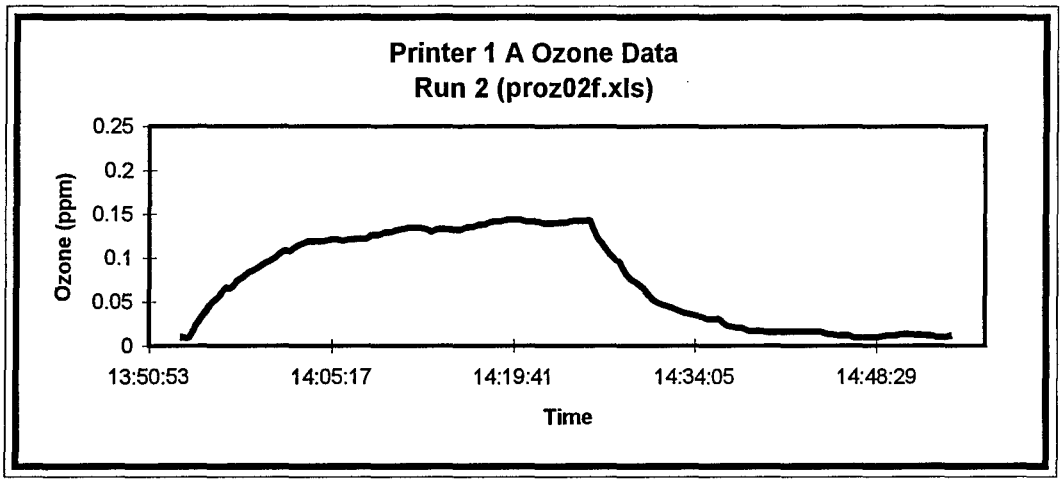
Particulate Data (Mass) Printer 2 B #23312

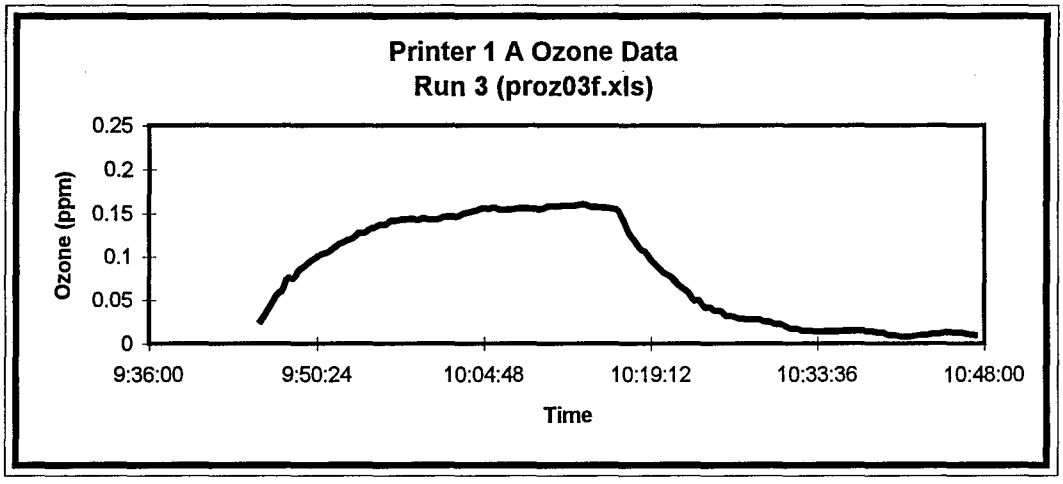
Run	Particle Mass (μg/particle)	Particle Generation (particles/min)	Mass Generation (μg/min)
PRINT37	7.1499E-08	163338.4419	0.01167853
PRINT38	9.10064E-08	34552.75225	0.00314452
PRINT39	8.65536E-08	23472.02586	0.00203159
PRINT40	6.00538E-08	448404.9295	0.02692842
PRINT41	7.13412E-08	37014.40593	0.00264065
PRINT42	9.98444E-08	34000.29815	0.00339474

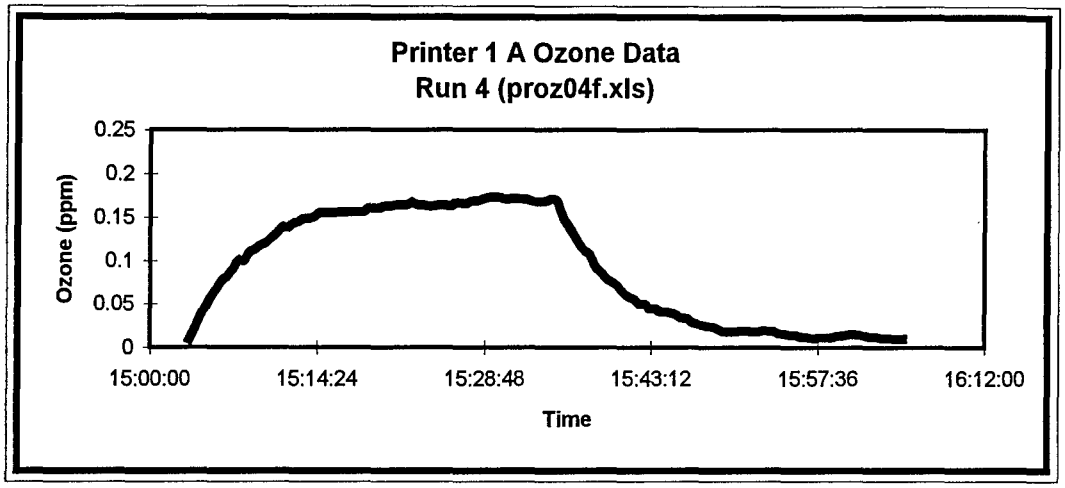
Mean Mass Generation (μg/min)	0.008303
95% CI	0.007843

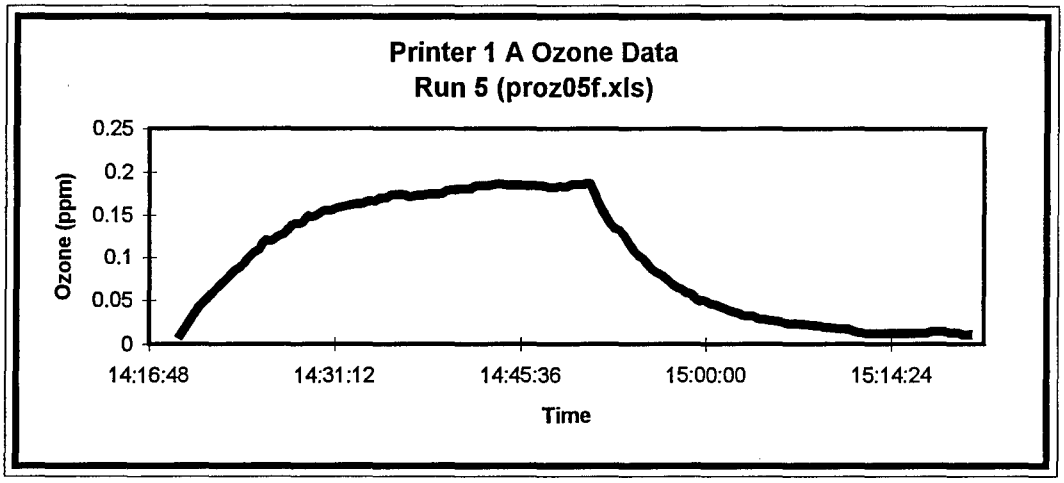
APPENDIX D -- Concentration and Generation Rate Data

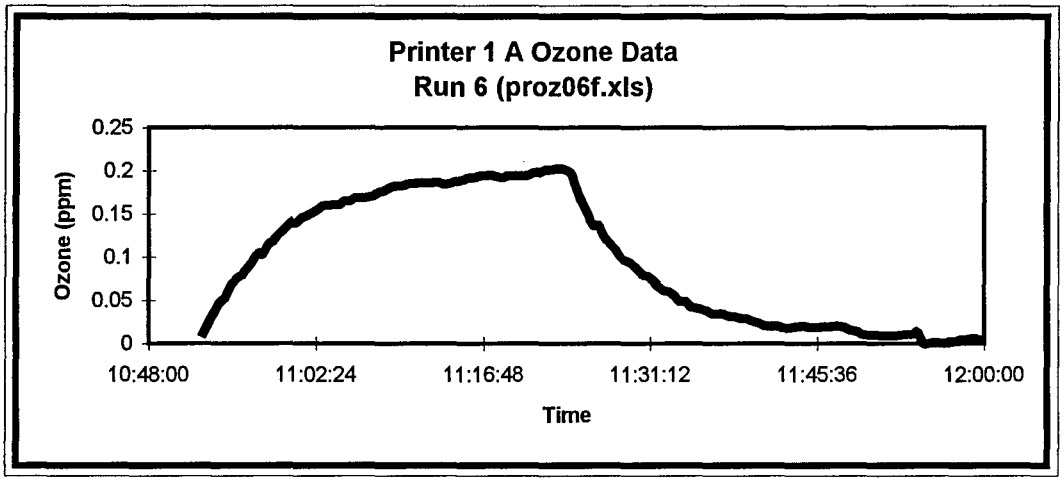




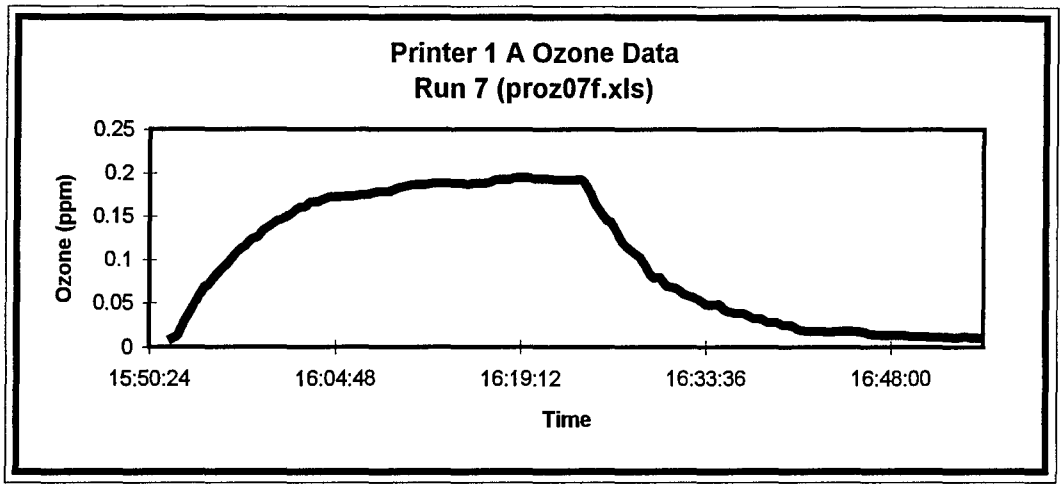


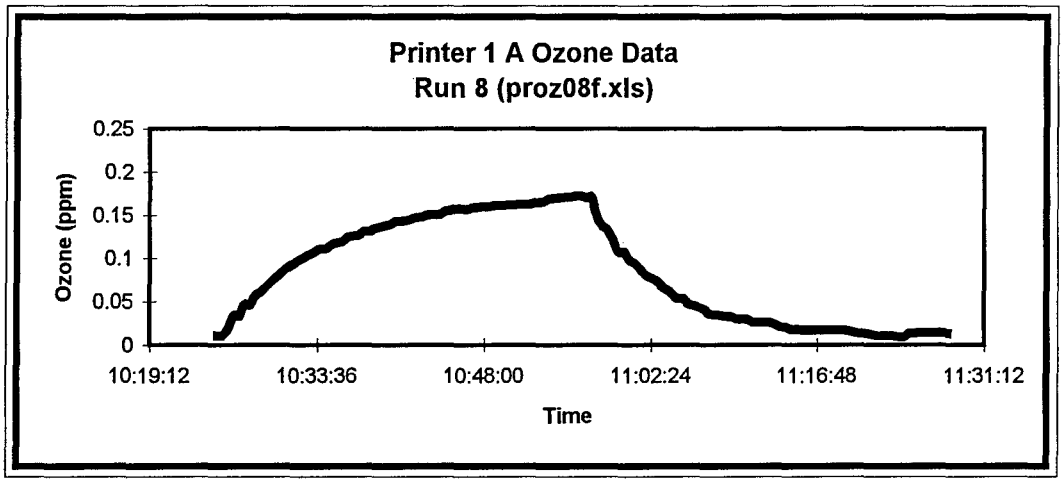

Printer 1 A Ozone Data
Run 4 (proz04f.xls)
Ozone (ppm)
0.25
0.2
0.15
0.1
0.05
0
15:00:00
15:14:24
15:28:48
15:43:12
15:57:36
16:12:00
Time

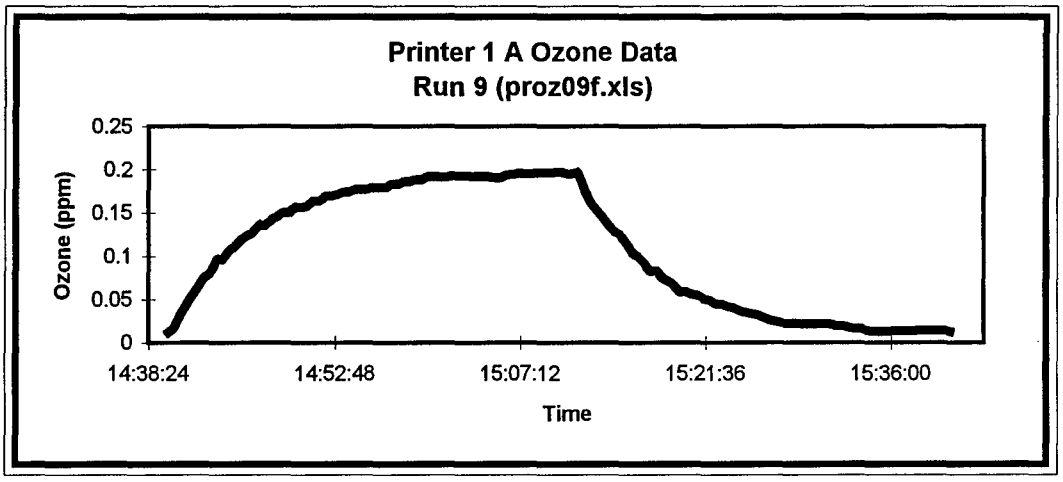

Printer 1 A Ozone Data
Run 5 (proz05f.xls)
Ozone (ppm)
0.25
0.2
0.15
0.1
0.05
0
14:16:48
14:31:12
14:45:36
15:00:00
15:14:24
Time


Printer 1 A Ozone Data
Run 6 (proz06f.xls)
Ozone (ppm)
0.25
0.2
0.15
0.1
0.05
0
10:48:00
11:02:24
11:16:48
11:31:12
11:45:36
12:00:00
Time

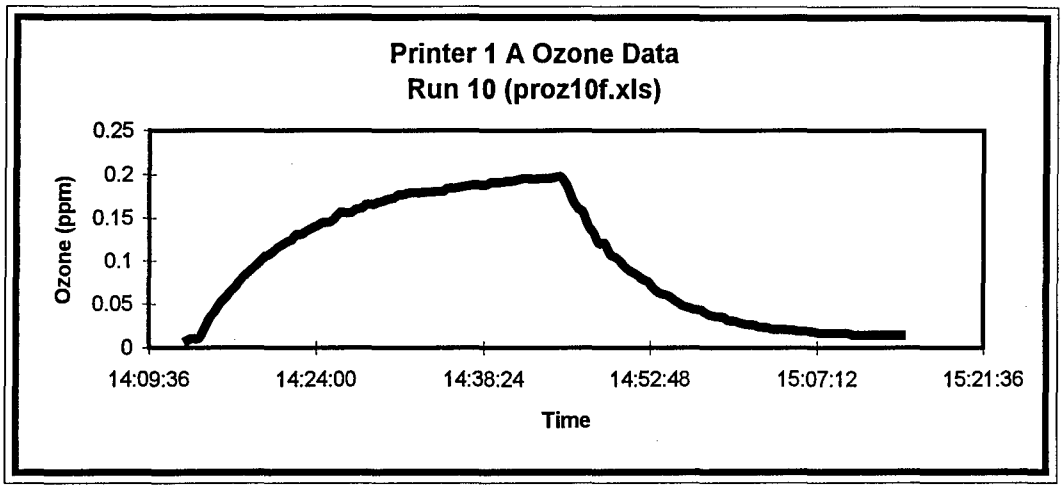
APPENDIX D -- Concentration and Generation Rate Data

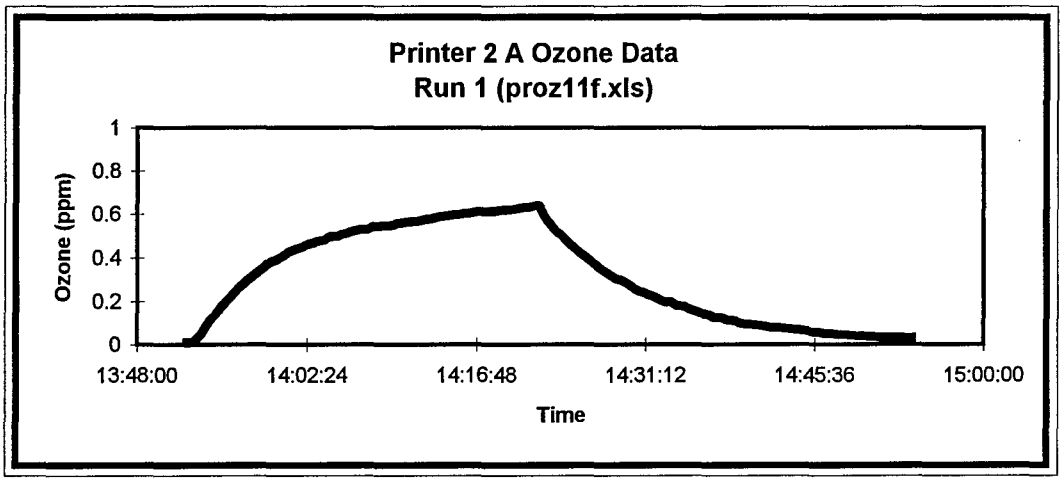


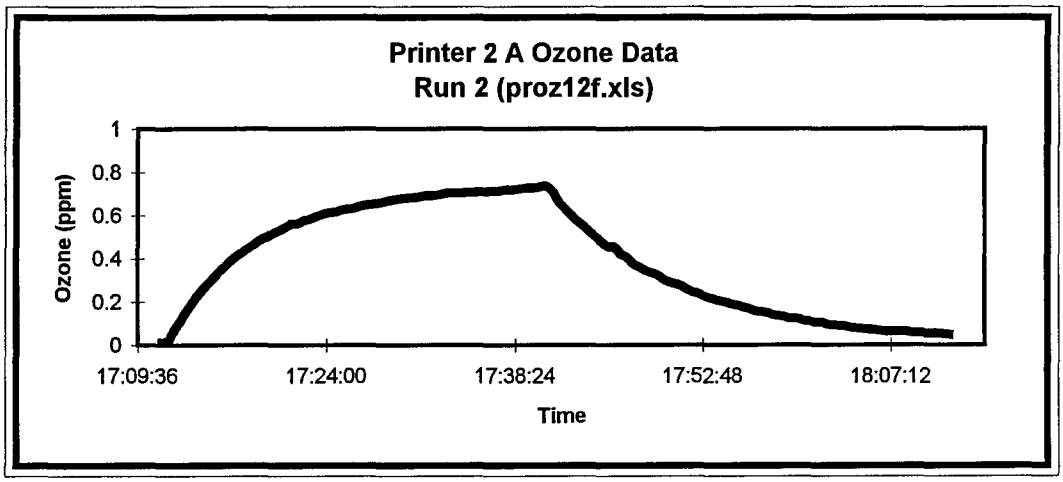




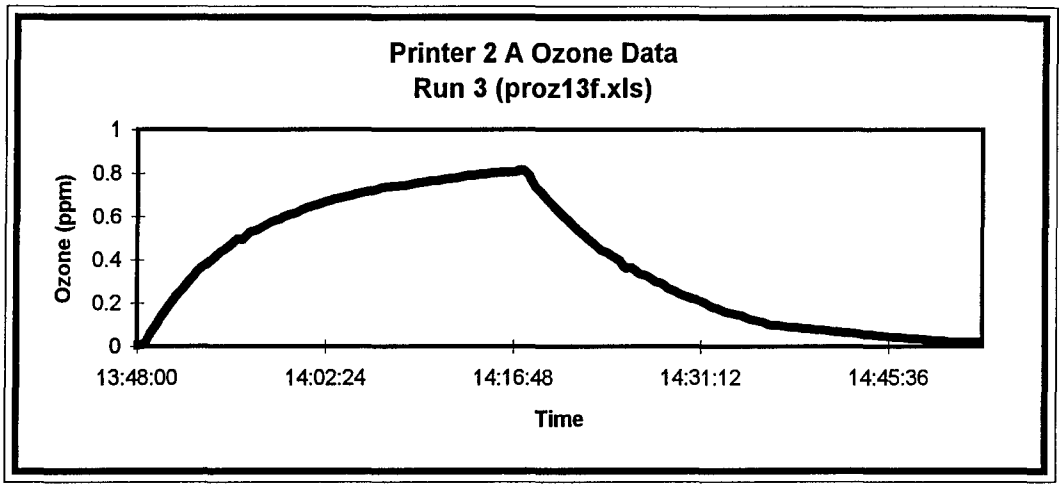
APPENDIX D -- Concentration and Generation Rate Data

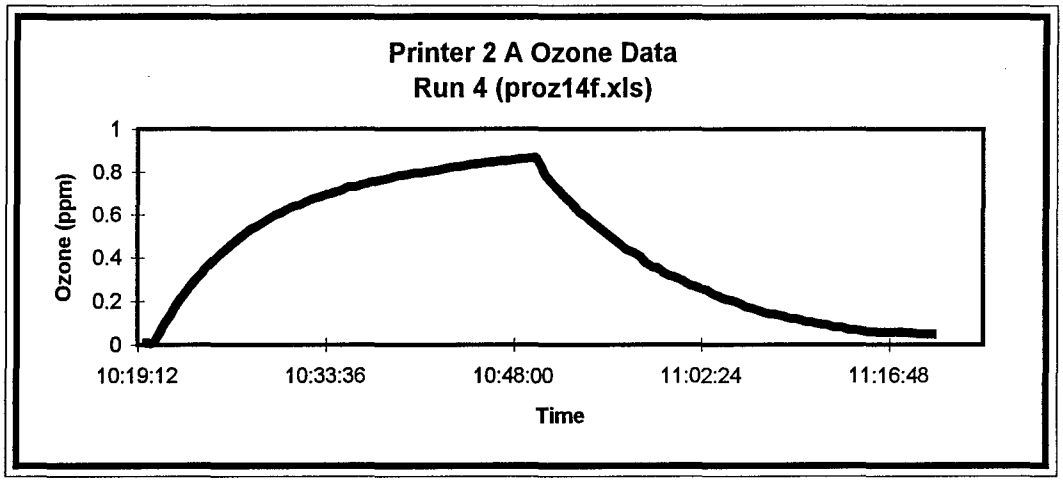


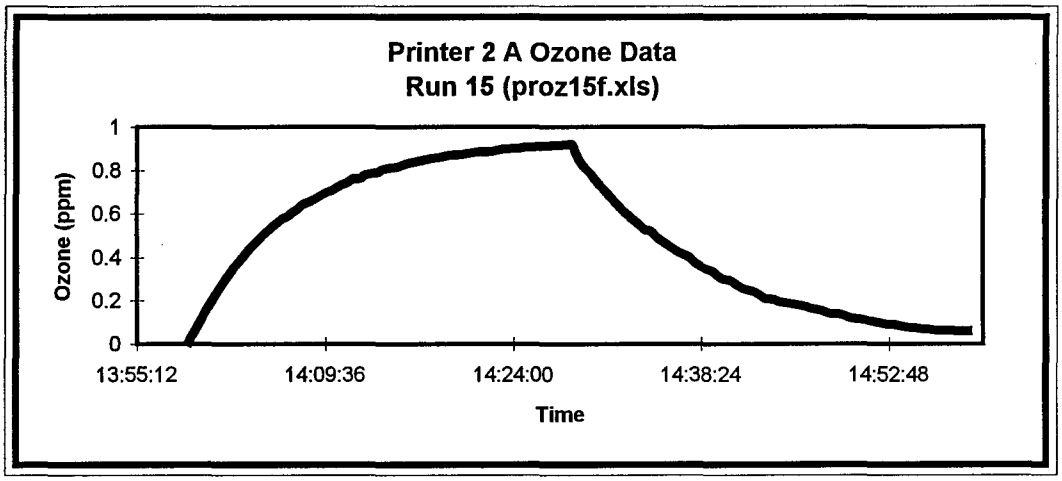




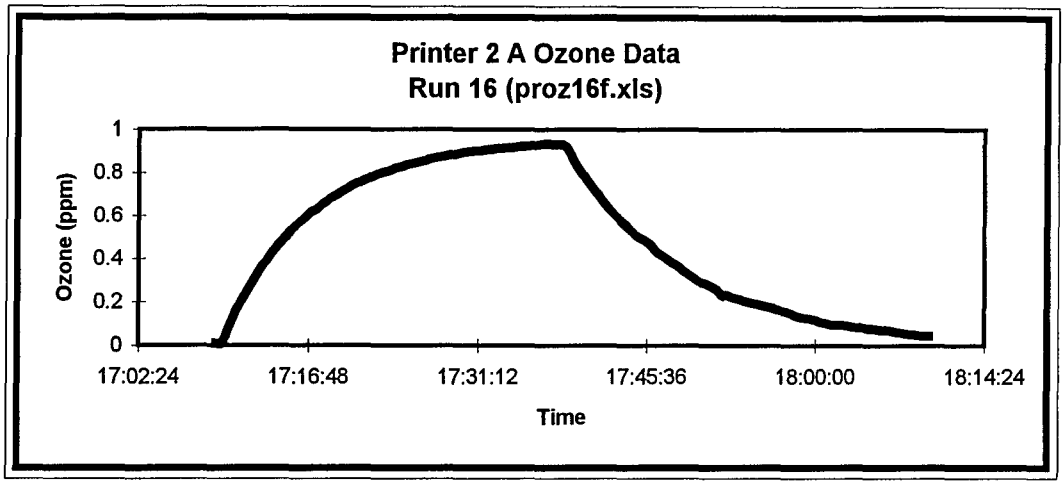
APPENDIX D -- Concentration and Generation Rate Data

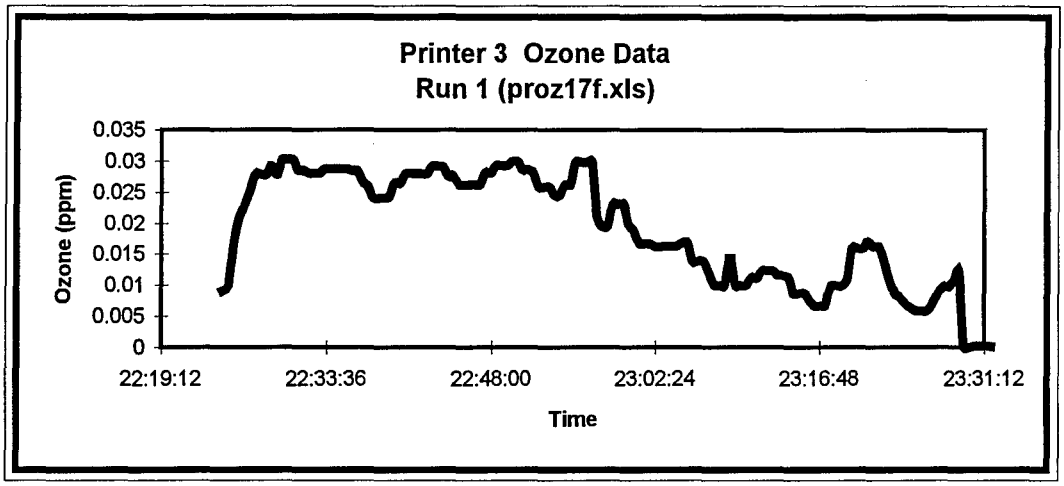


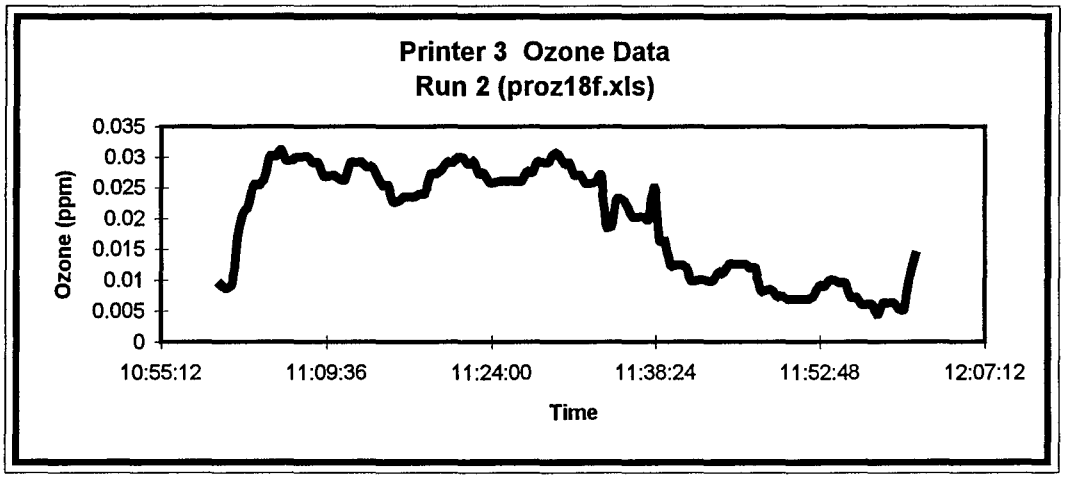


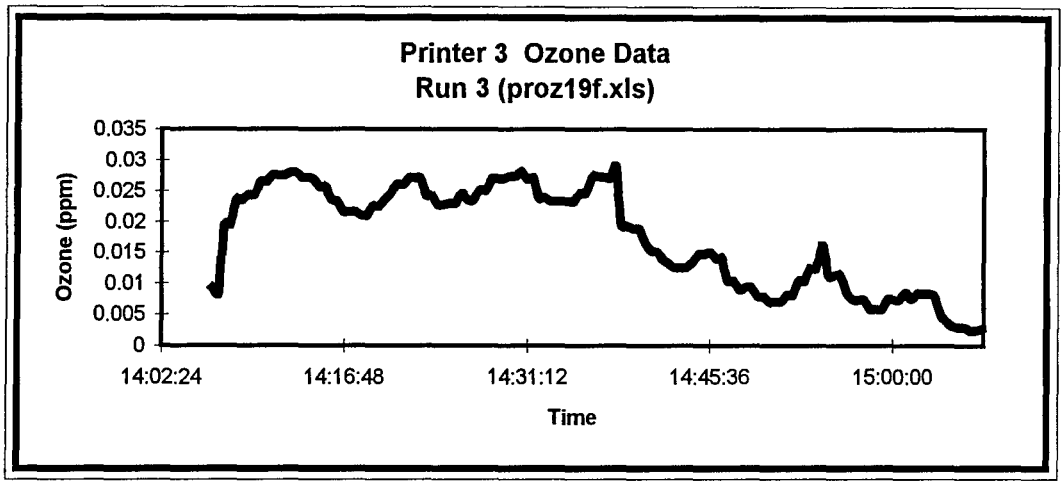


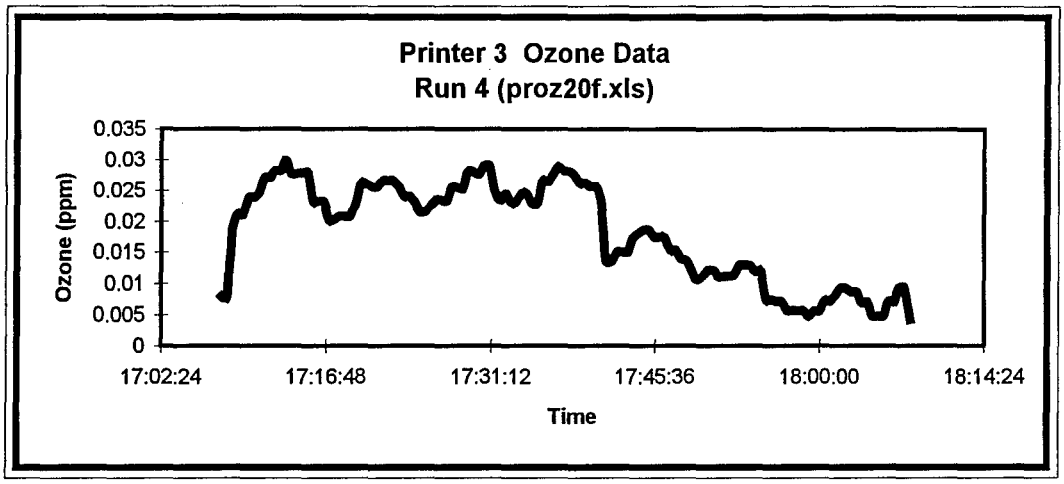
APPENDIX D -- Concentration and Generation Rate Data

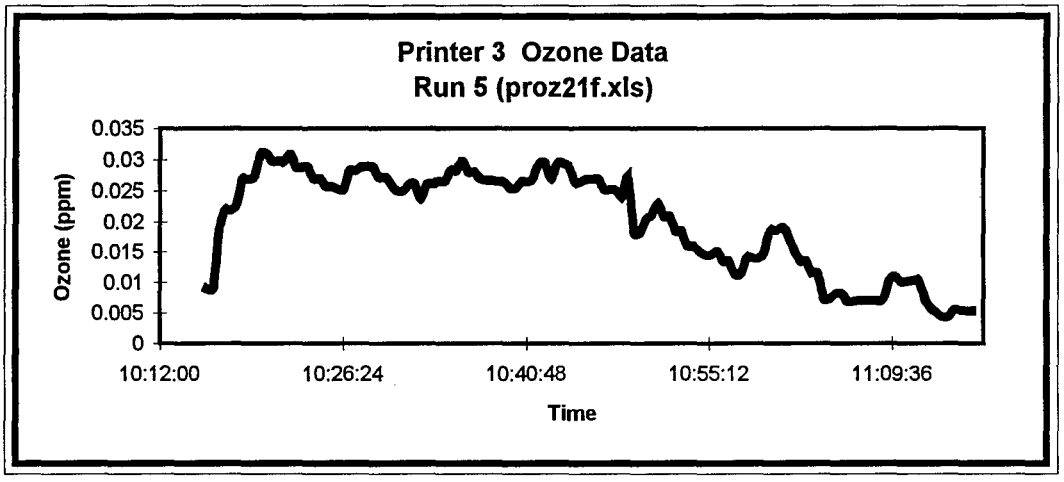




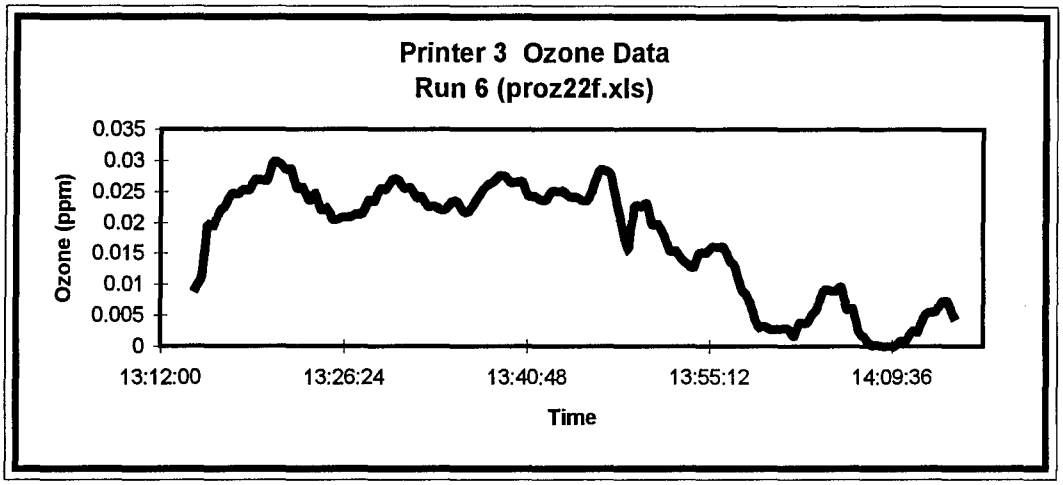


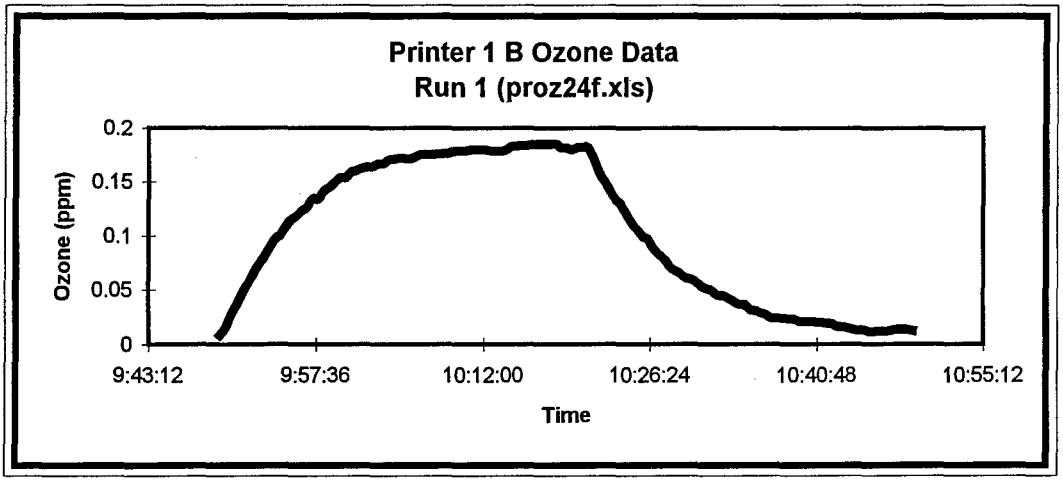

Printer 3 Ozone Data
Run 3 (proz19f.xls)
Ozone (ppm)
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
14:02:24
14:16:48
14:31:12
14:45:36
15:00:00
Time

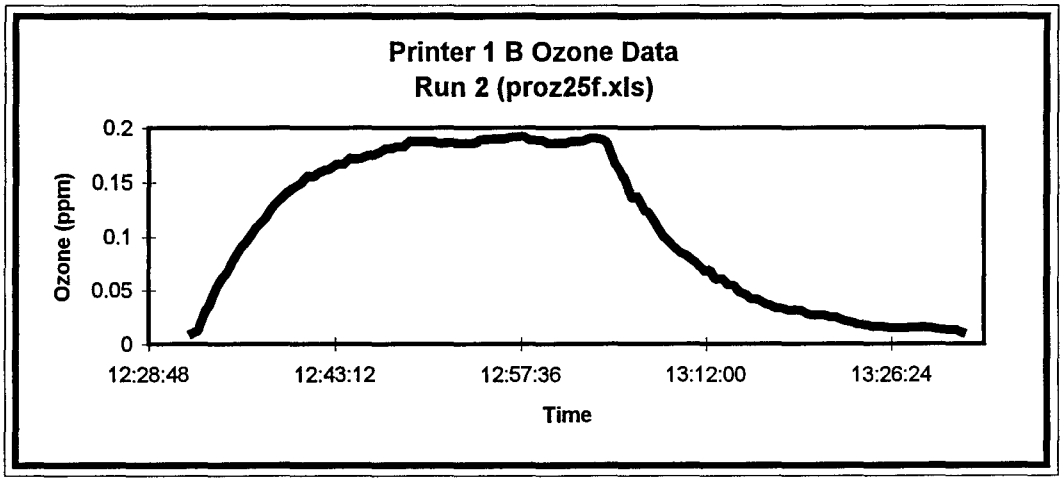

Printer 3 Ozone Data
Run 4 (proz20f.xls)
Ozone (ppm)
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
17:02:24
17:16:48
17:31:12
17:45:36
18:00:00
18:14:24
Time


Printer 3 Ozone Data
Run 5 (proz21f.xls)
Ozone (ppm)
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
10:12:00
10:26:24
10:40:48
10:55:12
11:09:36
Time

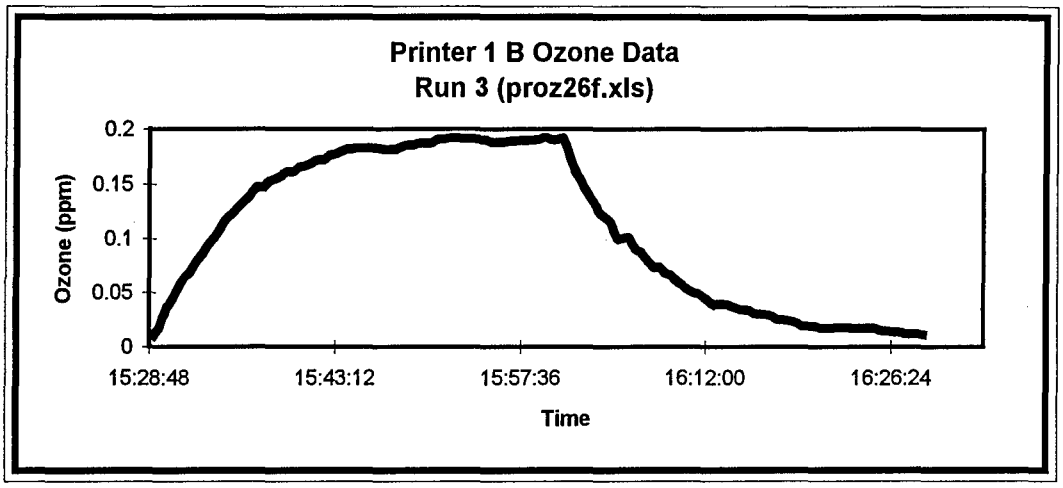
APPENDIX D -- Concentration and Generation Rate Data

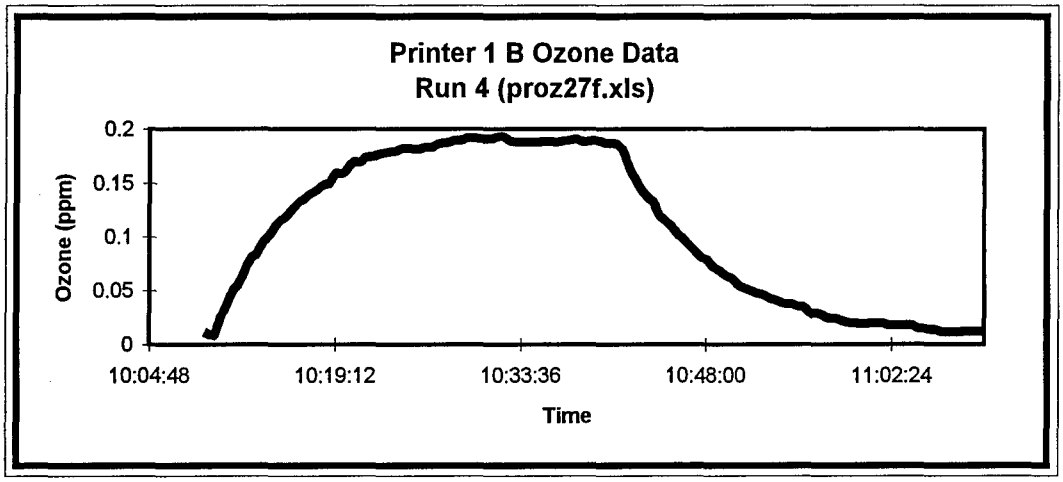


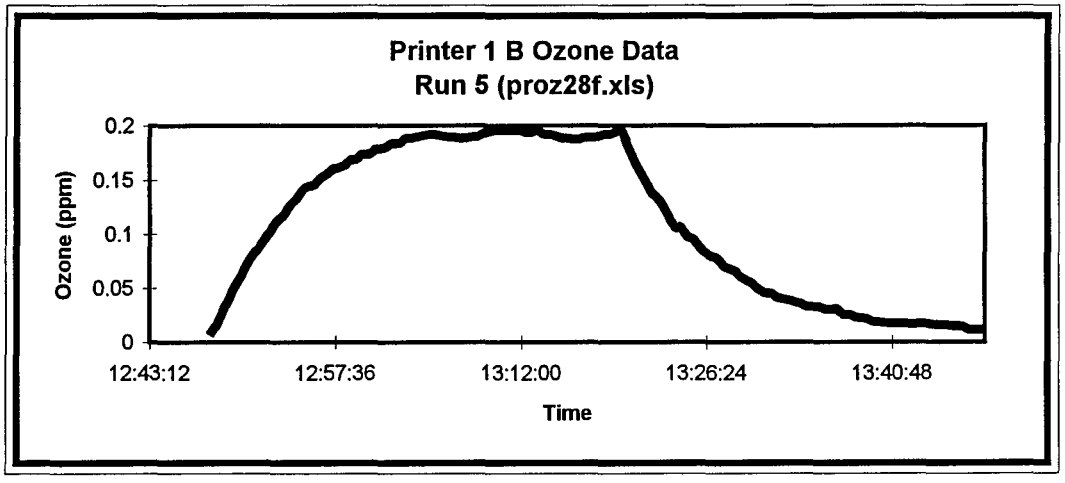




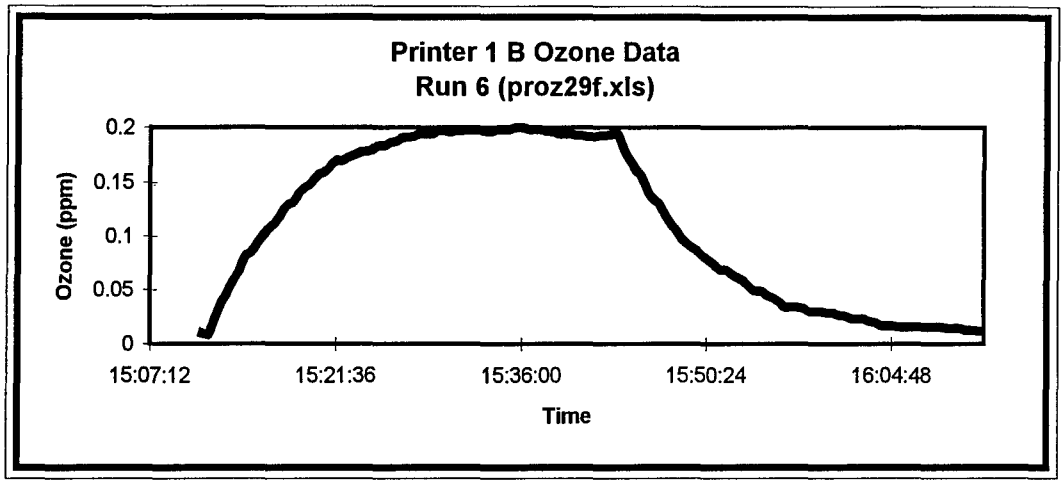
APPENDIX D -- Concentration and Generation Rate Data

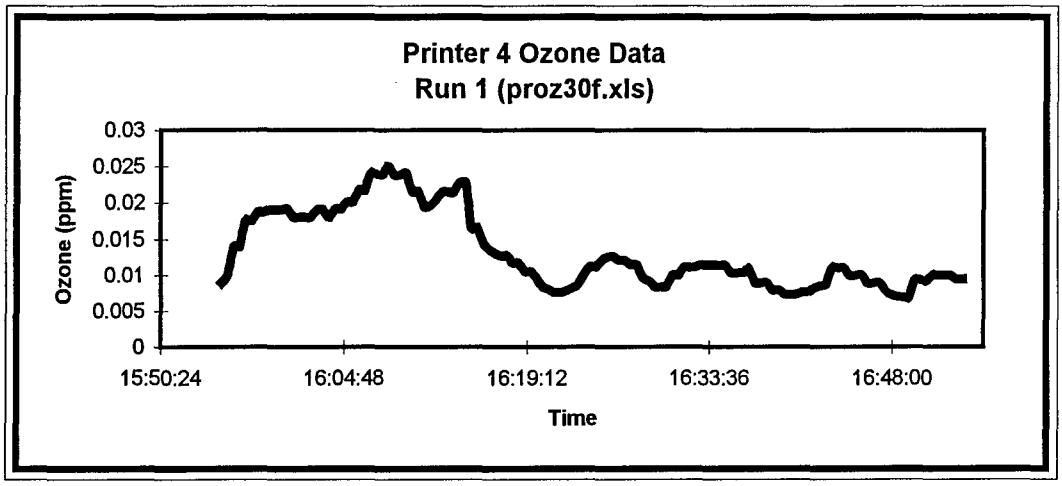


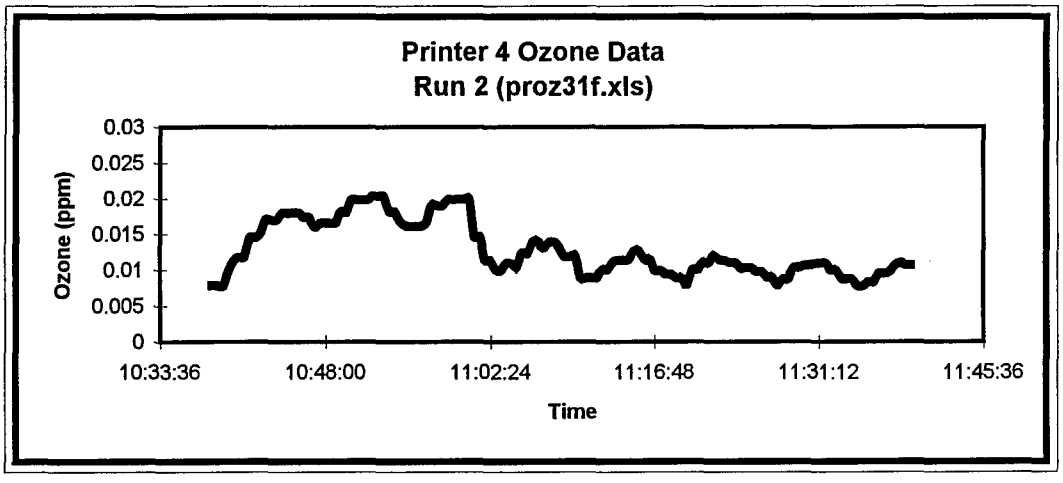




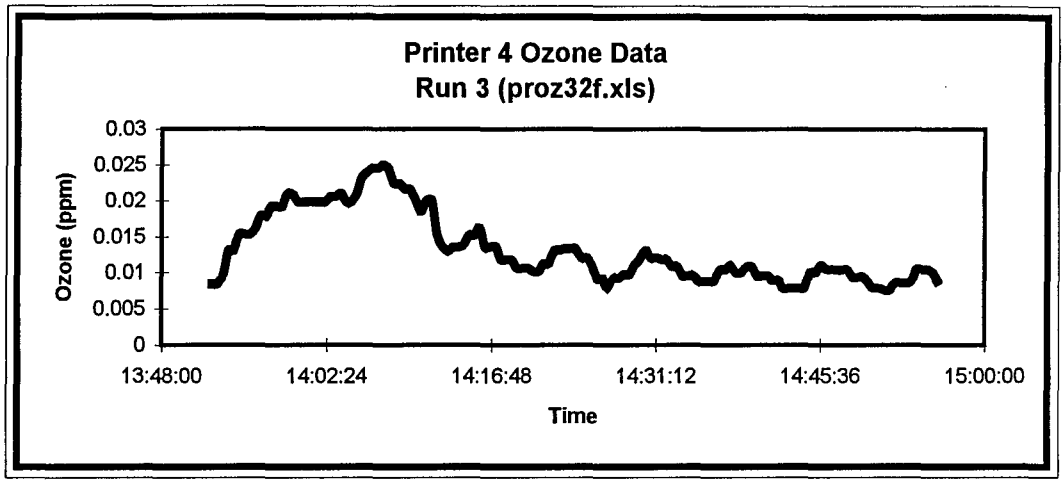
APPENDIX D -- Concentration and Generation Rate Data

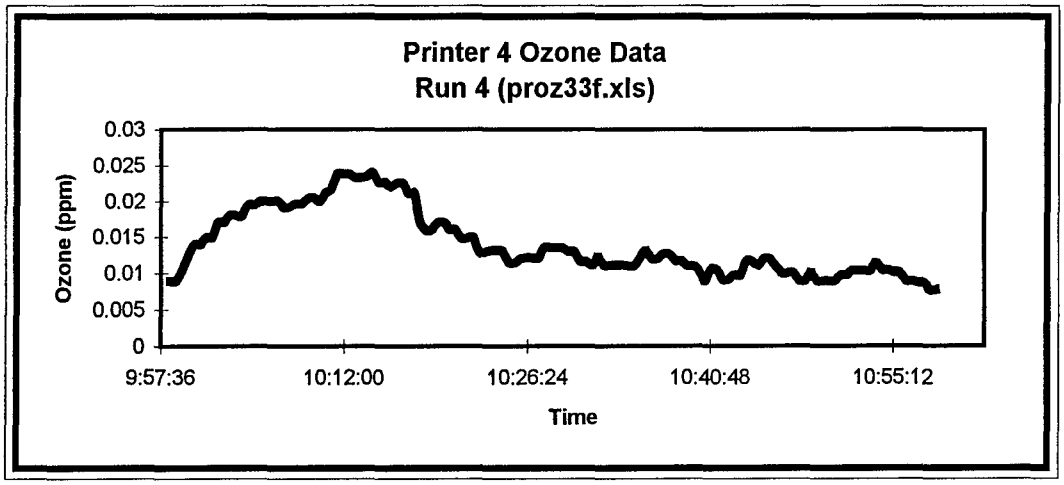


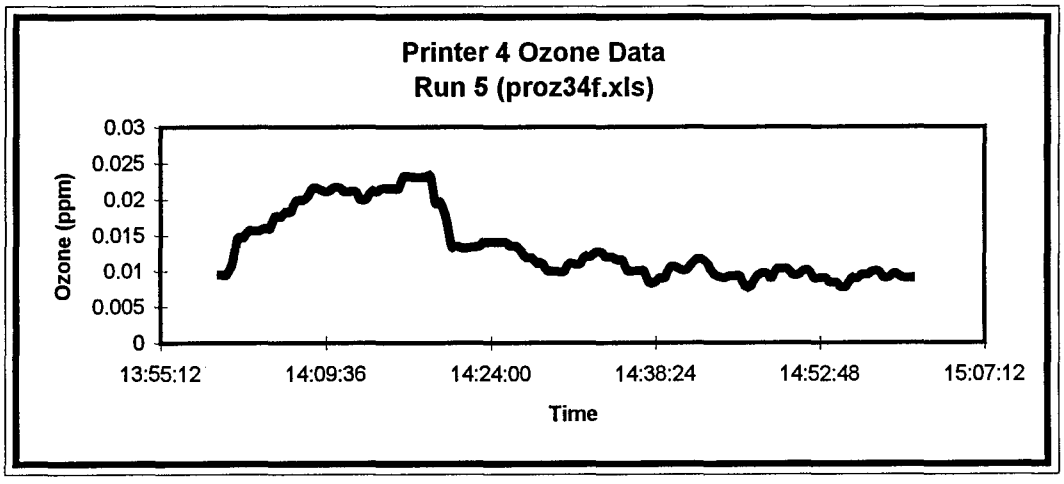




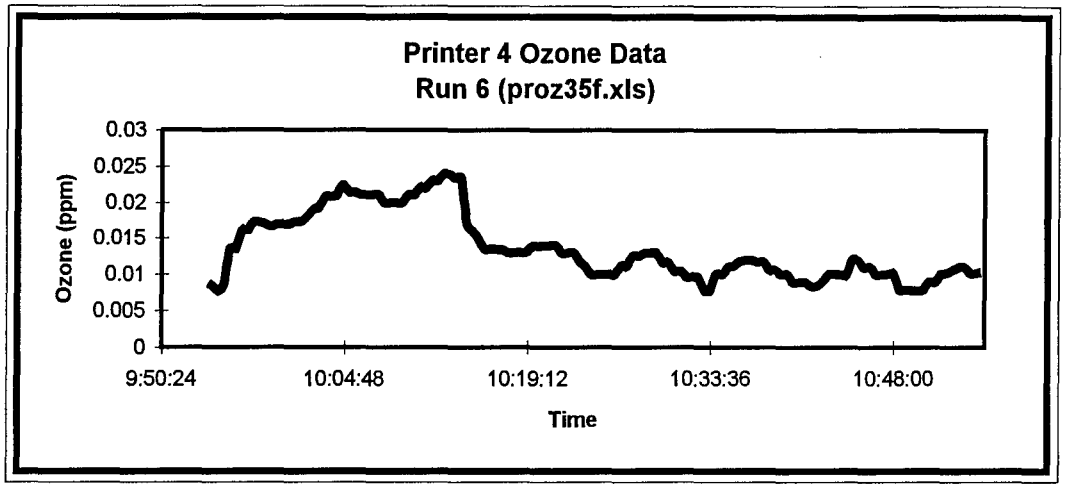
APPENDIX D -- Concentration and Generation Rate Data

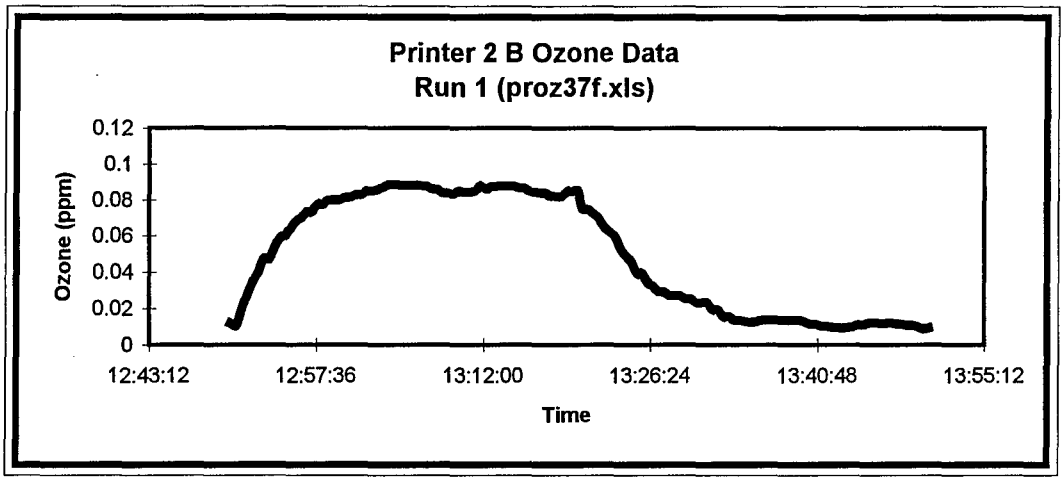


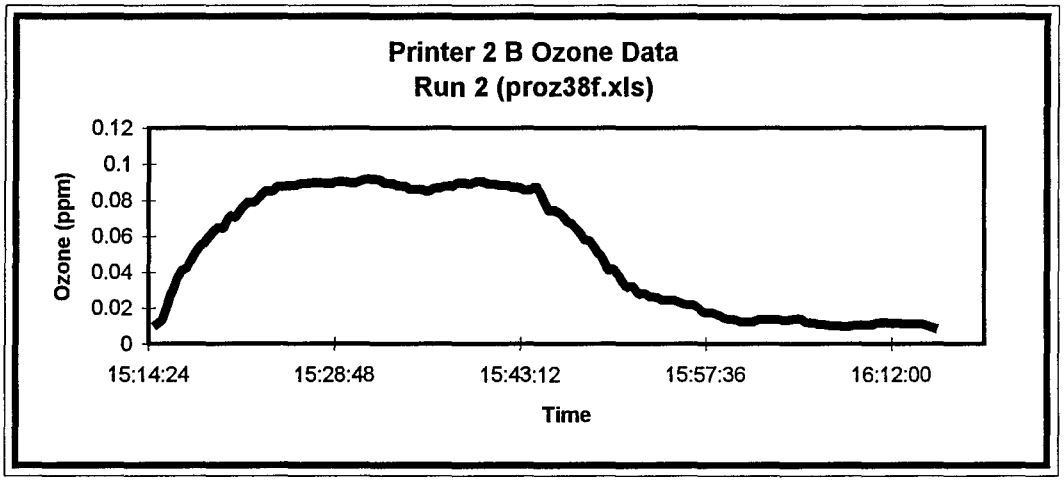




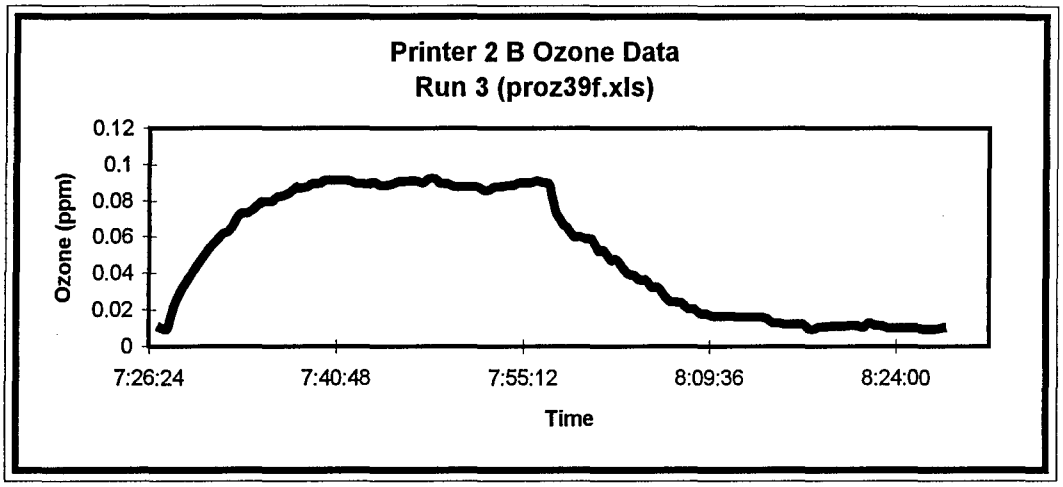
APPENDIX D -- Concentration and Generation Rate Data

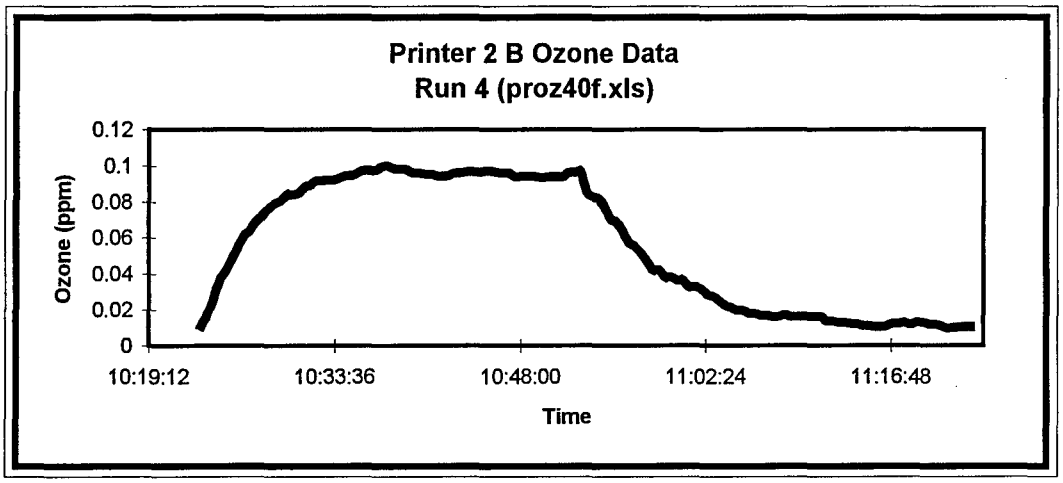


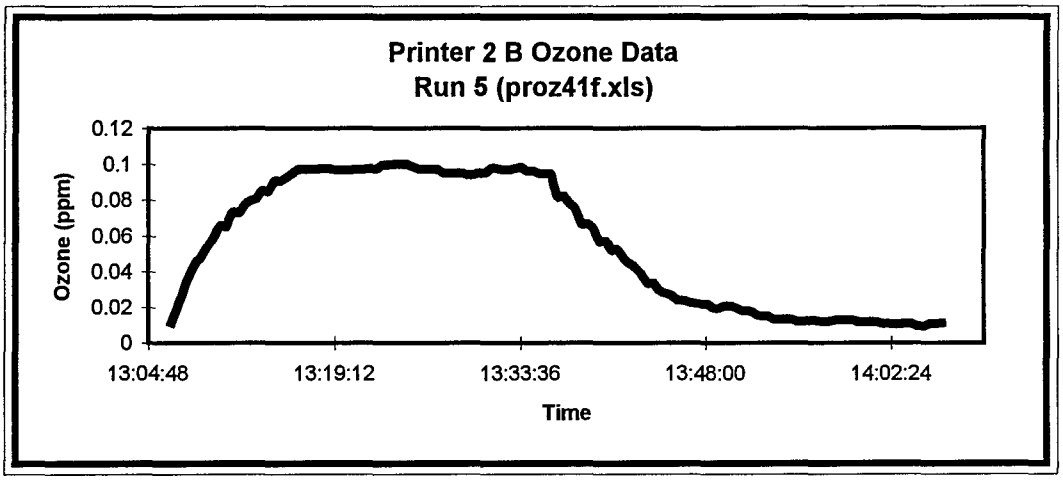




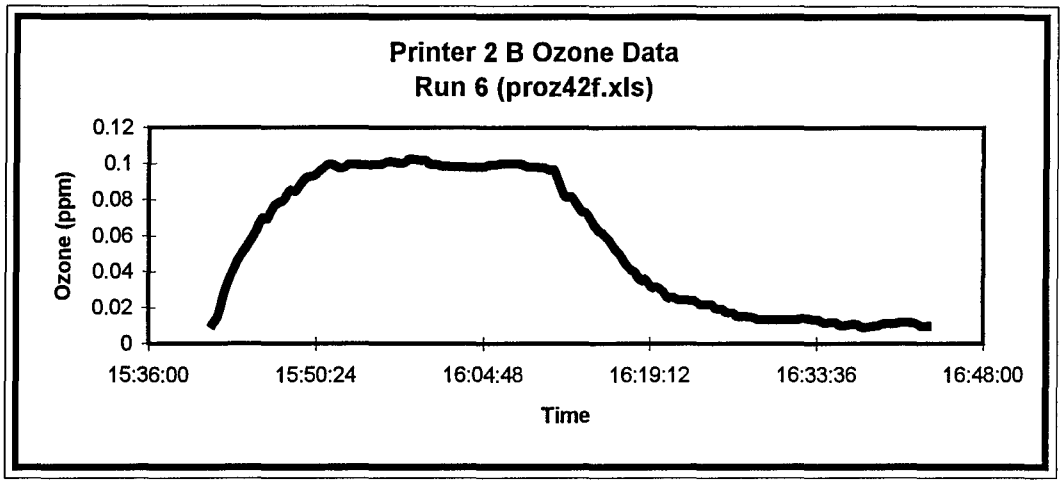
APPENDIX D -- Concentration and Generation Rate Data

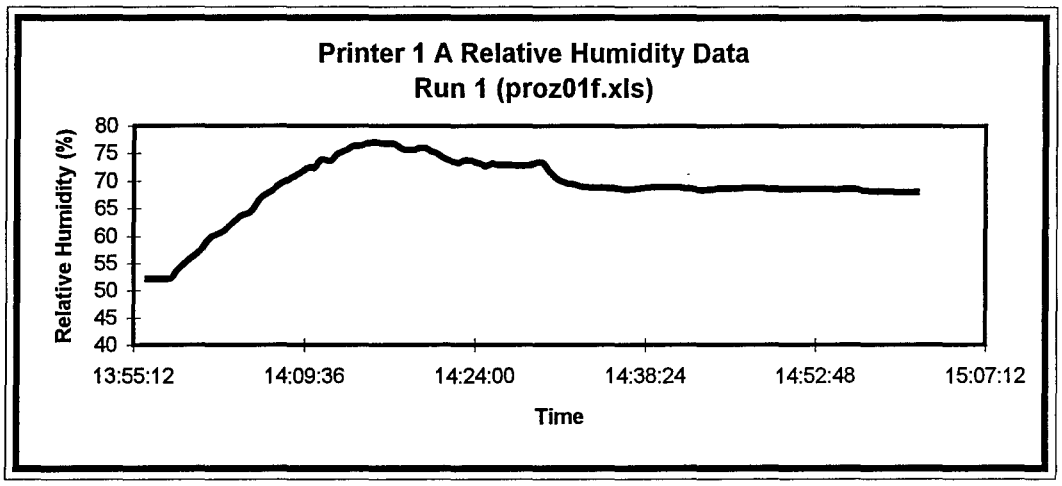


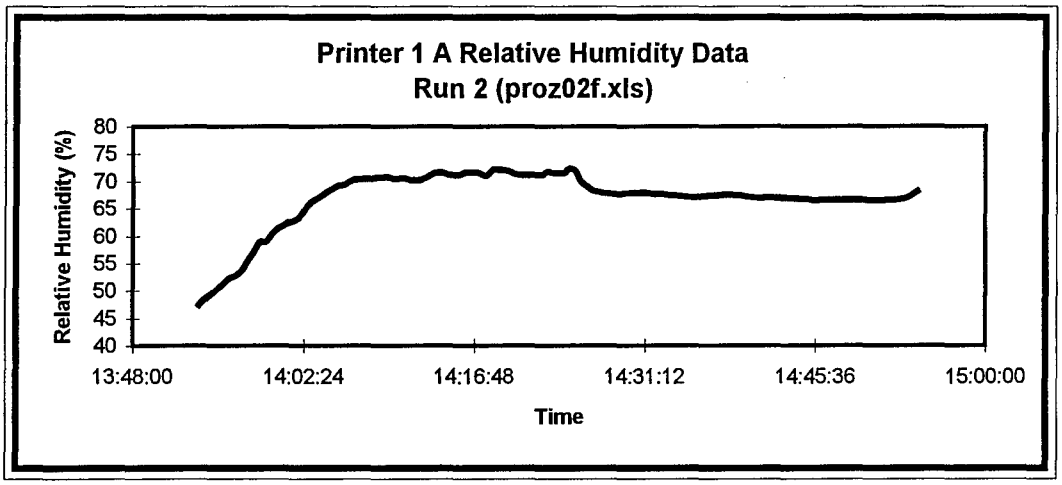


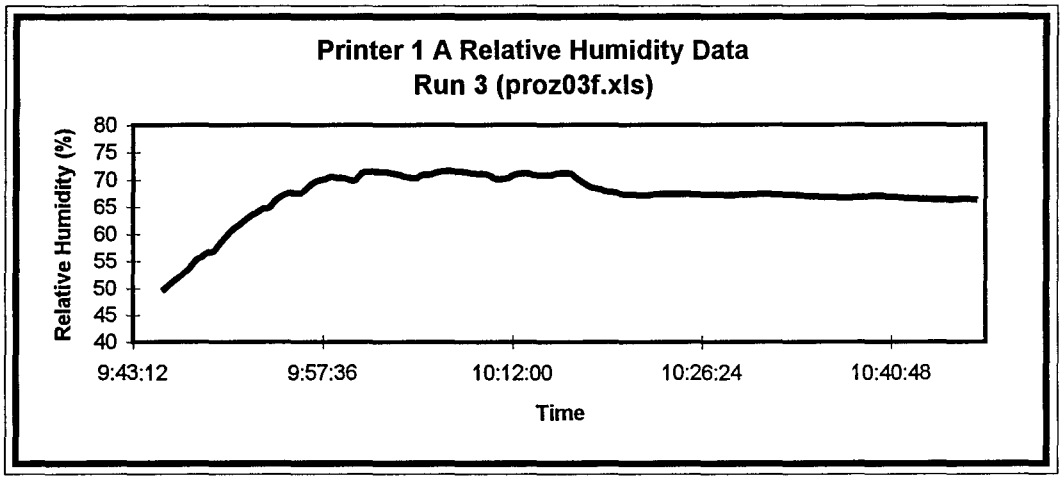


APPENDIX D -- Concentration and Generation Rate Data

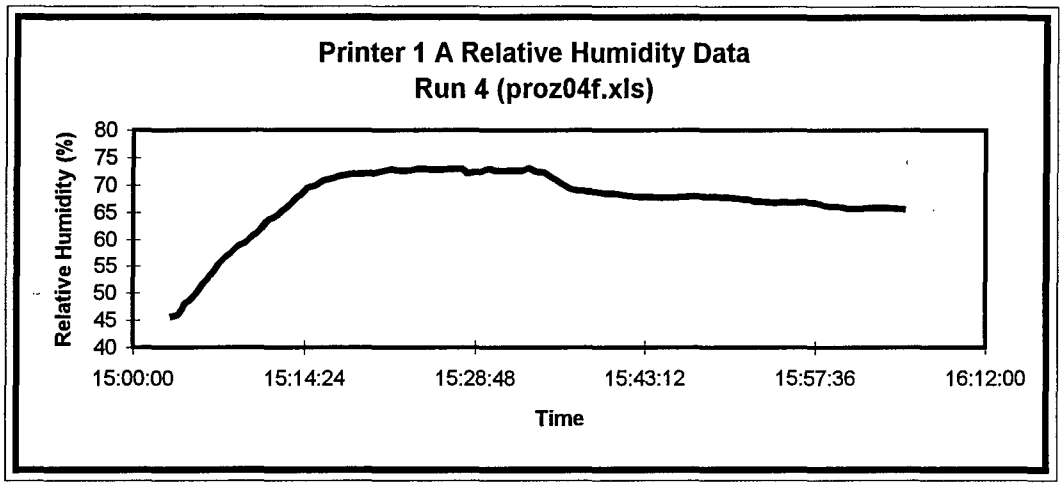


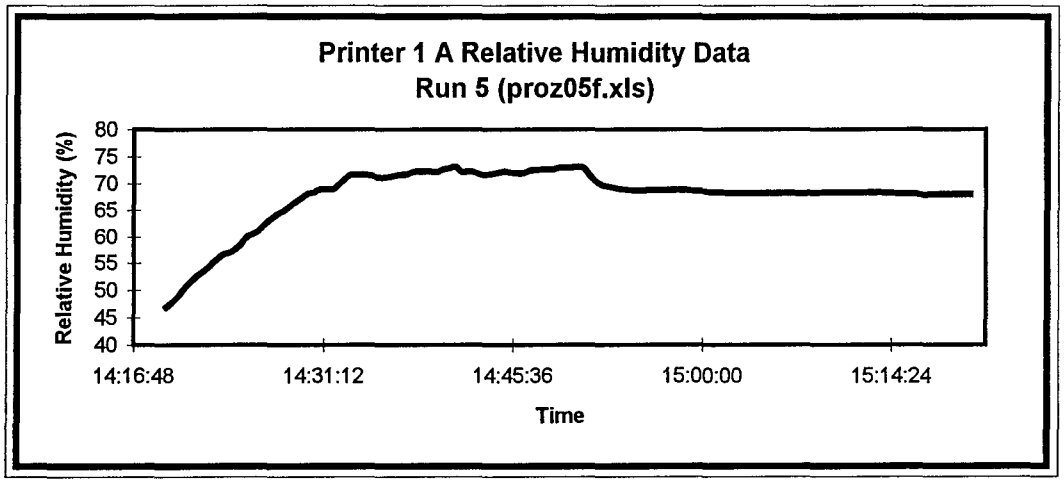

Printer 1 A Relative Humidity Data
Run 1 (proz01f.xls)
Relative Humidity (%)
80
75
70
65
60
55
50
45
40
13:55:12
14:09:36
14:24:00
14:38:24
14:52:48
15:07:12
Time

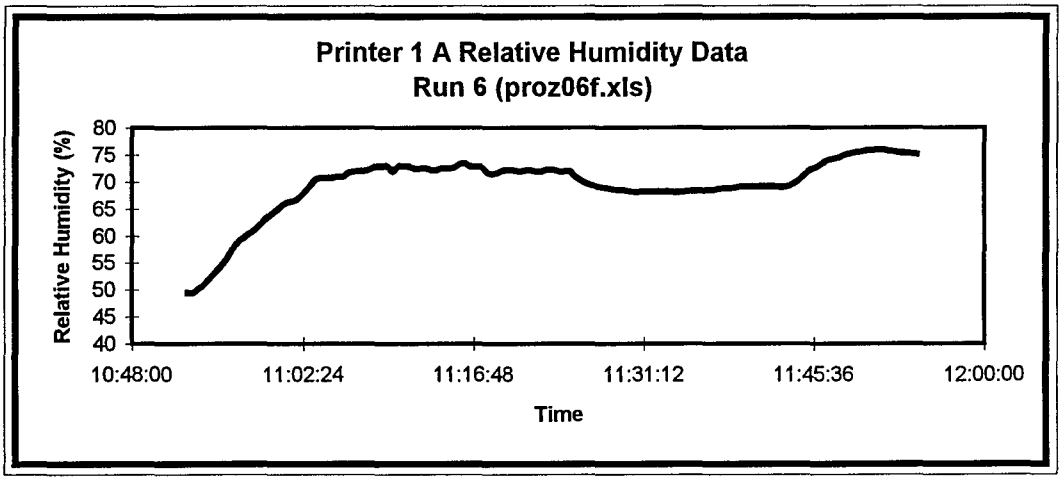

Printer 1 A Relative Humidity Data
Run 2 (proz02f.xls)
Relative Humidity (%)
80
75
70
65
60
55
50
45
40
13:48:00
14:02:24
14:16:48
14:31:12
14:45:36
15:00:00
Time


Printer 1 A Relative Humidity Data
Run 3 (proz03f.xls)
Relative Humidity (%)
80
75
70
65
60
55
50
45
40
9:43:12
9:57:36
10:12:00
10:26:24
10:40:48
Time

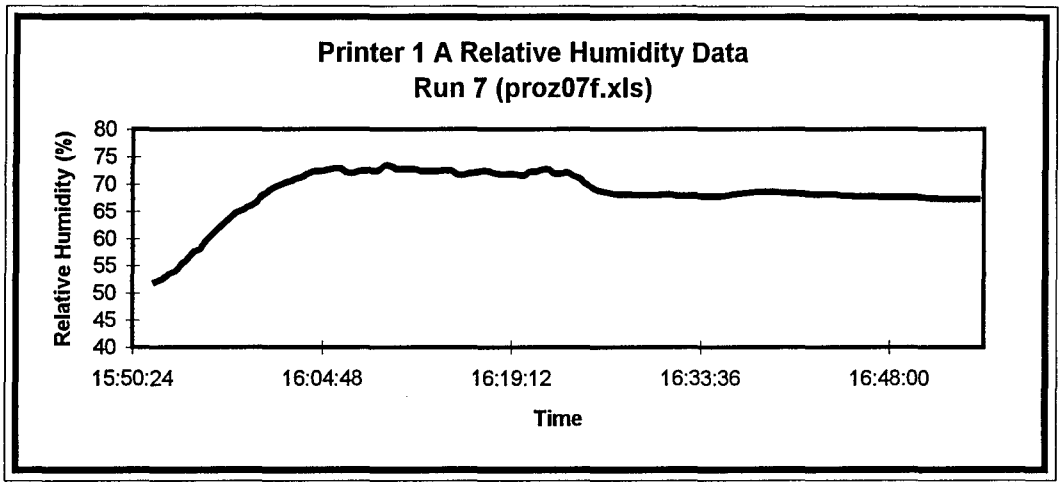
APPENDIX D -- Concentration and Generation Rate Data

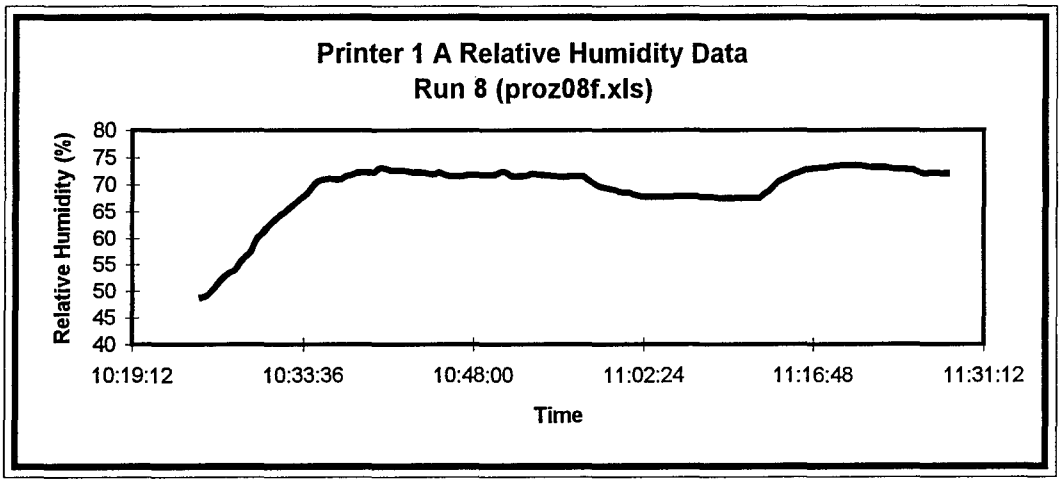


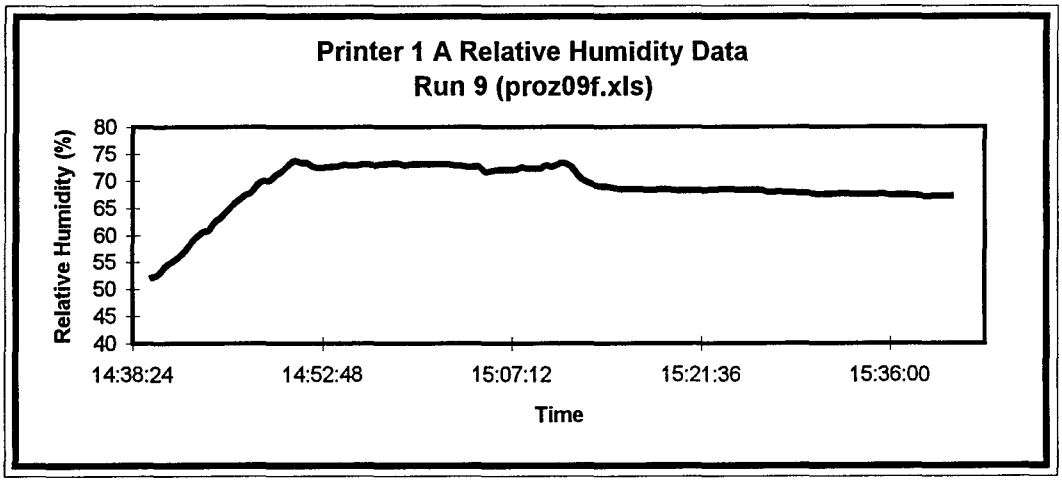


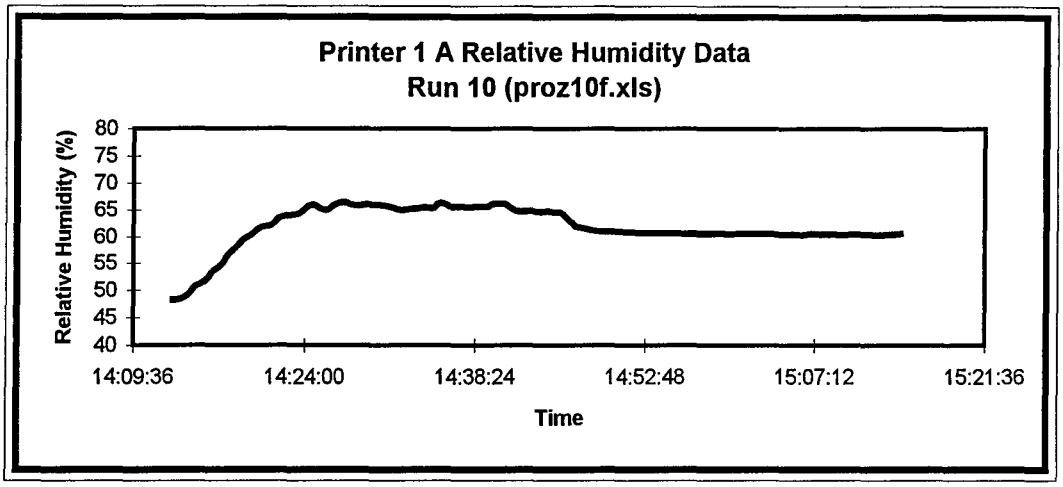


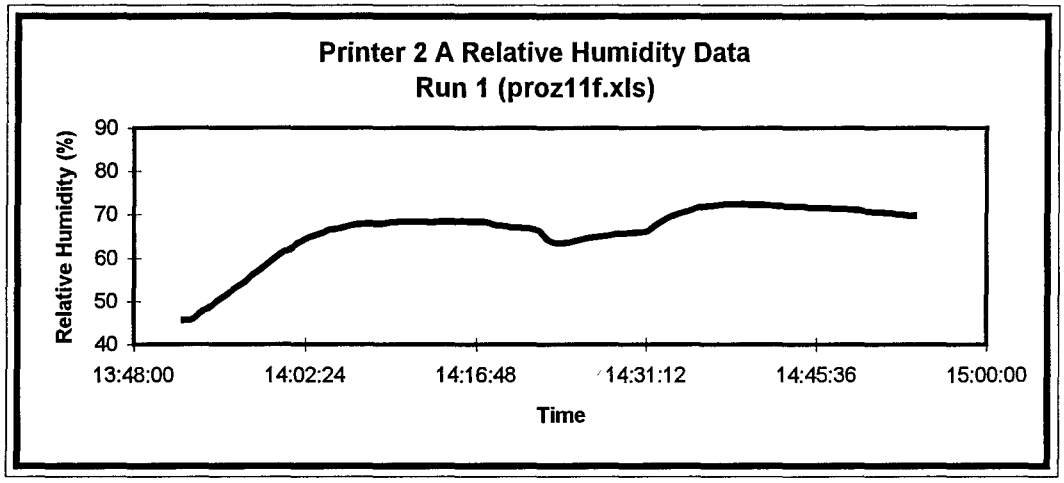
APPENDIX D -- Concentration and Generation Rate Data

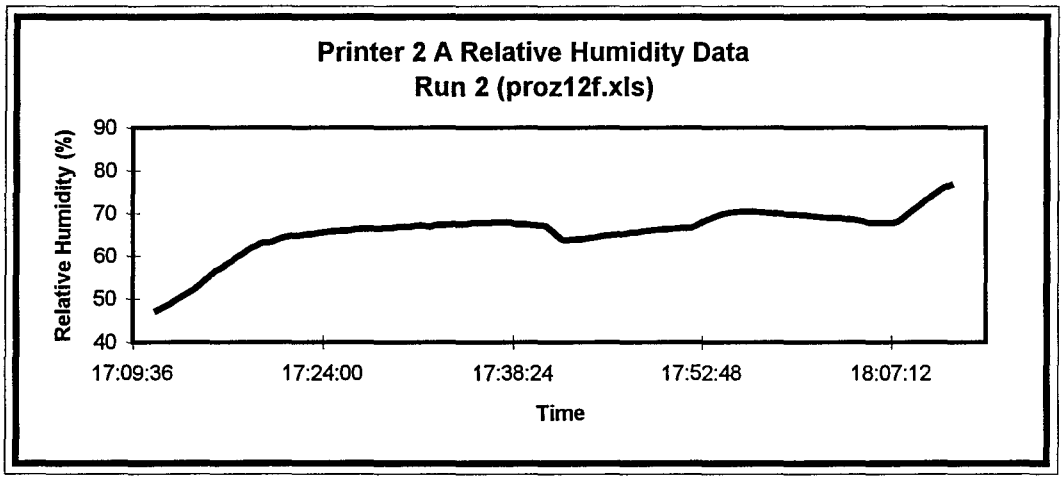


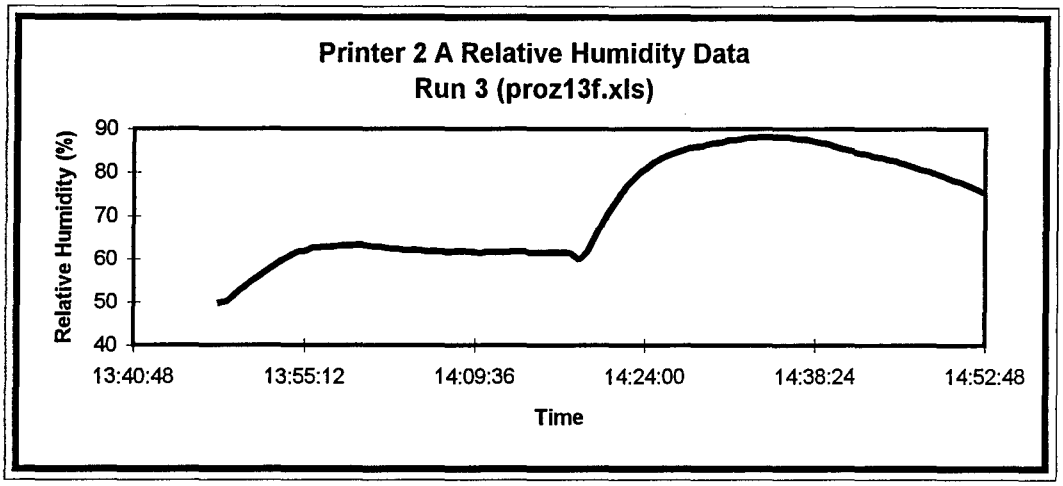


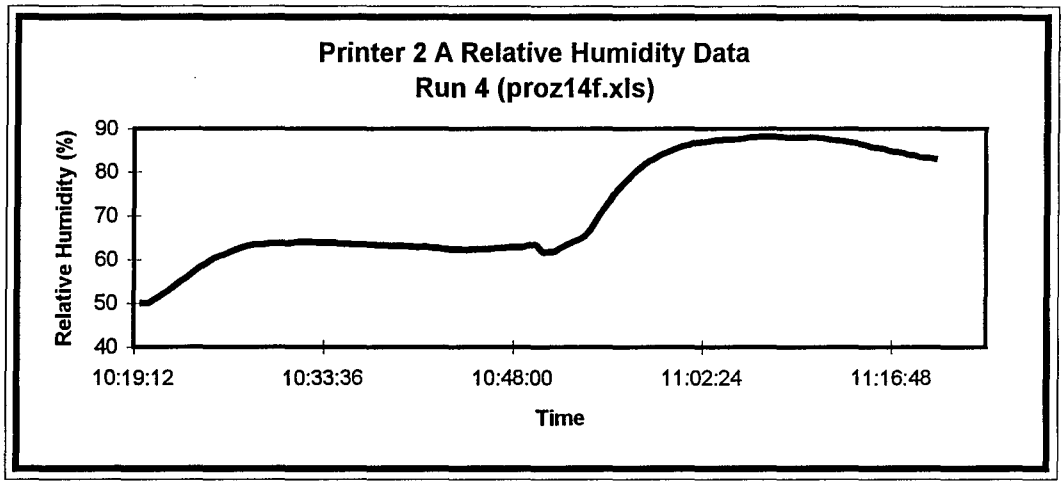


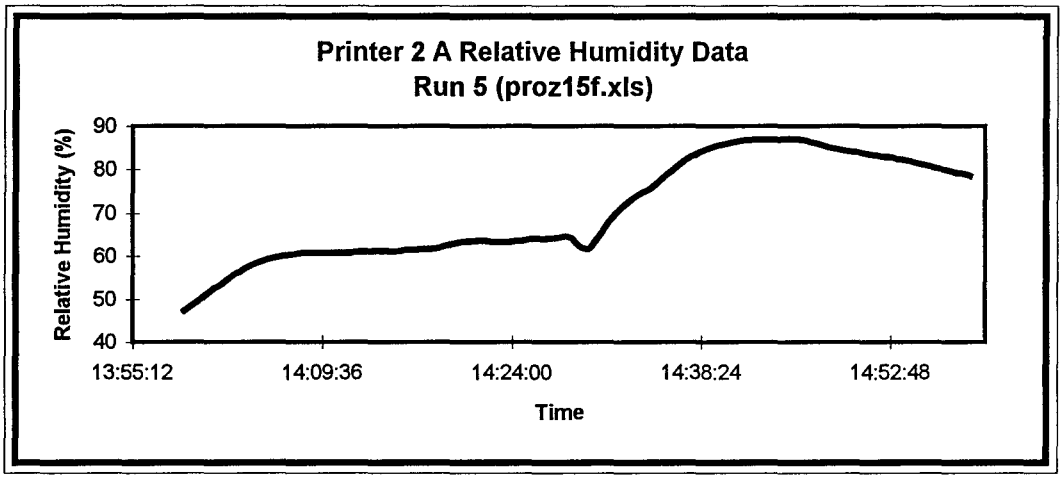

Printer 1 A Relative Humidity Data
Run 10 (proz10f.xls)
Relative Humidity (%)
80
75
70
65
60
55
50
45
40
14:09:36
14:24:00
14:38:24
14:52:48
15:07:12
15:21:36
Time

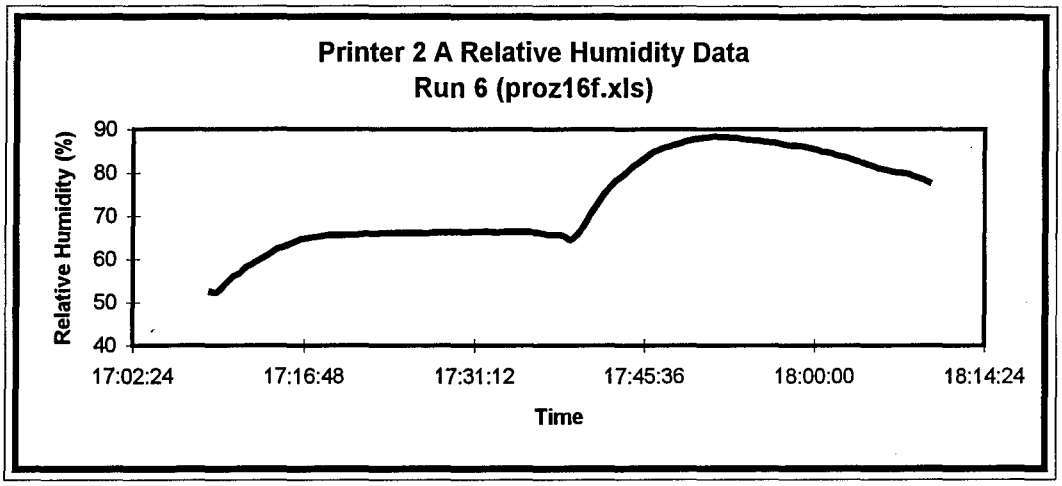

Printer 2 A Relative Humidity Data
Run 1 (proz11f.xls)
Relative Humidity (%)
90
80
70
60
50
40
13:48:00
14:02:24
14:16:48
14:31:12
14:45:36
15:00:00
Time

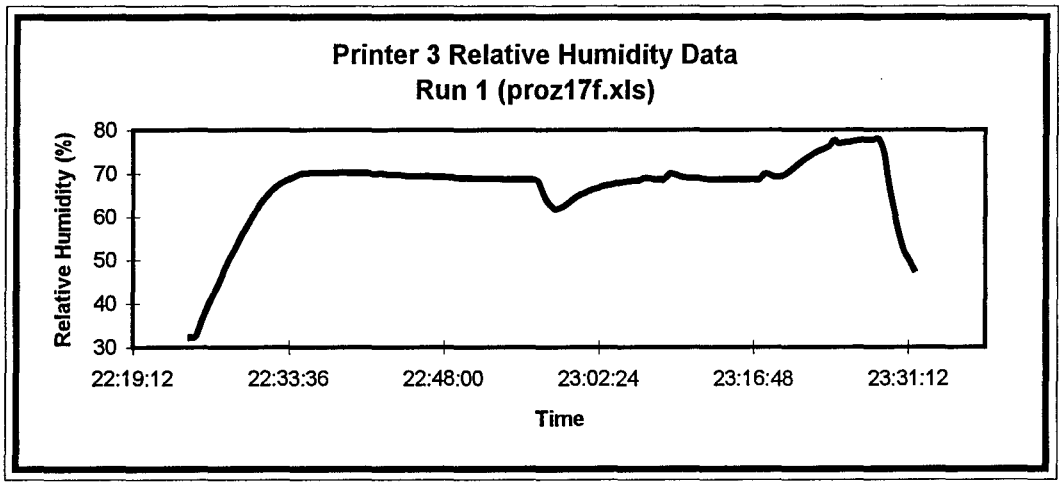

Printer 2 A Relative Humidity Data
Run 2 (proz12f.xls)
Relative Humidity (%)
90
80
70
60
50
40
17:09:36
17:24:00
17:38:24
17:52:48
18:07:12
Time

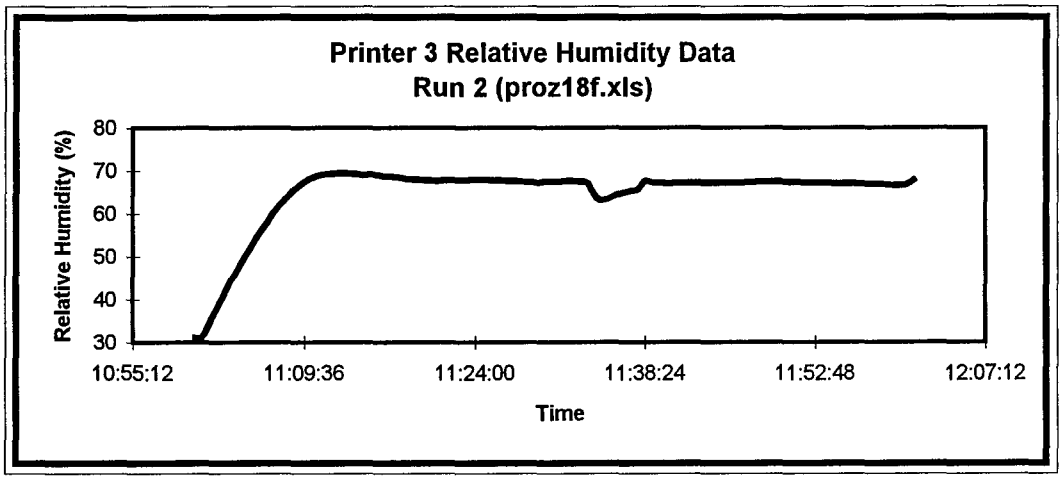

Printer 2 A Relative Humidity Data
Run 3 (proz13f.xls)
Relative Humidity (%)
90
80
70
60
50
40
13:40:48
13:55:12
14:09:36
14:24:00
14:38:24
14:52:48
Time

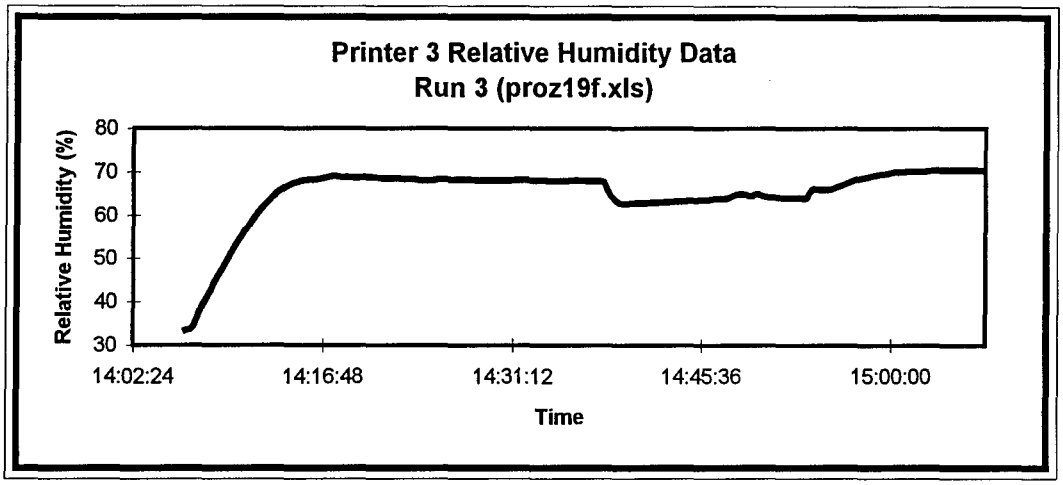

Printer 2 A Relative Humidity Data
Run 4 (proz14f.xls)
Relative Humidity (%)
90
80
70
60
50
40
10:19:12
10:33:36
10:48:00
11:02:24
11:16:48
Time

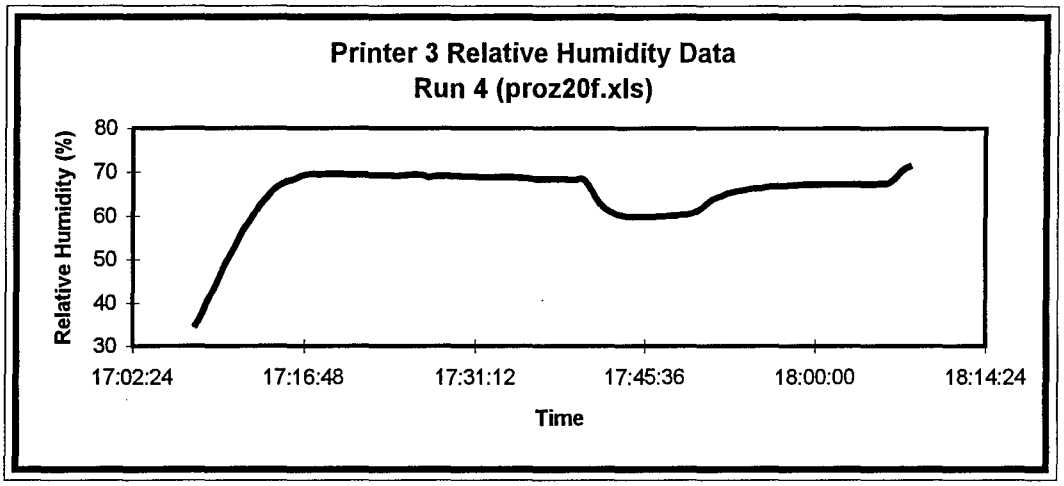

Printer 2 A Relative Humidity Data
Run 5 (proz15f.xls)
Relative Humidity (%)
90
80
70
60
50
40
13:55:12
14:09:36
14:24:00
14:38:24
14:52:48
Time

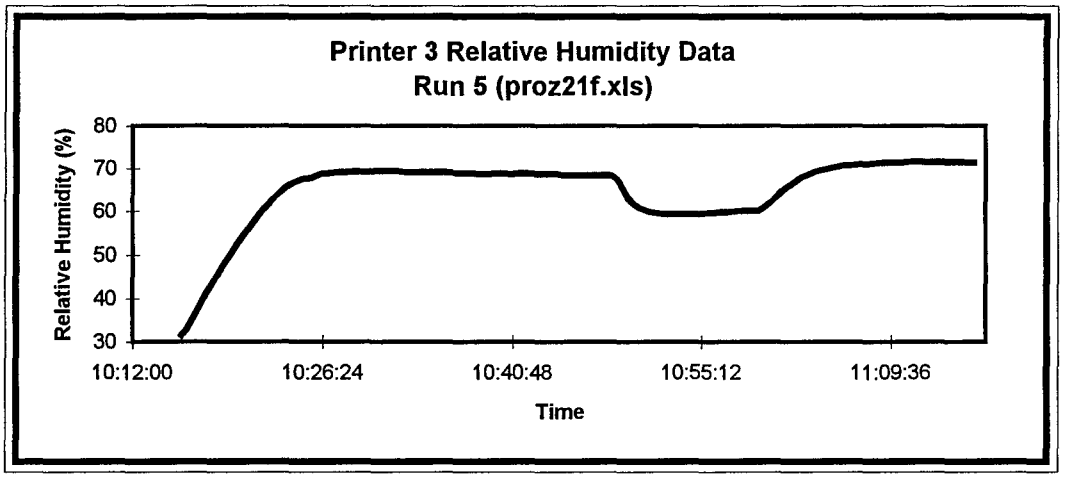

Printer 2 A Relative Humidity Data
Run 6 (proz16f.xls)
Relative Humidity (%)
90
80
70
60
50
40
17:02:24
17:16:48
17:31:12
17:45:36
18:00:00
18:14:24
Time

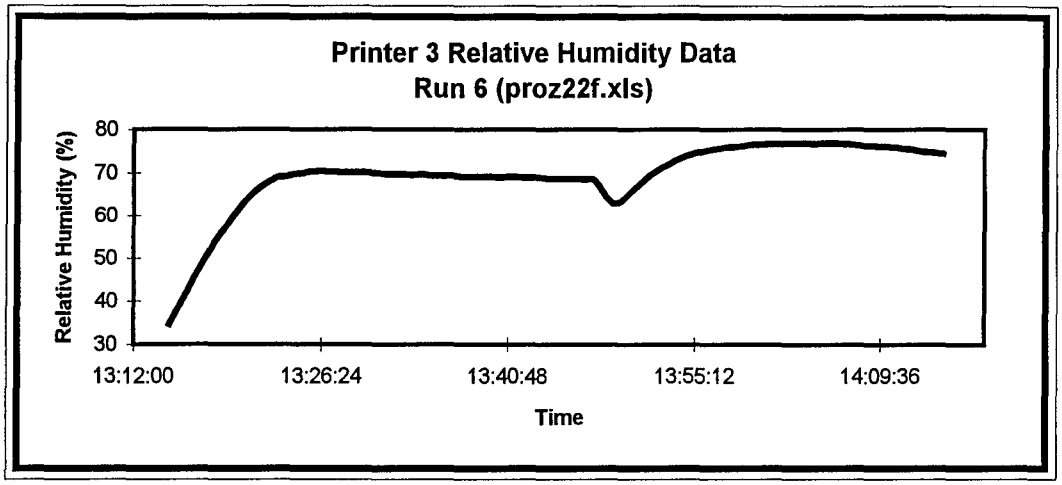

Printer 3 Relative Humidity Data
Run 1 (proz17f.xls)
Relative Humidity (%)
80
70
60
50
40
30
22:19:12
22:33:36
22:48:00
23:02:24
23:16:48
23:31:12
Time

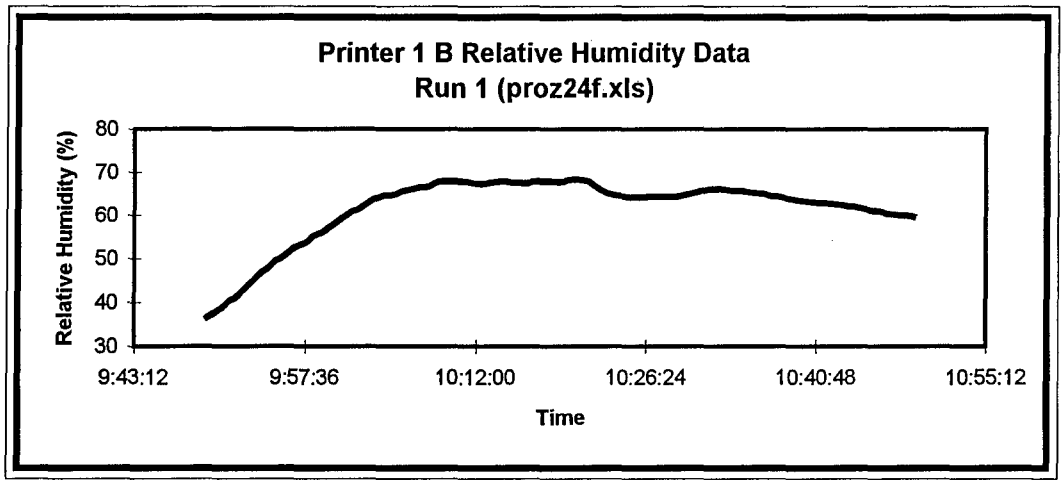

Printer 3 Relative Humidity Data
Run 2 (proz18f.xls)
Relative Humidity (%)
80
70
60
50
40
30
10:55:12
11:09:36
11:24:00
11:38:24
11:52:48
12:07:12
Time

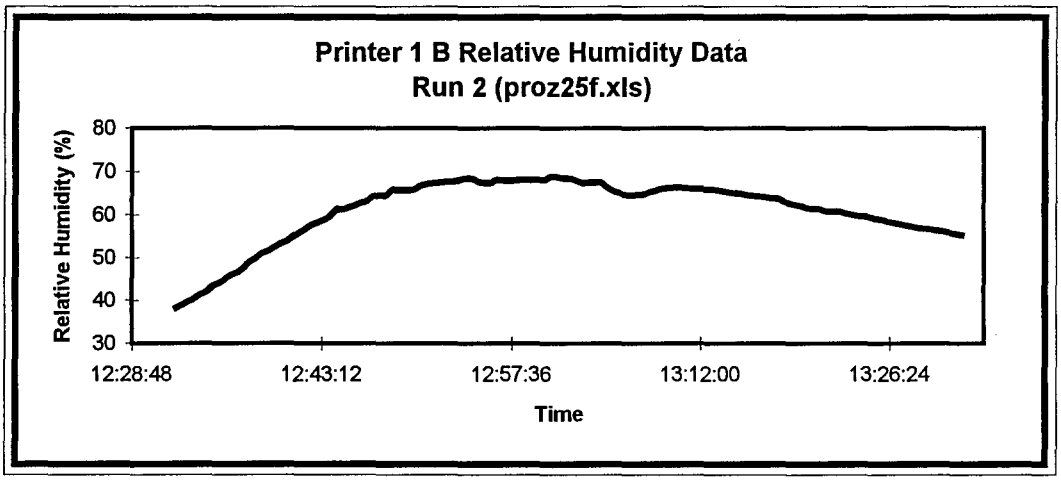

Printer 3 Relative Humidity Data
Run 3 (proz19f.xls)
Relative Humidity (%)
80
70
60
50
40
30
14:02:24
14:16:48
14:31:12
14:45:36
15:00:00
Time

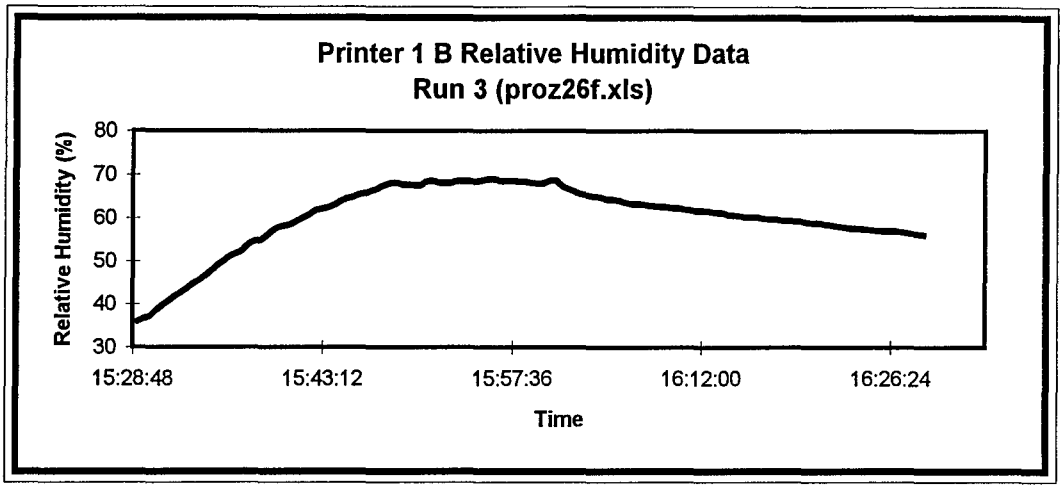

Printer 3 Relative Humidity Data
Run 4 (proz20f.xls)
Relative Humidity (%)
80
70
60
50
40
30
17:02:24
17:16:48
17:31:12
17:45:36
18:00:00
18:14:24
Time

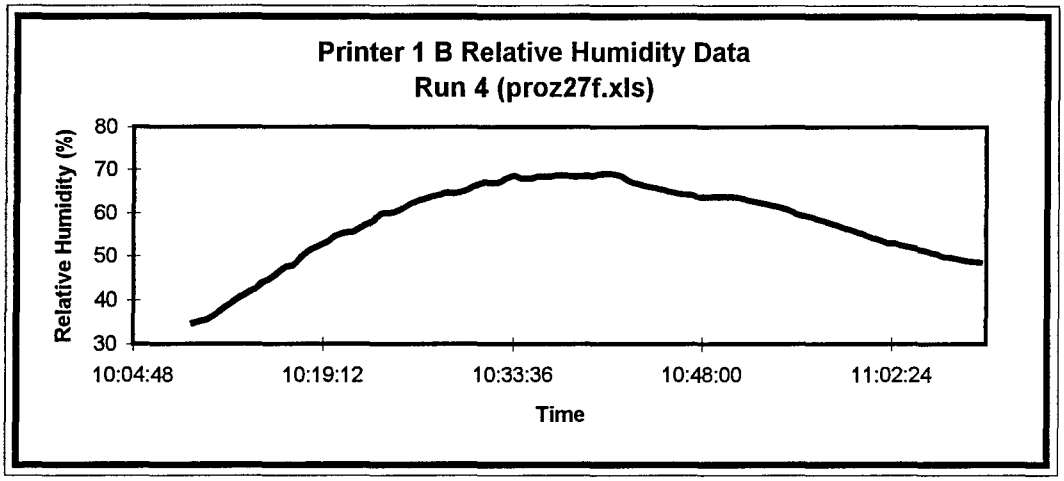

Printer 3 Relative Humidity Data
Run 5 (proz21f.xls)
Relative Humidity (%)
80
70
60
50
40
30
10:12:00
10:26:24
10:40:48
10:55:12
11:09:36
Time

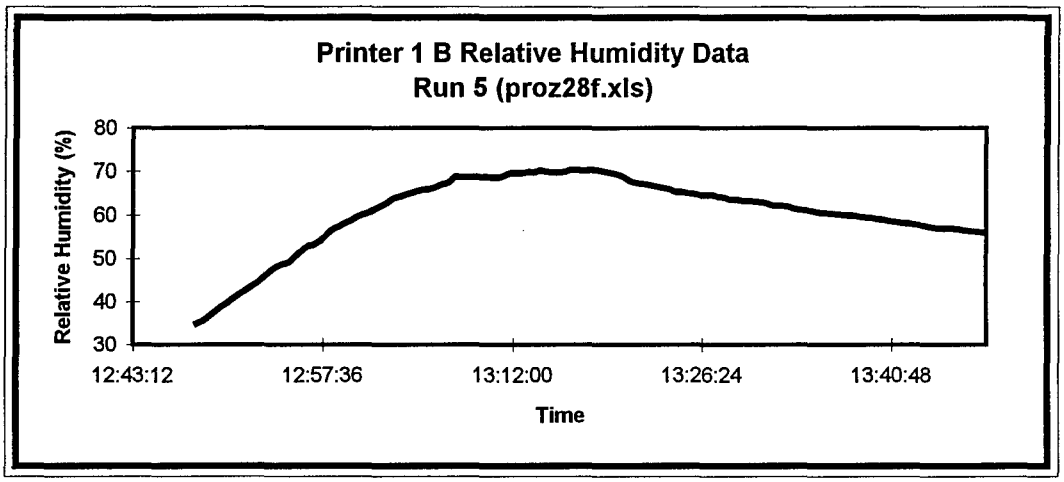

Printer 3 Relative Humidity Data
Run 6 (proz22f.xls)
Relative Humidity (%)
80
70
60
50
40
30
13:12:00
13:26:24
13:40:48
13:55:12
14:09:36
Time


Printer 1 B Relative Humidity Data
Run 1 (proz24f.xls)
Relative Humidity (%)
80
70
60
50
40
30
9:43:12
9:57:36
10:12:00
10:26:24
10:40:48
10:55:12
Time

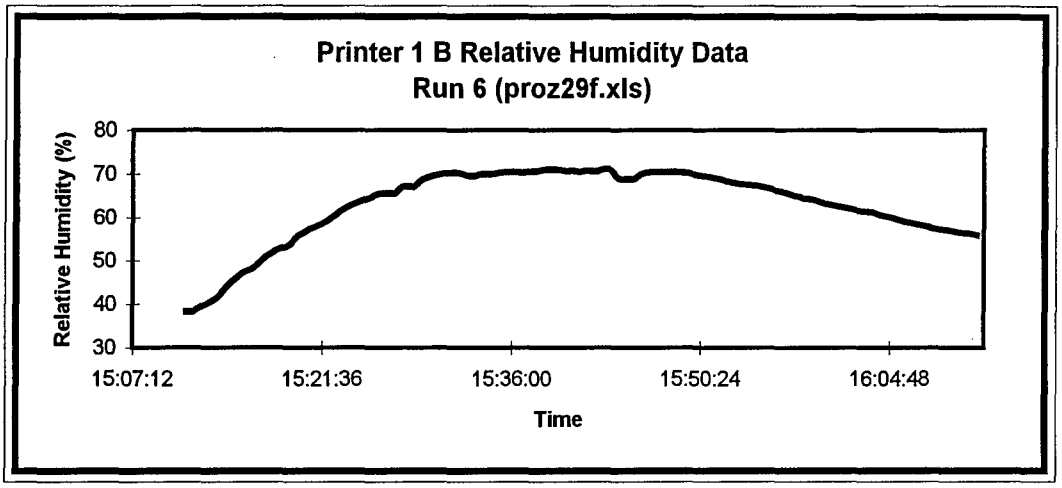

Printer 1 B Relative Humidity Data
Run 2 (proz25f.xls)
Relative Humidity (%)
80
70
60
50
40
30
12:28:48
12:43:12
12:57:36
13:12:00
13:26:24
Time

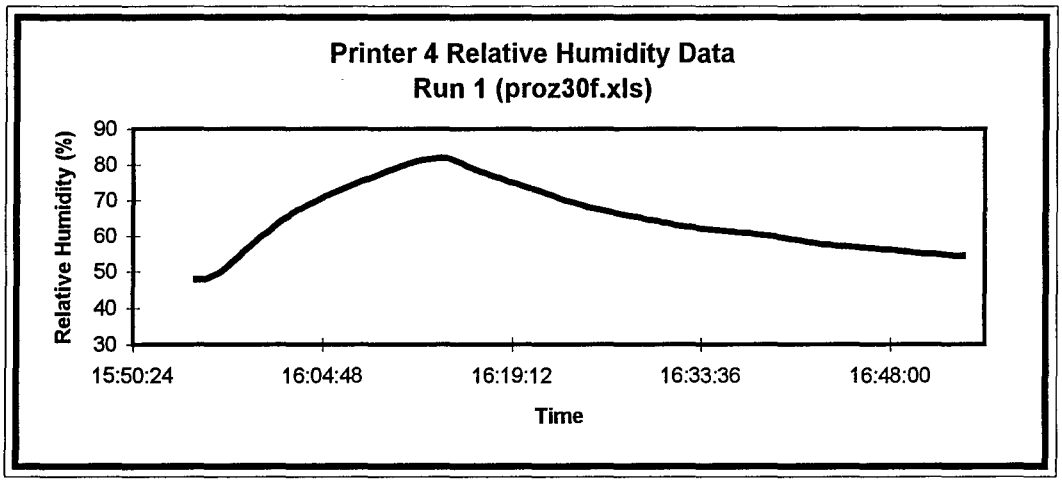

Printer 1 B Relative Humidity Data
Run 3 (proz26f.xls)
Relative Humidity (%)
80
70
60
50
40
30
15:28:48
15:43:12
15:57:36
16:12:00
16:26:24
Time

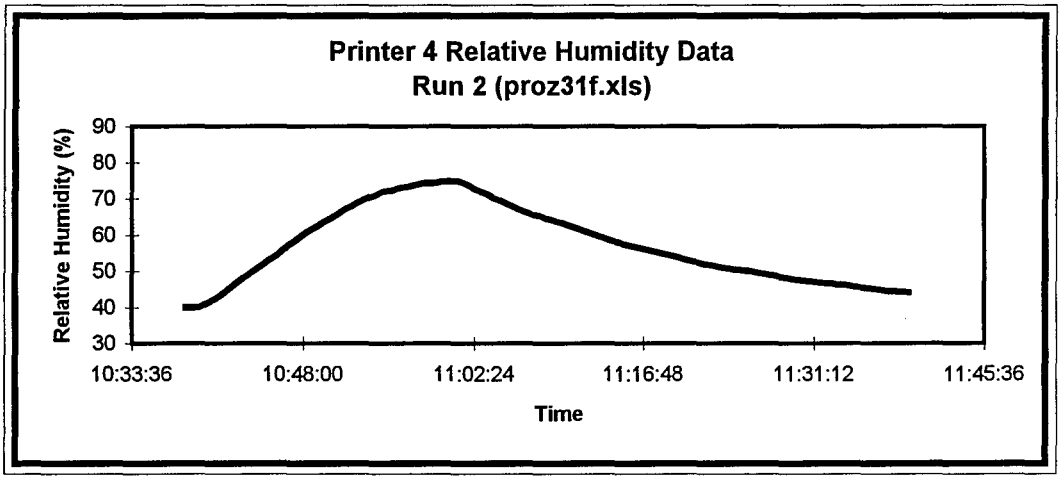

Printer 1 B Relative Humidity Data
Run 4 (proz27f.xls)
Relative Humidity (%)
80
70
60
50
40
30
10:04:48
10:19:12
10:33:36
10:48:00
11:02:24
Time


Printer 1 B Relative Humidity Data
Run 5 (proz28f.xls)
Relative Humidity (%)
80
70
60
50
40
30
12:43:12
12:57:36
13:12:00
13:26:24
13:40:48
Time

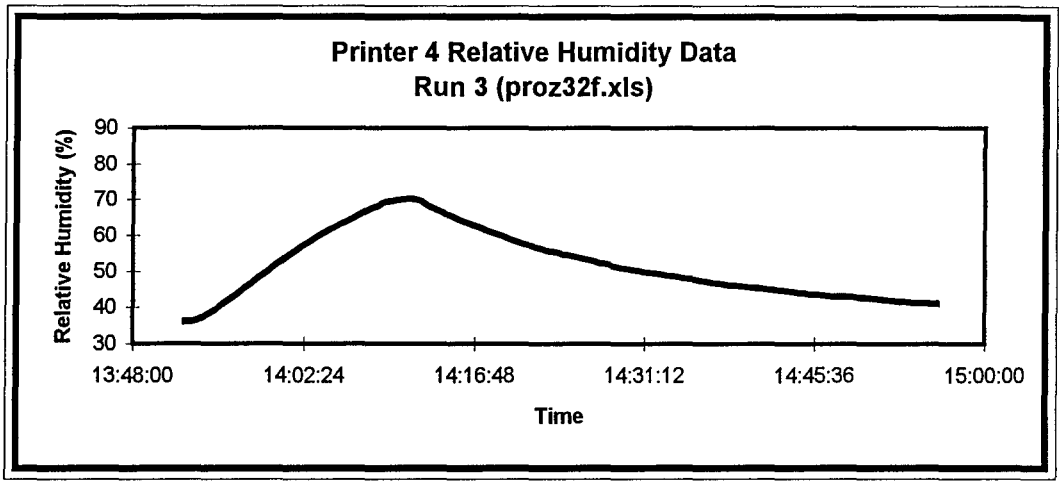
APPENDIX D -- Concentration and Generation Rate Data

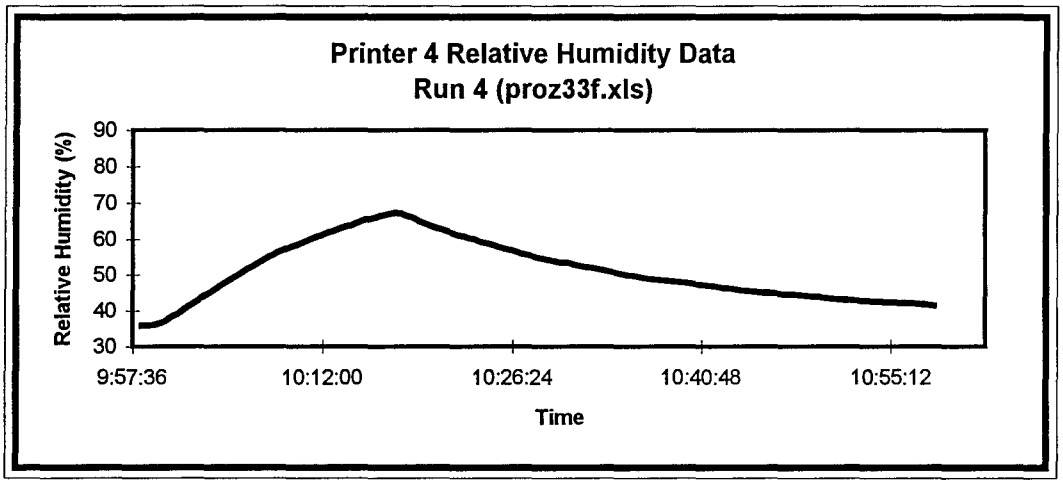


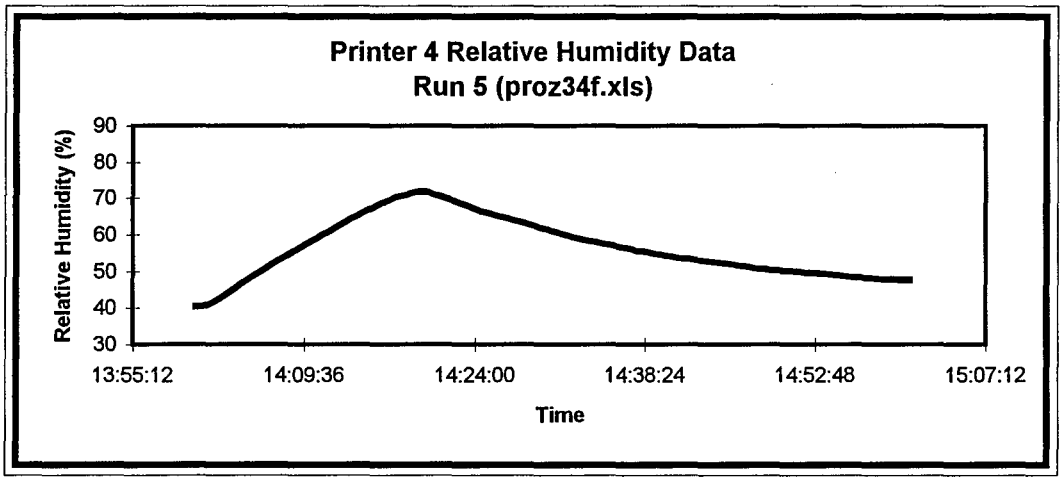




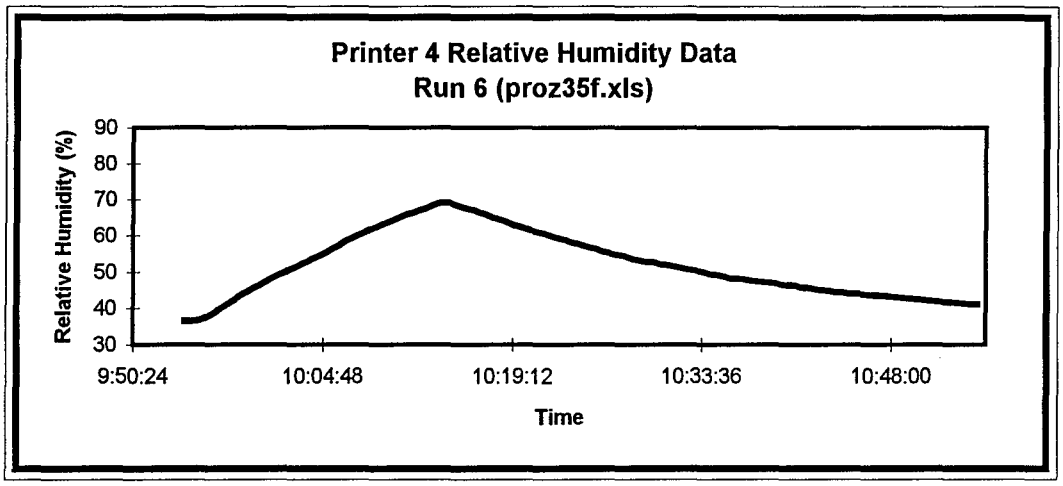
APPENDIX D -- Concentration and Generation Rate Data

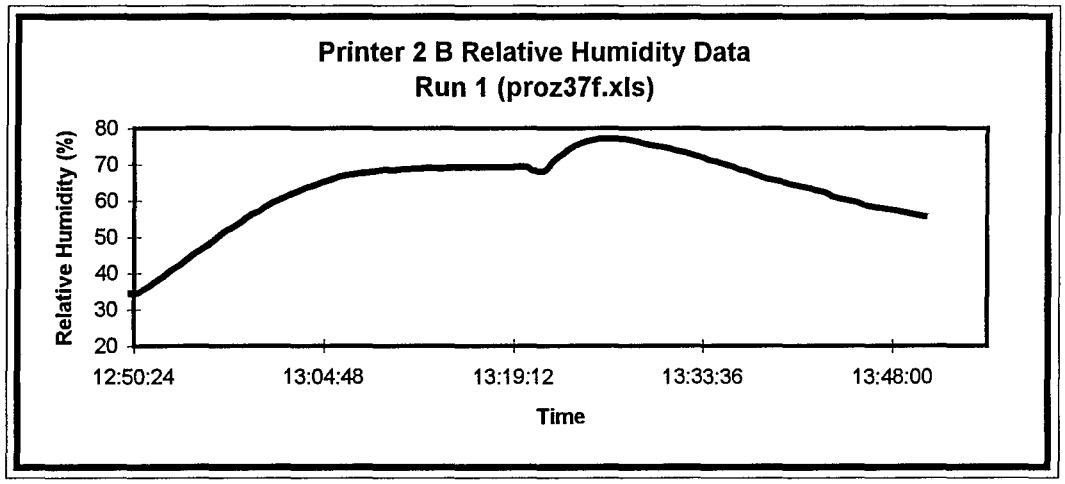


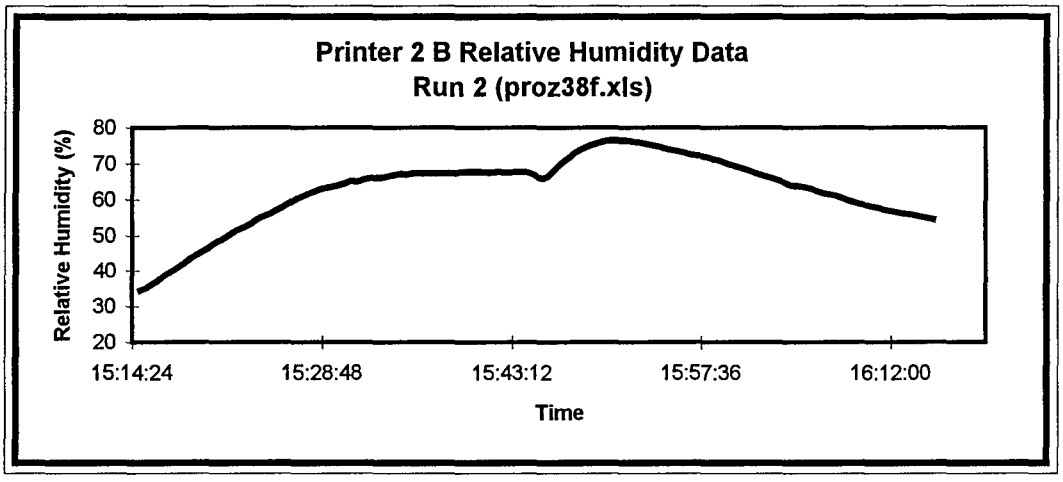


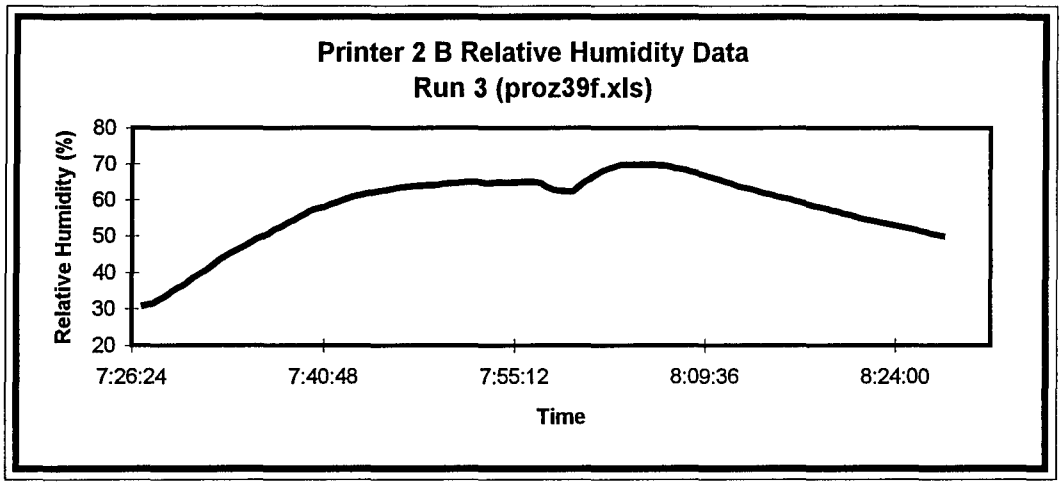


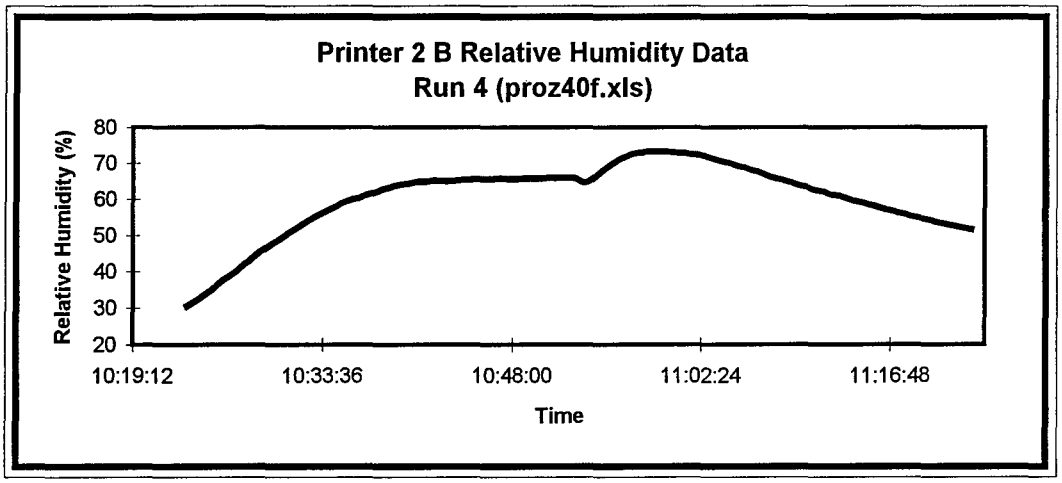
APPENDIX D -- Concentration and Generation Rate Data

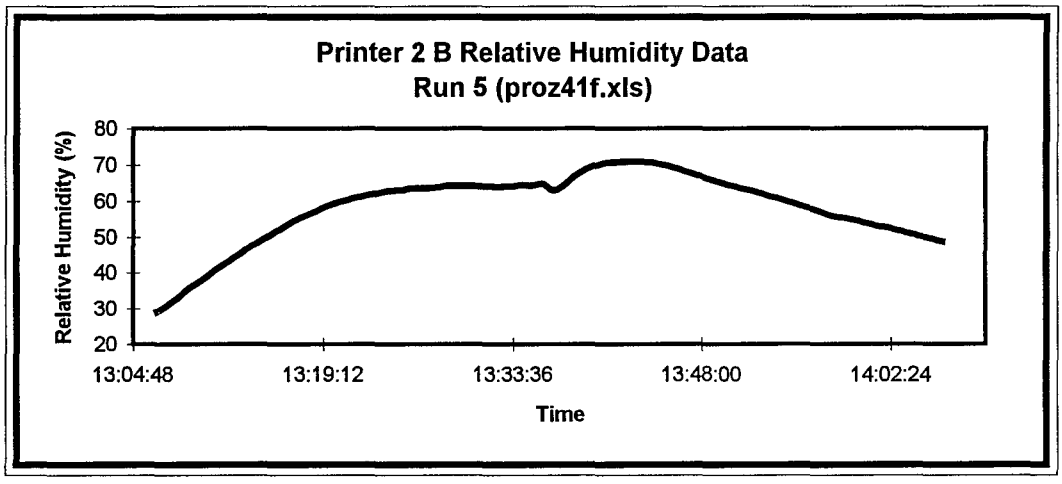




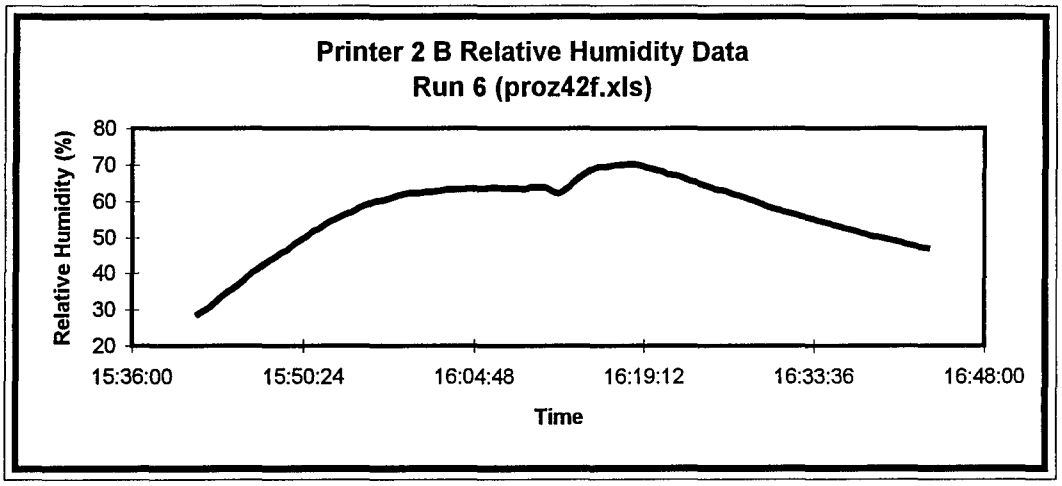



Printer 2 B Relative Humidity Data
Run 3 (proz39f.xls)
Relative Humidity (%)
80
70
60
50
40
30
20
7:26:24
7:40:48
7:55:12
8:09:36
8:24:00
Time


Printer 2 B Relative Humidity Data
Run 4 (proz40f.xls)
Relative Humidity (%)
80
70
60
50
40
30
20
10:19:12
10:33:36
10:48:00
11:02:24
11:16:48
Time


Printer 2 B Relative Humidity Data
Run 5 (proz41f.xls)
Relative Humidity (%)
80
70
60
50
40
30
20
13:04:48
13:19:12
13:33:36
13:48:00
14:02:24
Time

APPENDIX D -- Concentration and Generation Rate Data



Ozone Data Printer 1 A #56392

Run	Printer Term	Relative Humidity Term	Decay Term
PRINT01	1.85E-02	-2.15E-04	-1.962
PRINT02	2.96E-02	-3.69E-04	-1.080
PRINT03	3.89E-02	-5.00E-04	-0.822
PRINT04	4.01E-02	-5.05E-04	-0.797
PRINT05	3.47E-02	-4.20E-04	-0.649
PRINT06	4.03E-02	-4.93E-04	-0.632
PRINT07	4.88E-02	-6.09E-04	-0.512
PRINT08	2.41E-02	-2.70E-04	-0.779
PRINT09	4.81E-02	-5.92E-04	-0.577
PRINT10	2.88E-02	-3.53E-04	-0.464
Mean	0.03518	-4.33E-04	-0.82733
Stand Err	9.9E-06	1.71E-09	0.019088

Covariances	
Printer, Relative Humidity	-1.298E-07
Printer, Decay	2.90E-04
Relaive Humidity, Decay	-3.708E-06

Ozone Data Printer 2 A #23312

Run	Printer Term	Relative Humidity Term	Decay Term
PRINT11	9.93E-02	-1.22E-03	-0.128
PRINT12	1.66E-01	-2.21E-03	-0.089
PRINT13	2.01E-01	-2.84E-03	-0.074
PRINT14	1.83E-01	-2.49E-03	-0.077
PRINT15	2.74E-01	-4.00E-03	-0.072
PRINT16	2.66E-01	-3.62E-03	-0.062
Mean	1.98E-01	-2.73E-03	-0.084
Stand Err	7.11E-04	1.67E-07	9.23E-05

Covariances	
Printer, Relative Humidity	-1.09E-05
Printer, Decay	2.29E-04
Relaive Humidity, Decay	-3.47E-06

Ozone Data Printer 3 #74440

Run	Printer Term	Relative Humidity Term	Decay Term
PRINT17	8.49E-04		
PRINT18	8.65E-04	No Relative Humidity	
PRINT19	8.14E-04	Or Decay Terms	
PRINT20	8.44E-04		
PRINT21	8.66E-04		
PRINT22	8.22E-04		

	Mean
Ozone Generation	8.43E-04
95% CI	1.34E-05

Ozone Data Printer 1 B #56392

Run	Printer Term	Relative Humidity Term	Decay Term
PRINT24	2.72E-02	-3.45E-04	-0.489
PRINT25	3.03E-02	-3.92E-04	-0.429
PRINT26	2.82E-02	-3.59E-04	-0.559
PRINT27	2.60E-02	-3.35E-04	-0.465
PRINT28	2.74E-02	-3.42E-04	-0.489
PRINT29	2.89E-02	-3.55E-04	-0.463
Mean	2.80E-02	-3.55E-04	-0.482
Stand Err	3.74E-07	6.83E-11	3.14E-04

Covariances	
Printer, Relative Humidity	-4.75E-09
Printer, Decay	3.24E-06
Relaive Humidity, Decay	-4.97E-08

Ozone Data Printer 4 #80203

Run	Printer Term	Relative Humidity Term	Decay Term
PRINT30	9.44E-04		
PRINT31	6.90E-04	No Relative Humidity	
PRINT32	9.46E-04	Or Decay Terms	
PRINT33	8.98E-04		
PRINT34	8.11E-04		
PRINT35	8.95E-04		

	Mean
Ozone Generation	8.64E-04
95% CI	6.08E-05

Ozone Data Printer 2 B #23312

Run	Printer Term	Relative Humidity Term	Decay Term
PRINT37	1.47E-02	-1.96E-04	-0.732
PRINT38	1.72E-02	-2.39E-04	-0.851
PRINT39	1.46E-02	-2.06E-04	-0.779
PRINT40	1.78E-02	-2.52E-04	-0.717
PRINT41	1.77E-02	-2.58E-04	-0.727
PRINT42	1.75E-02	-2.57E-04	-0.637
Mean	1.66E-02	-2.35E-04	-0.741
Stand Err	3.78E-07	1.24E-10	8.39E-04

Covariances	
Printer, Relative Humidity	-6.646E-09
Printer, Decay	4.3812E-06
Relaive Humidity, Decay	-1.128E-07

Total VOC as Toluene Data Printer 1 A #56392

Run	Generation (mg/min)
PRINT01	2.015
PRINT02	2.145
PRINT03	1.925
PRINT04	1.626
PRINT05	1.509
PRINT06	1.472
PRINT07	1.632
PRINT08	1.529
PRINT09	1.403
PRINT10	1.440

Generation Rate	
Mean (mg/min)	1.670
95% CI	0.163

Total VOC as Toluene Data Printer 2 A #23312

Run	Generation (mg/min)
PRINT11	1.804
PRINT12	1.508
PRINT13	1.534
PRINT14	2.139
PRINT15	0.988
PRINT16	1.301

Generation Rate	
Mean (mg/min)	1.546
95% CI	0.318

Total VOC as Toluene Data Printer 3 #74440

Run	Generation (mg/min)
PRINT17	1.074
PRINT18	1.099
PRINT19	1.136
PRINT20	1.082
PRINT21	0.706
PRINT22	1.121

Generation Rate	
Mean (mg/min)	1.036
95% CI	0.131

Total VOC as Toluene Data Printer 4 #80203

Run	Generation (mg/min)
PRINT30	1.300
PRINT31	0.682
PRINT32	1.056
PRINT33	1.013
PRINT34	1.066
PRINT35	1.050

Generation Rate	
Mean (mg/min)	1.028
95% CI	0.158

Toluene Data HP Printer 3 #74440

Run	Generation (mg/min)
PRINT17	0.0753
PRINT18	0.0808
PRINT19	0.0791
PRINT20	0.0772
PRINT21	0.0452
PRINT22	0.0758

Generation Rate	
Mean (mg/min)	0.0723
95% CI	0.0107

Toluene Data HP Printer 4 #80203

Run	Generation (mg/min)
PRINT30	0.0140
PRINT31	0.0321
PRINT32	0.0116
PRINT33	0.0110
PRINT34	0.0112
PRINT35	0.0116

Generation Rate	
Mean (mg/min)	0.0153
95% CI	0.00666

Benzene Data HP Printer 3 #74440

Run	Generation (mg/min)
PRINT17	0.0204
PRINT18	0.0320
PRINT19	0.0262
PRINT20	0.0197
PRINT21	0.0123
PRINT22	0.0216

Generation Rate	
Mean (mg/min)	0.0220
95% CI	0.00532

APPENDIX D -- Concentration and Generation Rate Data

Butanol Data Printer 1 A #56392

Run	Generation (mg/min)
PRINT01	0.266
PRINT02	0.280
PRINT03	0.226
PRINT04	0.315
PRINT05	0.307
PRINT06	0.275
PRINT07	0.280
PRINT08	0.297
PRINT09	0.231
PRINT10	0.257

Generation Rate	
Mean (mg/min)	0.273
95% CI	0.018

Butanol Data Printer 2 A #23312

Run	Generation (mg/min)
PRINT11	0.170
PRINT12	0.152
PRINT13	0.157
PRINT14	0.259
PRINT15	0.101
PRINT16	0.098

Generation Rate	
Mean (mg/min)	0.156
95% CI	0.047

Butanol Data Printer 3 #74440

Run	Generation (mg/min)
PRINT17	0.044
PRINT18	0.051
PRINT19	0.041
PRINT20	0.030
PRINT21	0.019
PRINT22	0.033

Generation Rate	
Mean (mg/min)	0.037
95% CI	0.009

Butanol Data Printer 4 #80203

Run	Generation (mg/min)
PRINT30	0.191
PRINT31	0.092
PRINT32	0.128
PRINT33	0.133
PRINT34	0.168
PRINT35	0.155

Generation Rate	
Mean (mg/min)	0.144
95% CI	0.028

APPENDIX D -- Concentration and Generation Rate Data

Xylene Data Printer 1 A #56392

Run	Generation (mg/min)
PRINT01	0.627
PRINT02	0.656
PRINT03	0.638
PRINT04	0.380
PRINT05	0.366
PRINT06	0.366
PRINT07	0.407
PRINT08	0.371
PRINT09	0.336
PRINT10	0.375

Generation Rate	
Mean (mg/min)	0.452
95% CI	0.081

Xylene Data HP Printer 2 A #23312

Run	Generation (mg/min)
PRINT11	0.351
PRINT12	0.333
PRINT13	0.353
PRINT14	0.457
PRINT15	0.208
PRINT16	0.257

Generation Rate	
Mean (mg/min)	0.326
95% CI	0.069

Xylene Data Printer 3 #74440

Run	Generation (mg/min)
PRINT17	0.028
PRINT18	0.031
PRINT19	0.030
PRINT20	0.030
PRINT21	0.018
PRINT22	0.029

Generation Rate	
Mean (mg/min)	0.028
95% CI	0.004

Xylene Data Printer 4 #80203

Run	Generation (mg/min)
PRINT30	0.147
PRINT31	0.073
PRINT32	0.143
PRINT33	0.144
PRINT34	0.147
PRINT35	0.137

Generation Rate	
Mean (mg/min)	0.132
95% CI	0.023

APPENDIX E
Aerosol Loss Calculation Results

APPENDIX E -- Aerosol Loss Calculation Results

Penetration efficiency of an inclined tube under laminar and turbulent flow conditions, gravitational settling (W&B 6-37, 6-40)

Temperature	293.15	degrees Kelvin
Pressure	101.3	Kilopascals
Particle diameter	10	µm
Particle density	1	grams/cm^3
Tube diameter	15.24	cm
Tube length	561	cm
Incline angle (0-90)	0	degrees from horizontal
Mean flow velocity	310.00	cm/sec
Air density =	0.0012	g/cm^3
Air viscosity =	0.00018	poise
Flow Reynolds number =	31497.2	-laminar-
Slip correction factor =	1.01659	
Settling velocity =	0.30659	cm/sec
This value must be << 1 -->	0	
-intermediate number (k)-	0.0273	
-intermediate number-	0.30587	
-intermediate number-	0.95493	
Fraction penetrating =	0.95493	for laminar flow
Fraction penetrating =	0.9547	for turbulent flow

Penetration efficiency of a tube under turbulent flow conditions, inertial deposition (W&B 6-47 to 6-51)

Temperature	293.15	degrees Kelvin
Pressure	101.3	Kilopascals
Particle diameter	10	µm
Particle density	1	grams/cm^3
Tube diameter	15.24	cm
Tube length	561	cm
Mean flow velocity	310.00	cm/sec
Air density =	0.0012	g/cm^3
Air viscosity =	0.00018	poise
Flow Reynolds number =	31497.2	-turbulent-
Slip correction factor =	1.01659	
Stokes number =	0.00636	
tau+ =	0.5937	
V+ =	0.00021	
V(t) =	0.00357	
Inertial deposition efficiency =	0.99831	

APPENDIX E -- Aerosol Loss Calculation Results

Losses in 90° bends of circular cross section tubing (turbulent flow)

Temperature	293.15	degrees Kelvin
Pressure	101.3	Kilopascals
Particle diameter	10	µm
Particle density	1	grams/cm^3
Flow rate	56634	cm^3/sec
Air velocity In tube	310	cm/sec
Tube diameter	15.24	cm
Air viscosity =	0.00018	poise
Air density =	0.0012	grams/cm^3
Slip correction factor =	1.01659	
Kinematic viscosity =	0.15044	
Mean axial velocity =	310.468	cm/sec
Reynolds number =	31451.4	ulent flow
Stokes number =	0.01273	
Fractional penetration =	0.97216	