Indoor Pollutant Emissions from Electronic Office Equipment

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Presentation Overview

- **Background, problem, and project goals**
- **Approach and methods**
  - Emissions chambers
  - Research approach and experimental design
  - Analyte selection
  - Equipment selection
- **Results**
  - Computers (VOCs & SVOCs)
  - Printers (VOCs, SVOCs, ozone & particulate matter)
- **Findings and conclusions**
- **Research recommendations**
Background & Problem

It's getting crowded out here!
The Problem

- People are spending more time in close proximity to computers, video display units, printers, fax machines and photocopiers

- Efforts to improve energy efficiency are leading to “tighter” buildings (i.e., less ventilated)

- As a result, even low emissions might lead to important indoor exposures
Project Goals

- Identify and quantify pollutants emitted by major categories of office equipment
- Measure unit-specific emission factors for identified pollutants from individual computers and printers
- Assess importance of aging and other operational factors on emission rates and emissions sources
Literature review insight

- **Target pollutant selection**
  - A wide range of pollutants have been identified in office equipment
  - Technologies are evolving rapidly

- **Office equipment selection**
  - Recently purchased (< 3 mo) computers including LCD monitors and peripherals
  - Printer types include ink jet, medium- and heavy-duty laser technology

- **Sampling and analysis methods identified**
  - A wide range of methods were required to assess the different target pollutants
Research Approach Overview

**Phase I - Category Specific Emissions**

Multiple unit, room-scale (20 m³) screening experiments monitoring particulate mass and number concentrations, ozone, aldehydes, VOCs and SVOCs under steady-state conditions for range of equipment states (off, on, active) for computers and printers.

**Phase II - Unit Specific Emissions**

Single unit, in Continuous Stirred Tank Reactor Chamber (0.4 m³) monitoring pollutants identified in Phase I and identifying factors that influence emissions.
Pollutants Considered

- Ozone
- Carbonyls
- Semi-volatile compounds
- Volatile compounds
- Particulate matter
Research Approach: Phase I

- **Test chamber design and operation**
  - 20 m³ stainless steel with carbon and filter conditioned air at 1-2 air changes per hour
  - Temperature controlled by external room temperature (target ~ 25 °C using a chiller on inlet air)
  - Humidity monitored

- **Duty cycles for office equipment**
  - Five computers tested in off and active state
  - Active represents full operation running “hot”
  - Five inkjets, three medium- and two high-output laser printers tested by category
Phase I Experiment Design

(A) Load computers

Purge chamber

Transition computers to active phase

Remove computers

Shutdown or next run

(*) = duplicate sample collected

(B) Load printers in purged chamber

Start printing

Stop printing

Start second printing

Stop printing

Shutdown or next run

(*) = duplicate sample collected
Research Approach: Phase II

- Single unit (computer or printer) placed in a continuous stirred tank reactor chamber (0.4 m³)
- More detailed monitoring of pollutants identified in Phase I
- Factors that increase/decrease emissions
## Sample Collection and Analysis

<table>
<thead>
<tr>
<th>Analytes</th>
<th>Sampling mode</th>
<th>Collection media</th>
<th>Sample processing</th>
<th>Analysis method</th>
</tr>
</thead>
<tbody>
<tr>
<td>VOCs</td>
<td>Integrated in duplicate</td>
<td>Tenax-TA + Carbosieve sorbent tubes</td>
<td>Thermal desorption</td>
<td>TDGC/MS</td>
</tr>
<tr>
<td>Volatile Carbonyls</td>
<td>Integrated in duplicate</td>
<td>DNPH-coated silica cartridges</td>
<td>Extract with acetonitrile</td>
<td>HPLC</td>
</tr>
<tr>
<td>SVOCs</td>
<td>12 hr 20 lpm (14.4 m³) integrated in duplicate</td>
<td>Polyurethane foam and/or XAD-4</td>
<td>Accelerated Solvent Extraction in 1:1 Ace:Hex</td>
<td>GC/MS (PAHs) GC-ECD (BFRs) GC-NPD (OPs)</td>
</tr>
<tr>
<td>Particle count</td>
<td>Continuous</td>
<td></td>
<td>Condensation particle counter</td>
<td>TSI P-Trak ultrafine particle counter</td>
</tr>
<tr>
<td>PM - mass</td>
<td>Integrated</td>
<td>Teflo® Teflon filters</td>
<td>Equilibrate filters at T/RH</td>
<td>Gravimetric</td>
</tr>
<tr>
<td>PM - BC</td>
<td>Semi- integrated</td>
<td>Filter strip in aethelometer</td>
<td></td>
<td>Light absorption (continuous)</td>
</tr>
<tr>
<td>PM - EC/OC</td>
<td>Integrated</td>
<td>Tissuquartz fiber filters</td>
<td>Light absorption (on filter)</td>
<td></td>
</tr>
<tr>
<td>Ozone</td>
<td>Continuous</td>
<td></td>
<td></td>
<td>UV photometric</td>
</tr>
</tbody>
</table>

VOC = volatile organic compounds; TDGC = thermo-desorption gas chromatograph; MS = mass selective detector; DNPH = dinitrophenylhydrazine; HPLC = high performance liquid chromatograph; PAH = polycyclic aromatic hydrocarbon; PUF = polyurethane foam; ECD = electron capture detector; NPD = nitrogen-phosphorus detector; OP = organophosphorus compounds; BC = black carbon; T/RH = temperature and relative humidity; EC/OC = elemental carbon/organic carbon.
Office Equipment Selection

- Detailed survey information from Gartner Research and IDC Market Research--private data very expensive

- We used other resources
  - PC World summary of Gartner and IDC reports on global PC sales
  - CNN/Money survey of computer sales
  - The American Customer Satisfaction Index (ACSI) lists major vendors along with customer satisfaction
  - The Consumer Reports provides information for selecting representative computers based on a wide range of parameters
Results

Phase I

Ozone and carbonyls
Semi-volatile compounds
Volatile compounds
Particles

Phase II

Computers
Printers
Phase I Results

- 5 Computers
- 10 Printers
  - 2 High-output laser printers
  - 3 Medium output laser printers
  - 5 Inkjet printers
- Emissions measured
  - Ozone
  - Carbonyls
  - Volatile compounds
  - Semi-volatile compounds
  - Particles
Phase I: Ozone & Carbonyls

- No change in ozone concentrations during Phase-I experiments for computers or printers

- No change in carbonyl concentrations for room-scale measurements
Phase I VOC Results

The graph shows the concentration (µg/m³) of various volatile organic compounds (VOCs) with air change rate (ACH) = 1. The x-axis represents different VOCs: naphtalene, hexadecane, dibutylphthalate, 1235 tetra methyl benzene, acetophenone, benzaldehyde, ethyl benzene, o-xylene, styrene, and toluene. The y-axis represents the concentration. The chart includes different scenarios:

- **empty chamber**
- **chamber loaded, computers off**
- **day 1, computers running**
- **day 3, computers running**
- **day 7, computers running**
- **chamber after computers are removed**

The concentrations vary significantly across different scenarios and VOCs.

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
Phase I: Semivolatile Organics (SVOCs)

- Polycyclic aromatic hydrocarbons (PAHs): could only quantify naphthalene & methylnaphthalenes, but other 2-and 3-ring congeners were elevated

- Brominated flame retardants (BFRs): penta congeners 47, 99 and 100 elevated in 2006 computers but not detected in 2007 computers

- Organophosphates (OPs): three of the six measured congeners were elevated in 2006 and 2007 computers

- Phthalates: were able to detect diethyl- and dibutyl-phthalate

- Large-peak unknowns: were found to be cyclic siloxanes
Desktop Organophosphates

- 3 of the organophosphates were > 5 times background during active phase
- Earlier studies link (TPP) to computer monitors (Carlsson et al., 2000)
- TBEP and TCEP are used as flame retardants

TBP = Tributyl phosphate, TCEP = Tris(2-chloroethyl) phosphate, TPP = Triphenyl phosphate, TBEP = Tris(2-butoxyethyl) phosphate, TEHP = Tris(2-ethylhexyl) phosphate
Other Computer SVOCs

Brominated flame retardants

PAHs
Phase I: Particles

- Background in chamber ~ 100 particles/cc
- Medium- and high-output laser printers show similar results with episodic particle emissions
- Inkjet technology had consistently low particle output
- 24 hour integrated particle mass measurement for printers ~ 1-3 µg/m³
- Black carbon (athelometer) levels very low
- Elemental carbon / total carbon ratios ~ 0.02
Heavy Duty Office Laser Printers

![Graph showing the number of particles emitted by laser printers over time.](image)

- **Particle Emission**: The graph illustrates the number of particles (in particles per cubic centimeter, pt/cc) emitted from heavy-duty office laser printers over a period of time. The y-axis represents the number of particles, ranging from 0.0E+00 to 6.0E+04.

- **Active Print Period**: The shaded area within the graph indicates the active print period for a specific day.

- **Day 1 and Day 2**: Two distinct days are shown, with one marked as Day 1 and the other as Day 2. The graph highlights an increase in particle emission during the active print period on each day.

- **Time Axis**: The x-axis represents time in hours and minutes, from 7:12 to 21:36.

- **Particle Count**: The graph shows a significant increase in particle emission on Day 2 compared to Day 1, particularly during the active print period.
Indoor and outdoor particle number concentration (particle cm\(^{-3}\)) variation during Friday - Saturday March 17 and 18, 2006.

Phase II Results

5 Computers
- Volatile organic compounds (VOCs)
- Semivolatile organic compounds (SVOCs)
- PM and ozone
- Time and power-use trends

8 Printers (7 laser & 1 inkjet)
- Volatile organic compounds (VOCs)
- Semivolatile organic compounds (SVOCs)
- Ozone
- Ultrafine particles
- Paper, ink, and power-use trends
Phase II Results

Computers
Computer Emissions

• VOCs and SVOCs coming out of new and operating computers include some 40 compounds and amount to 300 to 500 µg/h of total chemical emissions

• SVOC emissions include polycyclic aromatic hydrocarbons (PAHs), brominated flame retardants (BFRs), organophosphate flame retardants (OPFRs), phthalates, and siloxanes

• Siloxanes accounted for the largest SVOC emissions

• The only low-molecular-weight aldehyde emissions were formaldehyde releases (~13.5 ± 9 µg/h/unit) from computers
Computer Emissions (cont’d)

• Computers show an “aging” effect with most VOC/SVOC emissions decreasing in time

• Brominated flame retardants (BFR), organophosphate flame retardants (OPFR), and siloxane emissions show little or no “aging” effect

• VOC emissions tend to increase with increasing power consumption

• Ozone and PM emissions were not detected for computers
Out-of-Box “Active” VOC Emissions

![Graph showing emission rates for different VOCs from units 1 to 5 in a desktop and laptop setting. The graph compares emissions rates (µg/h/unit) for various VOCs such as p-Xylene, Toluene, Ethylbenzene, α-Xylene, Styrene, Phenol, 1-Hexanol, 2-ethyl-1,2,3-trimethylbenzene, Acetophenone, Benzaldehyde, Tetradeacne, and Butylated Hydroxytoluene.]
Decline of VOC Emissions after “Aging”

Data points indicate average ± stdev for all VOCs with emissions > 5 µg/h for each computer at each time point.

All data normalized to out-of-box emission rates.
Changes in VOC Profile with "Aging"

Out-of-box: 295 μg/h
100 hours: 98 μg/h
250 hours: 70 μg/h
400 hours: 55 μg/h

Represents >98% of VOC mass in emission stream for Dell desktop unit

p-xylene
toluene
ethyl-benzene
α-xylene
styrene
phenol
VOC Emissions and Power Use

- Total measured VOC emission during active computer processing
- Increased power use also likely relates to an increase in air flow and heat generation
Out-of-Box “Active” Siloxane Emissions

[Graph showing emission rates for different units and siloxanes.]

MolWt: 370.78   C10 H30 O5 Si5
005541-02-6 Decamethylcyclodisiloxane
Organophosphate Emissions from Individual Computers

TEP = Triethyl phosphate, TBP = Tributyl phosphate, TCEP = Tris(2-chloroethyl) phosphate, TPP = Triphenyl phosphate, TBEP = Tris(2-butoxyethyl) phosphate
Phase II Results

Printers
Printer Emissions

- VOCs, SVOCs, and siloxanes coming out of operating printers include some 30 compounds and amount to 2000 to 4000 µg/h of total chemical emissions.

- Ozone emissions from laser printers varied among the units tested but were relatively low.

- Laser printers emit large number counts of ultrafine particles (UFP) to fine particles--these emissions occur during printing but are often elevated further during initial cold start prints.

- PM emissions for inkjet printers are several orders of magnitude lower than for laser printers.

- The magnitude of UFP emissions tended to track power consumption in laser printers.
Small Chamber Emission Model

- measured
- actual

Chamber chemical concentration (µg/m³)

- Printing stops
- Emissions from 200 pages printed in 12 min.
- 2nd 30-min chamber air sample
- 100 min. period used to purge chamber
- Baseline 30-min chamber air sample
- 3rd 30-min chamber air sample

Elapsed Time (min)
VOC emissions during active printing

- Laser Printer TVOC = 2580 ± 950 µg/h
- Inkjet TVOC = 54 µg/h

> 95% of TVOC in emissions
VOC emissions versus toner coverage

Some VOCs are related to toner.
VOC emissions versus toner coverage (cont.)

But some VOCs are not related to toner use.
No Correlation of Printer VOC Emissions with Power Use
# Ozone emissions during printing

<table>
<thead>
<tr>
<th>Printer</th>
<th>Emission Rate (µg/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Printer 1</td>
<td>Trace</td>
</tr>
<tr>
<td>Laser Printer 2</td>
<td>583 ± 111</td>
</tr>
<tr>
<td>Laser Printer 3</td>
<td>Trace</td>
</tr>
<tr>
<td>Laser Printer 4</td>
<td>Trace</td>
</tr>
<tr>
<td>Laser Printer 5</td>
<td>1750 ± 92</td>
</tr>
<tr>
<td>Laser Printer 6</td>
<td>Trace</td>
</tr>
<tr>
<td>Laser Printer 7</td>
<td>Non-Detect</td>
</tr>
</tbody>
</table>
Laser Printers

Ultrafine Particle (UFP) Emissions
Particle emissions profile

Cold prints (pages)

(100) (1)

Warm prints (pages)

(10) (10) (10) (20) (30) (30)

Particle number conc. (#/cc)

Power use (W)

elapsed time (h)
Cold print particle emissions versus page count

Cold-print emissions are only partially related to number of pages printed.
Particle emission versus toner coverage

Particle emissions are related to toner use but only after “residue effect” is reduced by printing blank pages (or cleaning).
Correlation of UFP Emissions with Power Use

\[ y = 4577e^{0.0155x} \]

\[ R^2 = 0.9239 \]
Findings

• Emissions summary
• Exposure potential
• Health impacts
• Sources of UFP
• Mitigation actions
Emissions Summary

• Both computers and printers have detectable emissions of many VOCs and SVOCs

• Computers show a VOC/SVOC “aging” effect; printers do not

• Printers emit greater overall amounts of VOC than computers during a print sequence

• Some of the compounds emitted are on lists of potentially harmful chemicals (this is discussed below)

• Printers emit large numbers of UFP
Computer Out-of-Box Versus Printer VOC and SVOC Emissions
Contributions of Office Equipment to Indoor Exposure

Indoor Volume
Room: 20 m³
House: 100 m³

Air exchange
0.2 ACH
Modeled versus measured concentrations for a house volume of 100 m³
A single piece of office equipment in a 20 m³ room can have emissions during its use that are comparable to and sometimes greater than other observed indoor sources.
Ranking Office-Equipment Emissions

• For the analyte emissions we measure and relative other indoor sources

Computers are potentially important sources for
- dodecamethyl cyclohexasiloxane (D6)
- decamethyl-cyclopentasiloxane (D5)
- p-xylene

Printers are potentially important indoor sources for
- ultrafine PM
tetradecane
- hexanal
pentadecane
- nonanal
tridecane
- octanal
hexamethyl-cyclotrisiloxane (D3)
- p-xylene
decamethyl-cyclopentasiloxane (D5)
- benzaldehyde
styrene
- ethylbenzene
2-ethyl-1-hexanol
- o-xylene
dodecane
- acetophenone
hexadecane
Health Impacts

• Eighteen compounds detected in computer/printer emissions are listed in one or more national or state health-based guidelines
  – California Chronic Reference Exposure Limit (CREL)
  – California No Significant Risk Level (NSRL) for cancer
  – California Maximum Allowable Dose Level (MADL) for reproductive toxicity
  – USEPA’s Reference Dose (RfD) and Reference Concentrations (RfC)

• Compounds without available guidelines are not necessarily safe
• Concentrations for these eighteen compounds in the 20-m³ room were compared to guideline levels
• In almost all cases the computer and printer emissions give rise to concentrations well below guideline levels
• Formaldehyde emissions from computers and dibutylphthalate emissions from printers are possible exceptions—emissions are estimated to come close to or exceed the guideline limits
Hypotheses for laser printer particle sources

- Particles generated when internal components of printer become hot at the initiation of a print
- Ozone-initiated reactions with VOCs may generate secondary aerosols
- Rapidly condensing SVOCs and water (from toner, paper or printer components) that are vaporized during printing (residue buildup and/or toner use)
Mitigation Actions

- Experiments to assess operational parameters that could mitigate emissions

  - For computers
    - “Aging” of computers led to a reduction in chemical emissions
    - Emissions seem to be low with units that use less power

  - For printers
    - Brand choice, power use, and the amount of toner coverage used per page had an impact on emissions
    - Other user-selected factors had little effect on emissions relative to the machine-to-machine variability in emissions magnitude
      - print sequencing
      - toner selection
      - paper choice
Conclusions

- **Computer emissions**
  - VOCs emissions that decline with age
  - Little or no PM emissions

- **Printer emissions**
  - VOCs and large bursts of ultra-fine particles and some printers also emit ozone
  - These emissions primarily from laser technology printers
  - Inkjet printers have lower VOC/SVOC emissions and significantly lower PM emissions
Conclusion (cont.)

- Sources of particle emissions from laser printers not yet known
- There are currently three postulated sources
  - Particles generated from hot surfaces
  - Ozone initiated reactions with VOCs
  - Rapidly condensing SVOCs and water
Recommendations

- Trend (and history) of emissions should be better characterized
  - This study focused on new units
  - Many older computers are used in schools and child care facilities, often in poorly ventilated spaces

- Long-term, low level SVOC emissions may be accumulating indoors
  - Need further studies designed specifically to assess SVOC emissions and indoor fate to determine exposure concentrations
  - Both dust and air samples are needed
Recommendations (Cont.)

- **Exposure factors needed for office equipment users**
  - This study found that, during operation, emissions from office equipment can result in room concentrations comparable to those from other indoor sources.
  - Data is currently lacking for assessing exposures.

- **Source and composition of ultrafine particles needs to be determined**
  - Several hypotheses are available but further testing is needed – results will influence mitigation choices.