Air Resources Board
The Chair's Air Pollution Seminar Series
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Indoor Pollutant Emissions from Electronic Office Equipment

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Legal notice

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

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 m^3) 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 m^3) 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

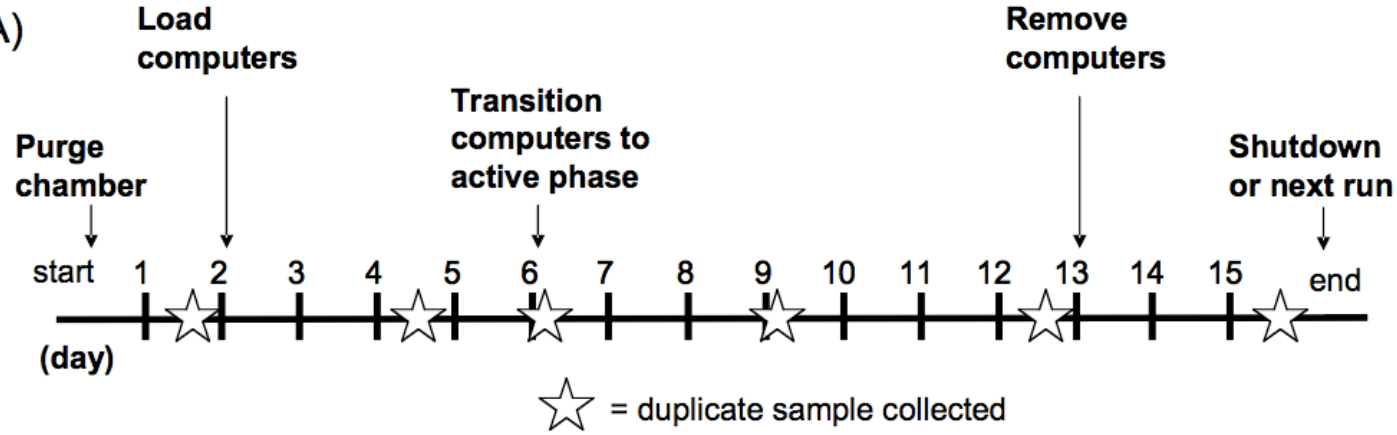
- 20 m^3 stainless steel with carbon and filter conditioned air at 1-2 air changes per hour
- Temperature controlled by external room temperature (target ~ 25 °C using a chiller on inlet air)
- Humidity monitored

➢ Duty cycles for office equipment

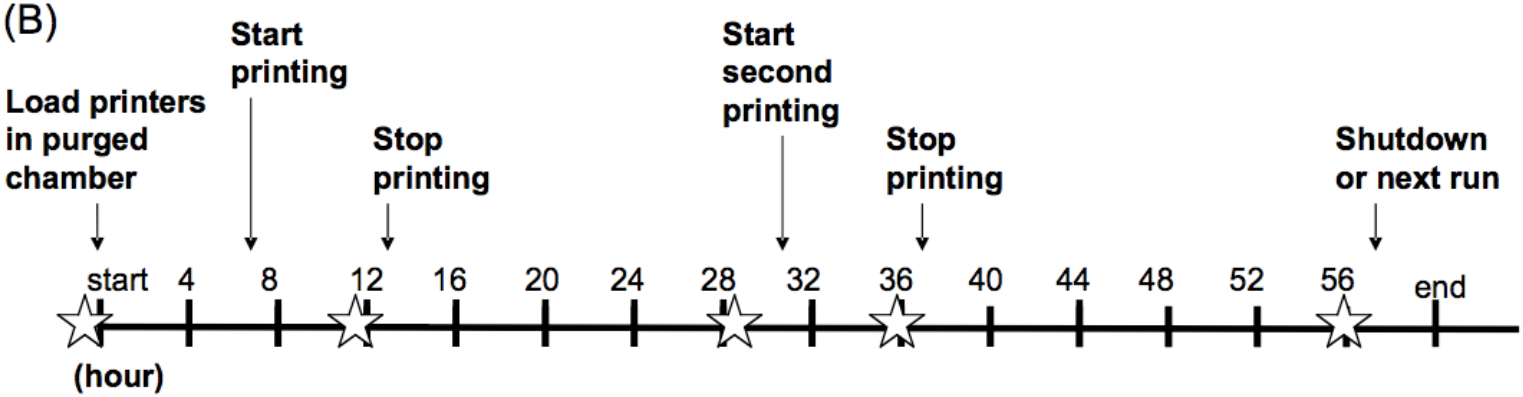
- Five computers tested in off and active state
- Active represents full operation running "hot"
- Five inkjets, three medium- and two high-output laser printers tested by category

Phase I Experiment Design

(A)



(B)



Research Approach: Phase II

- Single unit (computer or printer) placed in a continuous stirred tank reactor chamber (0.4 m^3)
- More detailed monitoring of pollutants identified in Phase I
- Factors that increase/decrease emissions

Sample Collection and Analysis

Analytes	Sampling mode	Collection media	Sample processing	Analysis method
VOCs	Integrated in duplicate	Tenax-TA + Carbosieve sorbent tubes	Thermal desorption	TDGC/MS
Volatile Carbonyls	Integrated in duplicate	DNPH-coated silica cartridges	Extract with acetonitrile	HPLC
SVOCs	12 hr 20 lpm (14.4 m^3) integrated in duplicate	Polyurethane foam and/or XAD-4	Accelerated Solvent Extraction in 1:1 Ace:Hex	GC/MS (PAHs) GC-ECD (BFRs) GC-NPD (OPs)
Particle count	Continuous		Condensation particle counter	TSI P-Trak ultrafine particle counter
PM - mass	Integrated	Teflo® Teflon filters	Equilibrate filters at T/RH	Gravimetric
PM - BC	Semi- integrated	Filter strip in aethelometer		Light absorption (continuous)
PM - EC/OC	Integrated	Tissuquartz fiber filters		Light absorption (on filter)
Ozone	Continuous			UV photometric

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

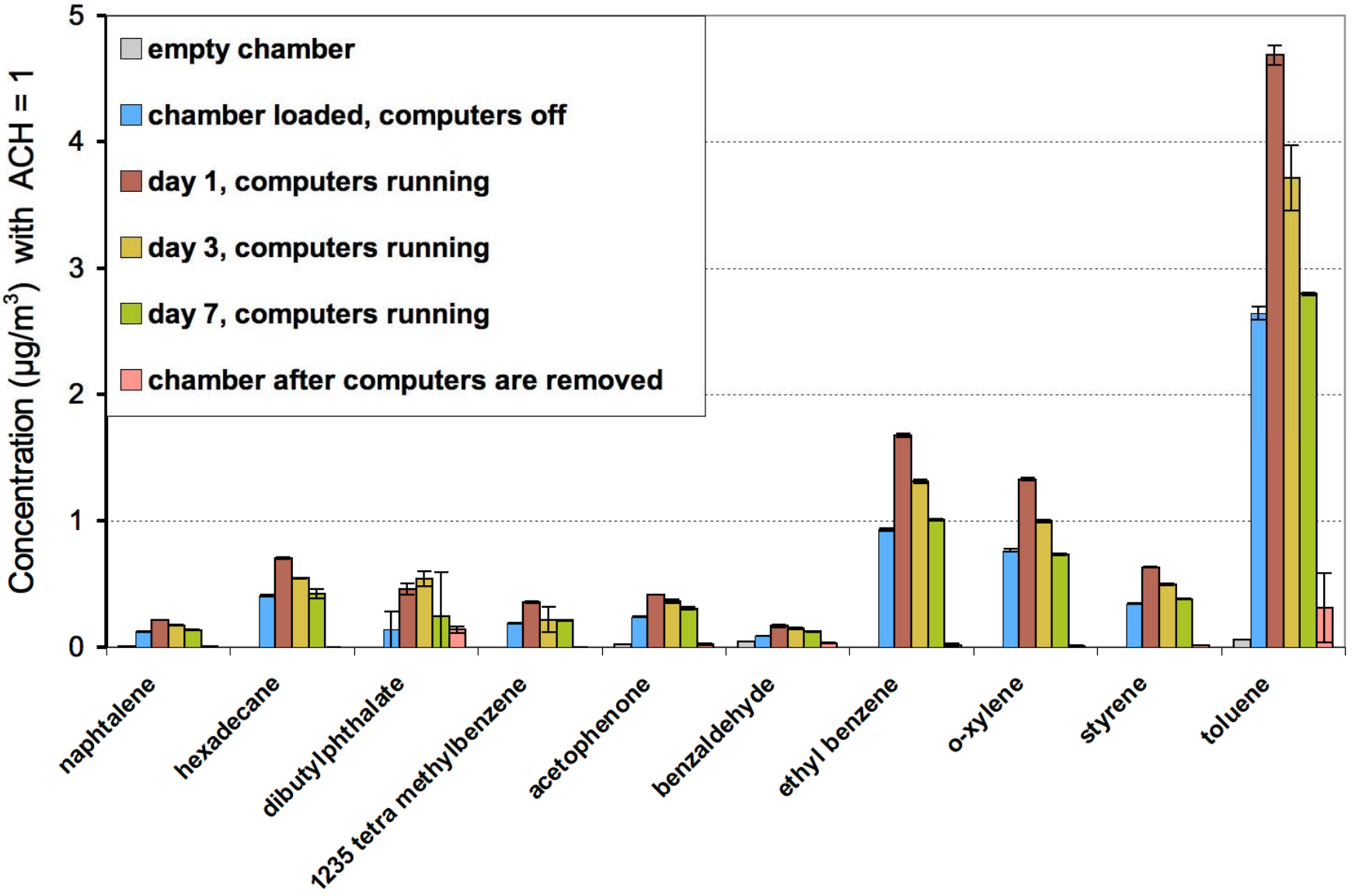
Phase I Results

- **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

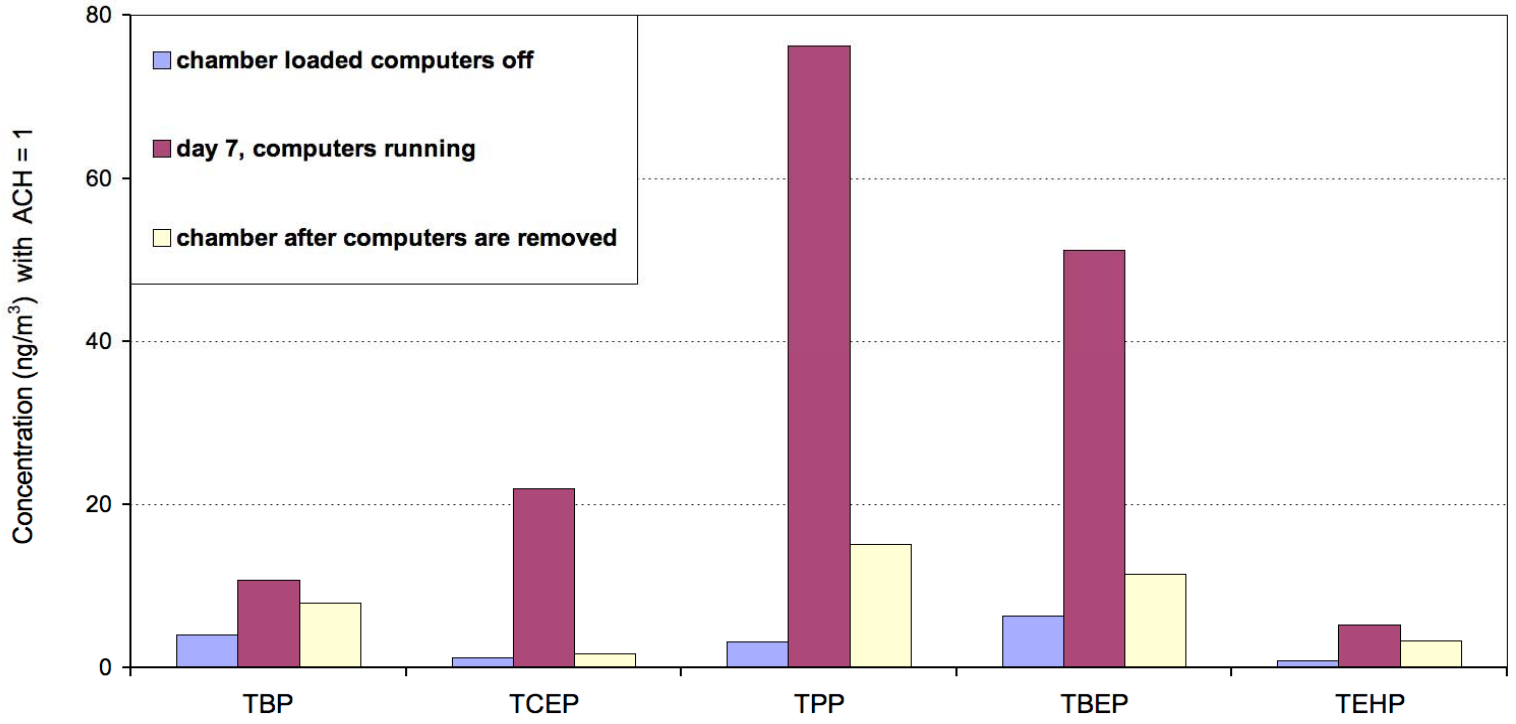
Phase I VOC Results



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

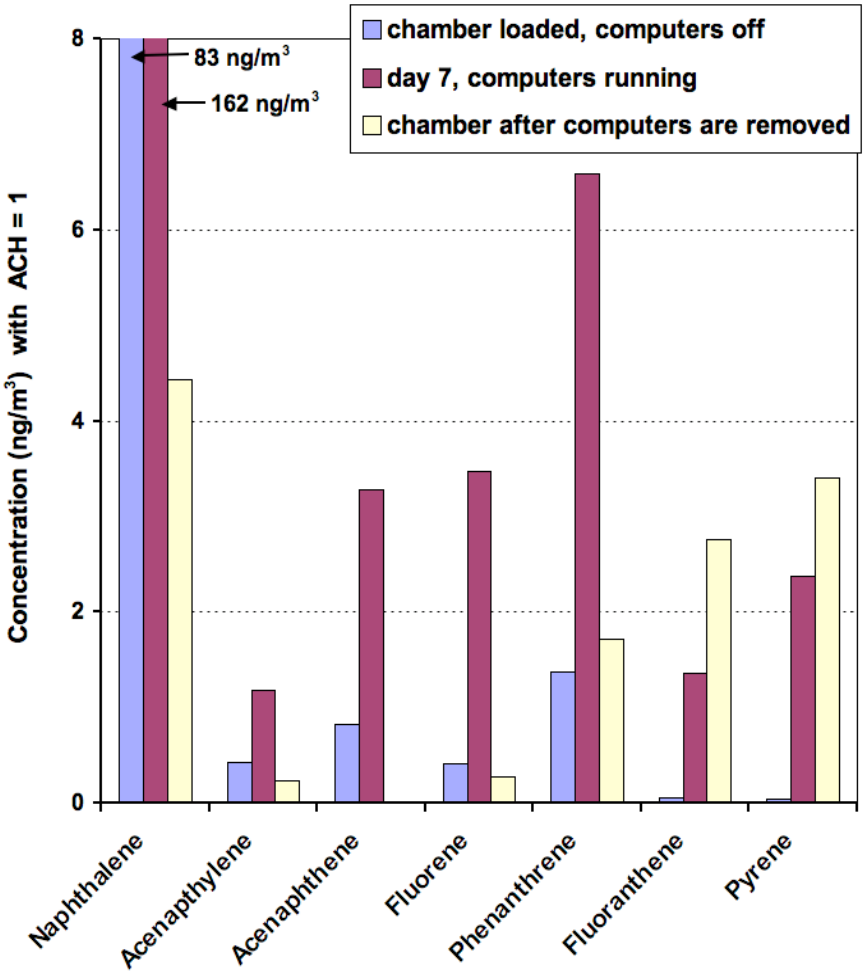
Desktop Organophosphates



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

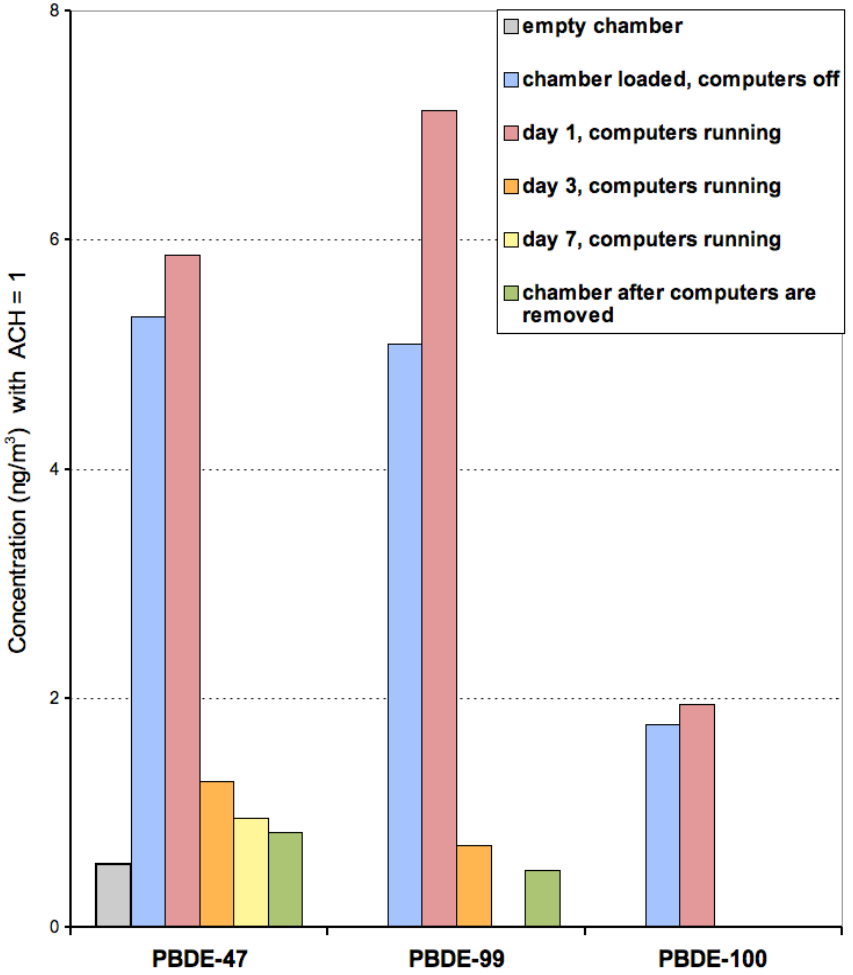
- 3 of the organophosphates were > 5 times background during active phase
- Earlier studies link (TPP) to computer monitors (Carlsson et al., 2000)
- TBEP and TCEP are used as flame retardants

Other Computer SVOCs



PAHs

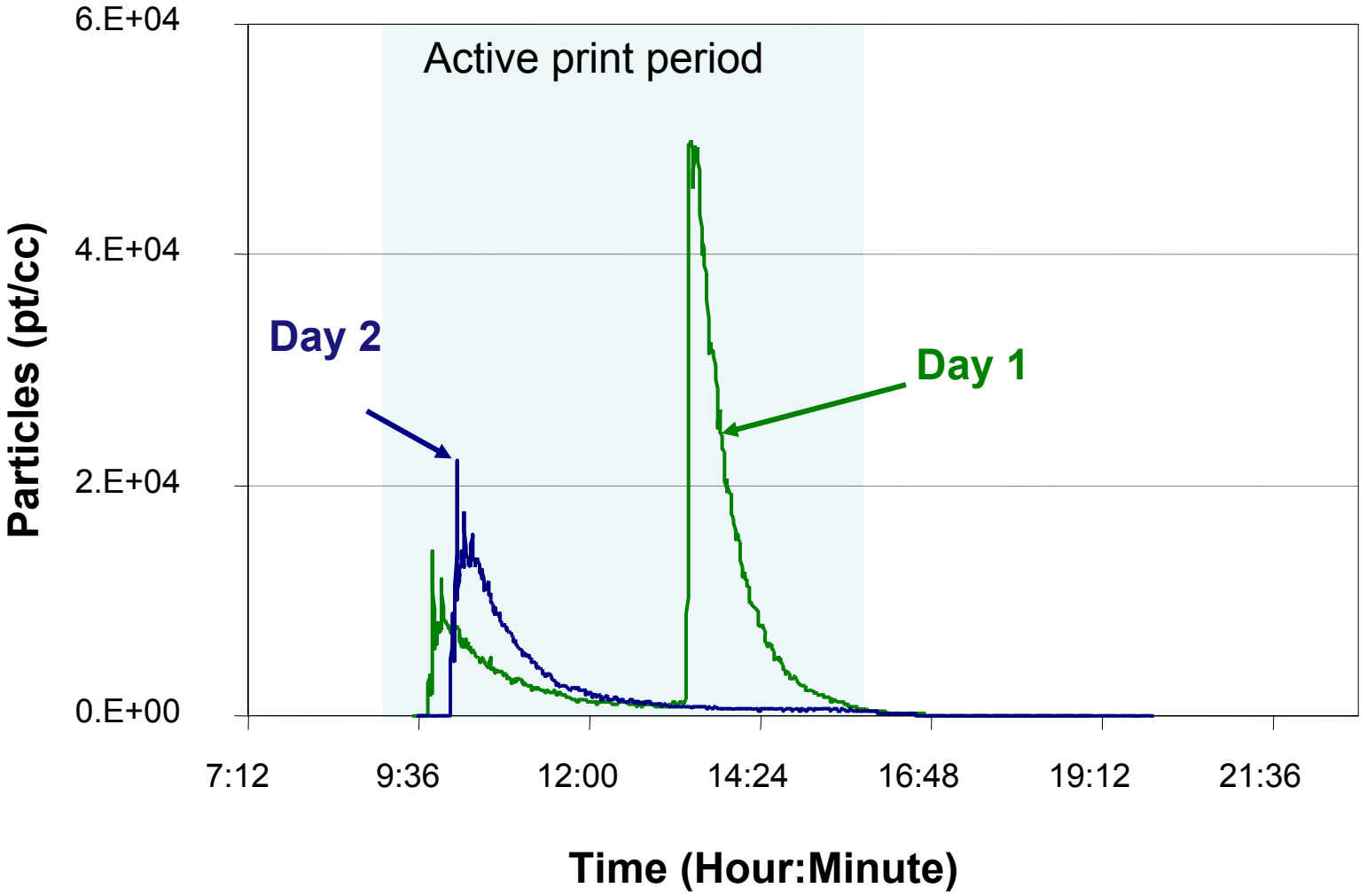
Brominated flame retardants

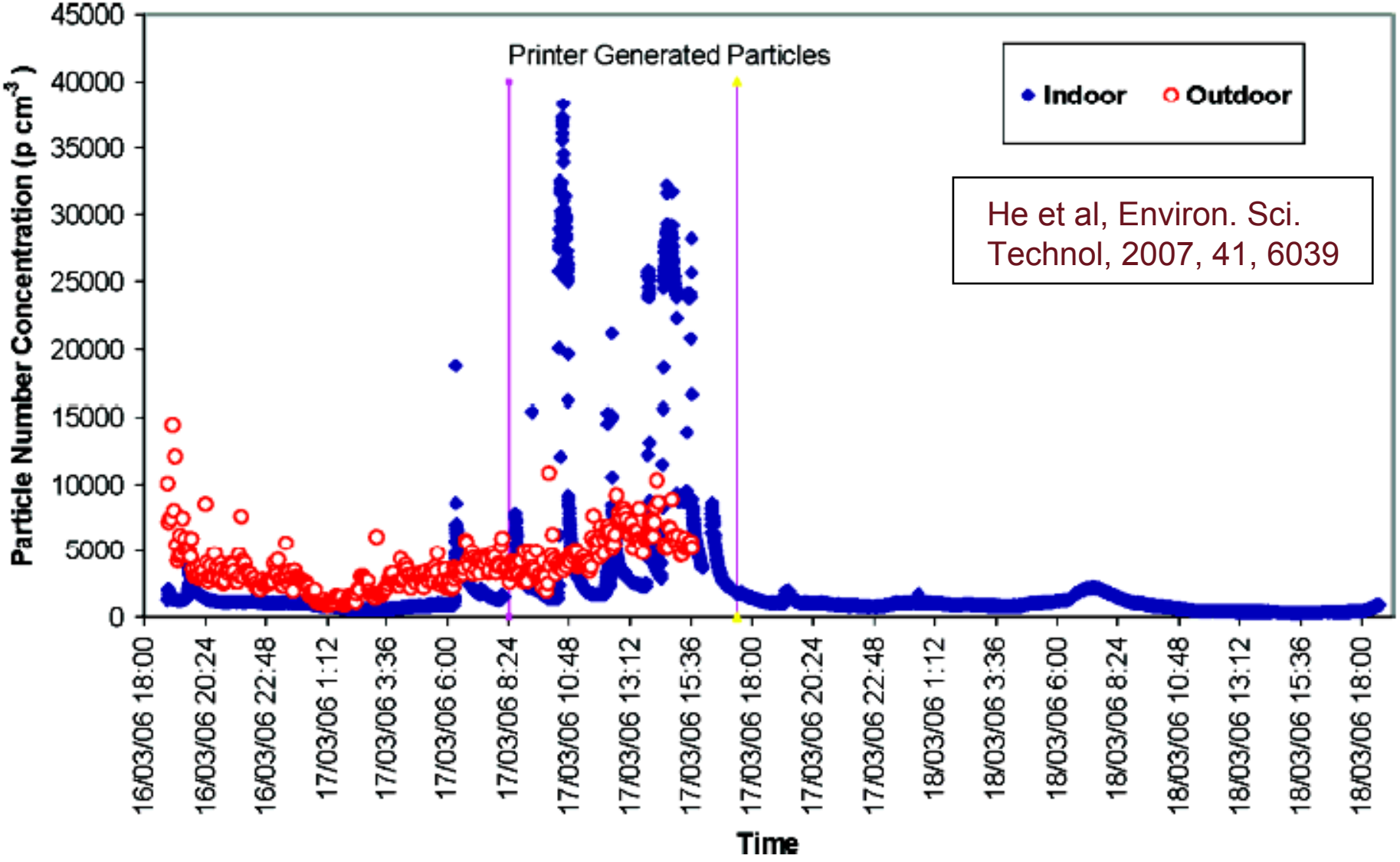


Phase I: Particles

- 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/m^3
- Black carbon (athelometer) levels very low
- Elemental carbon / total carbon ratios ~ 0.02

Heavy Duty Office Laser Printers





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

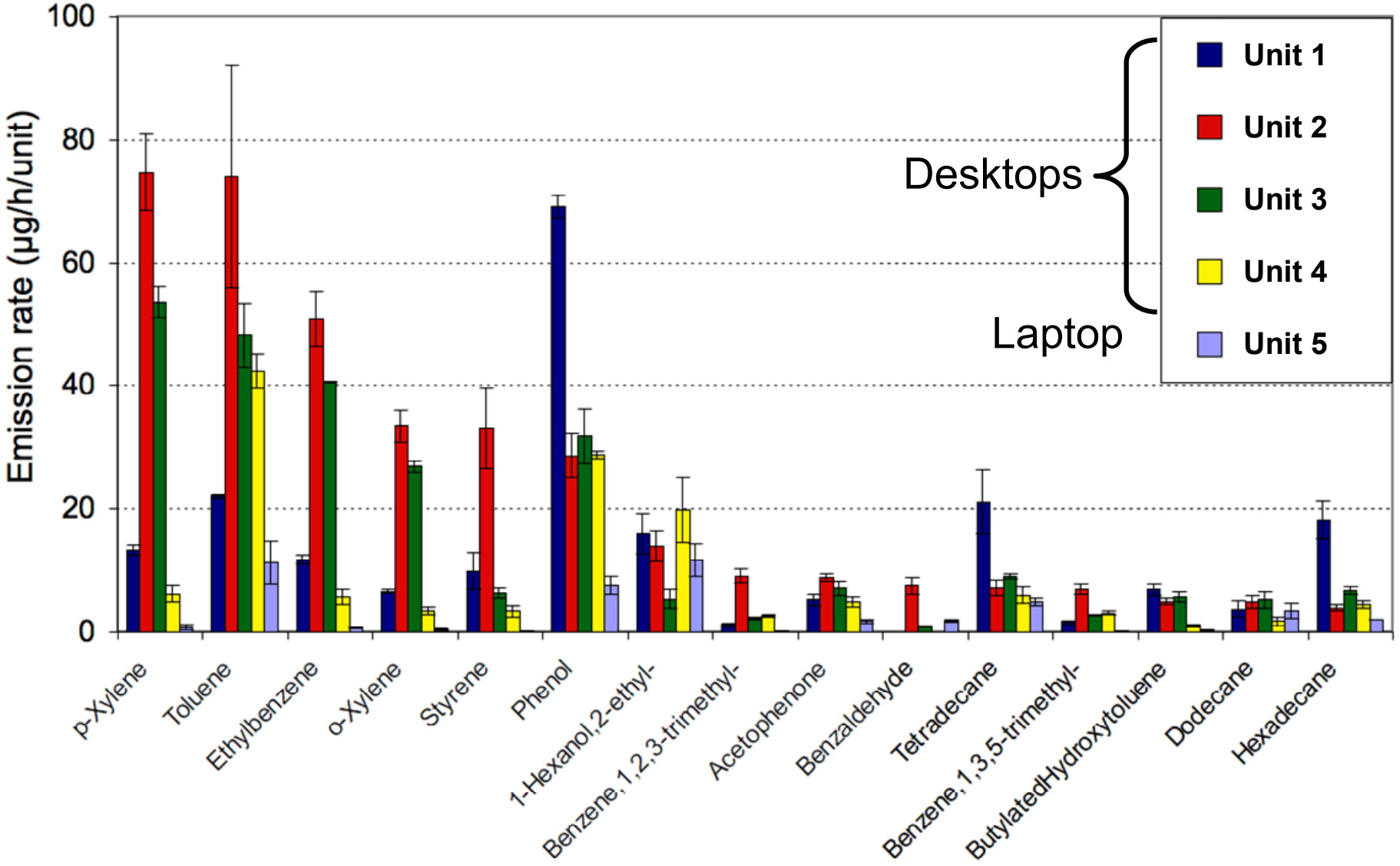
Computer Emissions

- 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

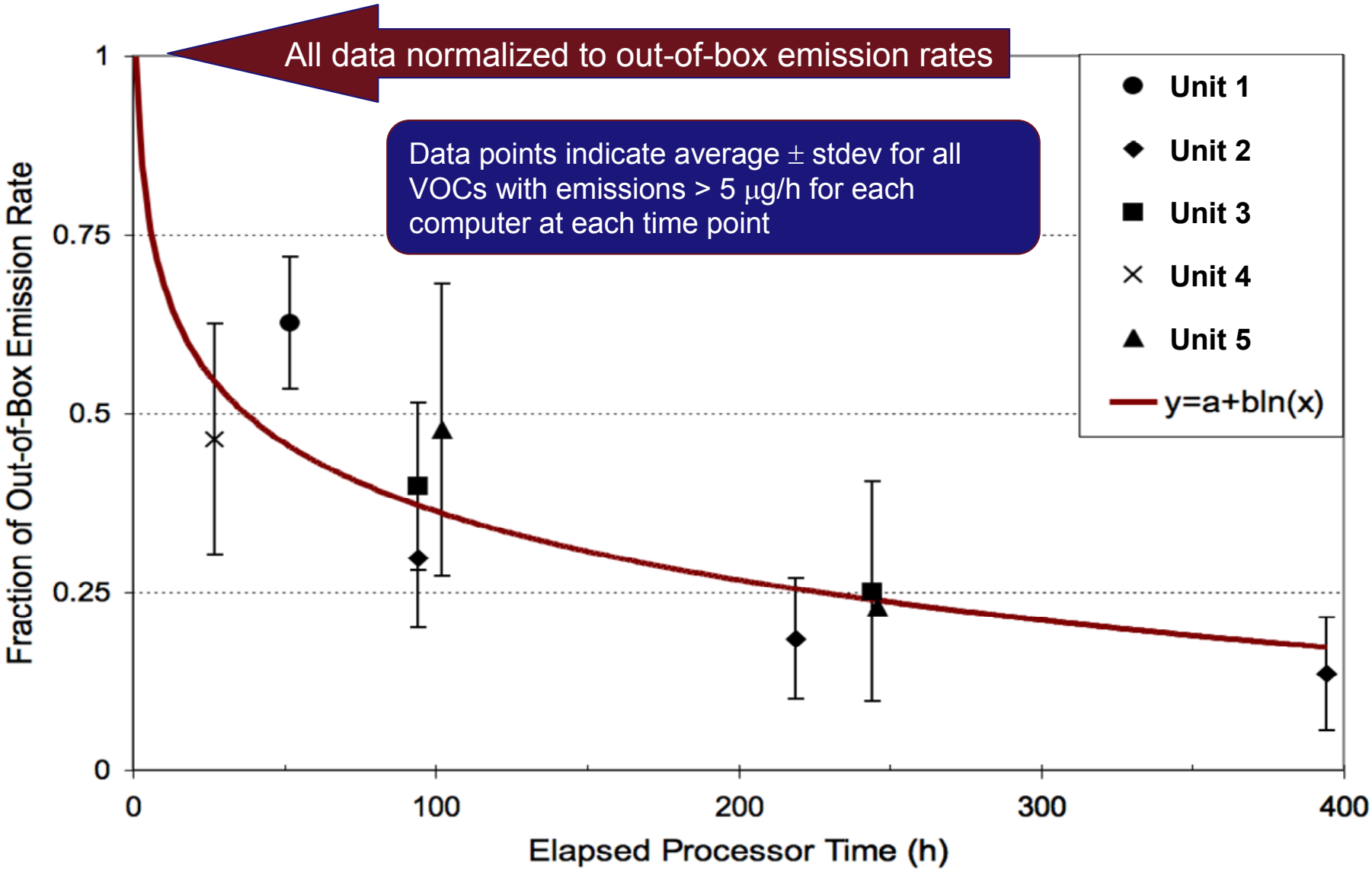
Computer Emissions (cont'd)

- 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

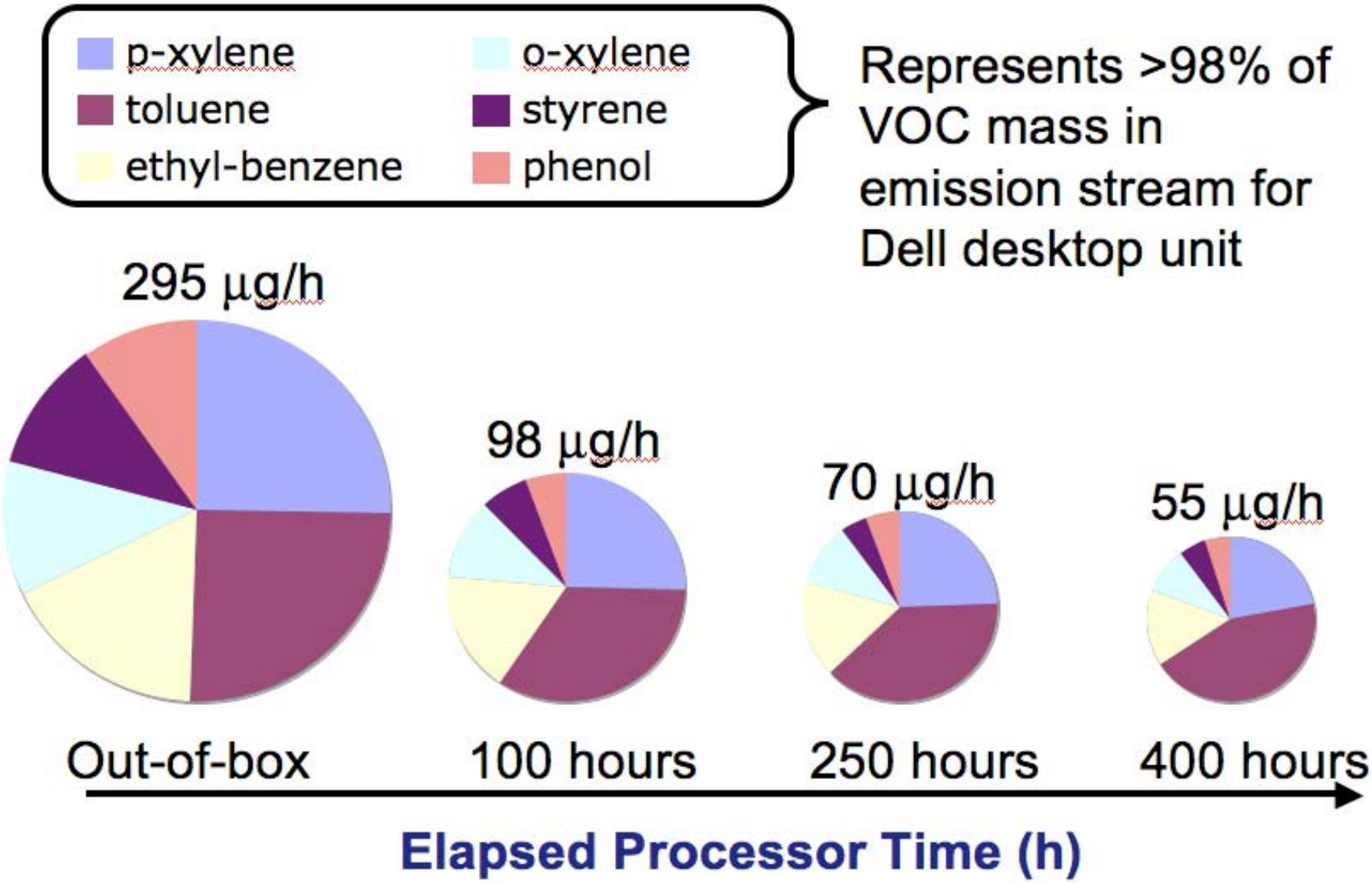
Out-of-Box “Active” VOC Emissions



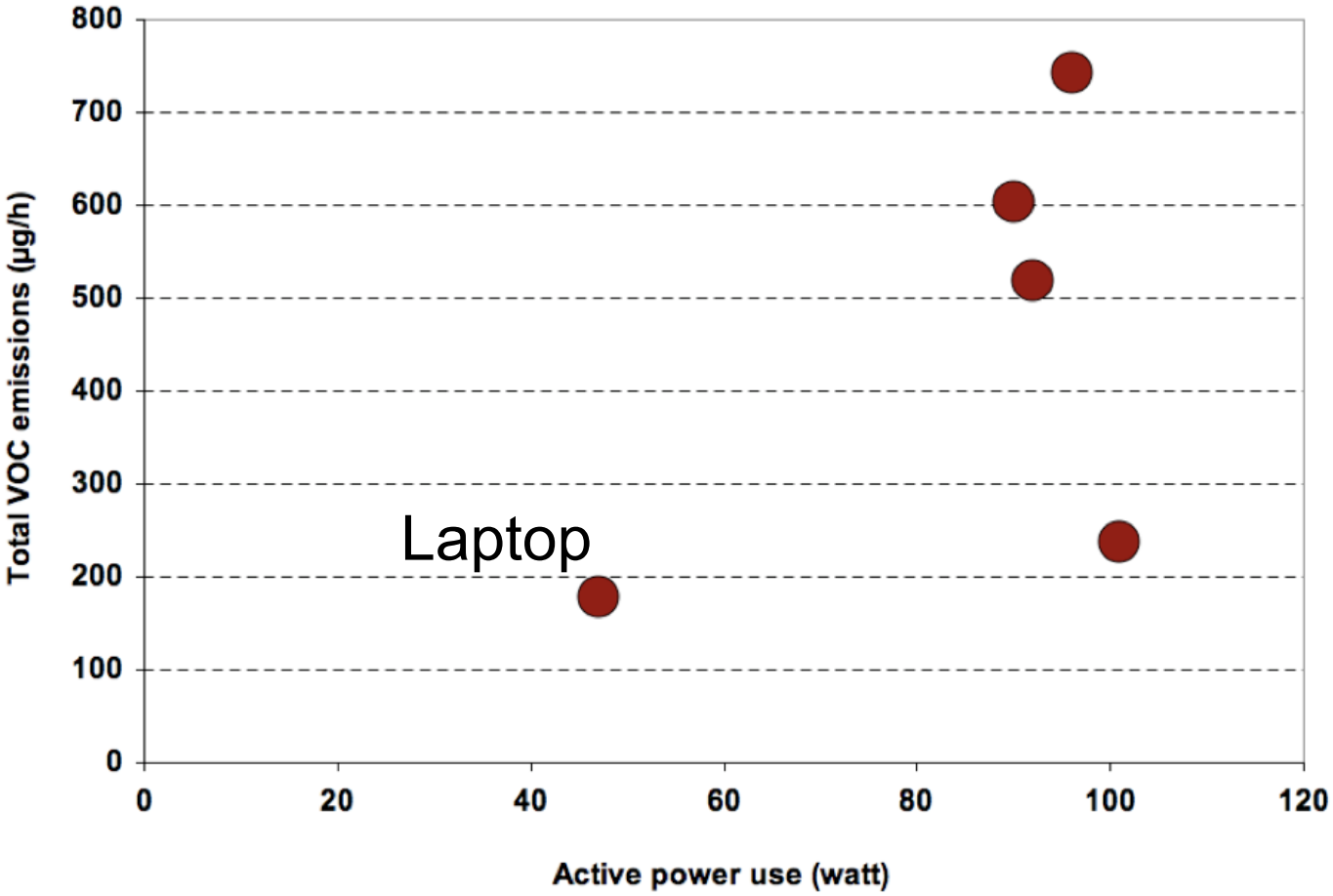
Decline of VOC Emissions after "Aging"



Changes in VOC Profile with "Aging"

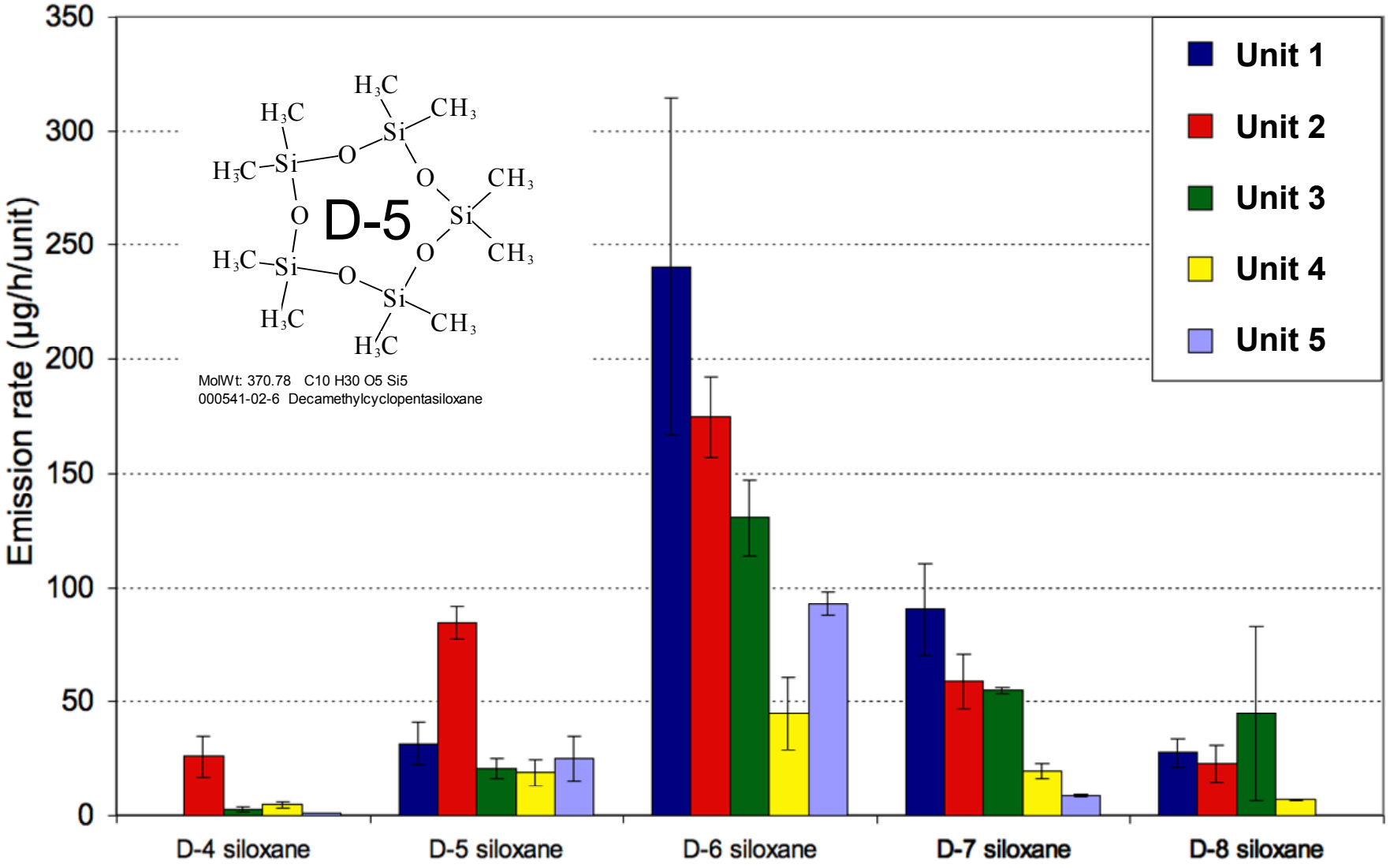


VOC Emissions and Power Use

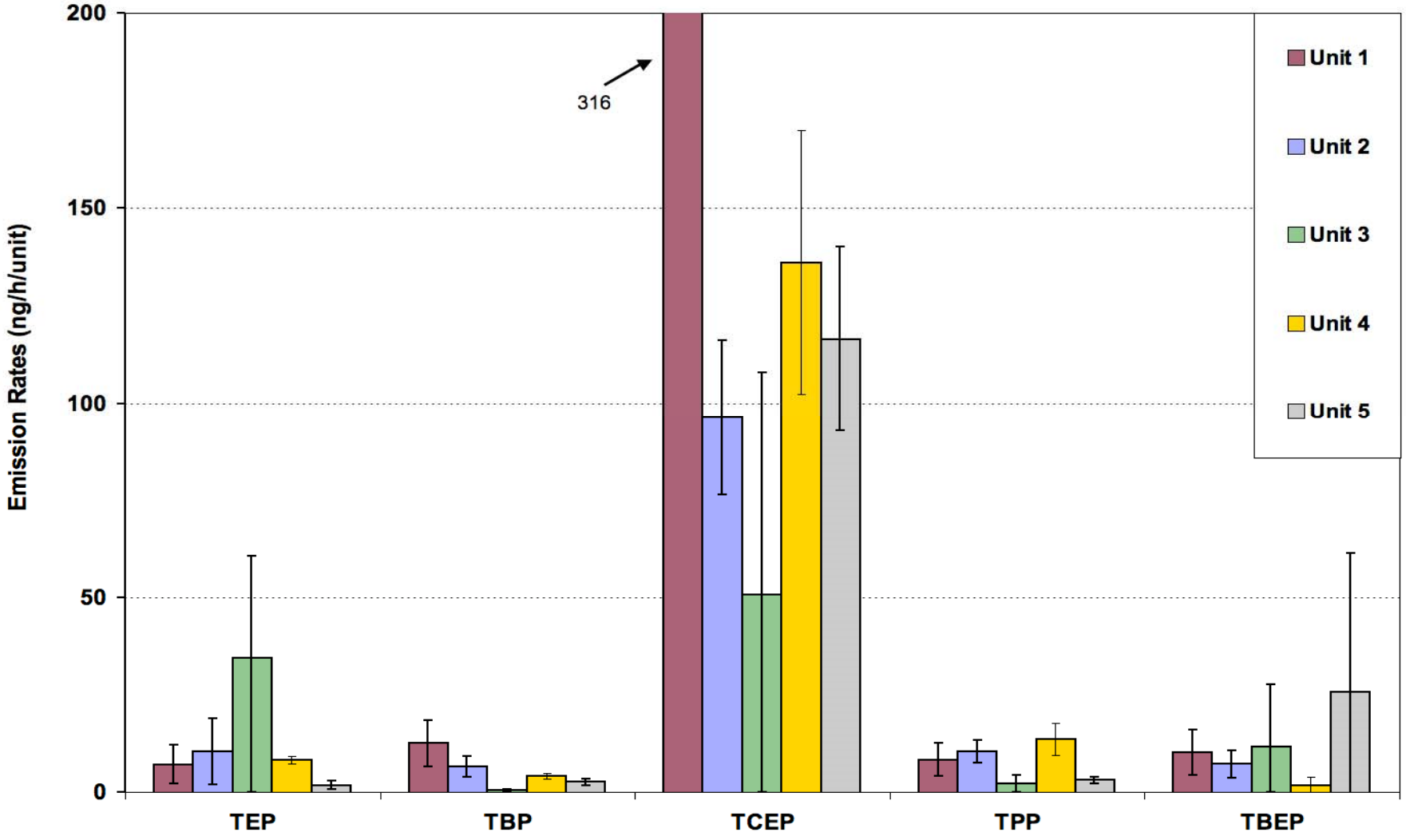


- Total measured VOC emission during active computer processing
- Increased power use also likely relates to an increase in air flow and heat generation

Out-of-Box “Active” Siloxane Emissions



Organophosphate Emissions from Individual Computers



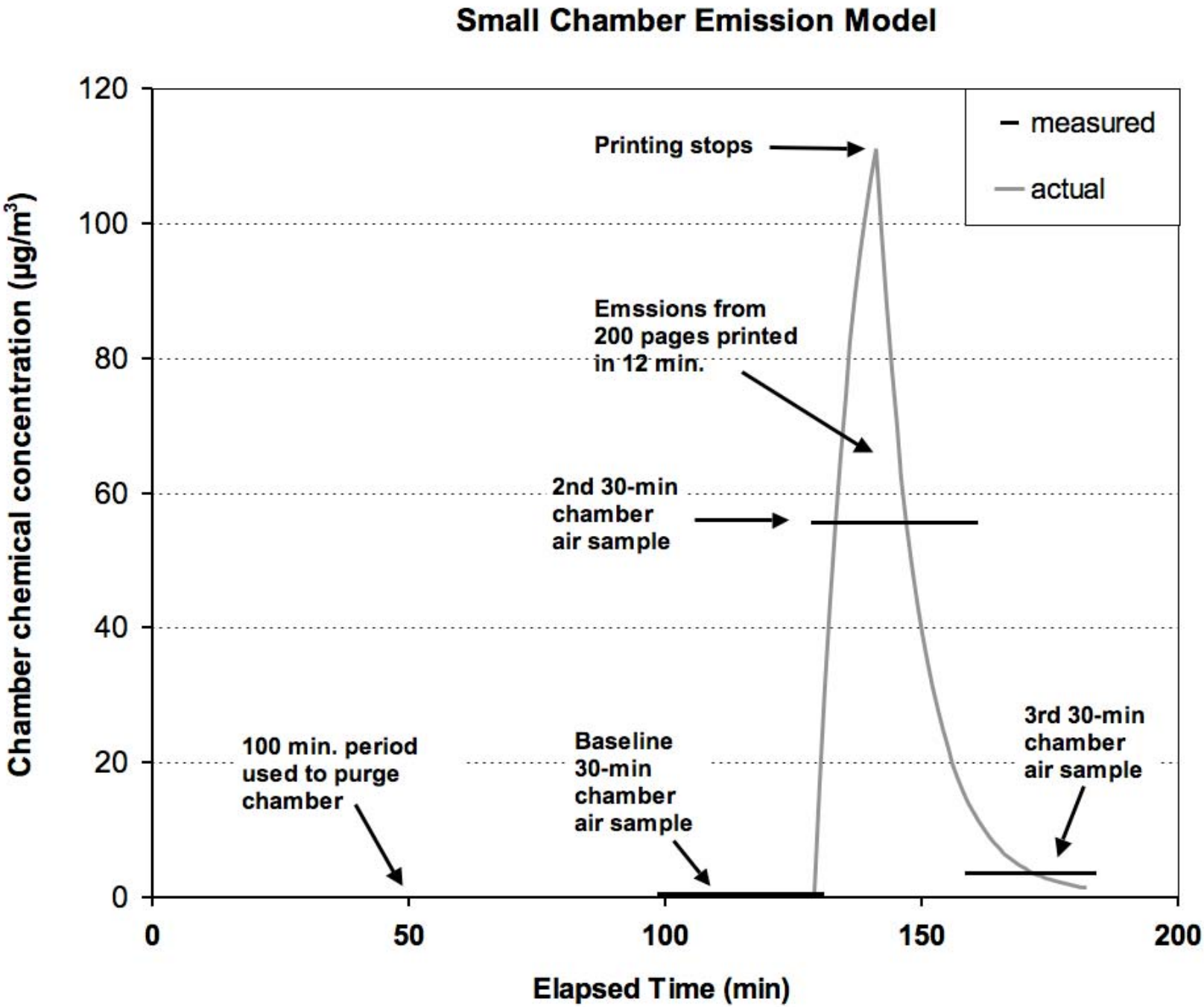
TEP = Triethly phosphate, TBP =Tributyl phosphate, TCEP = Tris(2-chloroethyl) phosphate,
TPP = Triphenyl phosphate, TBEP = Tris(2-butoxyethyl) phosphate

Phase II Results

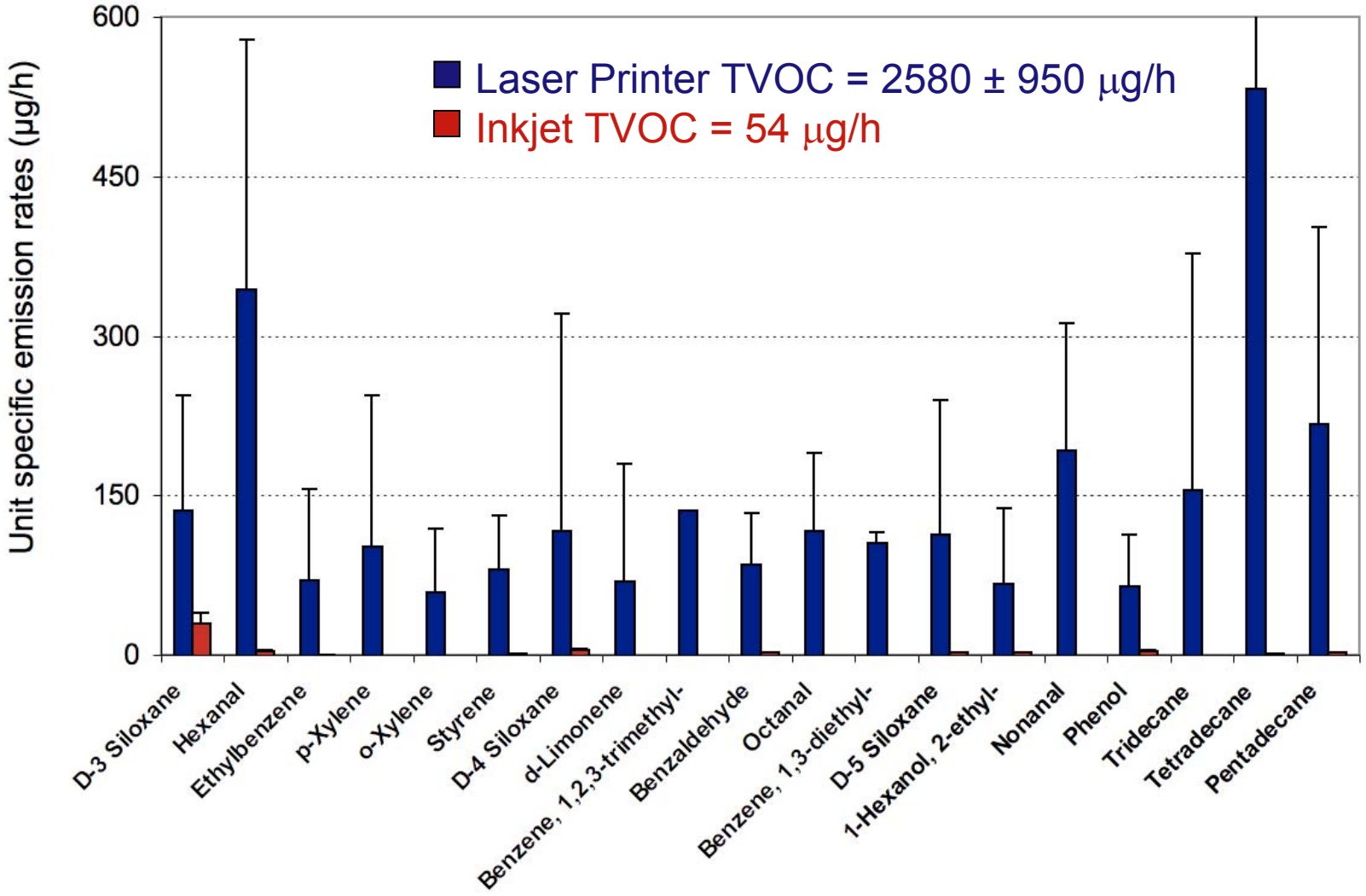
Printers

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

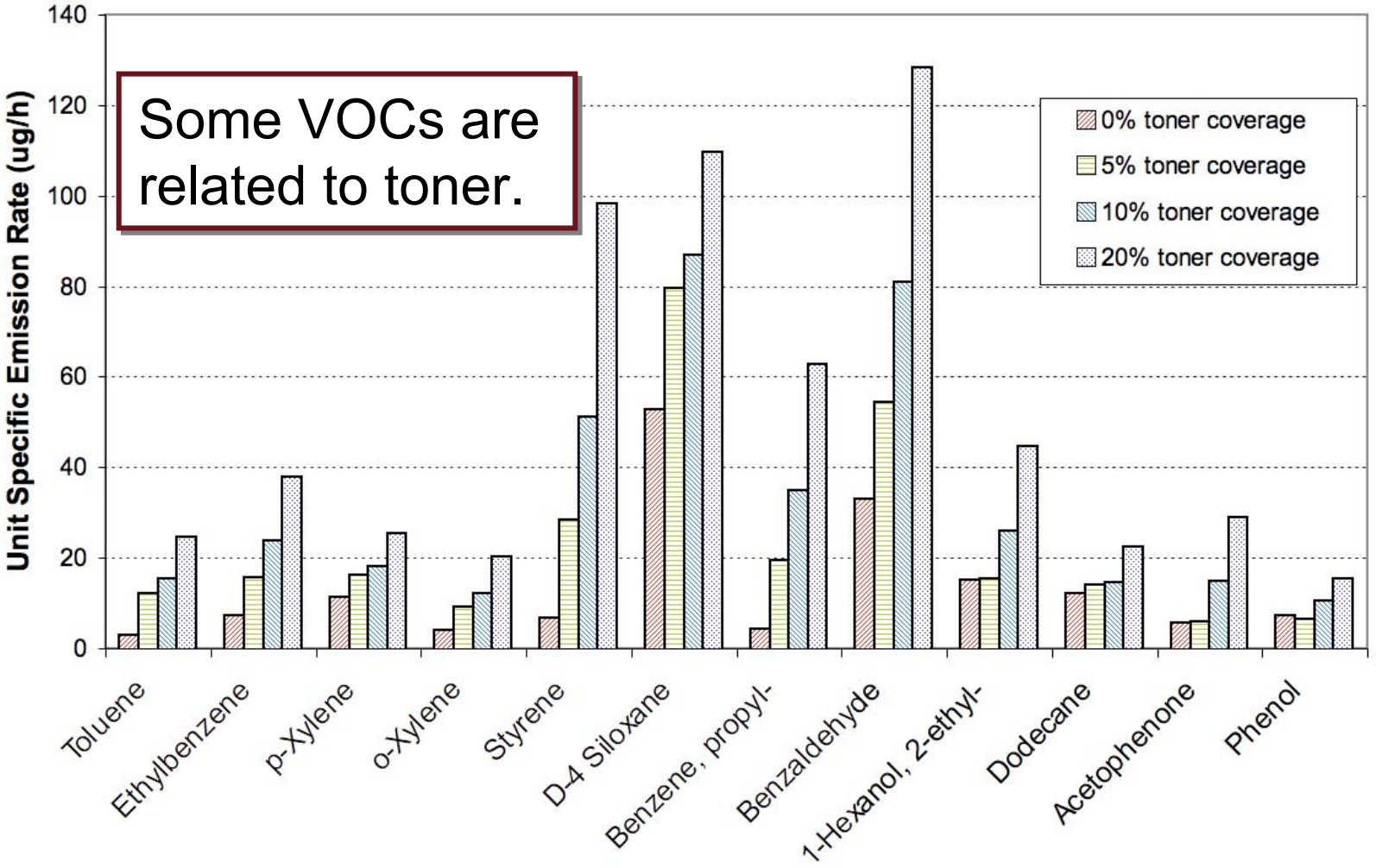

Small Chamber Emission Model
Chamber chemical concentration (µg/m3)
120
100
80
60
40
20
0
0
50
100
150
200
Elapsed Time (min)
measured
actual
Printing stops
Emssions from
200 pages printed
in 12 min.
2nd 30-min
chamber
air sample
100 min. period
used to purge
chamber
Baseline
30-min
chamber
air sample
3rd 30-min
chamber
air sample

VOC emissions during active printing

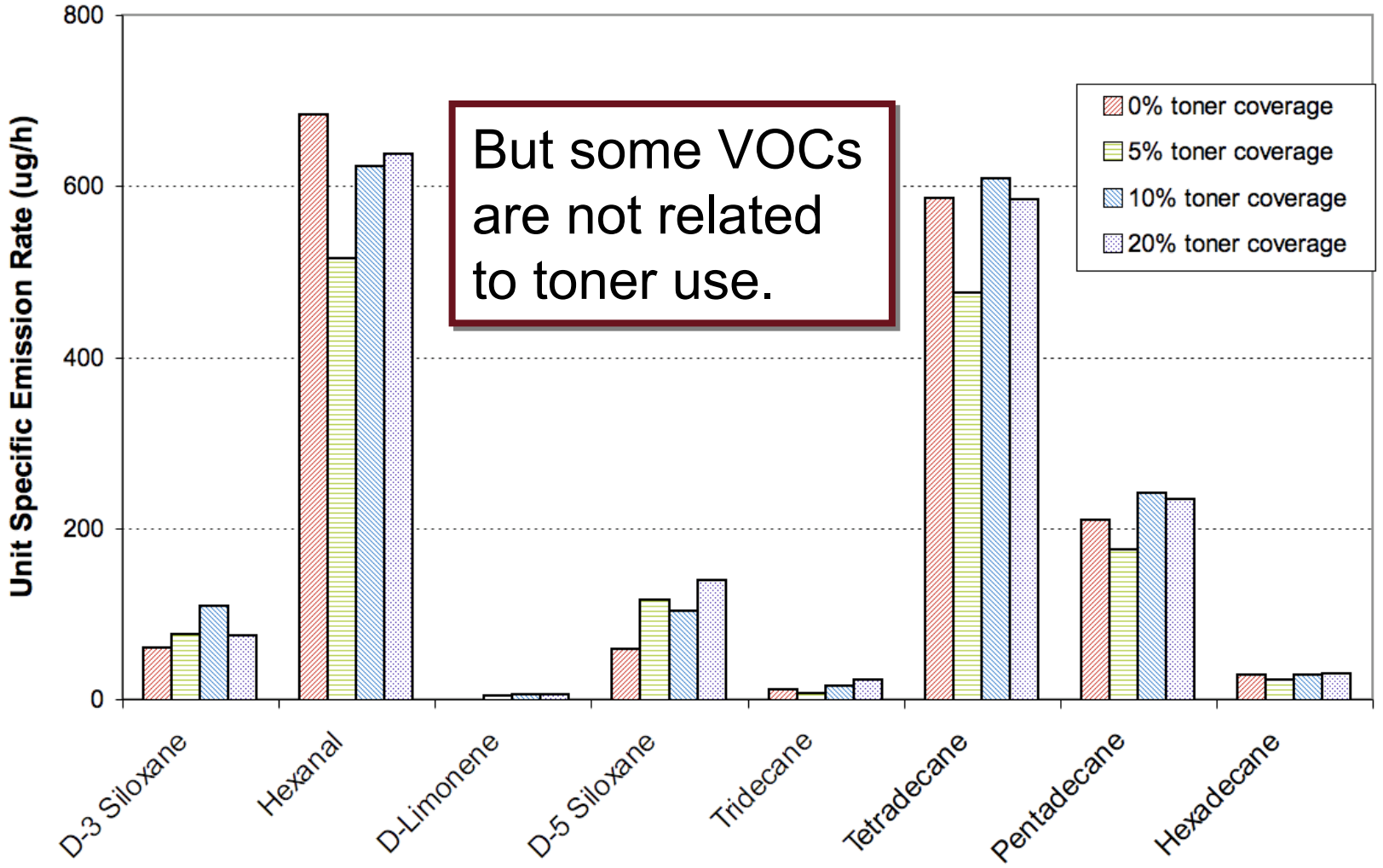


> 95% of TVOC in emissions

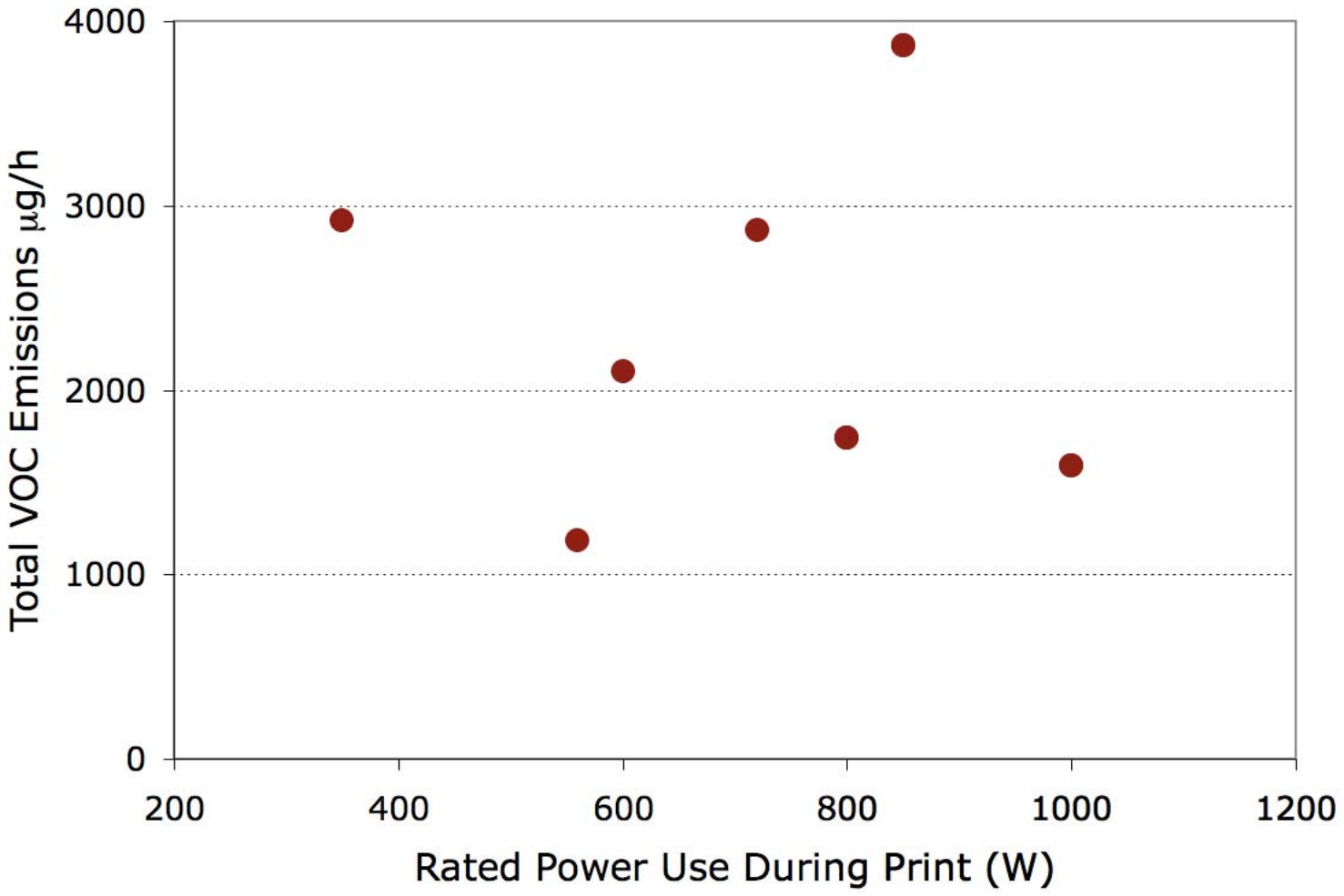
VOC emissions versus toner coverage



VOC emissions versus toner coverage (cont.)



No Correlation of Printer VOC Emissions with Power Use



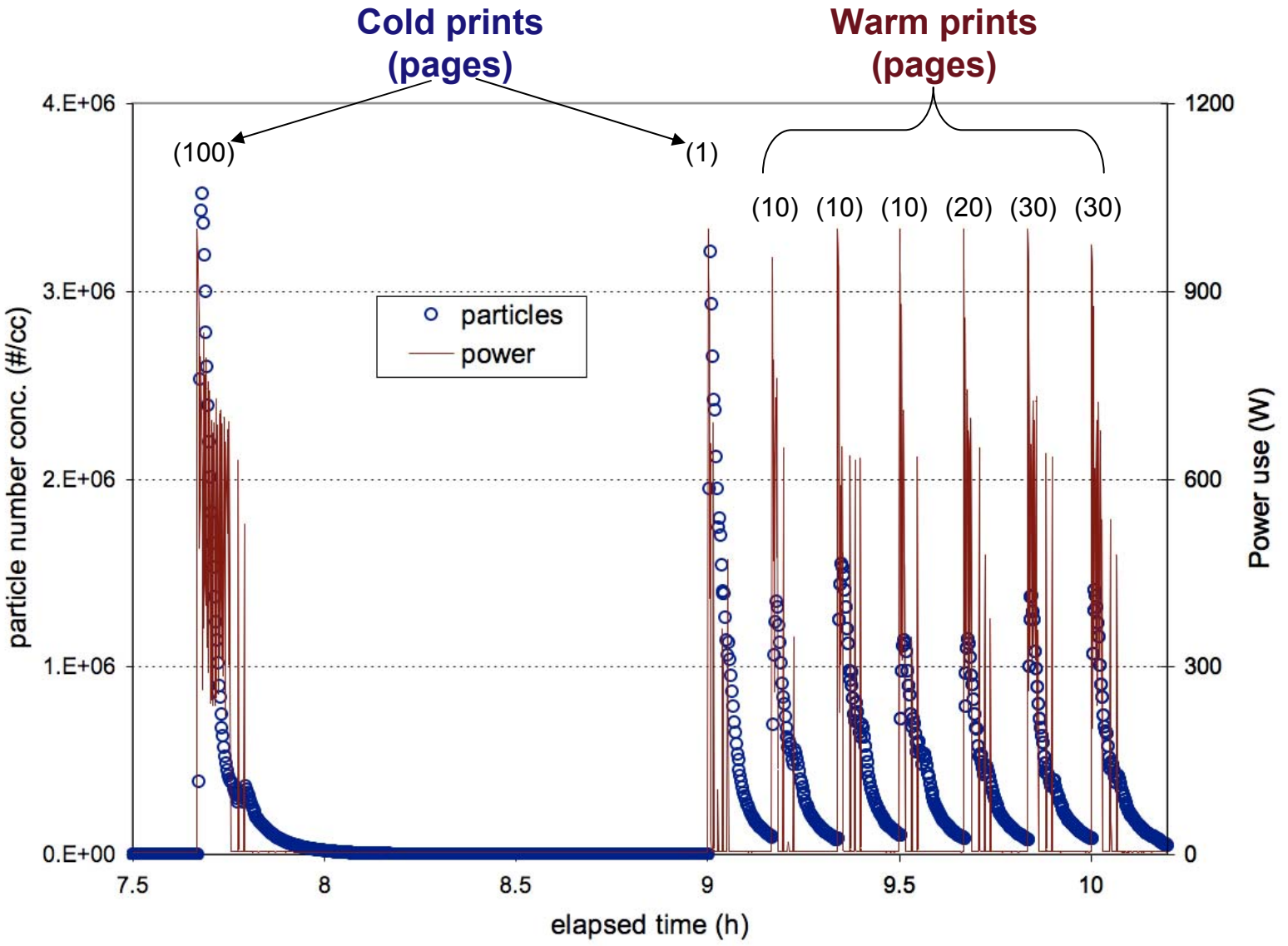
Ozone emissions during printing

Printer	Emission Rate (μg/hr)
Laser Printer 1	Trace
Laser Printer 2	583 ± 111
Laser Printer 3	Trace
Laser Printer 4	Trace
Laser Printer 5	1750 ± 92
Laser Printer 6	Trace
Laser Printer 7	Non-Detect

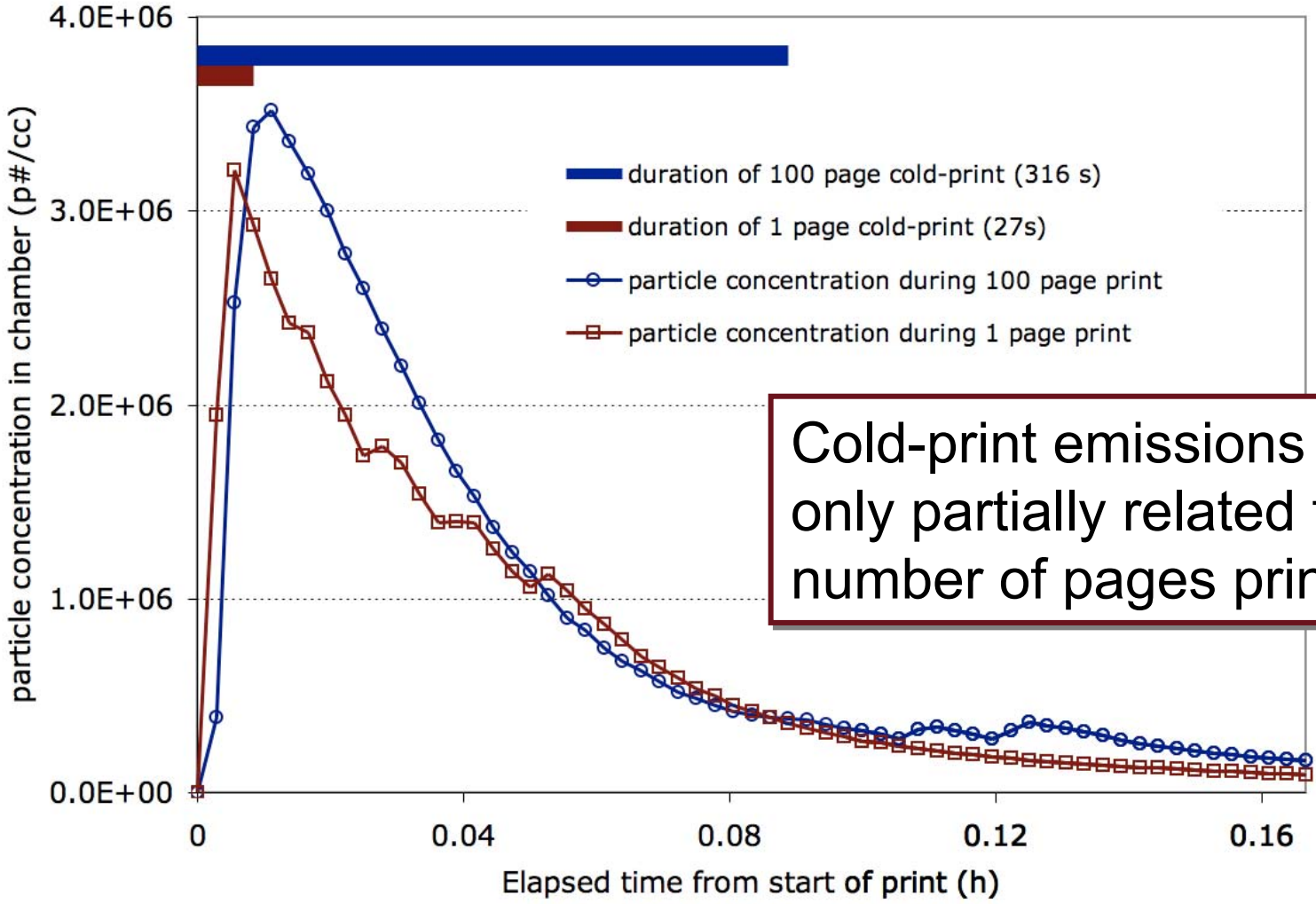
Laser Printers

Ultrafine Particle (UFP) Emissions

Particle emissions profile

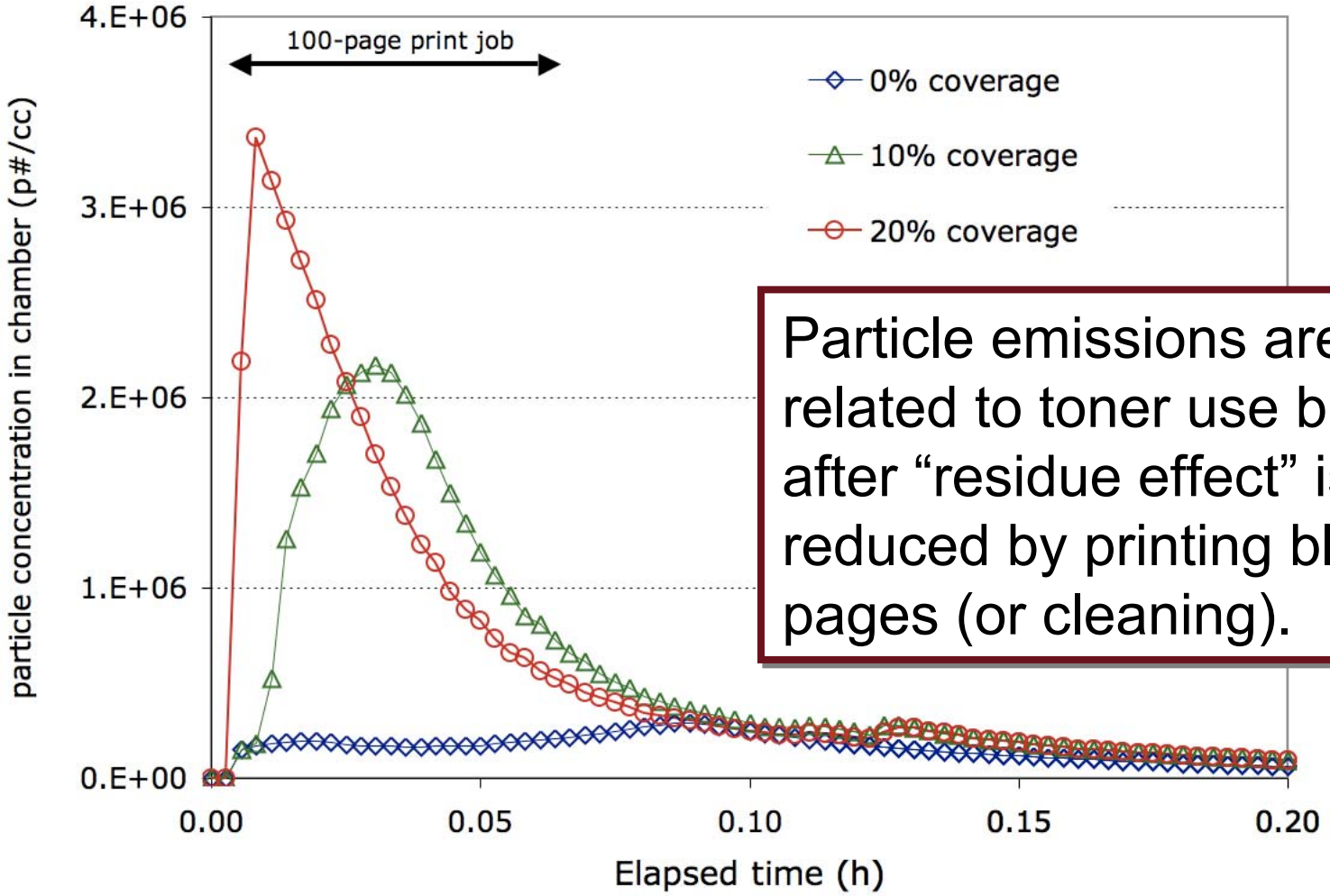


Cold print particle emissions versus page count



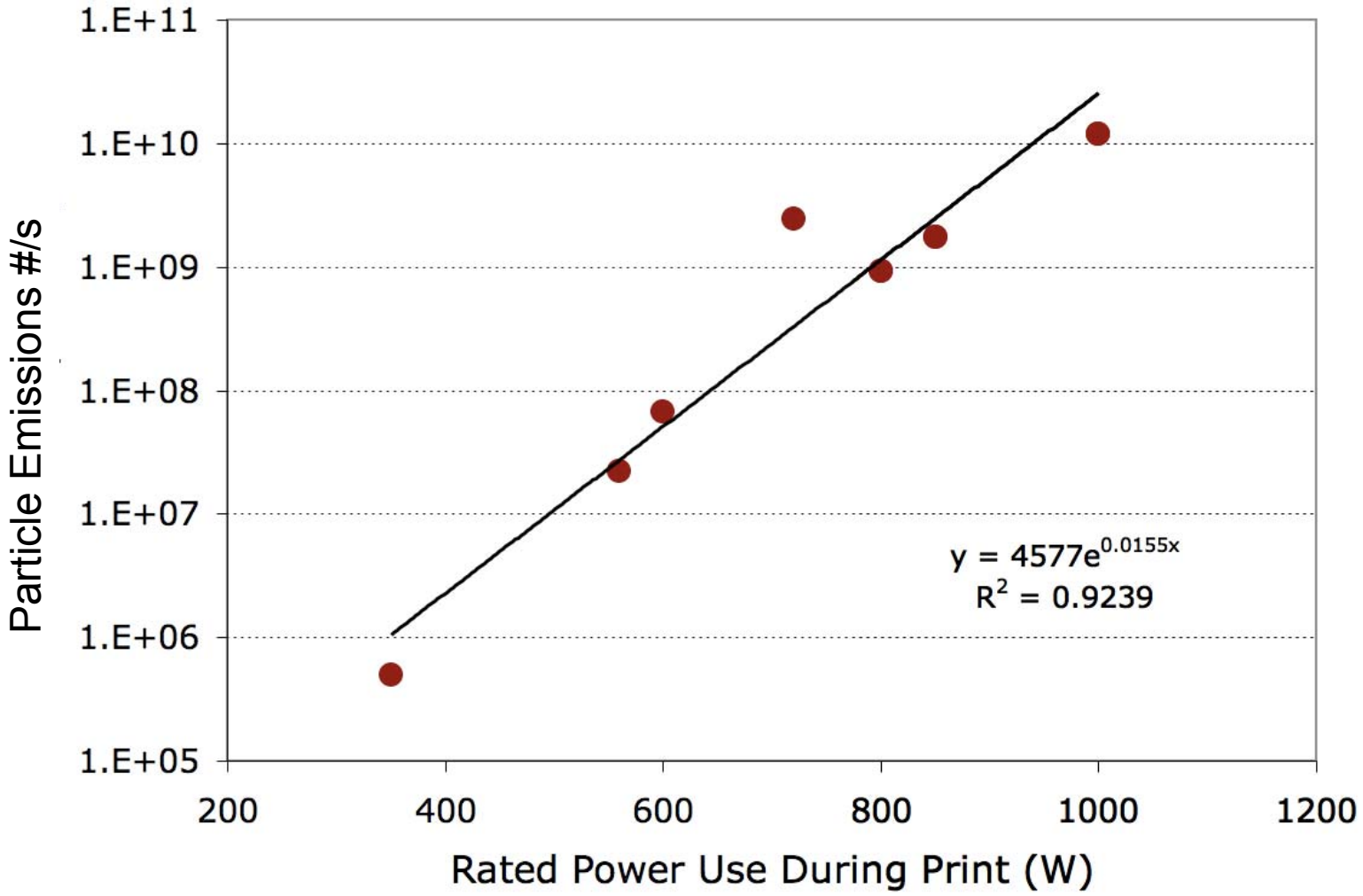
Cold-print emissions are only partially related to number of pages printed.

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



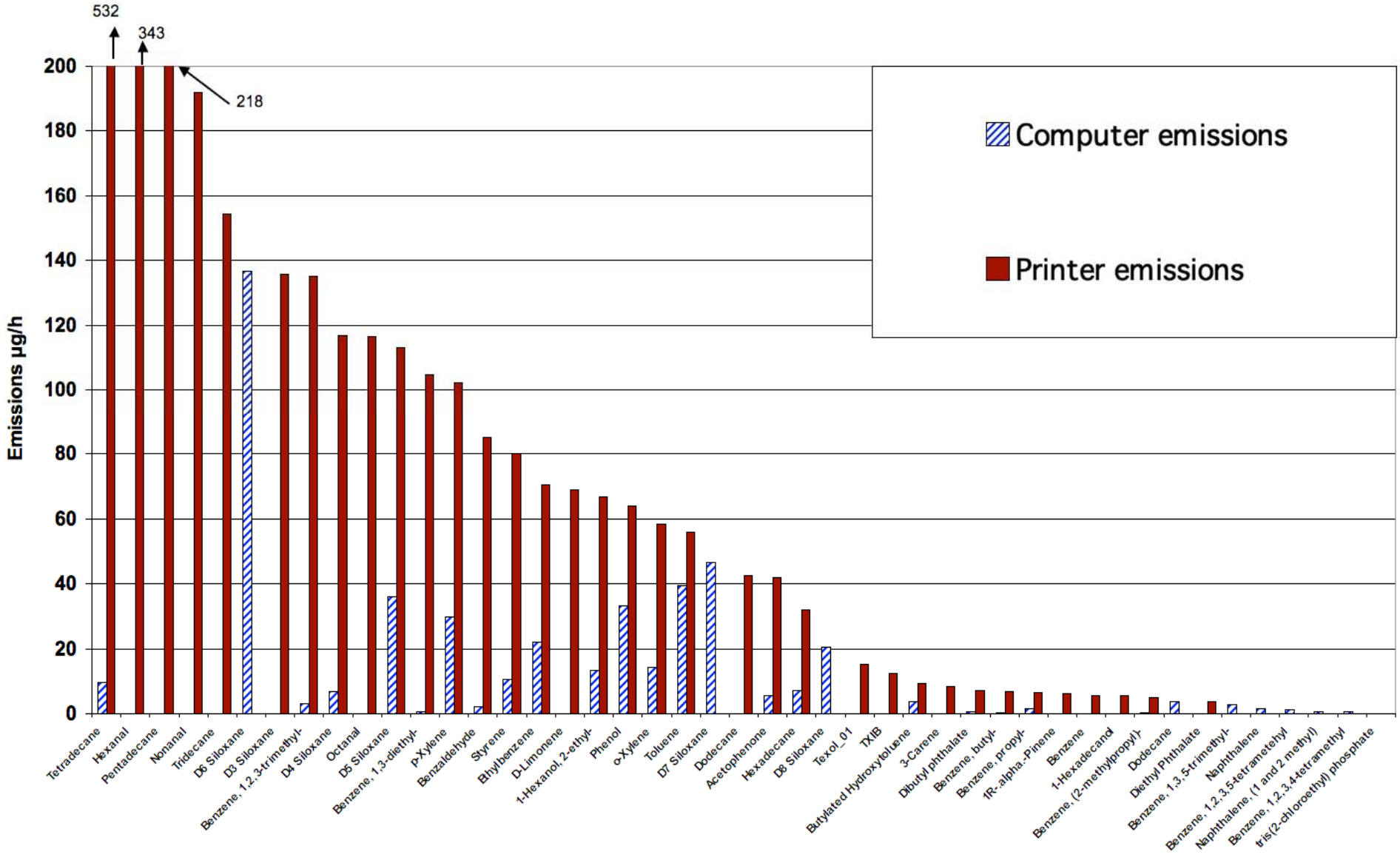
Findings

- Emissions summary
- Exposure potential
- Health impacts
- Sources of UFP
- Mitigation actions

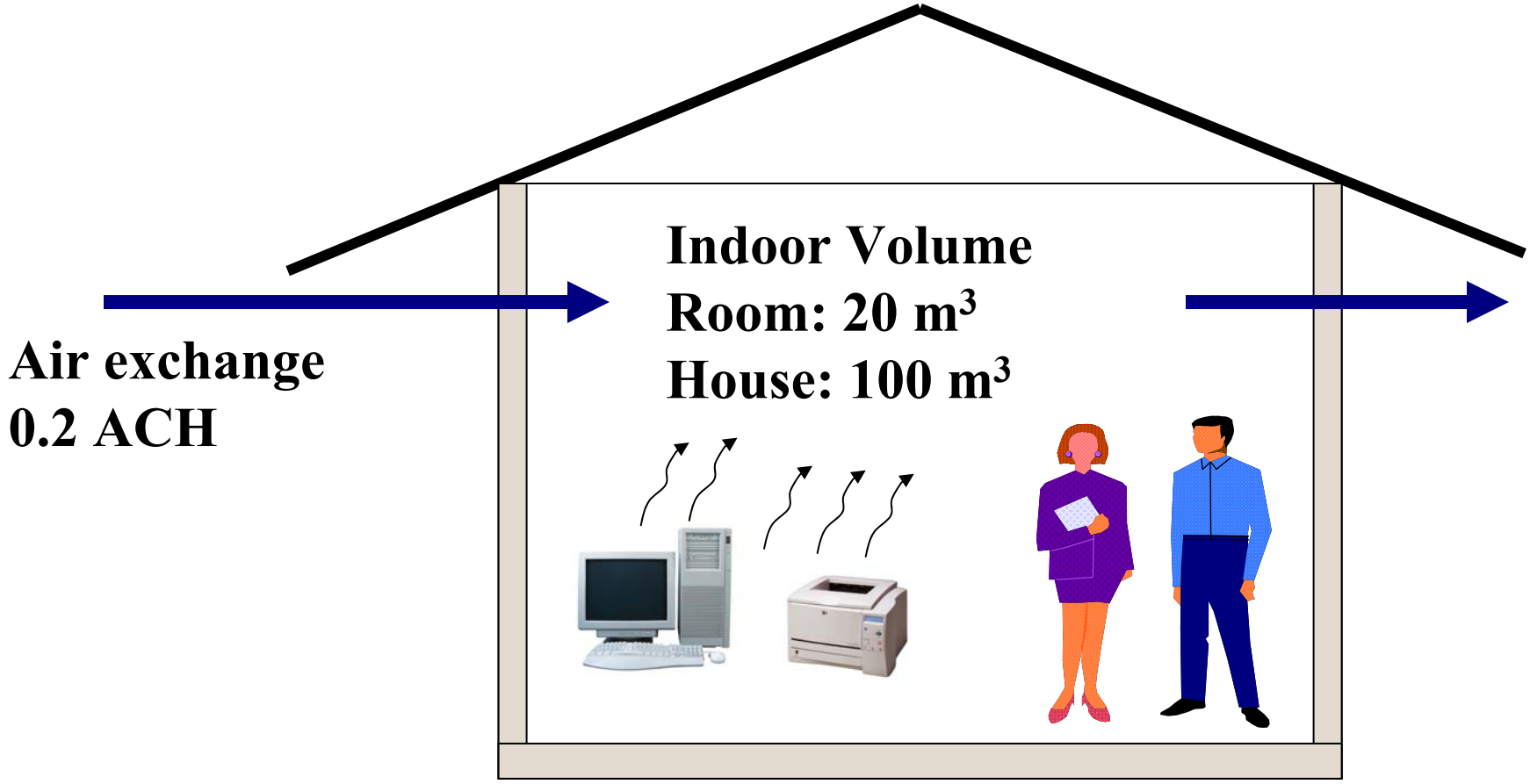
Emissions Summary

- 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

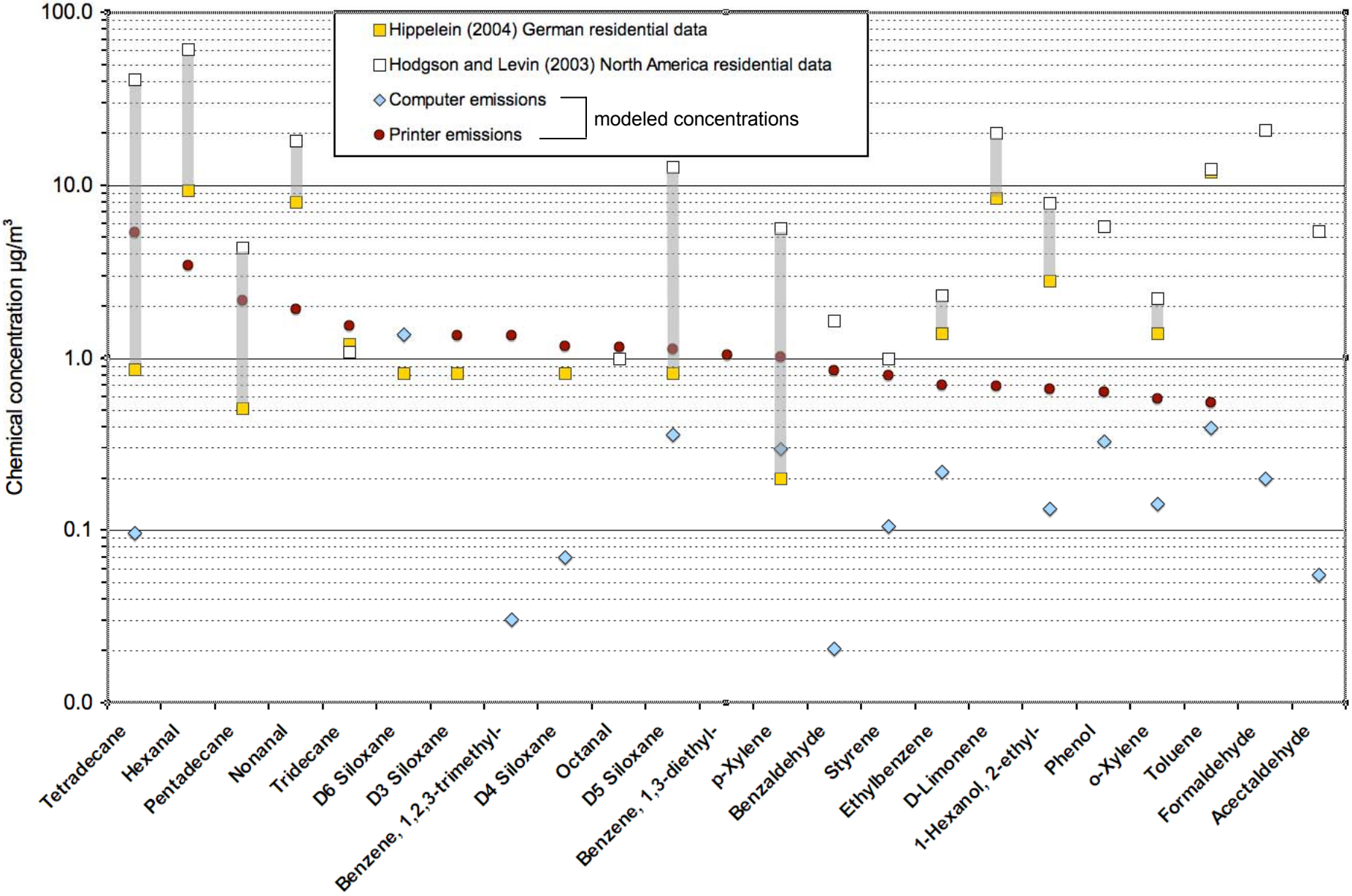
Computer Out-of-Box Versus Printer VOC and SVOC Emissions



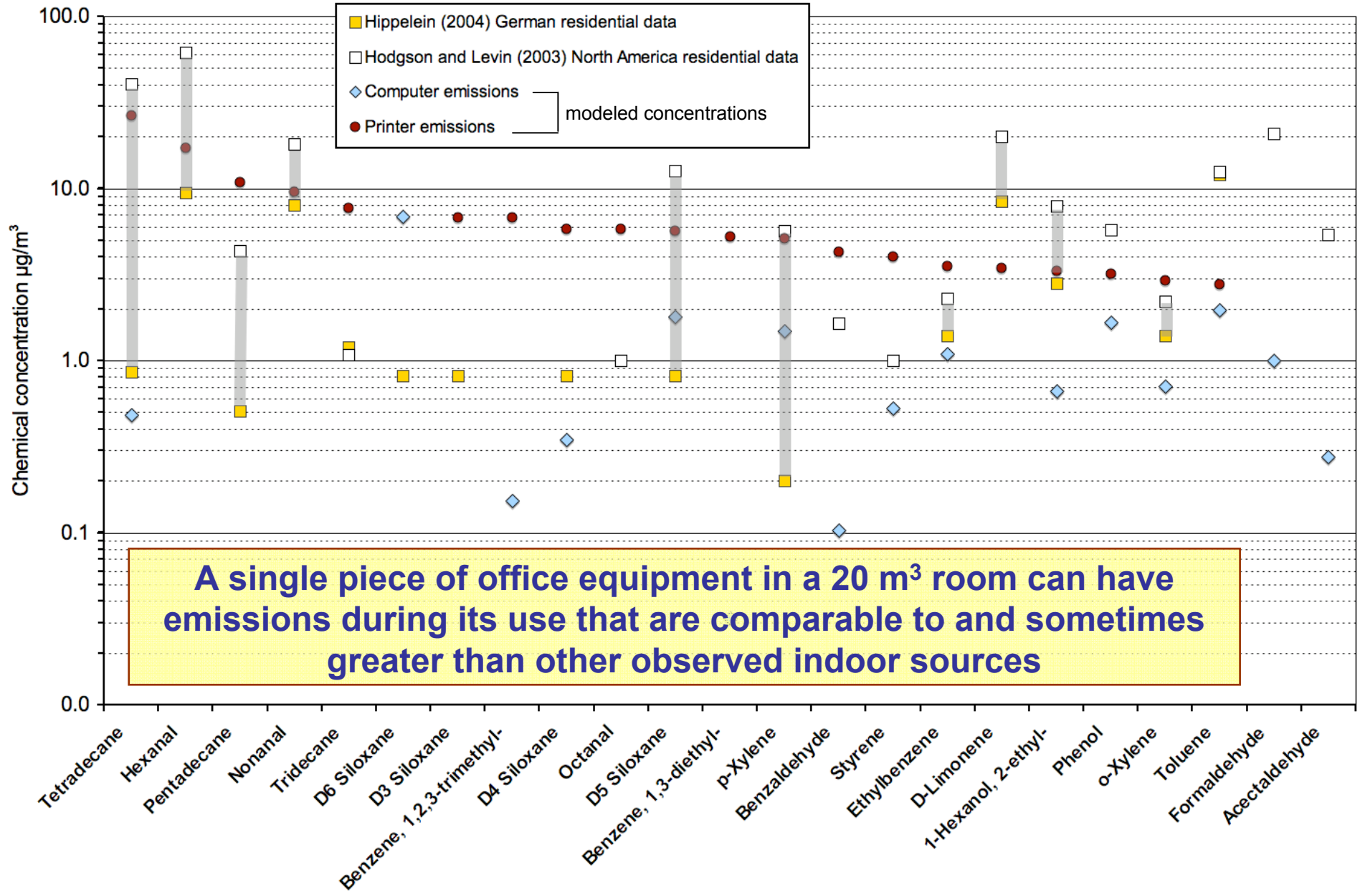
Contributions of Office Equipment to Indoor Exposure



Modeled versus measured concentrations for a house volume of 100 m^3



Modeled versus measured concentrations for a room volume of 20 m^3



A single piece of office equipment in a 20 m^3 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
- **hexanal**
- nonanal
- octanal
- p-xylene
- benzaldehyde
- ethylbenzene
- o-xylene
- acetophenone
- tetradecane
- pentadecane
- tridecane
- hexamethyl-cyclotrisiloxane (D3)
- decamethyl-cyclopentasiloxane (D5)
- styrene
- 2-ethyl-1-hexanol
- dodecane
- 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-m^3 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