Toward Understanding Ultrafine Particle Exposures in Indoor Environments

http://www.crln.org/files/images/candle_flame_0.jpg

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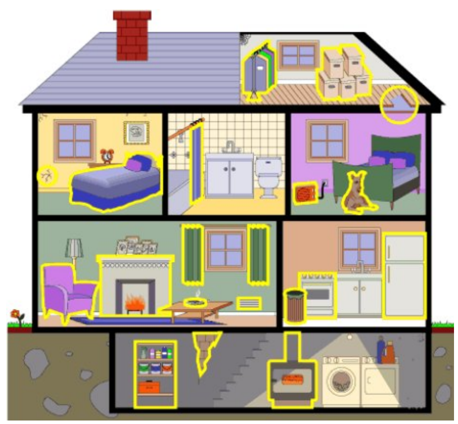
http://static.howstuffworks.com/gif/gas-vs-electric-cooking-1.jpg

http://yourtreasuredlegacy.com/images/elementary-classroom-2.jpg



http://www.coelhoconstruction.com/air_quality.htm

http://blog.aarp.org/shaarpsession/traffic.jpg

Acknowledgments & disclaimer

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- Disclaimer:
  - The statements and conclusions in this presentation are those of the researchers and not necessarily those of the California Air Resources Board. The mention of commercial products, their source, or their use in connection with material reported herein is not to be construed as actual or implied endorsement of such products.

Ultrafine particles indoors: Background

- Emerging health concerns about UFP exposure
- New evidence about atmospheric UFP
  - Regional nucleation events
  - Motor vehicles as prominent sources
- Independence of UFP from $PM_{2.5}$
- Likely, most UFP exposure occurs indoors
- However, little is known about
  - UFP levels indoors
  - Influencing factors

Study goals

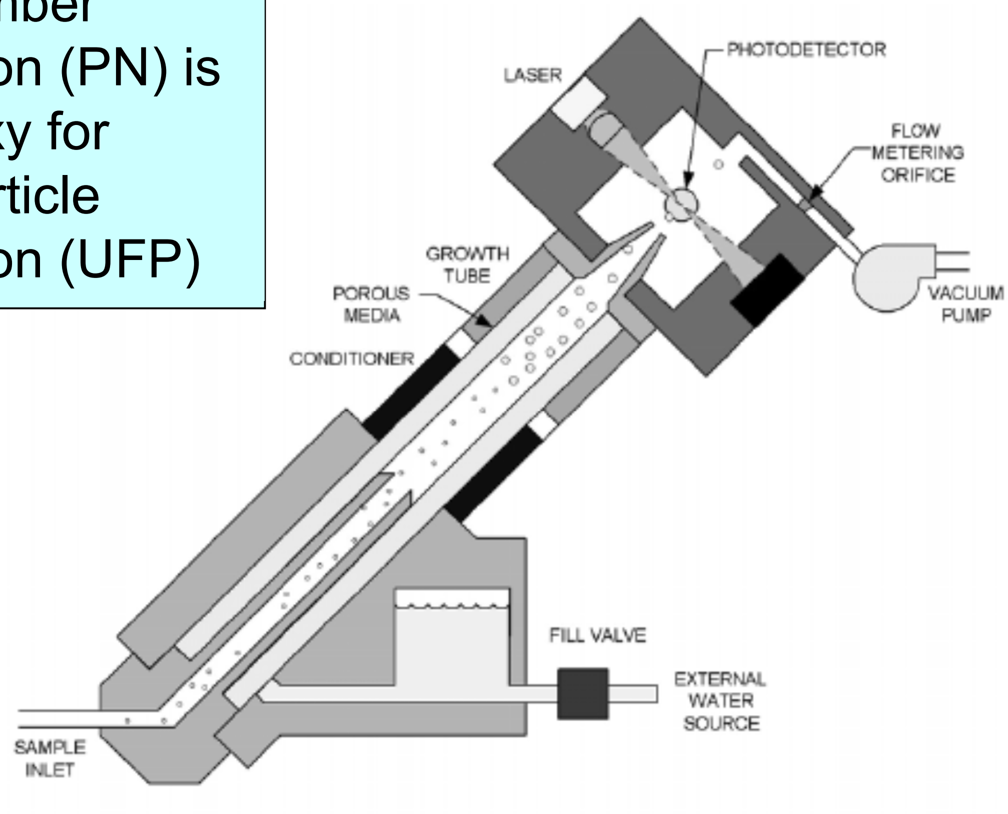
- Characterize UFP levels in Northern California
  - Convenience sample of seven houses
  - Convenience sample of six classrooms (4 schools)
- Intensive monitoring in each indoor environment
- Characterize factors that influence levels
- Quantify exposures of occupants
- Apportion exposures to major source categories

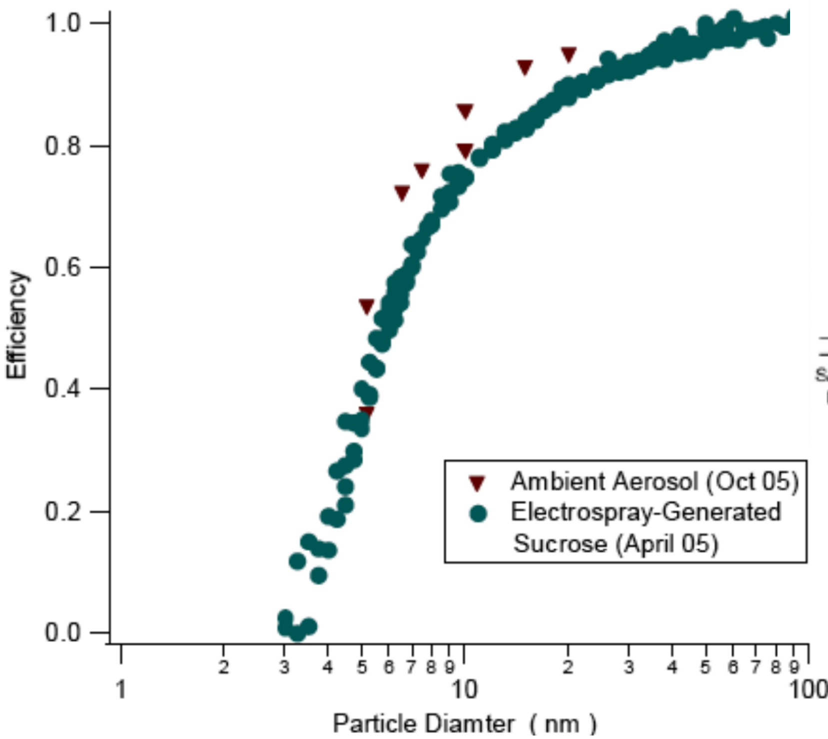
Study approach

- Experimental packages (indoor & outdoor)
  - Real-time measurement of UFP and copollutants
  - Temperature & proximity sensors w/ data loggers
  - Occupant questionnaires & site inspections
- Field monitoring campaign
  - 7 houses & 6 classrooms
  - Observational monitoring: ~ 3 days at each site
  - Manipulation experiments at each site
- Extensive interpretive analysis of data

Facilitating technology: WCPC

Particle number concentration (PN) is a good proxy for ultrafine particle concentration (UFP)





Reference: SV Hering et al., *Aerosol Science & Technology* **39**, 659-672, 2005.

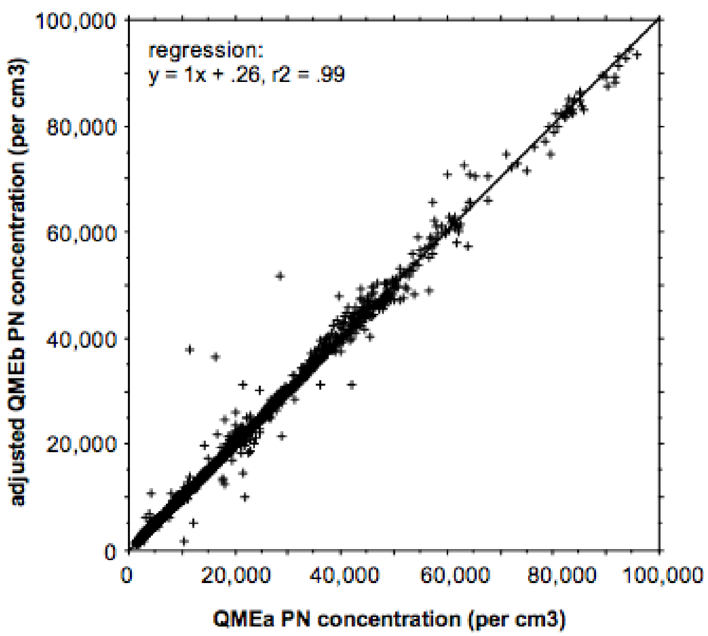
Array of real-time monitoring instruments

Parameter	**Instrument**	**In1**	**In2**	**Out**
PN (UFP) level	ME-WCPC (TSI 3781)	✓	✓	✓
CO_2 level	LI-COR 820	✓		
CO_2 level	TSI Q-Trak Plus 8554	✓		✓
CO level	TSI Q-Trak Plus 8554	✓		✓
Temperature	TSI Q-Trak Plus 8554	✓		✓
Relative humidity	TSI Q-Trak Plus 8554	✓		✓
Ozone level	2B Tech Model 202	✓		✓
Nitric oxide level	2B Tech Model 400	✓		✓

- Monitoring: 1-min time resolution; 1.5 m height

QA/QC: Overview

- Ozone, NO, CO, CO_2 monitors calibrated ~ monthly against either reference instrument or standard gases.
- WCPC flow rates routinely checked in field
- Side-by-side monitoring conducted at each site.



Sample WCPC side-by-side data (Indoor, H0)

Average WCPC side-by-side results

Parameter	QMEb	QMEc	QMEd
Average	0.95	1.02	1.04
Std. dev.	0.10	0.14	0.14

Slope of readings from instruments QMEb, QMEc, QMEd against reference instrument QMEa

Site selection: Houses

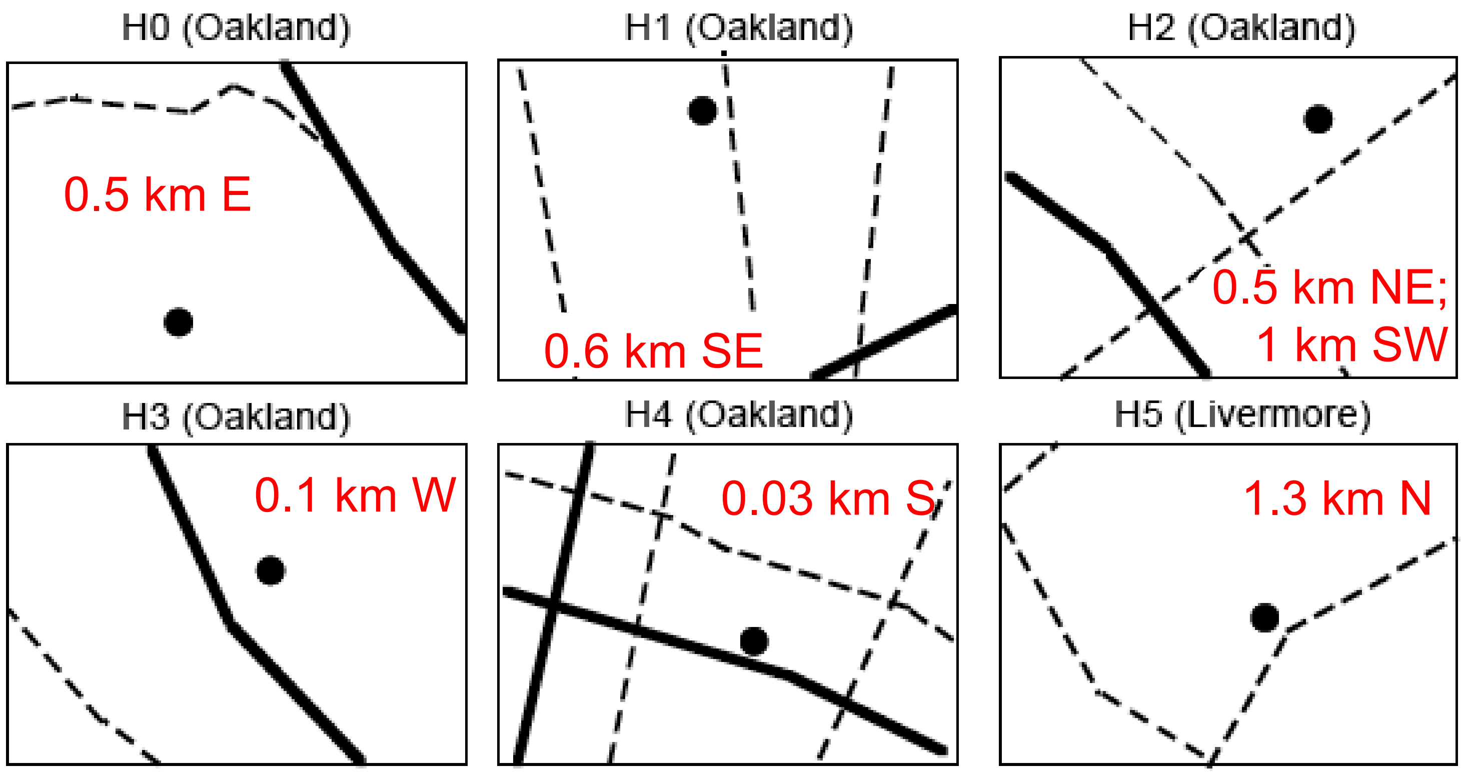
- Convenience sample
- All from East Bay area of Northern California
- Source-oriented selection criteria
- Aim for higher than average concentrations, but within normal range

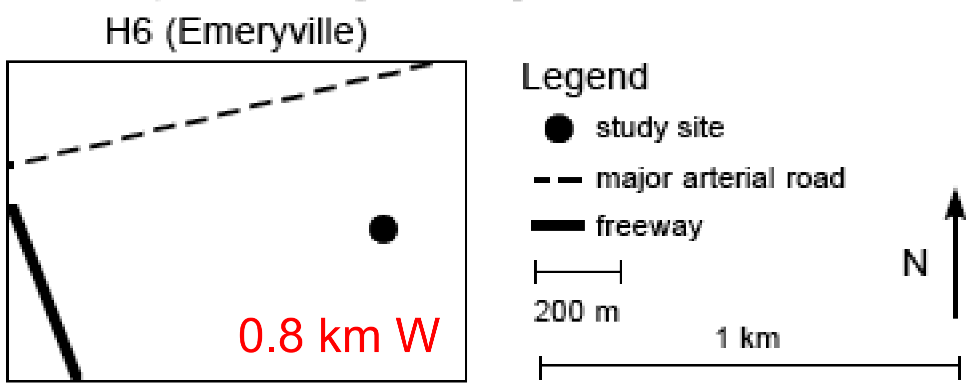
Some characteristics of house sites

ID	City	Y built	V (m^3)	Residents [a]
H0	Oakland	1938	320	2 (M, F)
H1	Oakland	1910	315	4 (M, F, m, m)
H2	Oakland	1949	328	4 (M, F, m, m)
H3	Oakland	1928	200	3 (M, F, m)
H4	Oakland	1904	386	4 (M, F, m, m)
H5	Livermore	1993	420	1 (F)
H6	Emeryville	1996	314	3 (M, M, F)

[a] M — male adult, F — female adult, m — male child

House sites: Proximity to major roadways



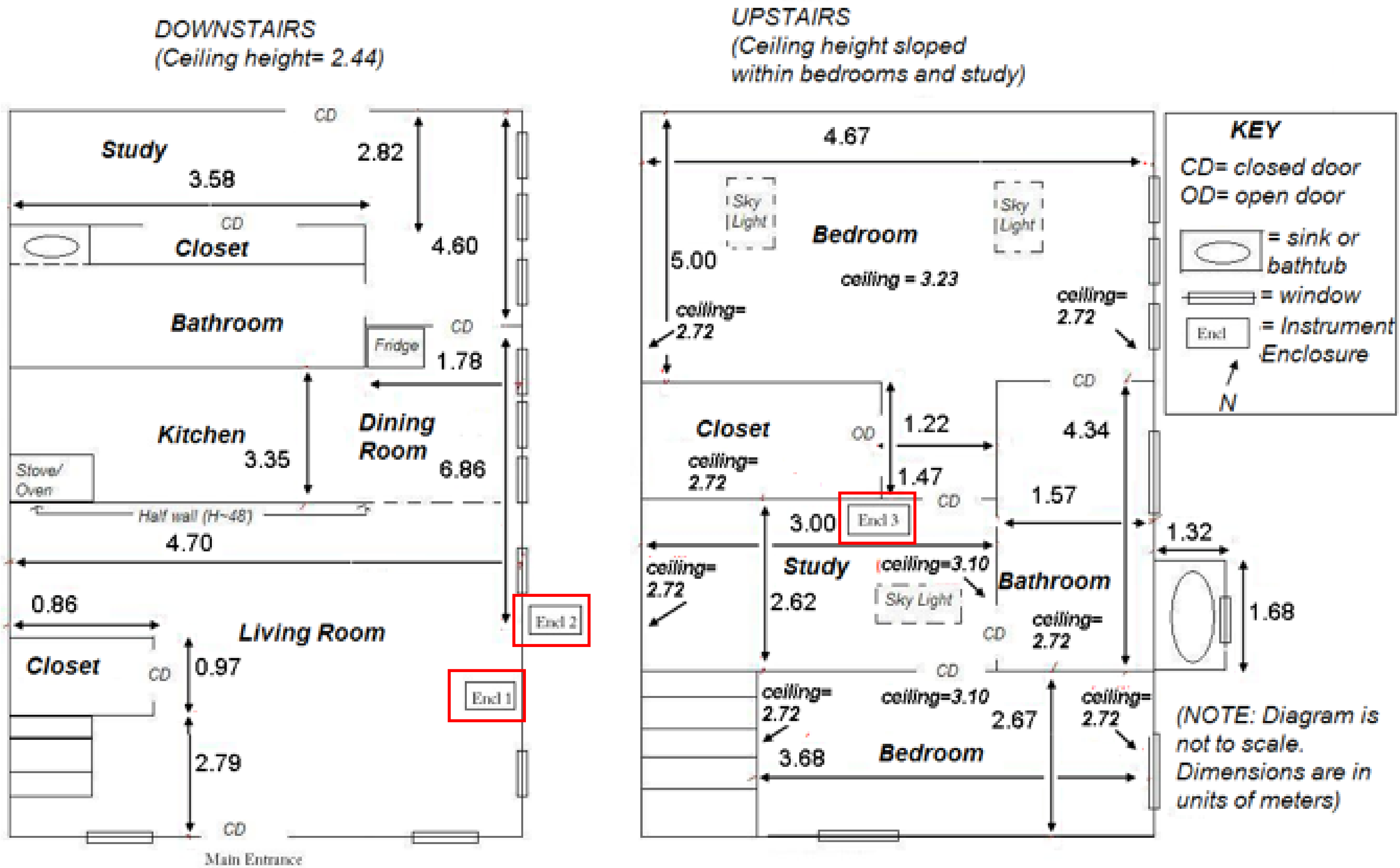


- Prevailing winds from W
- Acquired central station met data
- No clear influence of proximity to roadways on outdoor PN levels.

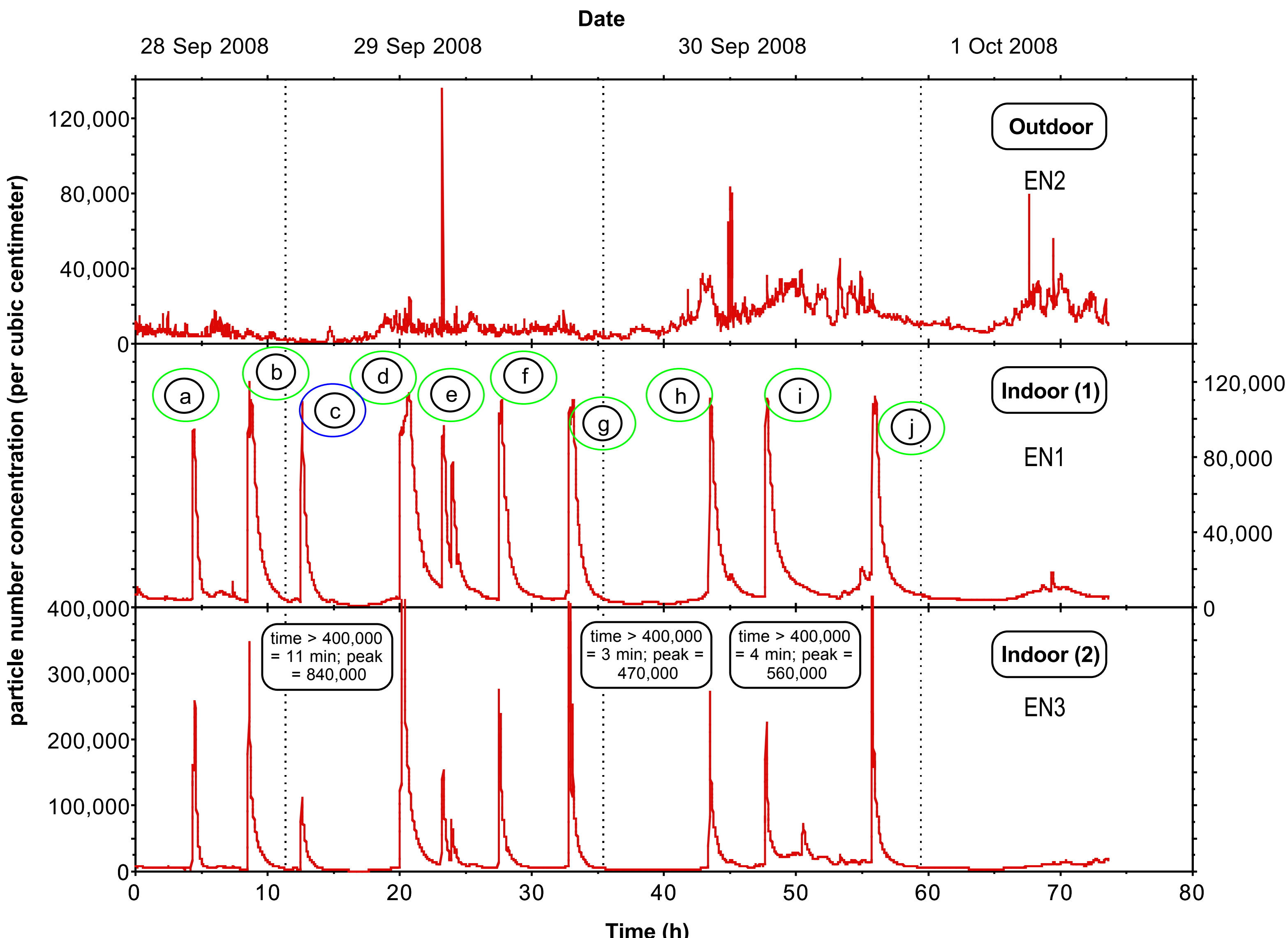
Some illustrative details: Attributes of H6

- Located in Emeryville, CA
- Built in 1996
- Occupants: 3 adults
- Pilotless gas cooking range
- Used candles one time
- Air-exchange rate (3 measurements): 0.8-0.9 h^{-1}

Site plan at H6

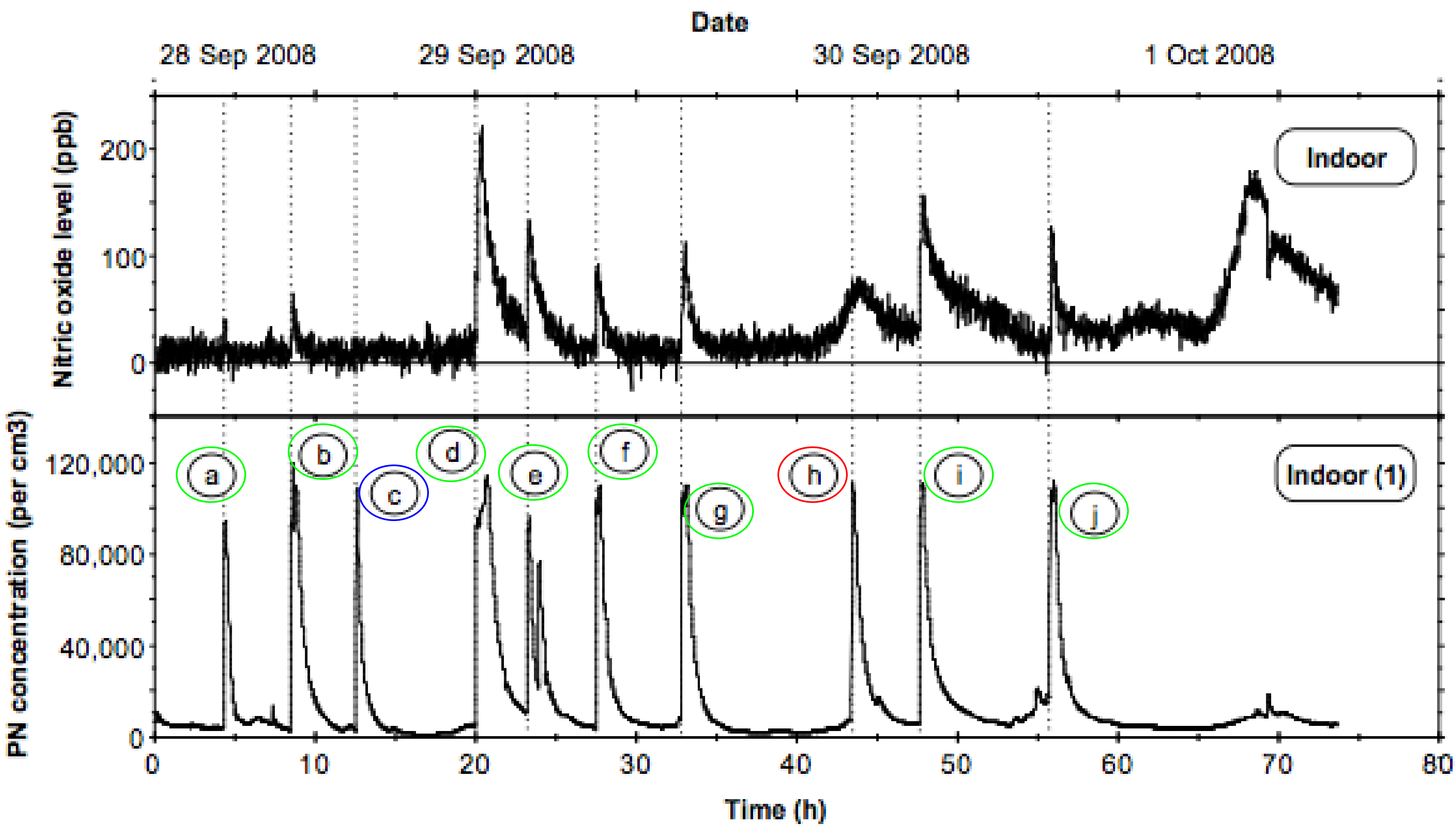


PN concentration time series at H6



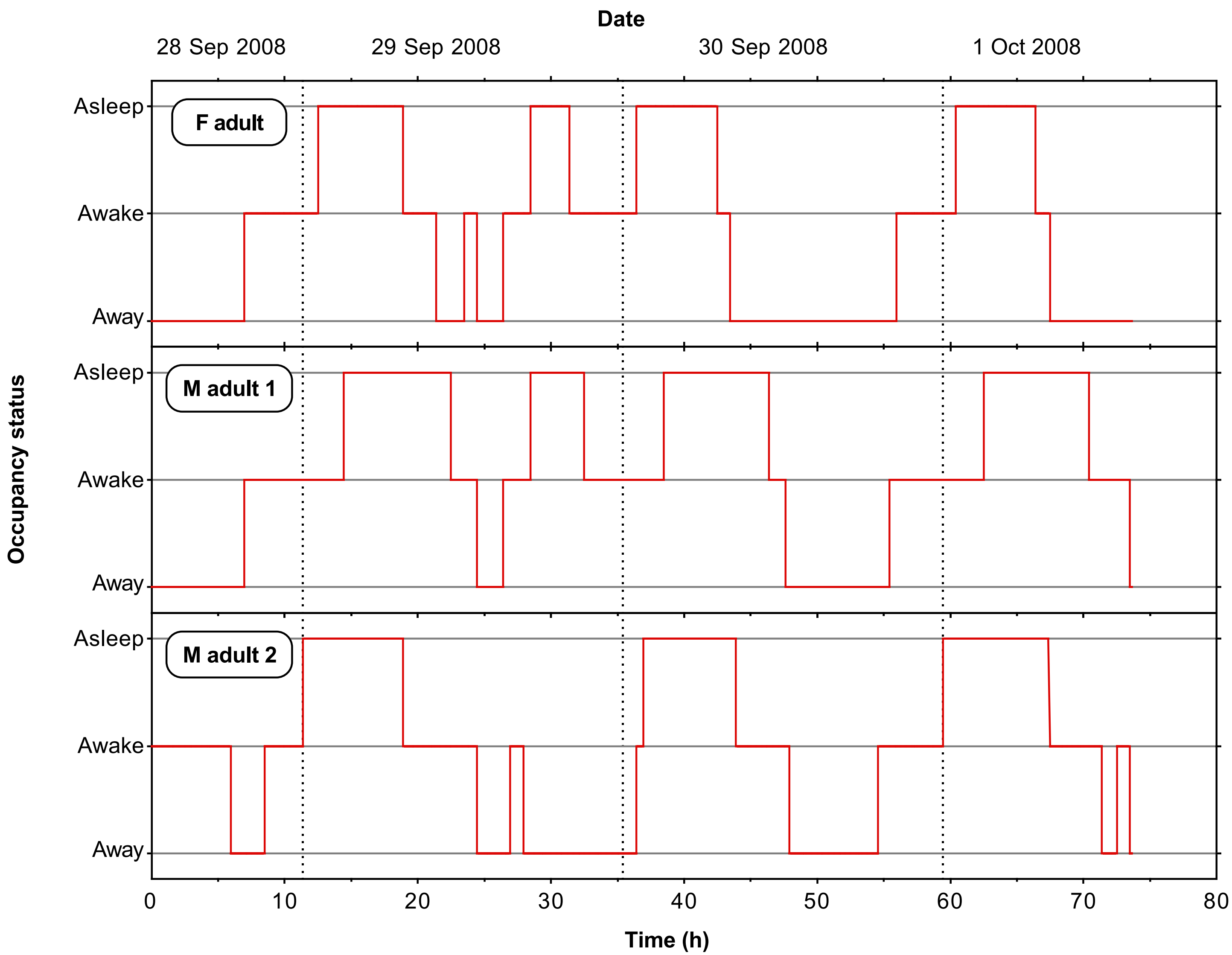
Cooking activities: (a), (b), (d), (e), (f), (g), (h), (i), (j); Use of candles: (c)

PN in relation to copollutant data: NO at H6



Cooking activities with gas range or oven: (a), (b), (d), (e), (f), (g), (i), (j); Candle use: (c); Toaster oven: (h)

Occupancy time-series data at H6



Indoor proportion of outdoor particles at H6

Indoor proportion of outdoor particles

Time (h)	f_1	f_2
14.5-18.9	0.54	0.50
25.3-26.4	0.81	0.87
38.5-42.4	0.30	0.28
51.5-54.6	0.33	0.74
62.5-66.4	0.47	0.48
Average	**0.44**	**0.51**

Approach: Ratio of average indoor to average outdoor PN level for periods when the house was either unoccupied or all occupants were asleep and there was no evidence of the influence of indoor sources on PN levels.

f_1 based on ground floor PN
f_2 based on upstairs PN level

Characterizing indoor PN sources at H6

ID	Source	Time (h)	σ (10^{12})	k+a (h^{-1})
a	Stove & rice cooker	4.2-5.4	44	3.6
b	Stove (frying)	8.5-10.8	42	1.5
c	Candle	12.5-13.9	26	1.9
d	Stove (frying)	20.0-23.1	56	1.2
e1	Stove (water)	23.1-23.9	36	2.8
e2	Toaster oven	23.9-26.2	5	1.9
f	Stove (frying)	27.4-29.8	39	1.6
g	Stove & microwave	32.8-34.8	46	1.8
h	Toaster oven	43.4-44.9	35	1.7
i	Stove (water & frying)	47.6-50.3	35	1.5
j	Stove & GF grill	55.6-59.1	40	1.5

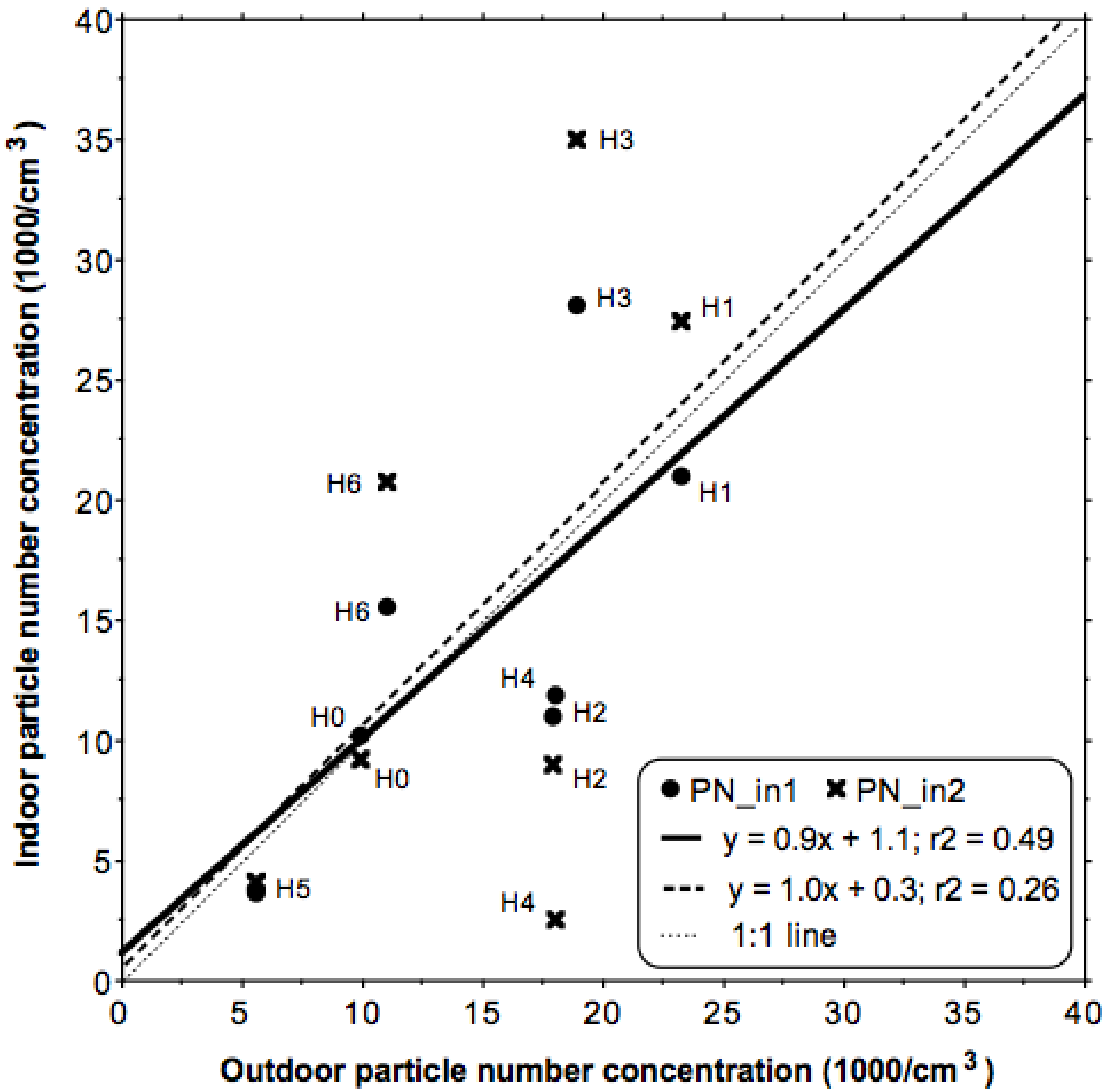
σ = PN emissions (count); k+a = 1st order decay constant

Exposure & apportionment at H6 (3.1 d)

Parameter	**R1(F)**	**R2(M)**	**R3(M)**
Time at home, awake (h)	22.5	28.8	29.8
Time at home, asleep (h)	21.5	28.0	22.5
Time away from home (h)	29.7	16.9	21.4
PN_in1, indoor awake (10^3 cm^{-3})	24.7	19.4	23.1
PN_in2, indoor asleep (10^3 cm^{-3})	5.3	17.4	7.3
Cumulative exposure (10^3 cm^{-3} h)	669	1045	854
Indoor exposure rate (10^3 cm^{-3} h/d)	218	341	278
Indoor particles of outdoor origin	23%	26%	29%
Indoor sources, peak events	76%	76%	72%
Indoor, unknown origin	1%	-2%	-1%

Indoor exposure rate = product of average indoor PN concentration (10^3 cm^{-3}) × occupancy (h/d)

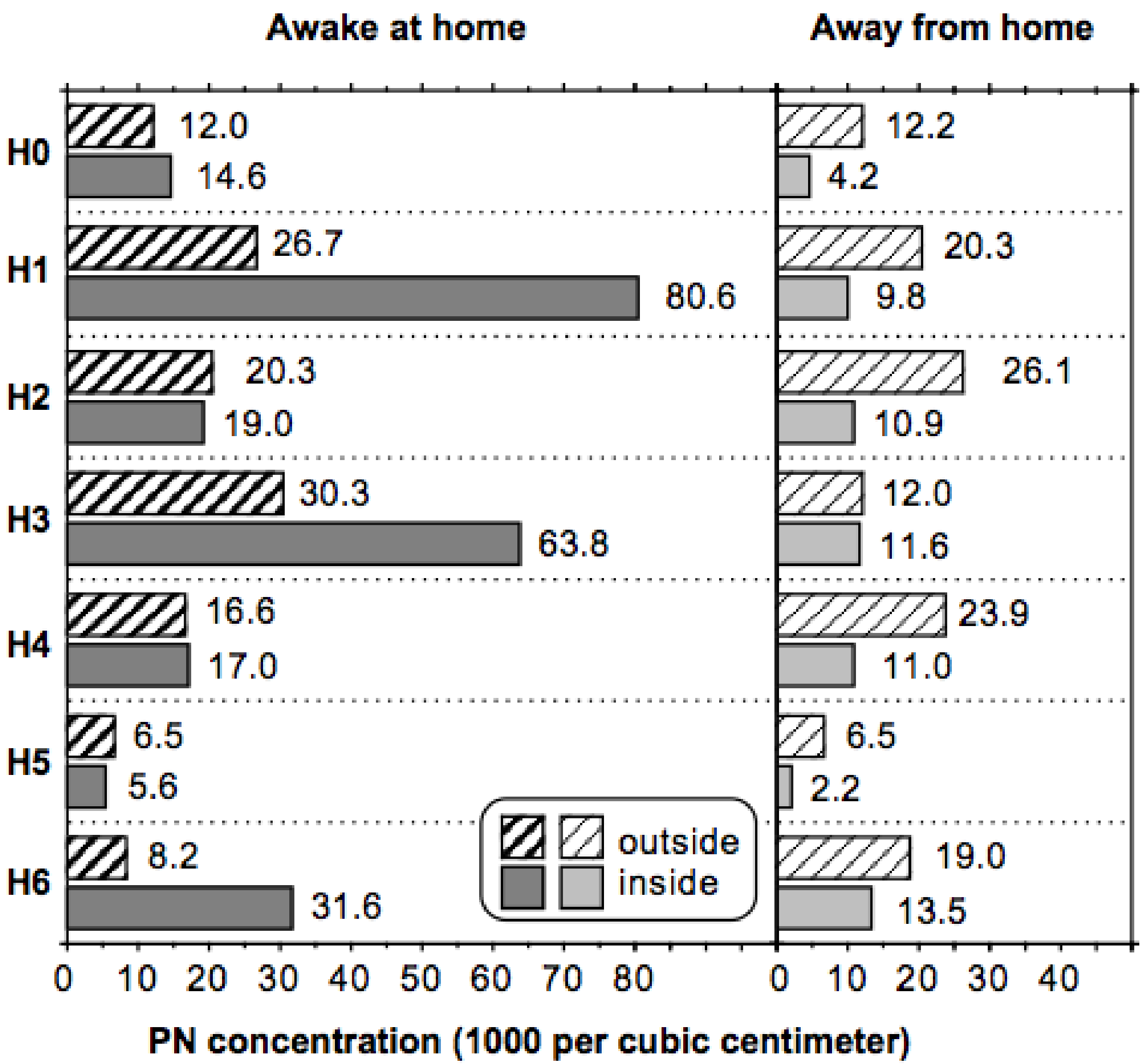
All houses: Relationship of PN in to PN out



Overall averages:
In1: 14.5 ± 8.0
In2: 15.4 ± 12.4
Out: 14.9 ± 6.2
(units: 10^3 per cm^3)

Averages are similar; correlations are not good.

Indoor PN: Higher when people are awake



Averages

awake at home:
outside — 17.2
inside (In1) — 33.2
inside (In2) — 35.6

asleep at home:
outside — 8.9
inside (In1) — 5.0
inside (In2) — 5.5

away from home:
outside — 17.1
inside (In1) — 9.0
inside (In2) — 9.7

All in units of 10^3 cm^{-3}

Indoor proportion of outdoor particles (f)

- Goal: Determine average indoor concentration of UFP only attributable to average outdoor concentrations.

Site	f_1	f_2
H0	0.36	0.37
H1	0.11	—
H2	0.51	—
H3	0.45	—
H4	0.47	0.11
H5	0.29	0.49
H6	0.44	0.51

- Results summary (f_1): avg ± stdev = 0.38 ± 0.14; median = 0.44

Qualitative summary of indoor sources

Source	H0	H1	H2	H3	H4	H5	H6
Gas stove or oven							
Gas clothes dryer							
Furnace (gas fired, central or wall)							
Electric stove (range) or oven							
Toaster or toaster oven							
Ironing clothes							
Candles							
Terpene -based cleaning product use							

= Reported as not used

= Used, no clear evidence of emissions

= Used, individual use associated with an indoor peak

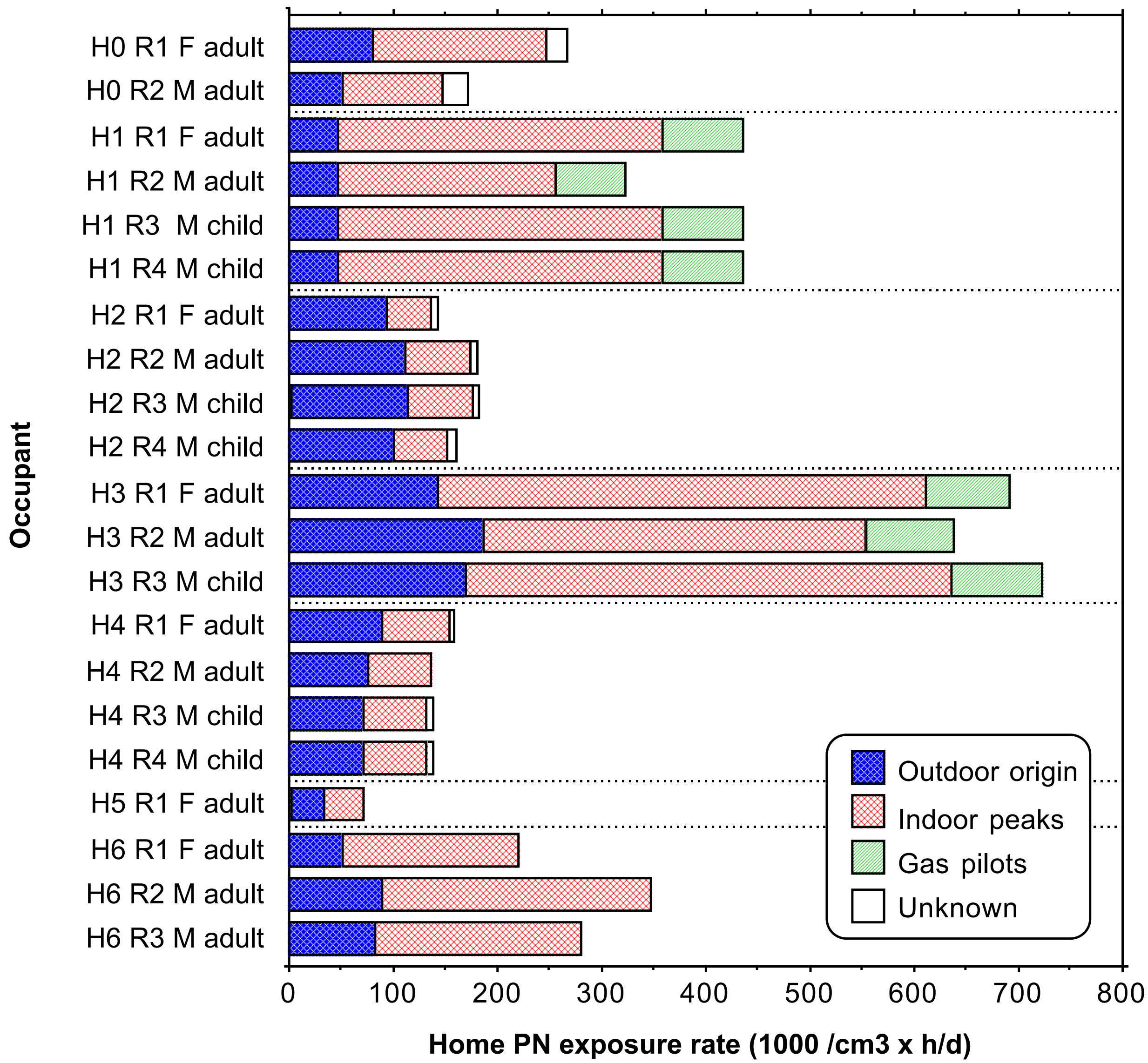
= Not used or tested alone, joint use with another potential source associated with an indoor peak

Episodic emissions characterization

- Overall summary: 59 peak events ~ 2.4 events per day
- For peaks associated with distinct activities:
  - — Characterized PN emissions (σ) for 40 events
  - — Characterized decay constant (k+a) for 38 events

Source	***k* + *a*, GM (GSD; N)**	**σ, GM (GSD; N)**
Gas stove	1.8 h^{-1} (1.4; 20)	38 × 10^{12} particles (2.1; 19)
Furnace, central	1.6 h^{-1} (1.5; 2)	41 × 10^{12} particles (1.1; 2)
Candle	1.9 h^{-1} (—; 1)	26 × 10^{12} particles (—; 1)
Toaster oven	1.7 h^{-1} (1.2; 4)	9 × 10^{12} particles (2.8; 4)
Electric stove	1.1 h^{-1} (1.3; 5)	10 × 10^{12} particles (2.1; 4)
Furnace, wall	1.3 h^{-1} (1.7; 3)	3.1 × 10^{12} particles (2.7; 7)
Clothes dryer	2.2 h^{-1} (—; 1)	2.2 × 10^{12} particles (—; 1)
Steam iron	1.5 h^{-1} (1.2; 2)	1.9 × 10^{12} particles (1.4; 2)

PN exposures and apportionment



Averages (21 people)

Total exposure: 298 ± 195
Outdoor origin: 86 ± 42
Indoor peaks: 182 ± 144
Gas pilots: 23 ± 34
Unknown: 5 ± 6

Units: 10^3 cm^{-3} h/d

Proportions (average)

Total exposure: 100%
Outdoor origin: 29%
Indoor peaks: 61%
Gas pilots: 8%
Unknown: 2%

Units: 10^3 cm^{-3} h/d

UFP in houses: Key findings

1. PN levels in houses were much higher when occupied than when vacant.
2. Indoor emission sources are important in study houses.
3. Daily average PN exposures per person in houses monitored: ~ 300×10^3 cm^{-3} h/d.
4. Indoor proportion of outdoor particles in houses monitored: 0.38 ± 0.14.

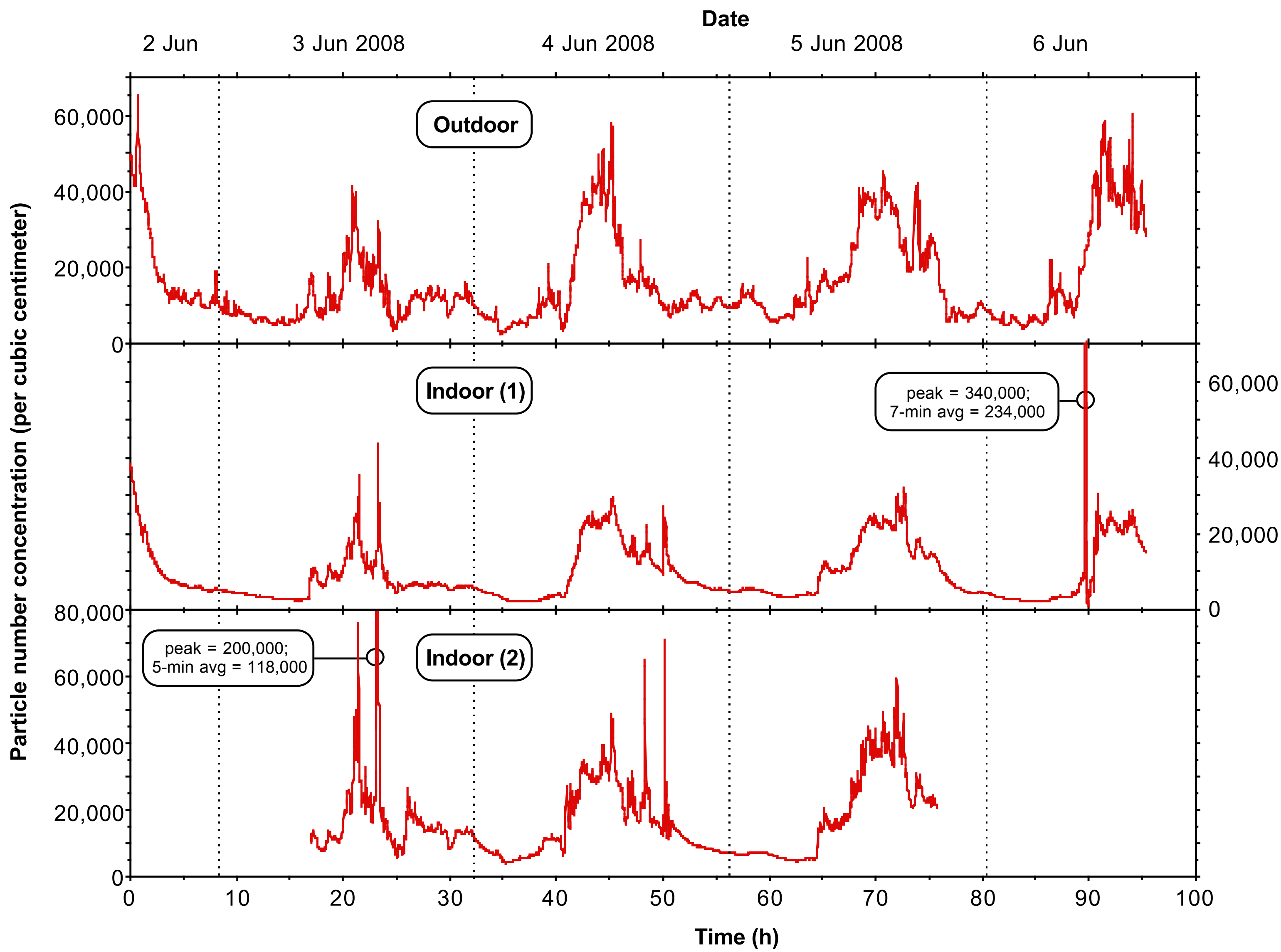
Caveats: Small sample of buildings, not statistically representative, few days monitored, one area of California.

Broad extrapolation not warranted!

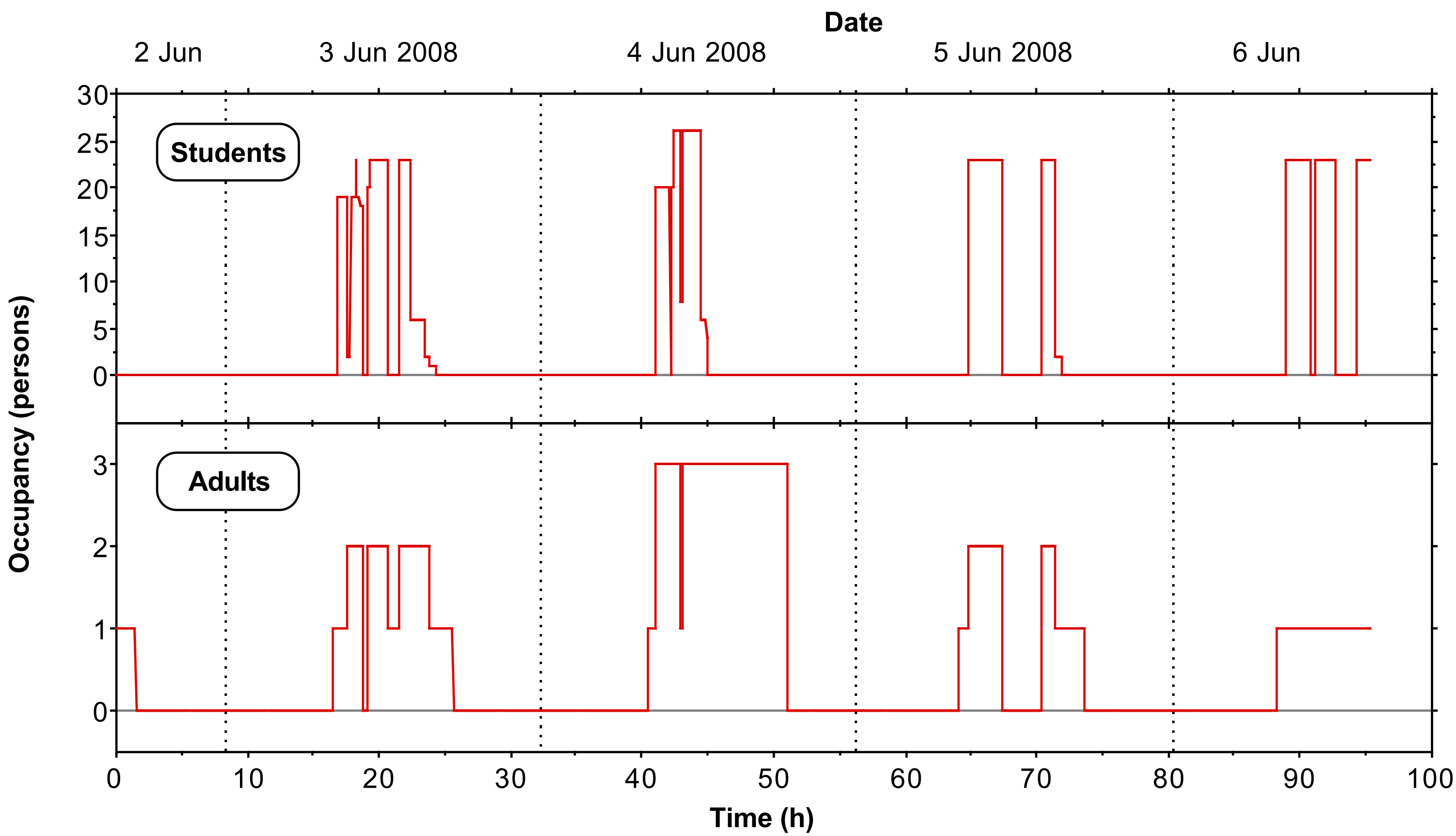
Site selection: Schools

- Convenience sample
- Elementary schools in the urban portion of the East Bay of Northern California

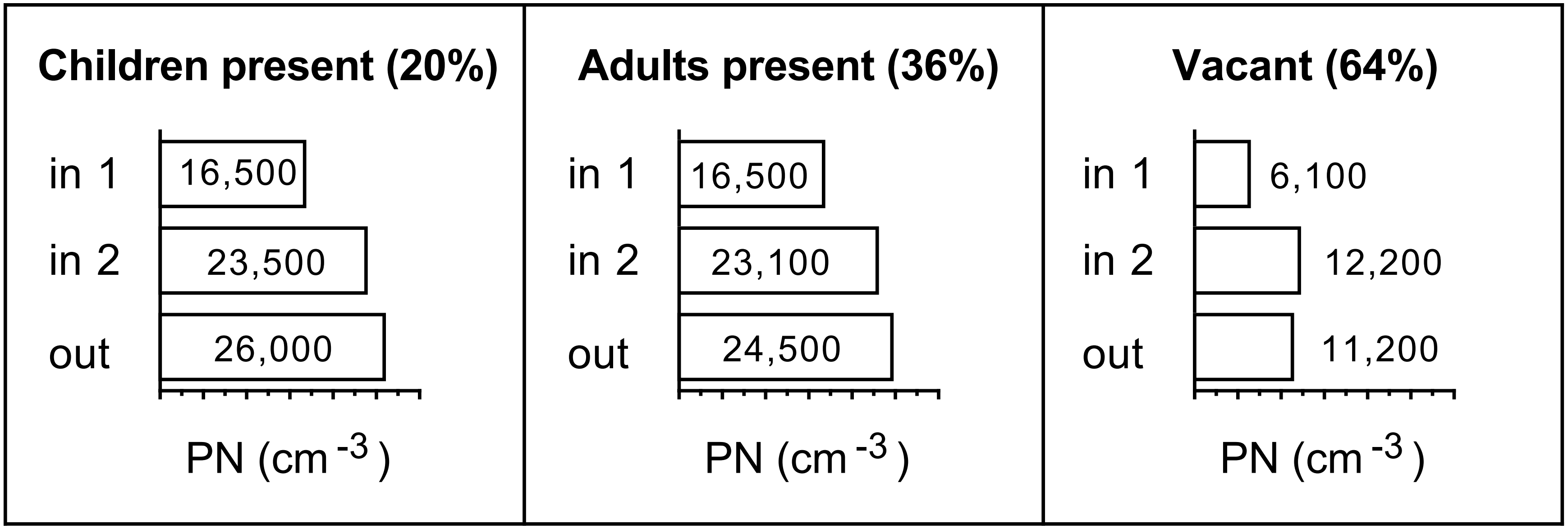
Sample data: PN concentration vs. time at S1



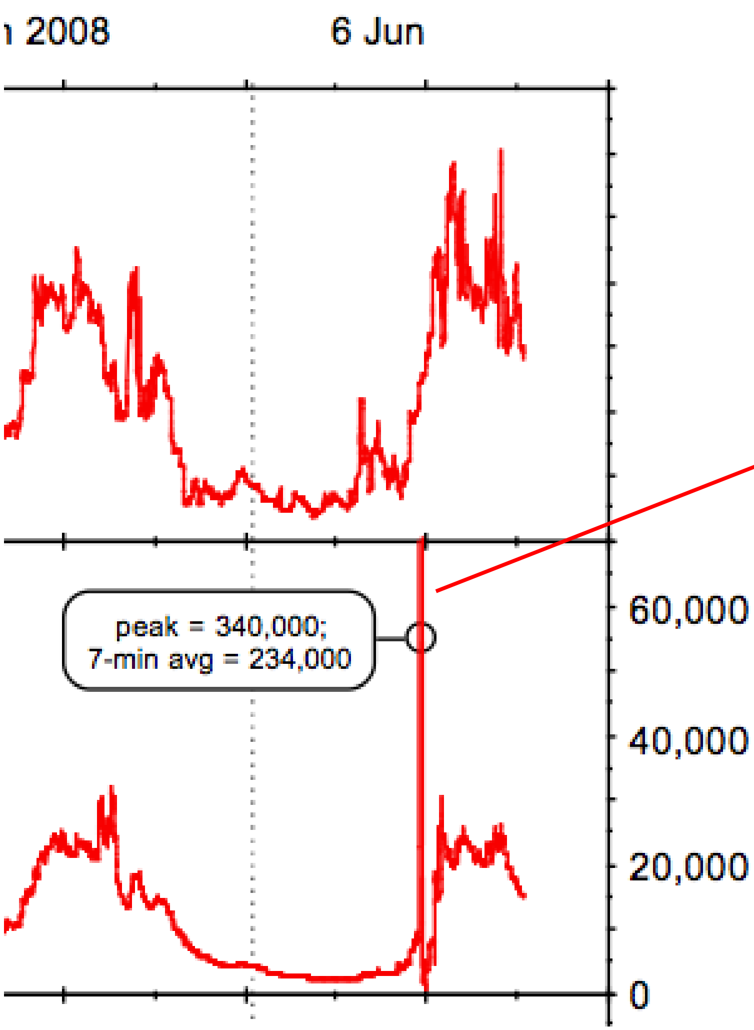
S1: Occupancy time-series data

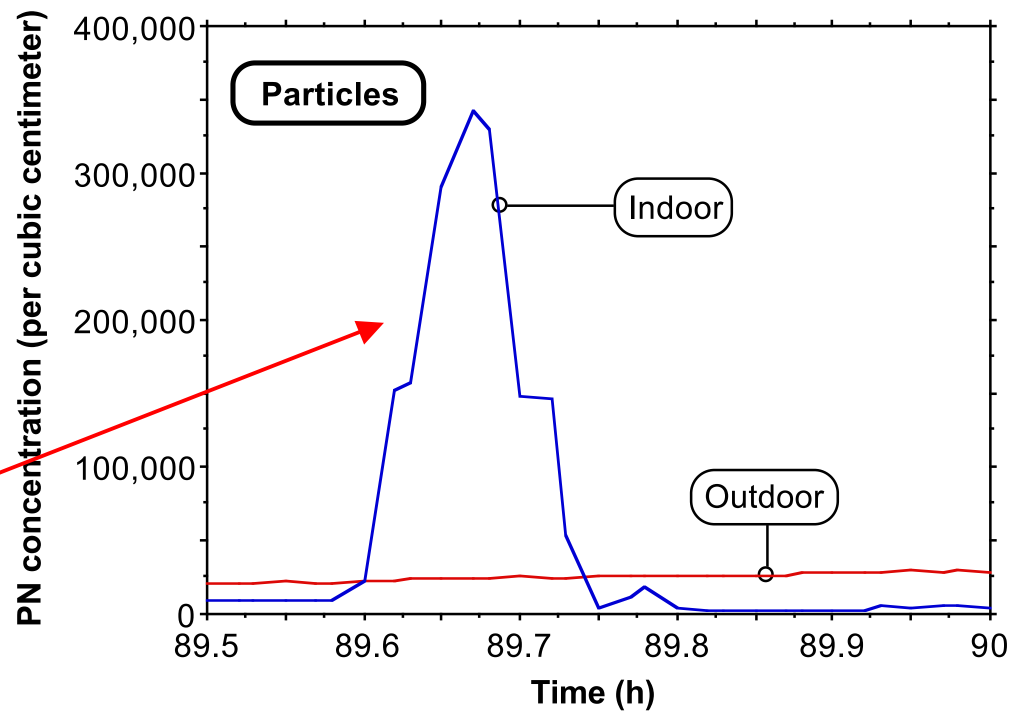


S1: Time-average PN levels with occupancy



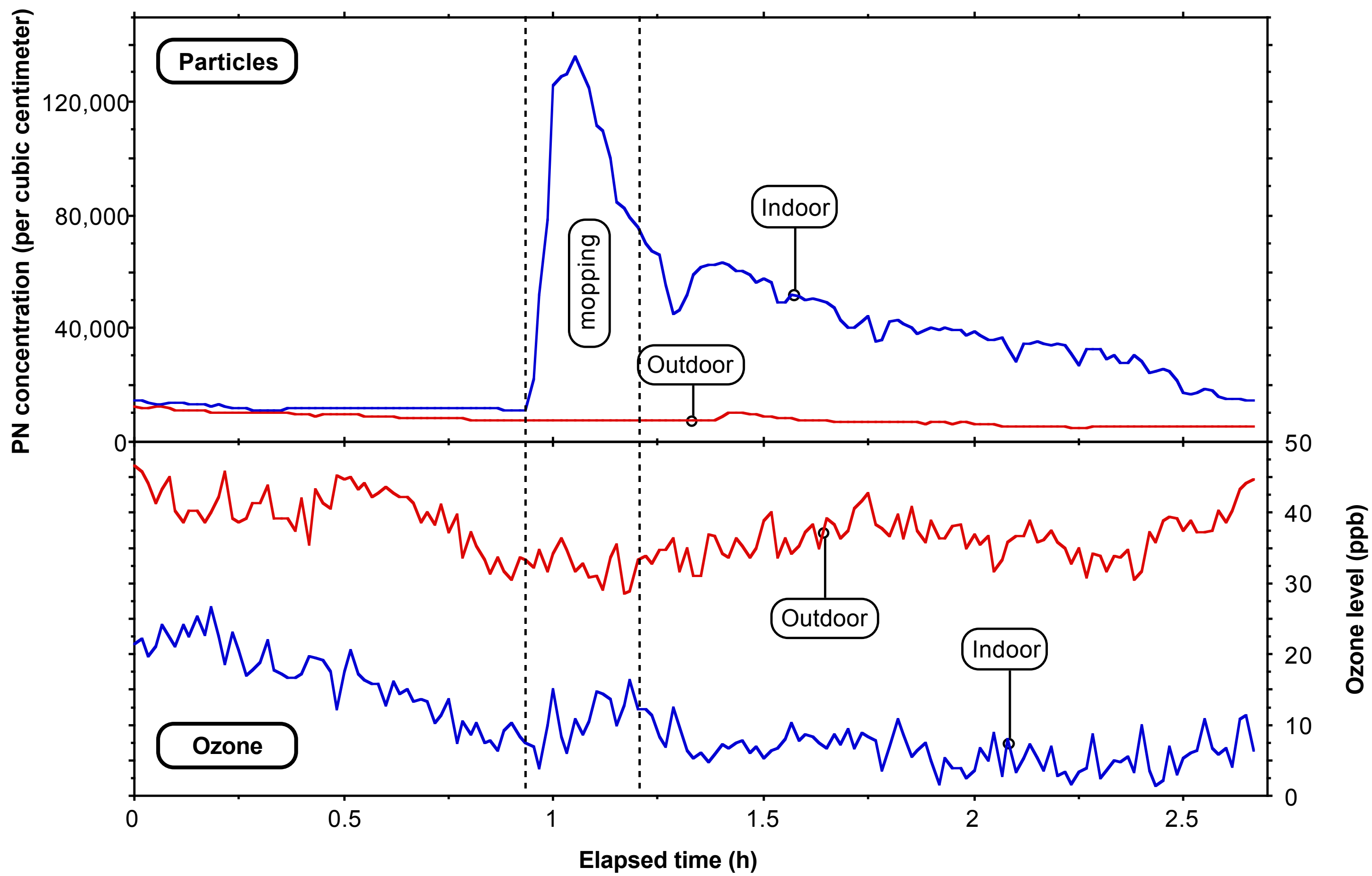
S1: Source peak from cooking pancakes





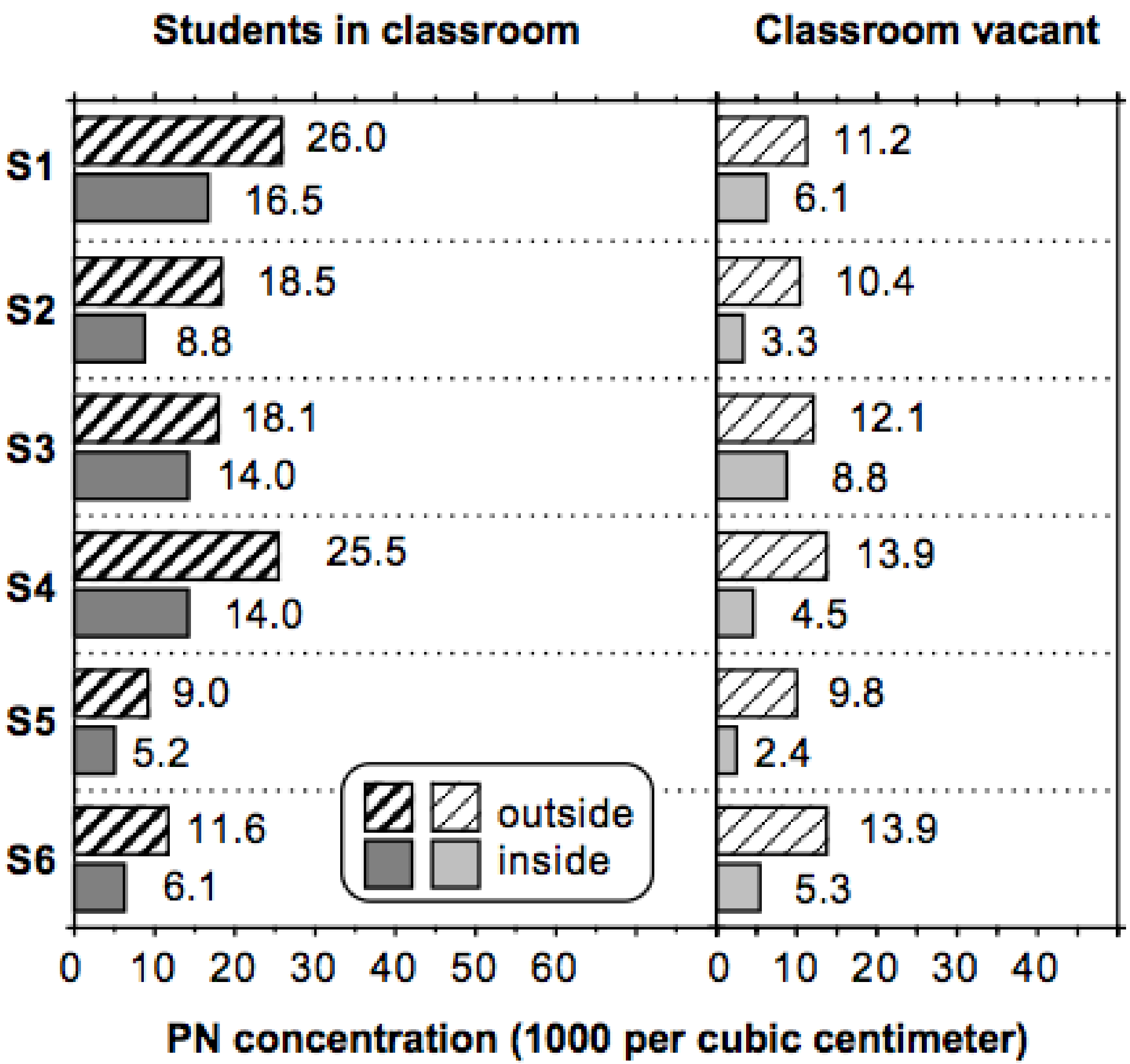
This brief peak contributed 10% to students' exposure and 5% to teacher's exposure for the three school days monitored.

S1: PN peak from mopping (manipulation)



Ozone reacts with terpenes in pine oil to form condensable species that first nucleate to form new particles and then condense to cause particle growth.

Summary for classrooms: PN levels



Averages

occupied:
outside — 18.1 ± 7.0
inside — 10.8 ± 4.7

vacant:
outside — 11.9 ± 1.7
inside — 5.1 ± 2.3

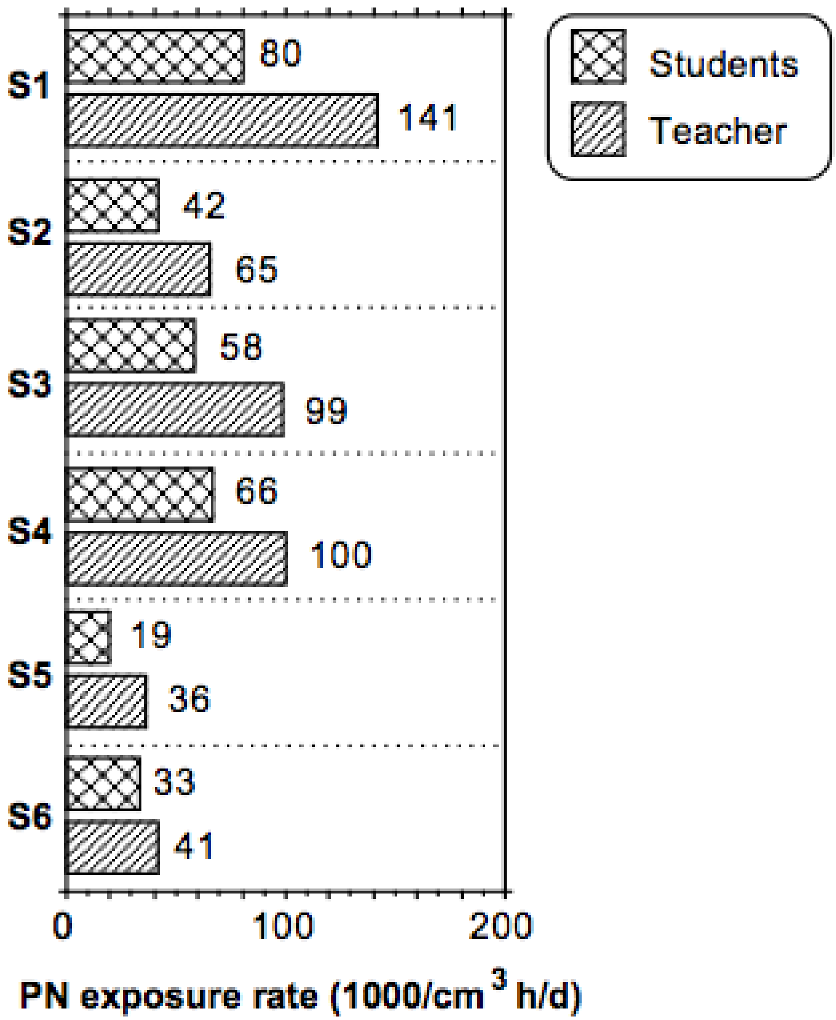
All in units of 10^3 cm^{-3}

Indoor proportion of outdoor particles (f)

	"Closed"			"Open"		
Site	**Time**	**AER**	**f_1 (—)**	**Time**	**AER**	**f_1 (—)**
S1	3%	0.5 h^{-1}	0.39	96%	2.2 h^{-1}	0.59
S2	35%	0.4 h^{-1}	0.16	53%	3.3 h^{-1}	0.54
S3	0%	—	—	100%	4.6 h^{-1}	0.76
S4	25%	0.3 h^{-1}	0.46	68%	3.9 h^{-1}	0.59
S5	0%	—	—	100%	1.9 h^{-1}	0.51
S6	76%	0.6 h^{-1}	0.51	17%	4.0 h^{-1}	0.60
Avg.	**23%**	**0.45 h^{-1}**	**0.38**	**72%**	**3.1 h^{-1}**	**0.60**

(*) "Closed" = doors closed and air off; "Open" = door(s) open and/or air on; all data apply for conditions when students were present in classroom.

Summary for classrooms: PN exposure rates



Average ± standard deviation

Students: 50 ± 22
Teachers: 80 ± 40

Units: 10^3 cm^{-3} h/d

- Exposure rate is product of average concentration (cm^{-3}) × average occupancy duration (h/d).

UFP in classrooms: Key findings

1. PN levels in classrooms were much higher when occupied than when vacant.
2. Indoor emission sources were not important in classrooms.
3. Daily average PN exposures per person:
   students ~ 50×10^3 cm^{-3} h/d
   teachers ~ 80×10^3 cm^{-3} h/d
4. Indoor proportion of outdoor particles in classrooms: 0.57 ± 0.10.

Caveats: Small sample of buildings, not statistically representative, few days monitored, one area.

$\Rightarrow$ Broad extrapolation not warranted!

For more information about this study…

NA Mullen, S Bhangar, SV Hering, NM Kreisberg, WW Nazaroff, Ultrafine particle concentrations and exposures in six elementary school classrooms in northern California, *Indoor Air* **21**, 77-87, 2011.

Nasim Mullen

Seema Bhangar

S Bhangar, NA Mullen, SV Hering, NM Kreisberg, WW Nazaroff, Ultrafine particle concentrations and exposures in seven residences in northern California, *Indoor Air* **21**, 132-144, 2011.

Summary remarks on UFP exposure

- High spatial (S) and temporal (T) variation $\Rightarrow$ Great challenge to use traditional monitoring approaches for characterizing exposure
- Source-oriented perspective
  - Regional nucleation events (T variability dominates)
  - Motor vehicle emissions: time spent in or near traffic (S variability dominates)
  - Indoor sources matter: combustion, high T, ozone + terpenes (S and T variability are both key)
- Importance of source-receptor proximity
- Control opportunities
  - Source reduction
  - Proximity management
  - Air filtration