EPA's Building Assessment Survey and Evaluation Study (BASE): What Have We Learned?

CARB Chair's Seminar Series

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January 8, 2009

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What is BASE?

Building Assessment Survey and Evaluation Study

- Cross-sectional study designed to define key characteristics of indoor air quality (IAQ) in 100 randomly selected public and commercial office buildings across the continental U.S.

- Conducted to fill a major data gap regarding indoor air quality in office buildings

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What Were the Goals of the BASE Study?

- Collect baseline data characterizing public and commercial office buildings
- Examine relationships among parameters and between parameters and occupants' perceptions and symptoms
- Establish information on important indoor air parameters for policy decisions and guidance development
- Assist in standardizing methodology and protocols for investigations

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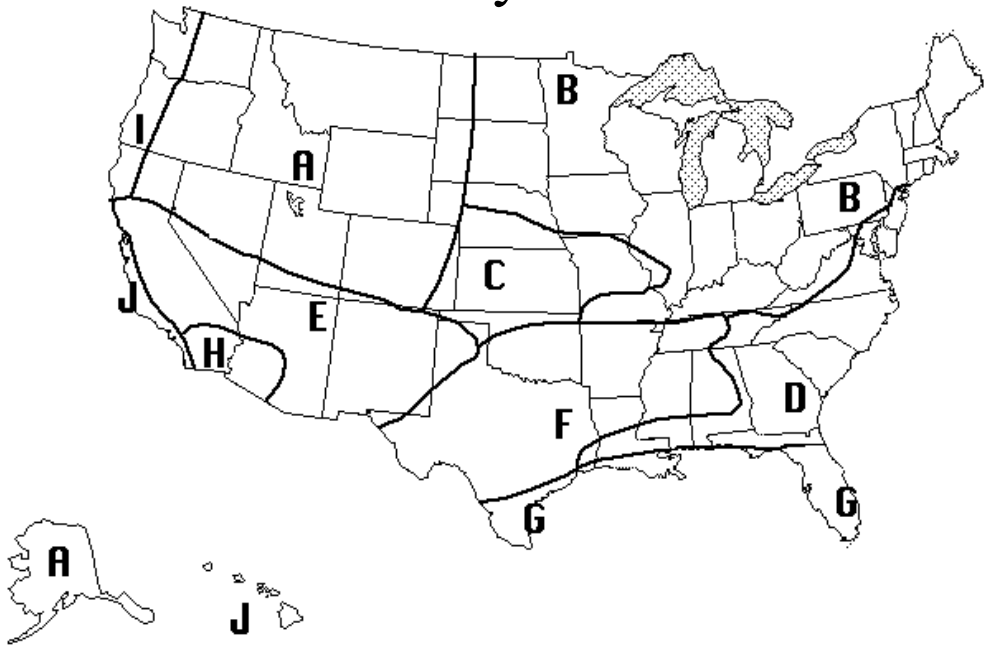
Conducting the BASE Study

- Designed through a series of workshops of 50 national experts
- Country divided into 10 climatic regions
- Region identified for study in either winter or summer



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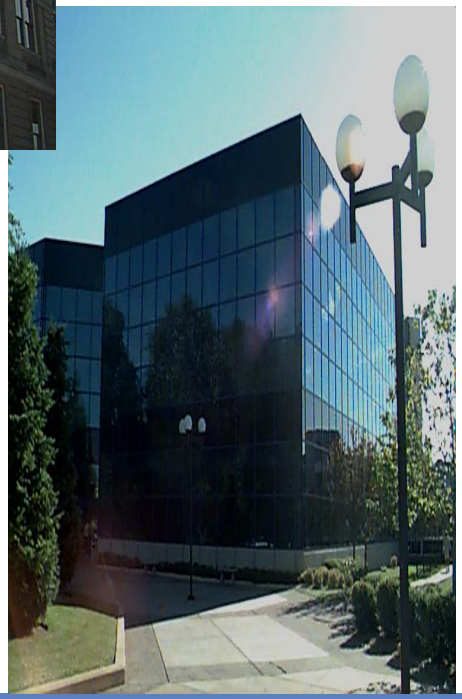
Geographic Range

- 25 States
- 37 Cities
  - 52 Summer buildings
  - 48 Winter buildings
- Variation
  - South Dakota: -18 °F (-28 °C)
  - Arizona: 108 °F (42 °C)



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Conducting the BASE Study

- Cities of 100,000 or greater population identified in each region
- City randomly selected for study
- Office Buildings randomly selected
  - At least 50 employees >20 hrs./week
  - No highly publicized IAQ problems
- Test space randomly selected
  - At least 50 employees >20 hrs./week (needed >25 for questionnaire)
  - Served by no more than 2 air handling units
  - No more than three floors
  - Environmental sampling at three randomly selected indoor sites and one outdoor site close to outdoor air intake

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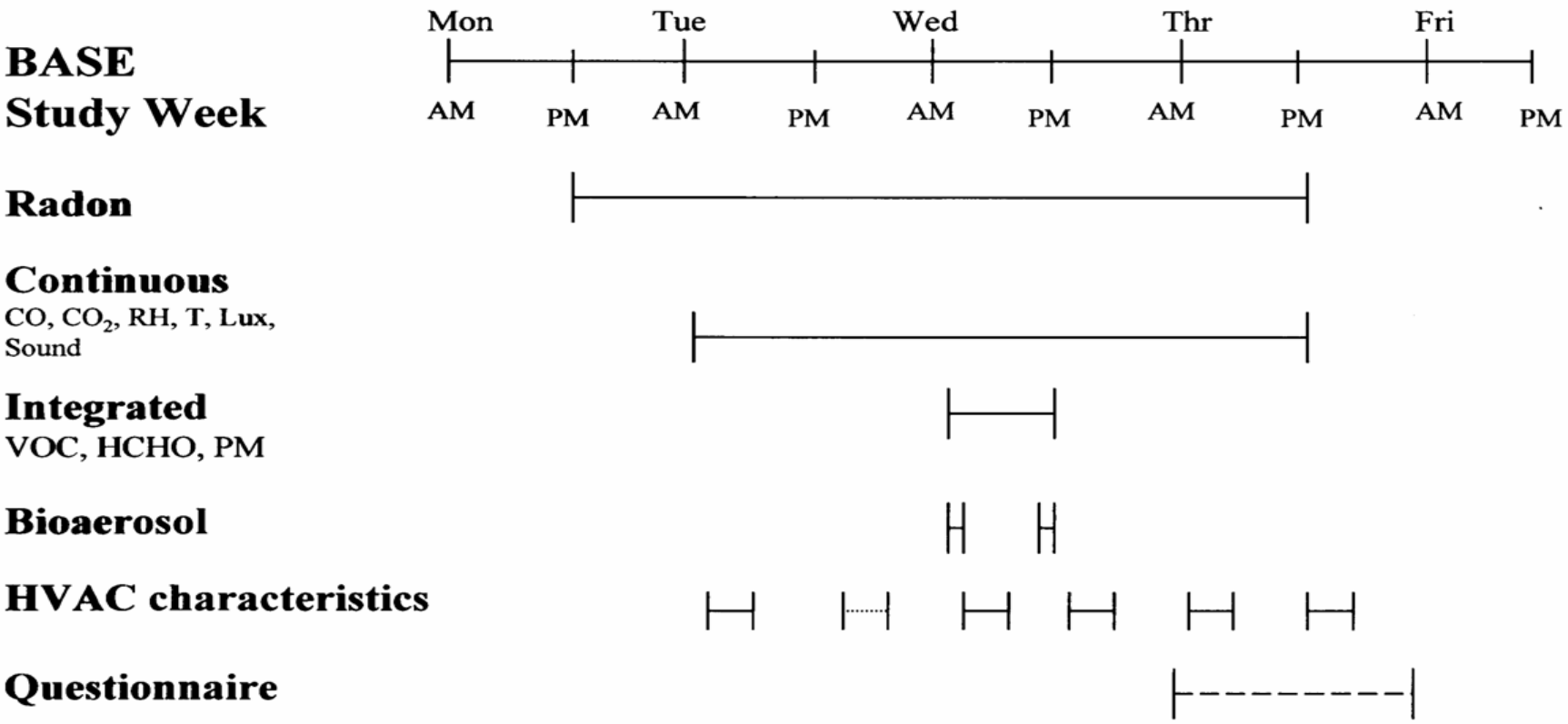
Conducting the BASE Study

Schedule



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Conducting the BASE Study

Core Parameters

ENVIRONMENTAL MEASURES	BUILDING CHARACTERISTICS	HVAC CHARACTERISTICS	OCCUPANT QUESTIONNAIRE
• Temperature • Relative Humidity • Carbon Dioxide • Carbon Monoxide • Sound • Light • Particles • VOCs • Formaldehyde • Biologicals • Radon	• Use • Occupancy • Physical Location • Ventilation Equip. • Construction • Outdoor Sources • Smoking Policy • Water Damage • Fire Damage • Renovation • Pest Control • Cleaning Practices	• Specifications • Filtration • Air Cleaning • Humidification • Maintenance • Inspection Sched. • Supply Air Flow • Outdoor Air Intake • % Outdoor Air • Supply Air Temp. • Supply Air RH • Exhaust Air Flow	• Work Place Characteristics • Health and Well-Being • Work Place Environmental Conditions • Job Characteristics

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Ownership of BASE Buildings
(n=100)

- Private & Commercial: 41
- Academic: 15
- Government: 44
  - Local: 15
  - County: 9
  - State: 13
  - Federal: 7

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Building Representativeness

- Using DOE Survey as a basis for comparison, the BASE buildings
  - represent the largest 11% of US office buildings and
  - represent the office buildings where 73% of US office workers work

What Have We Learned?

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BASE Buildings: All Shapes and Sizes

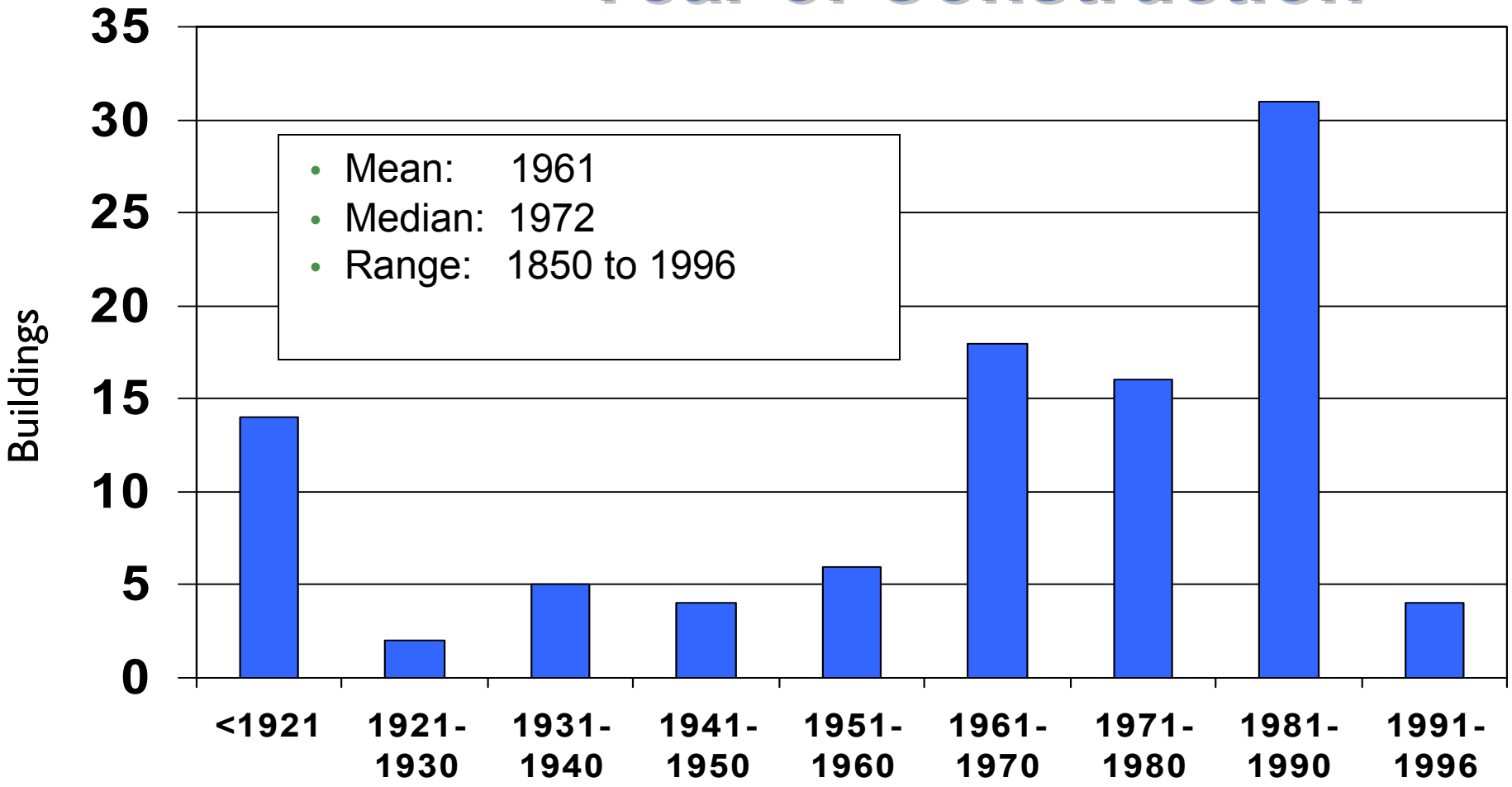
Number of Floors:

- Mean: 10
- Median: 6
- Range: 1 to 61

Gross Floor Area:

- Mean: 24,800 m^2
- Median: 14,000 m^2
- Range: 1,700 to 134,000 m^2

BASE Buildings: Year of Construction



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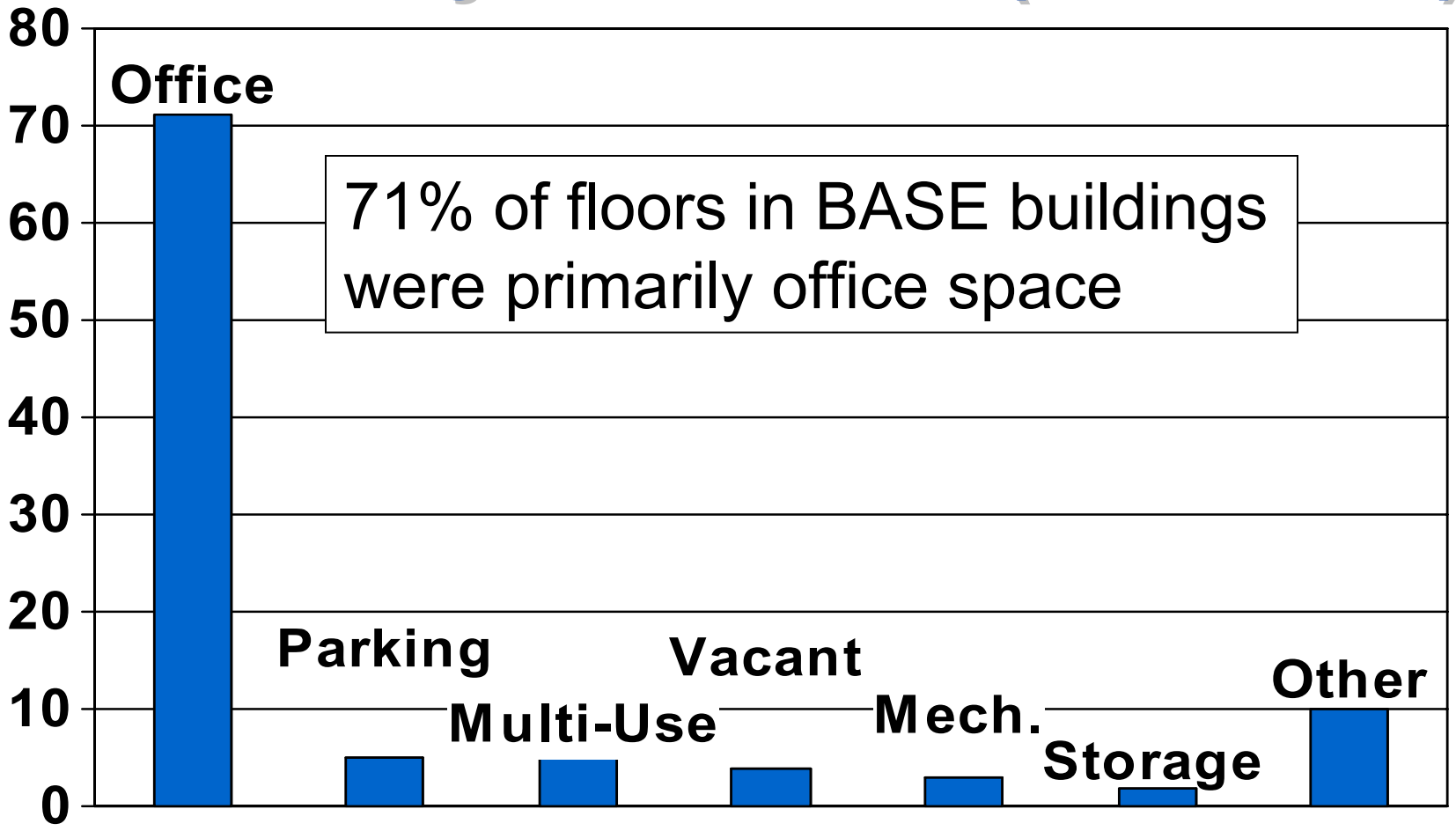
BASE Buildings: Primary Floor Use (% Floors)



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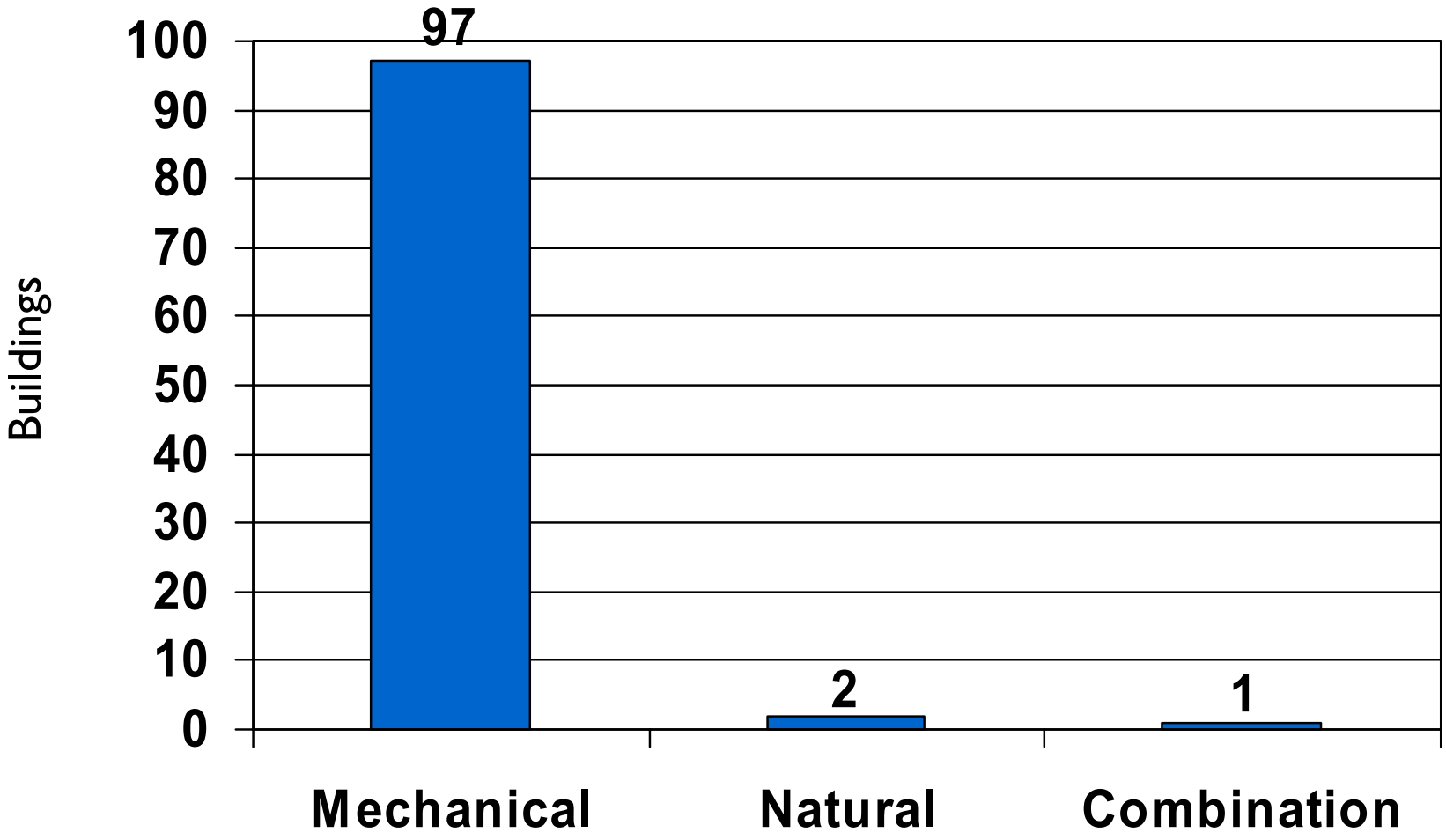
BASE Buildings HVAC



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BASE Buildings HVAC: Common Configurations

Cooling & Heating Equipment:

- **Primary:**
  - **Ducted Air Distribution**
  - **Central Systems w/ Coils**
  - **Chillers / Steam Boilers**
- **Secondary:**
  - **Individual Room AC**
  - **Split AC Systems**
  - **Electric Baseboard Heat**

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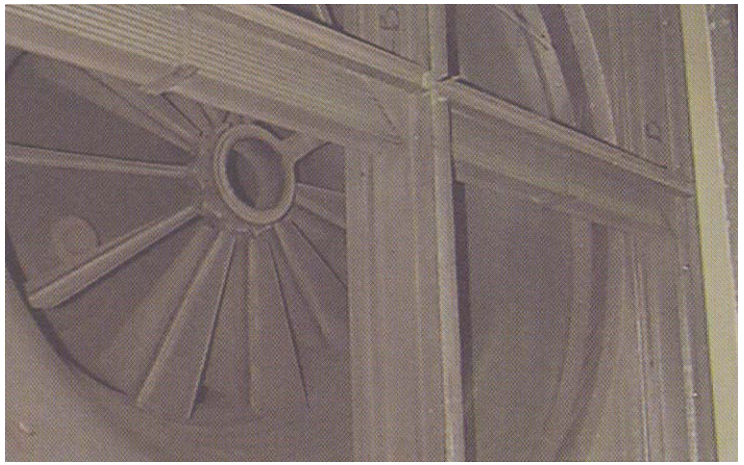
BASE Study Space HVAC Characteristics

- **141 air handling units (AHUs) characterized for mechanically-ventilated study spaces:**
  - **Constant-Air-Volume: 50**
  - **Variable-Air-Volume: 91**



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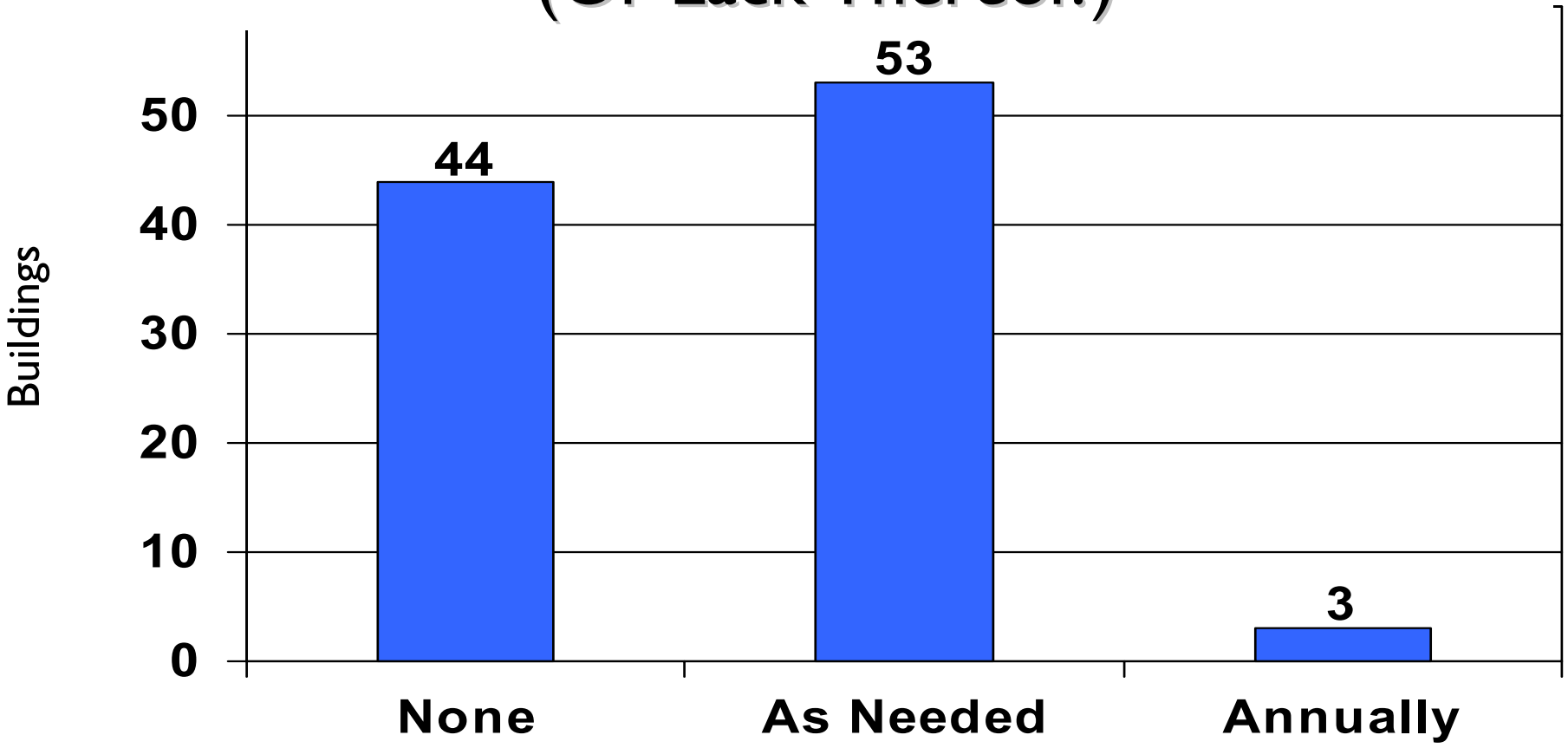
BASE Study Space HVAC: Outdoor Air Control Strategies

- **Outdoor Air Intake Control Strategy (# study spaces):**
  - **Economizer (Temp or Enthalpy): 71**
  - **Fixed Min. Outdoor Air Intake: 73**
  - **100% Outdoor Air: 5**
  - **Building Pressure Control: 4**

BASE HVAC Maintenance: Frequency of Test & Balance

(Or Lack Thereof?)



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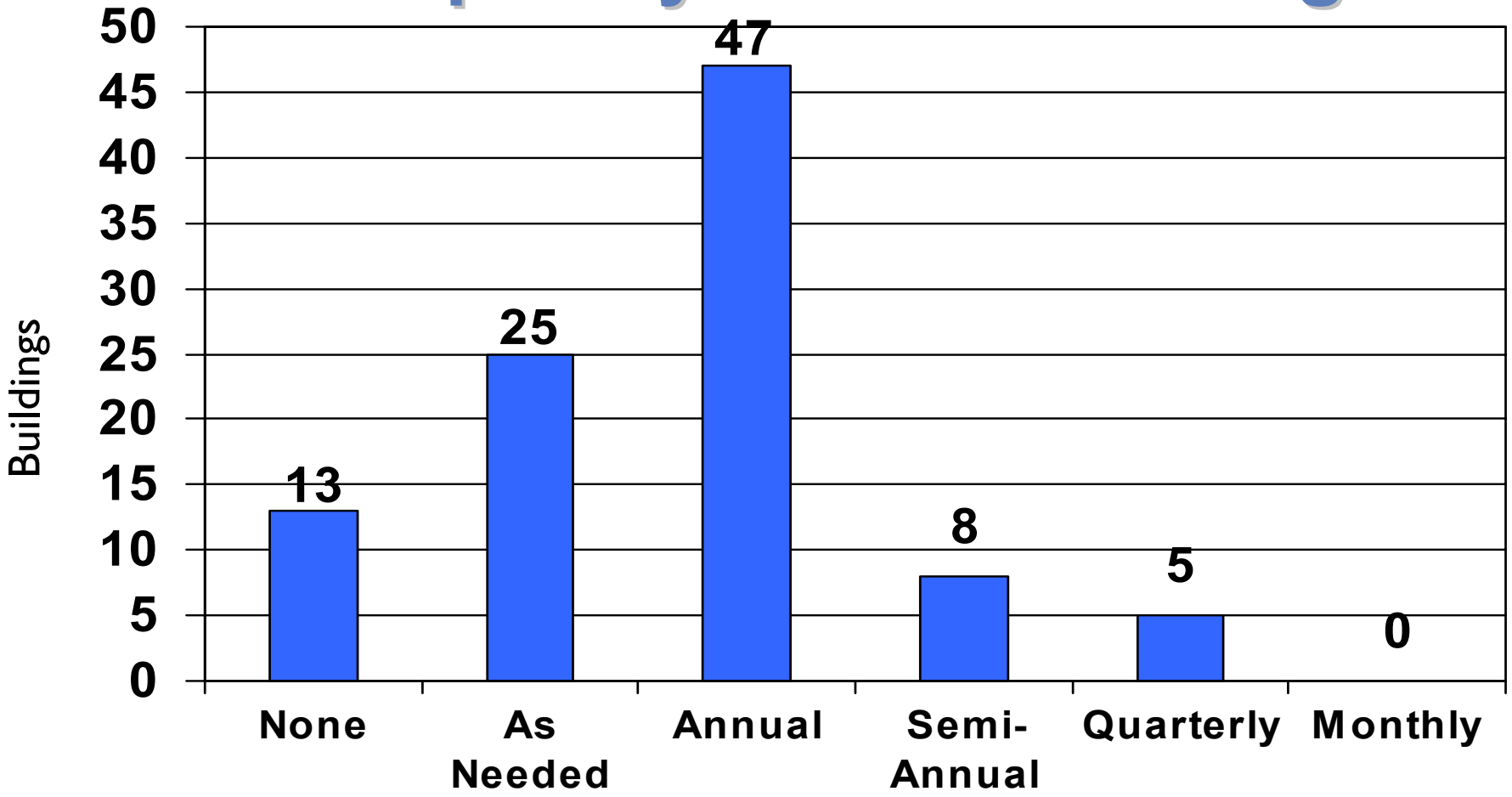
BASE HVAC Maintenance: Frequency of Coil Cleaning



Results

- BASE: 5 workstations/100 m^2 density
- ASHRAE 62.1: 5 occupants/100 m^2 (default)
- Lack of design information available at many BASE buildings
  - Design minimum outdoor flows available for only about half of the air handlers
- Many buildings don't have routine maintenance

Every Building Is Different!

Outdoor Air Intake via Bell Tower

One-Story Building, No Windows

Below-Grade (-3 m) Outdoor Air Intake, Covered w/ Leaves

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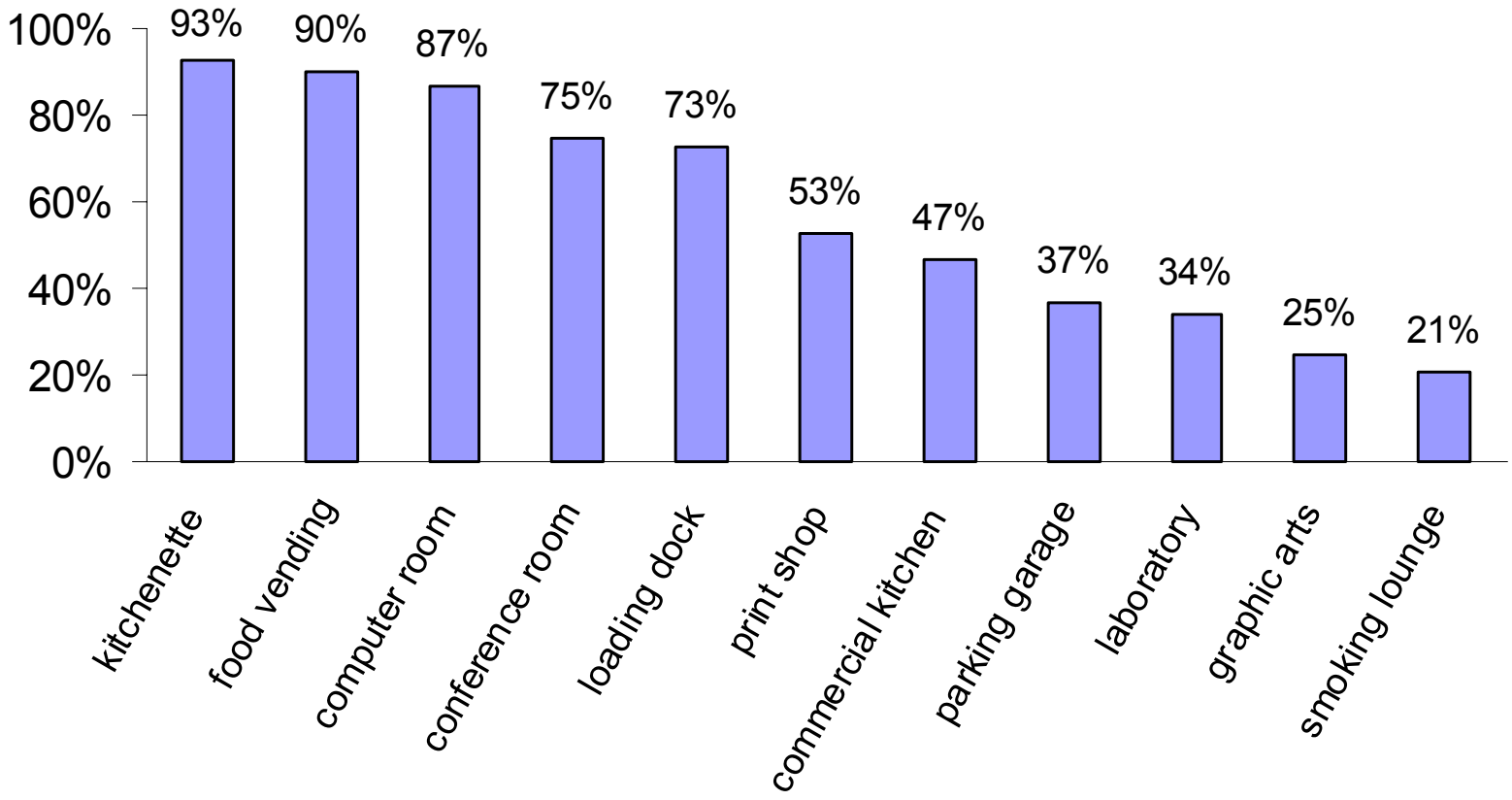
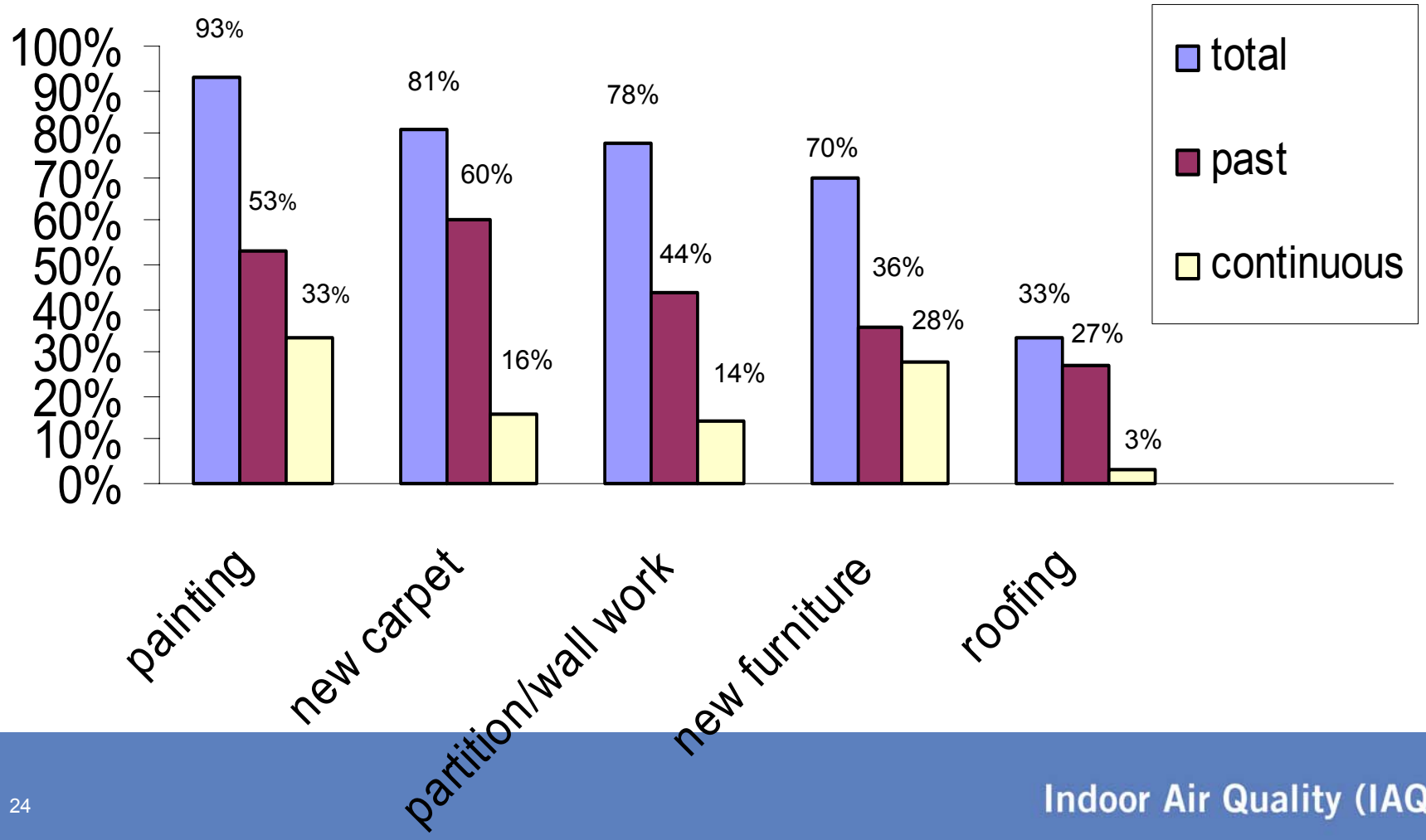
Special Use Areas in BASE Buildings

Prevalence Reported

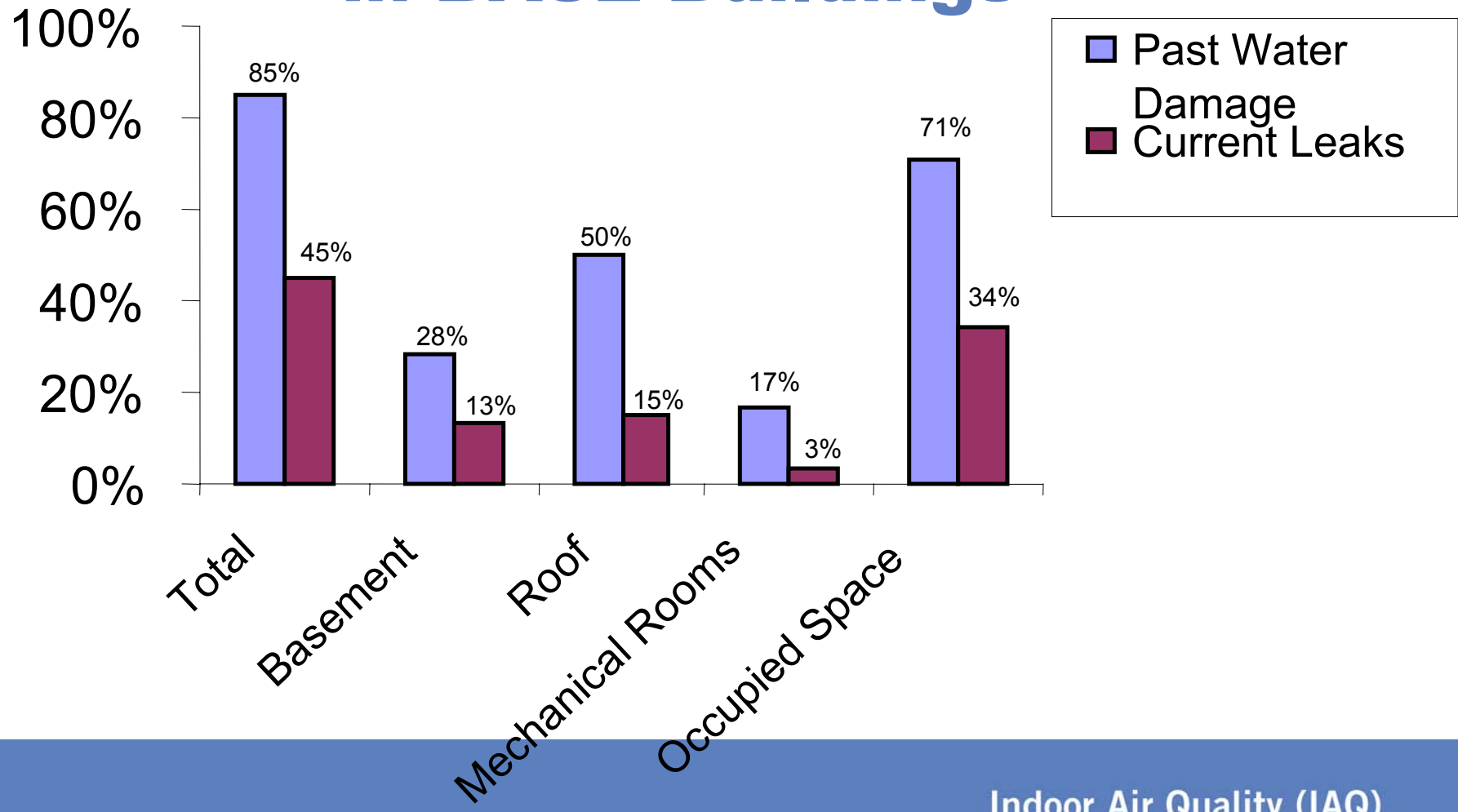


Renovation in BASE Buildings

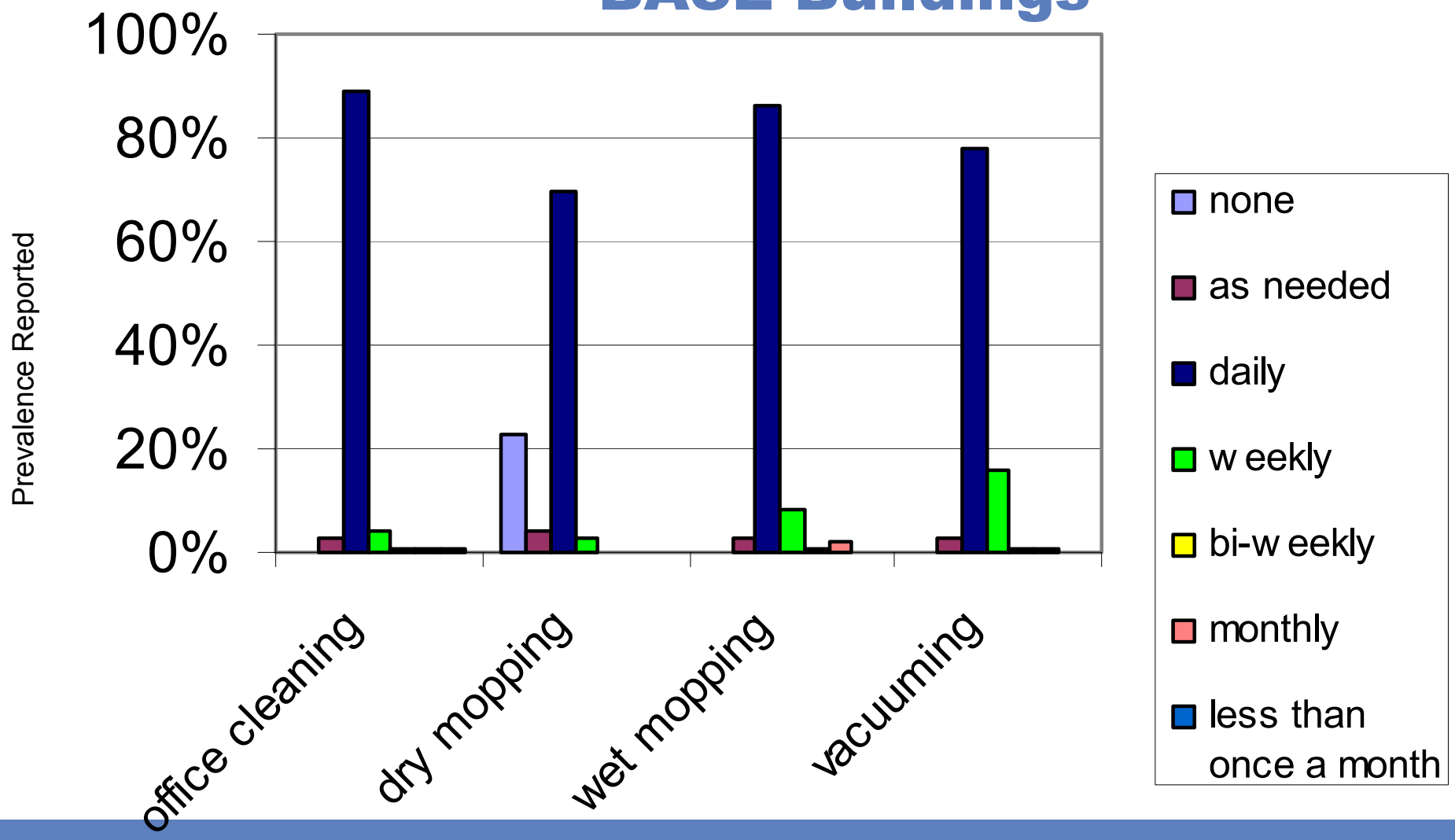
Prevalence Reported



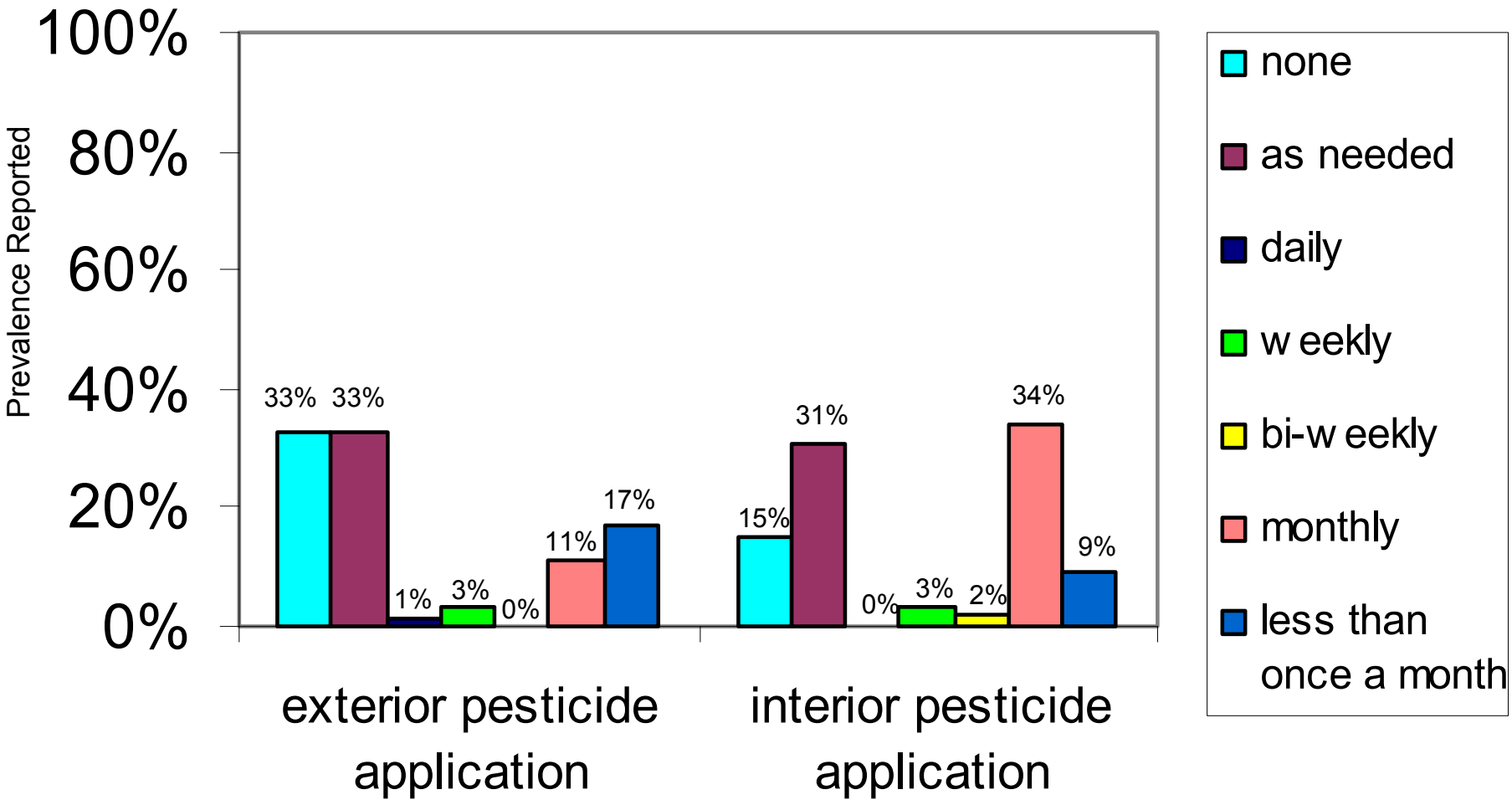
Water Damage and Current Water Leaks in BASE Buildings



Frequency of Office Cleaning in BASE Buildings



Frequency of Pesticide Application in BASE Buildings



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Conclusions

- Study provides numerical prevalence data on indoor sources useful for modelers, building designers and for policy makers
- Office buildings contain many potential sources
  - 34% contained laboratories; 47% contained commercial food preparation
  - Many buildings renovated nearly continuously (3-33%)
  - Water damage is common (45% have current leaks)
  - Most cleaning occurs daily; high prevalence of cleaning materials used
  - Monthly pesticide applications indoors are not unusual (34%)
- Data will be useful for focusing research and developing guidance

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Frequency of Quantifiable VOCs in Indoor Air

81-100 % Frequency

(Multisorb; n=56 buildings)

* Acetone
* Toluene
* m,p-Xylenes
* n-Undecane
* Nonanal
* n-Decane
* o-Xylene
* d-Limonene
* Benzene
* 1,1,1-Tricholoro-ethane
* Hexanal
* Ethylbenzene
* 1,2,4-Trimethyl-benzene
* Tetracholorethene
* Phenol
* Ethyl acetate
* 2-Butanone
* Styrene
* TXIB
* 4-Ethyltoluene
* 2-Butoxyethanol
* 2-Ethyl-1-hexanol
* Nonane
* Octane
* Butyl acetate
* n-Hexane
* Pentanal
* 1,3,5-trimethyl benzene
* a-Pinene
* 4-Methyl-2-pentanone
* Texanol 1&3
* Naphthalene
* 1-Butanol

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Frequency of Quantifiable VOCs in Indoor Air

(Multisorb; n=56 buildings)

61- 80 % Frequency

* 1,4-Dichlorobenzene

41-60 % Frequency

* 3-Methyl pentane
* Trichloroethene

21-40 % Frequency

* Methylene chloride
* Trichlorofluoromethane
* t-butyl methyl ether

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Frequency of Quantifiable VOCs in Indoor Air

(Multisorb; n=56 buildings)

1- 20 % Frequency

* Trichloro-trifluoroethane
* Chloroform
* Carbon tetrachloride
* 4-Phenylcyclohexene
* Carbon disulfide
* Chlorobenzene
* 1,2,4-Trichlorobenzene
* 1,2-Dichlorobenzene

VOCs with Highest Indoor Medians

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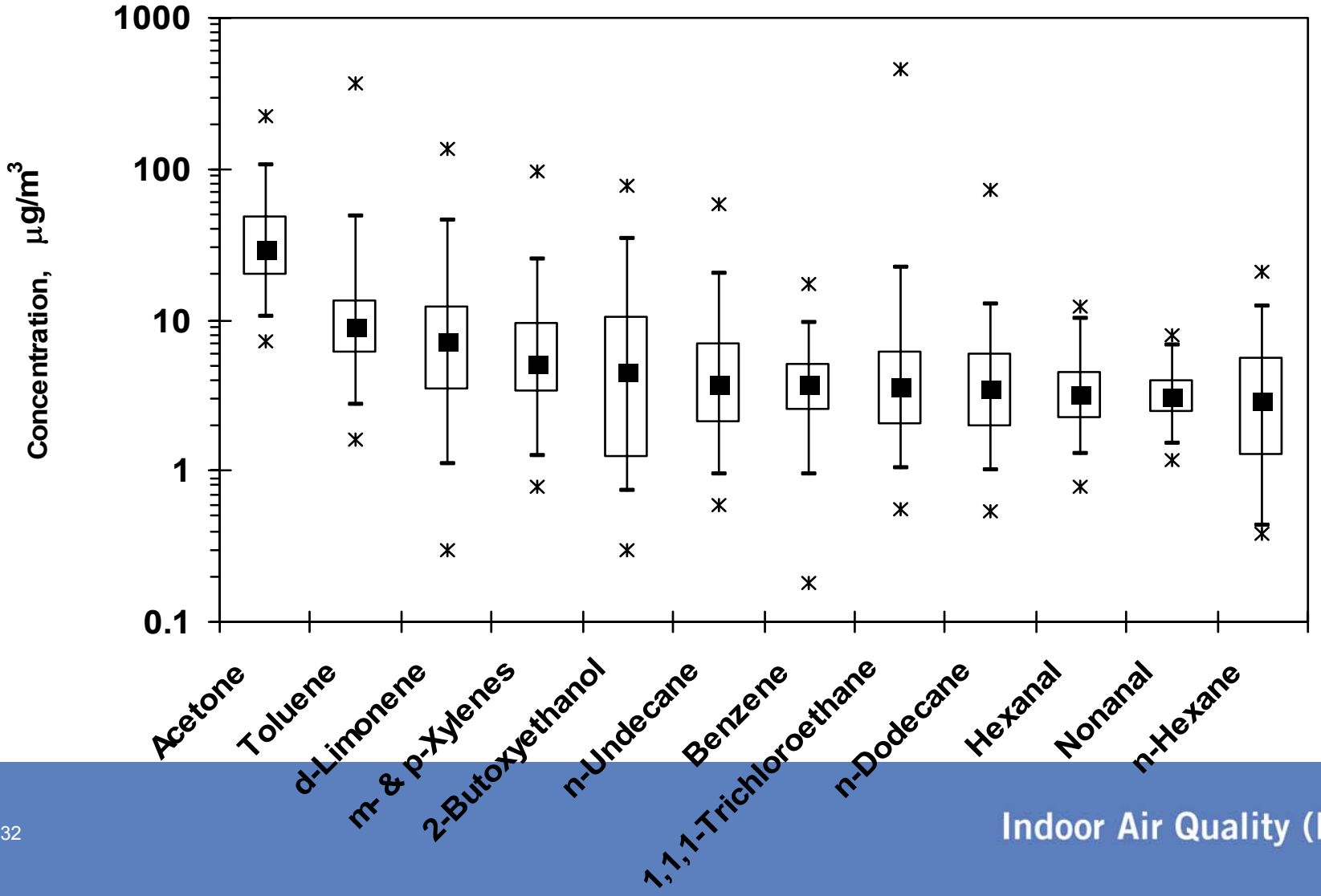
Multisorb n=56

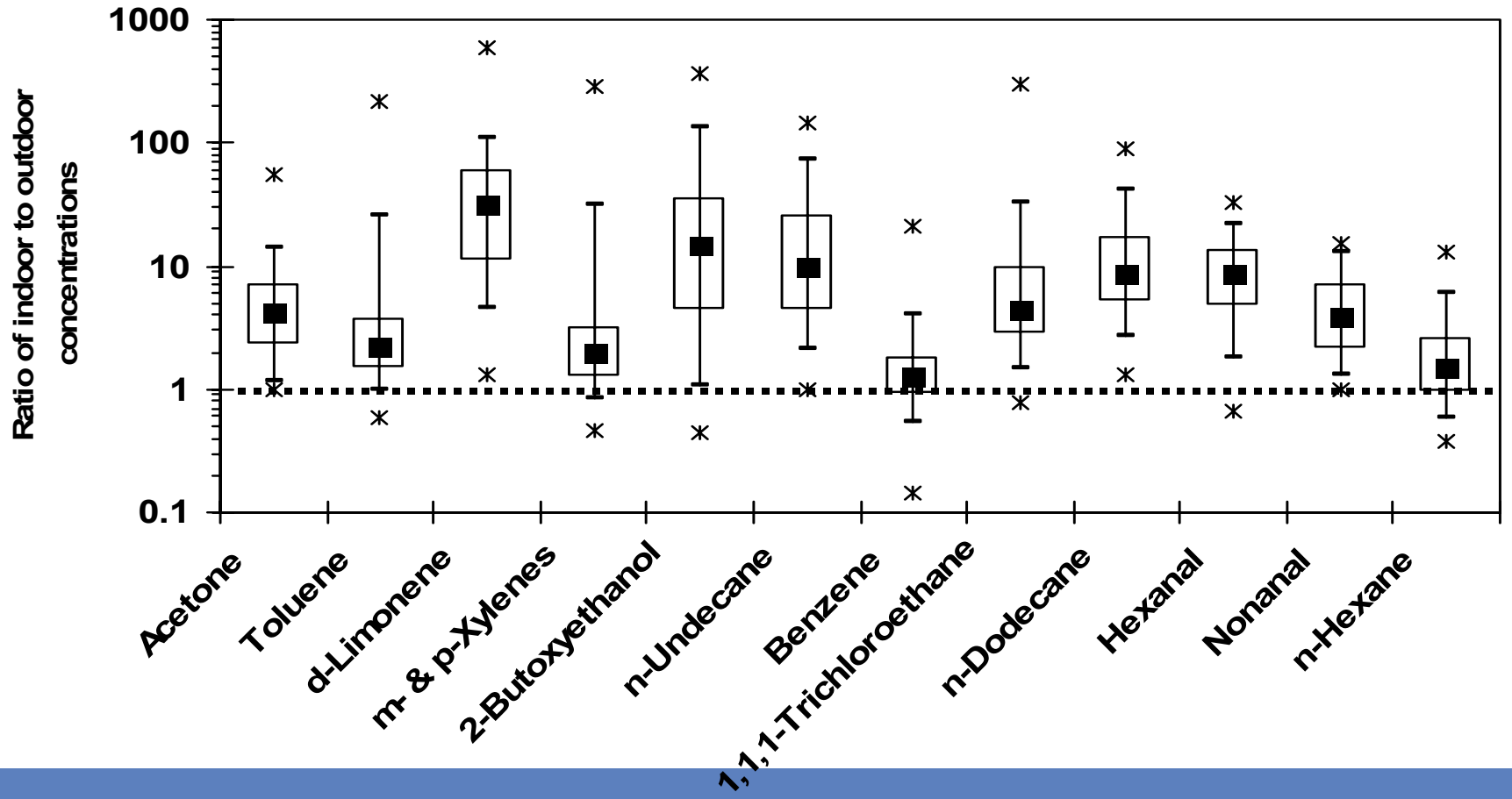
Minimum, 5th, 25th, 50th, 75th, 95th Percentile, and Maximum Concentrations for 12 VOCs



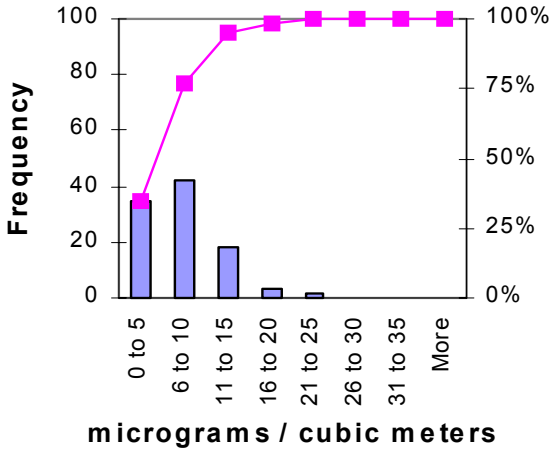
VOCs with Highest Indoor/Outdoor Ratios

Multisorb n=56

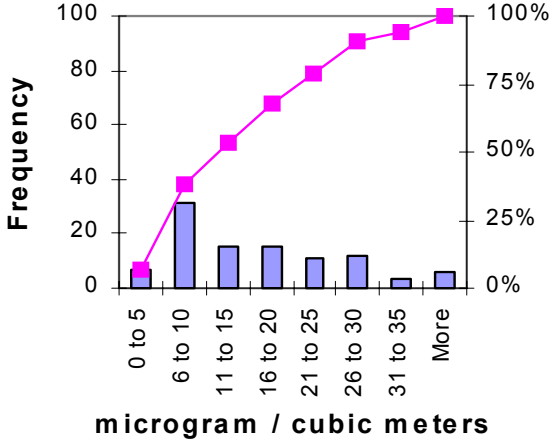
Minimum, 5th, 25th, 50th, 75th, 95th Percentile, and Maximum for Indoor to Outdoor Concentration Ratios for 12 VOCs



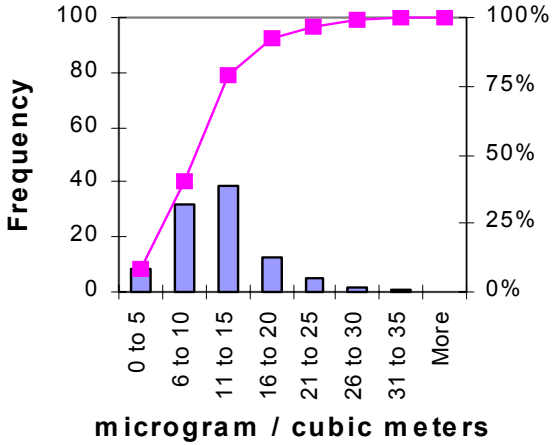
Indoor $PM_{2.5}$



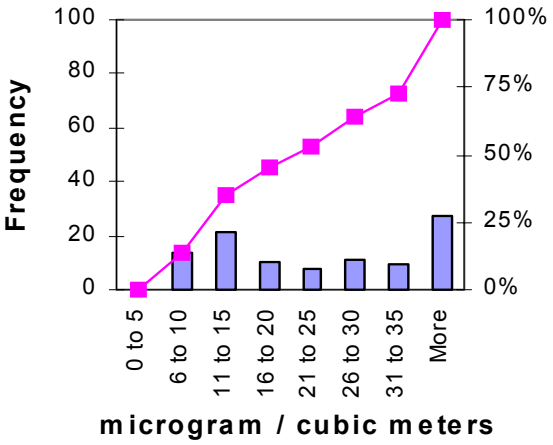
Outdoor $PM_{2.5}$

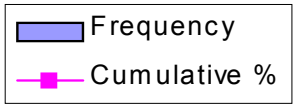


Indoor PM_{10}



Outdoor PM_{10}

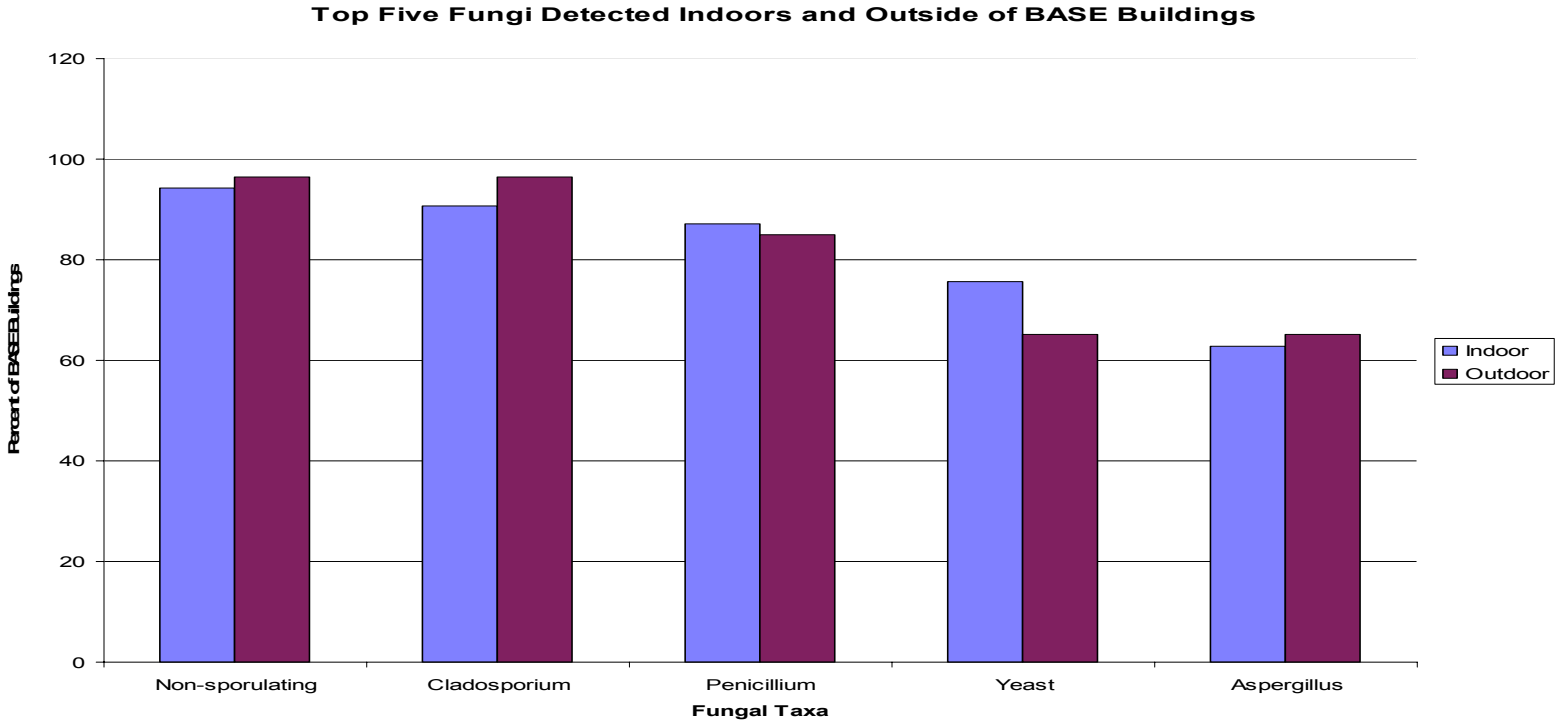




Top Five Fungi Indoors and Outdoors

Distribution of the Concentration in CFU/m^3 of Most Commonly Identified Taxa

Taxa	Indoor Percentiles				Outdoor Percentiles			
	50	75	95	100	50	75	95	100
Non-sporulating	7	14	64	593	28	71	325	6040
Cladosporium	7	28	106	3490	125	446	1410	5370
Penicillium	ND	8	44	763	16	42	166	1130
Yeast	ND	7	22	160	ND	14	88	1270
Aspergillus	ND	ND	14	63	ND	14	64	1130



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BASE Ventilation Data Analysis

- **Ventilation Background**
  - **Ventilation with clean outdoor air is a key component for maintaining good indoor air quality. Ventilation dilutes and removes contaminants generated by occupants and building-related sources.**
  - **American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) Standard 62-2001 recommends a minimum outdoor air ventilation rate of 20 cubic feet per minute (cfm) per person in offices.**

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BASE Ventilation Data Analysis

- **BASE protocol for outdoor air ventilation in study spaces**
  - **Collection of HVAC design data**
  - **Direct measurements of airflow quantities for air handlers serving study spaces (e.g., outdoor air intake, supply airflow), where possible, using a "velocity traverse" in the ductwork**
  - **Carbon dioxide (CO_2) measurements in HVAC air streams to enable estimation of percentage of outdoor air relative to total supply airflow, and subsequent calculation of outdoor airflow quantity.**

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BASE Ventilation Data Analysis

- **In-depth analysis of BASE ventilation data in NIST report: (http://www.bfrl.nist.gov/pdf/BASE-final.pdf)**
- **Outcomes of NIST effort include:**
  - **Analysis of ventilation performance parameters (outdoor air intake, supply airflow, etc.) for each BASE study space.**
  - **Comparison of ventilation parameters determined by different methods (i.e., direct measurements vs. calculated from CO_2 measurements).**
  - **Comparison of outdoor air ventilation rates to design values and industry standards.**

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BASE Ventilation Data Analysis

Some key findings from NIST analysis

- 97 of the monitored building spaces were mechanically-ventilated, three buildings were naturally-ventilated
  - Five study spaces had 100% outdoor air systems
- Design data confirms some common expectations
  - Supply airflow rates (1 cfm supply air / ft^2 floor area)
  - 10-20% minimum outdoor air
- Over 70% of the study spaces had air handlers equipped with economizers to provide "free-cooling" by increasing outdoor airflow during mild weather
- Lack of system design information on-site
  - Design minimum outdoor airflows only available for about half of the BASE study space air handlers

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BASE Ventilation Data Analysis

Some key findings from NIST analysis (cont.)

- Average outdoor air ventilation rate were higher than expected on a per person basis but about what would be expected for air change rates

Measured Outdoor Air Ventilation in Study Spaces

	cfm/person	cfm/ft^2	Air Changes/Hr.
No. of Values	367	369	369
Mean	105	0.40	2.00
Median	63	0.20	0.98
Std Dev	158	0.50	2.45

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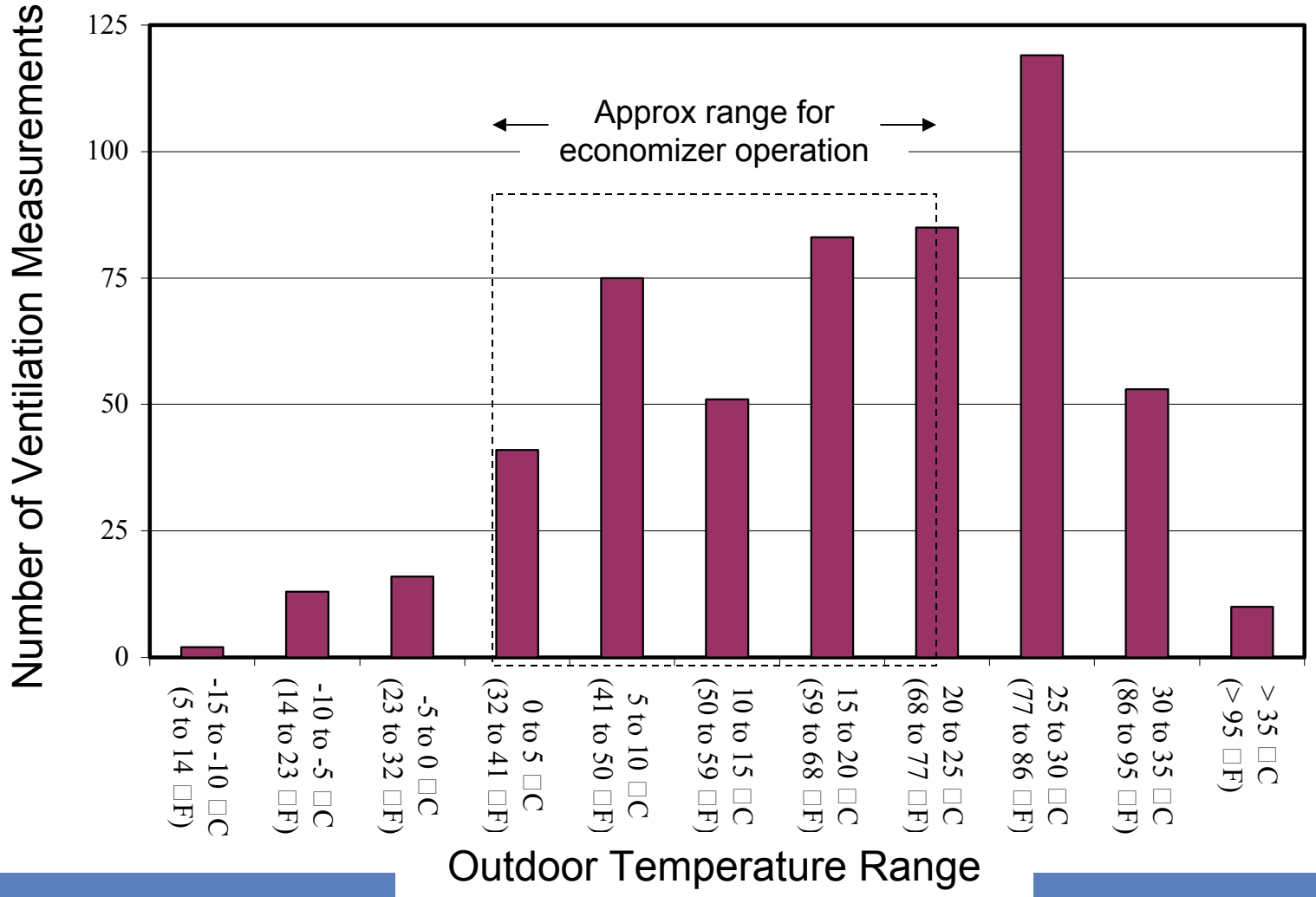
BASE Ventilation Data Analysis

- **Average outdoor air ventilation rate per person higher than expected**
  - **BASE protocol specified study weeks during either winter or summer; attempt to reduce daily weather variations**
    - **NIST analysis showed significant number of BASE measurements occurred during mild or moderate outdoor air temperatures (e.g., 32-70°F)**
    - **Result was increased outdoor air intake rates in systems equipped with economizers providing "free-cooling"**
    - **Average was about 40% outdoor air compared with 10-20% outdoor air that is typical under minimum intake conditions.**

Outdoor Temperature During BASE Evaluations



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BASE Ventilation Data Analysis

- **Average outdoor air ventilation rates (cfm/person) were also higher than expected due to reduced occupancy in study spaces**
  - **Less than 80% of workstations were occupied during study periods, on average.**

- **NIST adjusted the data to approximate minimum outdoor air intake conditions and 100% occupancy; revealed outdoor air ventilation rates closer to ASHRAE 62-2001:**

Adjustment	Based on # Occupants	Adjusted to # Workstations	Adjusted to # Workstations and Minimum Outdoor Air
Average Study Space Outdoor Air Ventilation Rate (cfm/person)	105	76	26

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BASE Ventilation Data Analysis

- Although average outdoor air ventilation rates were higher than expected, many study spaces had ventilation rates at or below ASHRAE 62-2001 recommendation of 20 cfm/person.
- For 42 study spaces at or near minimum outdoor air intake conditions (with less than 20% outdoor air):
  - Average ventilation rate was 22 cfm/workstation
  - About 50% of ventilation values were less than 20 cfm/workstation
  - About 25% of values were less than 10 cfm/workstation.

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BASE Ventilation Data Analysis

Other findings from NIST analysis

- Outdoor air ventilation rates calculated from CO_2 levels measured in HVAC air streams agree fairly well with those determined by direct airflow measurements, but with higher data uncertainties
- Many systems had measured airflows significantly different from design values; stresses importance of commissioning and re-commissioning
  - About 40% of systems with design data available had a measured outdoor airflows < design
  - 44% of buildings reported not performing HVAC testing and balancing
- About 20% of air handlers did not have direct measurements of outdoor airflow
  - Outdoor airflow based on (supply – recirculation) airflows
  - Access to intakes and ductwork for airflow measurements is an important design consideration

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BASE Ventilation Data Analysis

Additional work is needed to assess the potential for using peak CO_2 levels in occupied study spaces to estimate outdoor air ventilation rates (steady-state mass balance approach)

- **Analysis showed significant discrepancies between this approach and the other analytical methods examined for ventilation.**
- **Many critical assumptions not adhered to in the measured data (e.g., not steady-state conditions, variable occupancy, non-uniform CO_2 levels in the space, etc.)**

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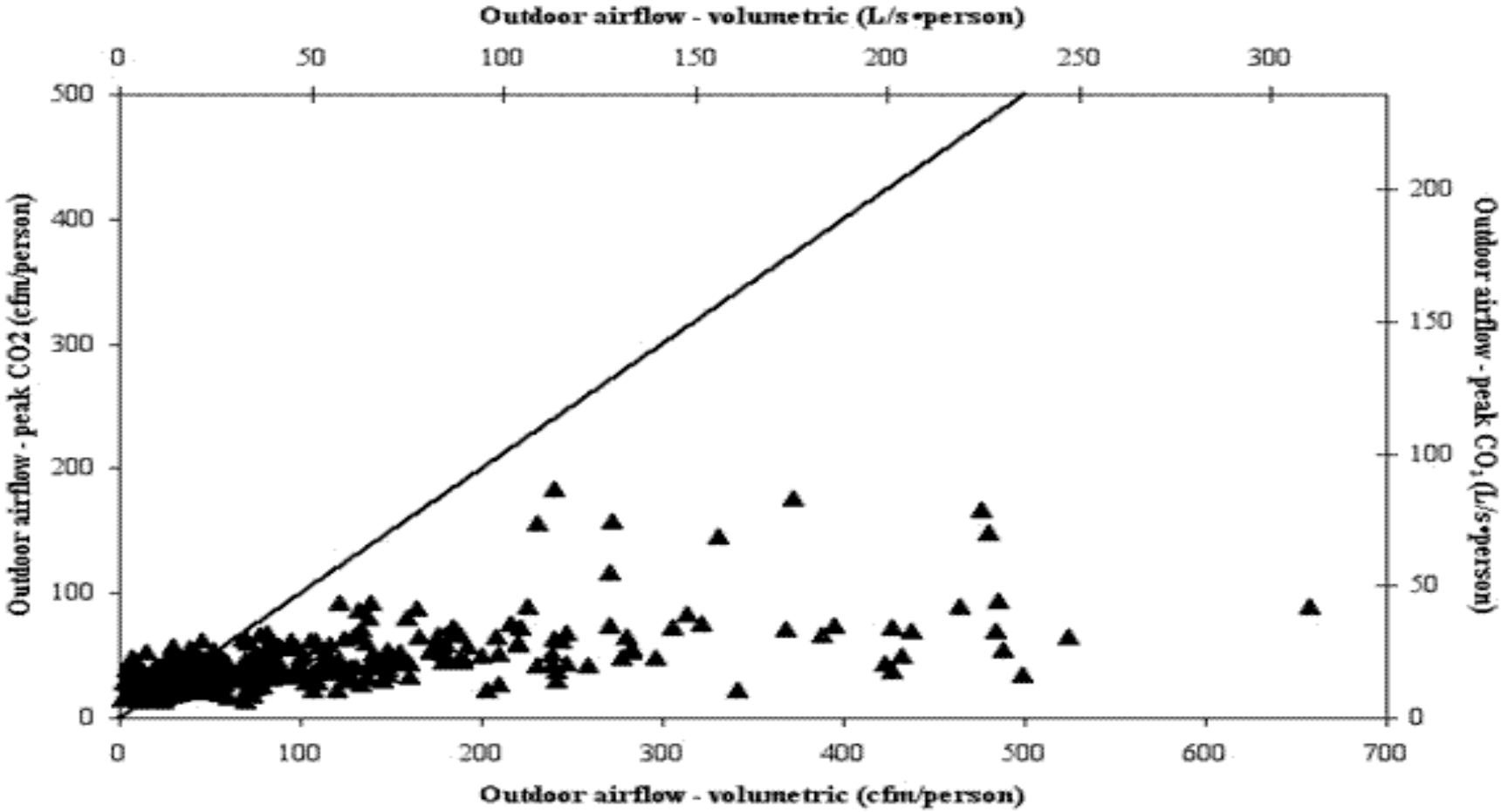
Ventilation: Peak Indoor CO_2 vs. Volumetric Traverse

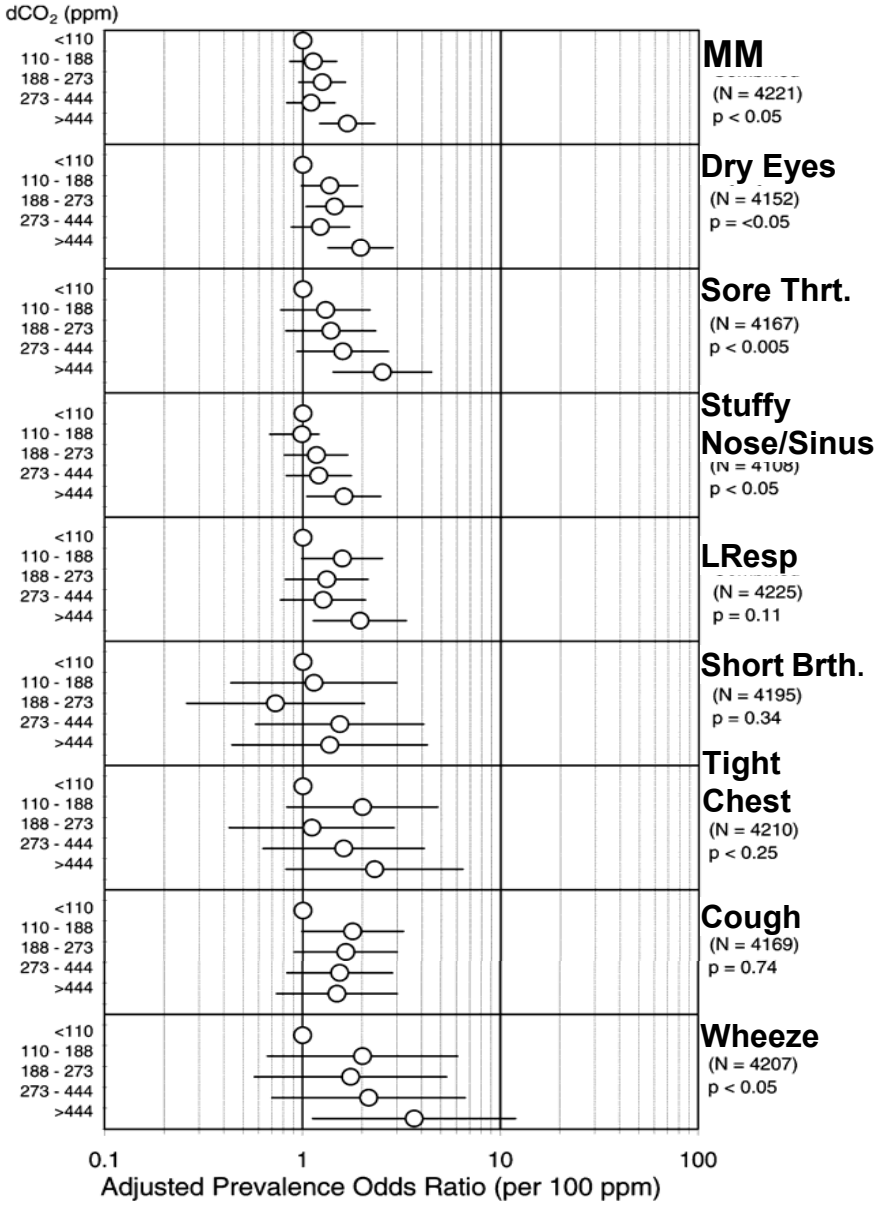


MLR Results: Exposure-Response

- Adjusted[a] analyses of trend used to identify exposure-response relationships between dCO_2 and symptoms
  - **Four elevated CO_2 concentration ranges vs. control**
- Statistically significant ($p < 0.05$) exposure-response relationships with increasing dCO_2 (except for cough)

[a]Adjusted for age, gender, presence of carpet in workspace, smoking status, thermal exposure, RH, and 1,2,4-TMB and SENSITIVE[e].

Adapted from Apte, 2000, 2002



PCA-derived VOC Exposure Metrics and SBS Symptoms

Adjusted Prevalence Odds Ratios[a] (Standardized Units)

SBS Symptom /covariate	Tentative source attribution	MM	Dry eyes	Sore Throat	Stuffy nose /sinus	LResp	Chest tight	Short breath	Cough	Wheeze
dCO_2 [b]	Occupant respiration	**1.07**	**1.07**	**1.17**	**1.09**					**1.24**
PC1	Motor vehicle emissions							**1.33**		
PC2	Furniture or wood product coatings									
PC3	Vinyl products or carpets	**1.08**	**1.08**					**1.21**		
PC4	Printing processes, printed materials									
PC5	Air fresheners	**0.89**				**0.84**			**0.82**	
PC6	Unassigned	**0.91**			**0.86**					
PC7	Cleaning products, deodorizers									

19 VOCs: 100 Buildings

[a]$p<0.05$; [b]per 100 ppm

- ORs from PCA derived from standardized data
- Unitless: should be interpreted with caution

from Apte 1999

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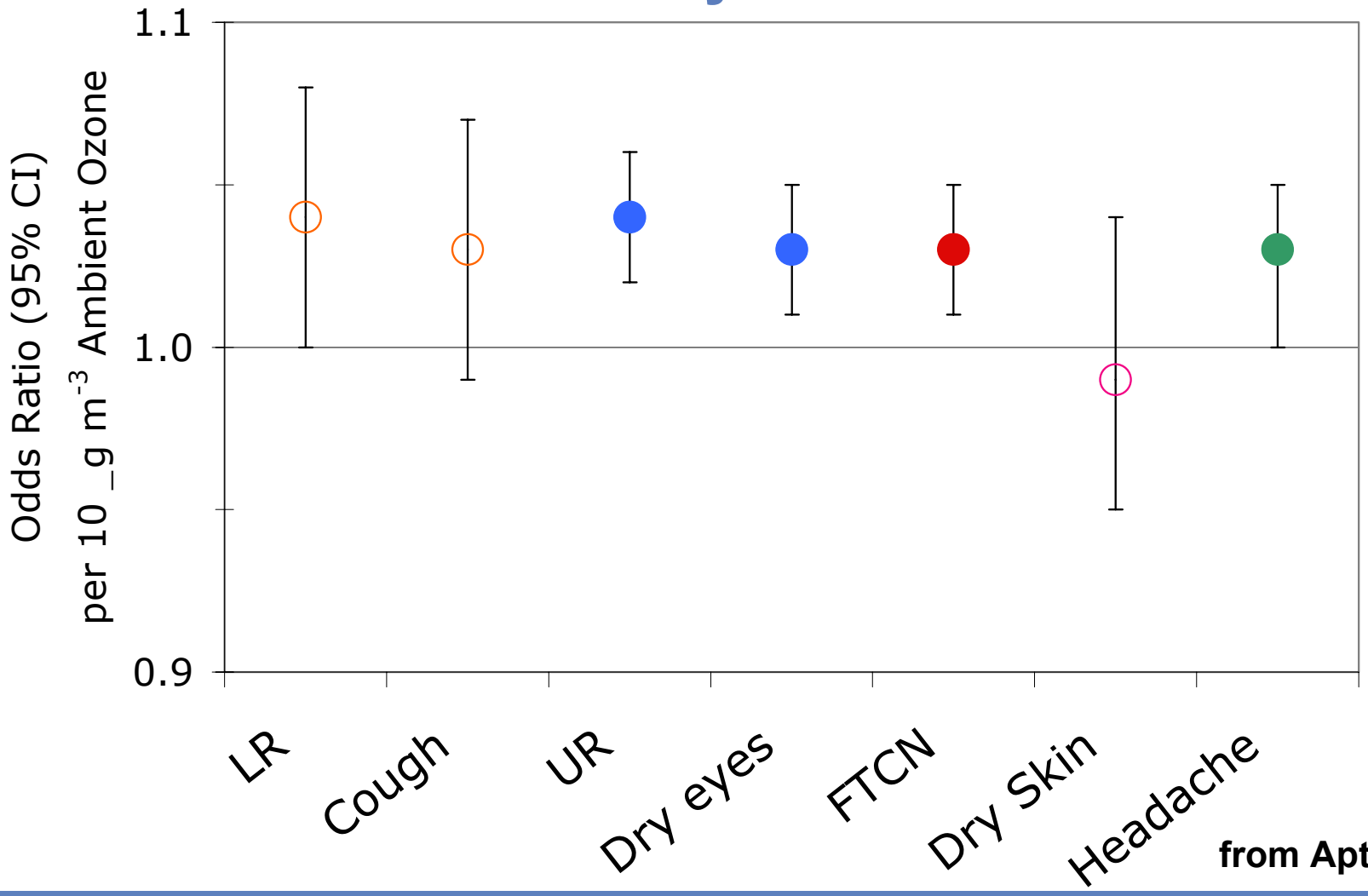
BRS & Outdoor Ozone

- Known products of indoor ozone chemistry identified in VOC data
  - Formaldehyde, acetaldehyde, pentanal, hexanal and nonanal
  - showed fairly large positive correlations with ozone
  - these compounds are known sensory irritants and some are known carcinogens
- Reducing entrained ozone
  - to BASE lowest ozone level (4.9 μg m^{-3})
  - assuming causality
  - could reduce upper respiratory, dry eyes, neurological and headache BRS by 45%, 35%, 35% and 33%, respectively
- Interpret with caution

from Apte, 2007

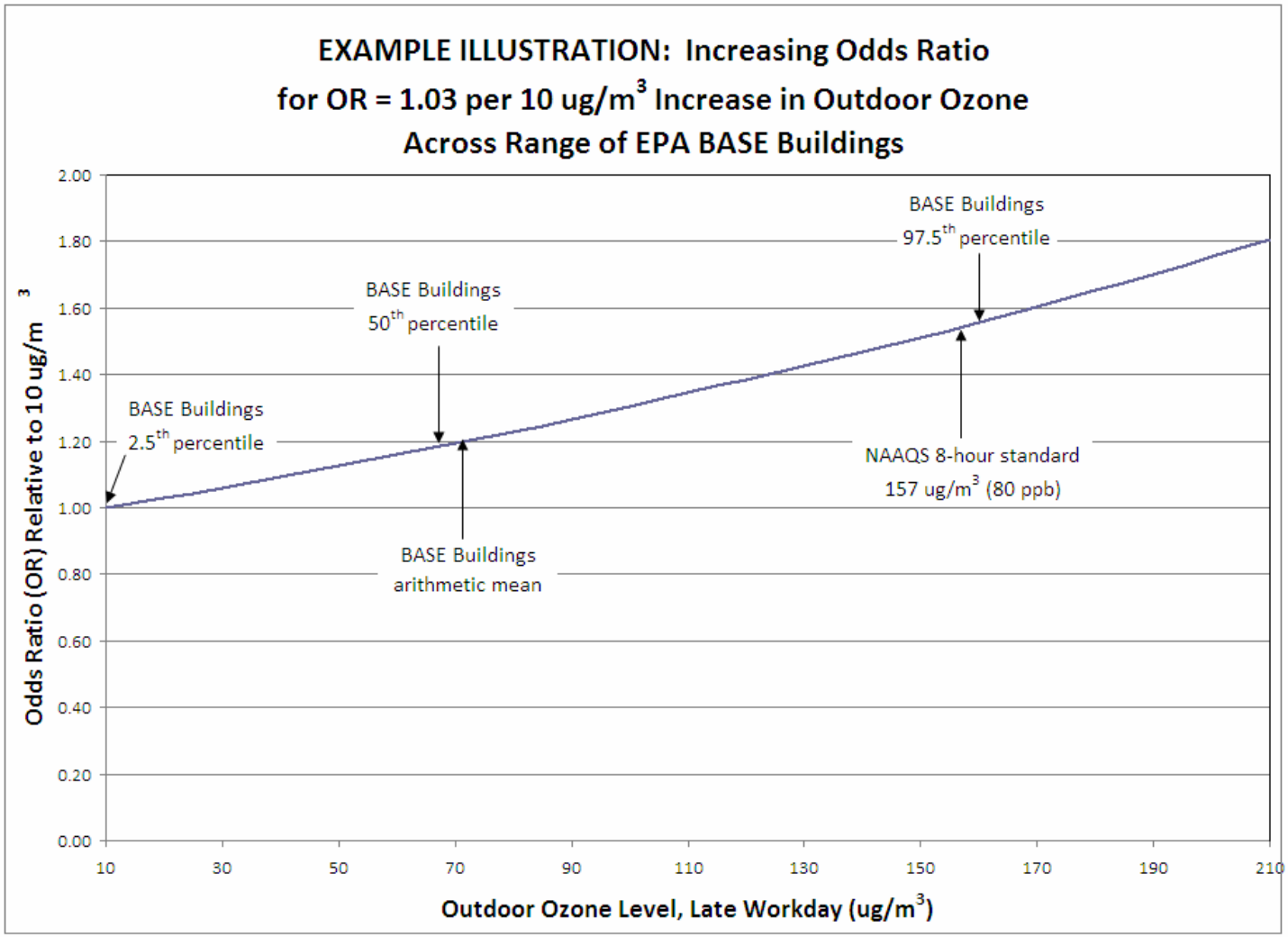
Multivariate BRS Risk per 10 μg m^{-3} Late Work Day Outdoor Ozone



from Apte, 2007

Solid circles statistically significant at 95% confidence level

Multivariate BRS Risk
Late Work Day Outdoor Ozone



from Apte, 2007; Brunner

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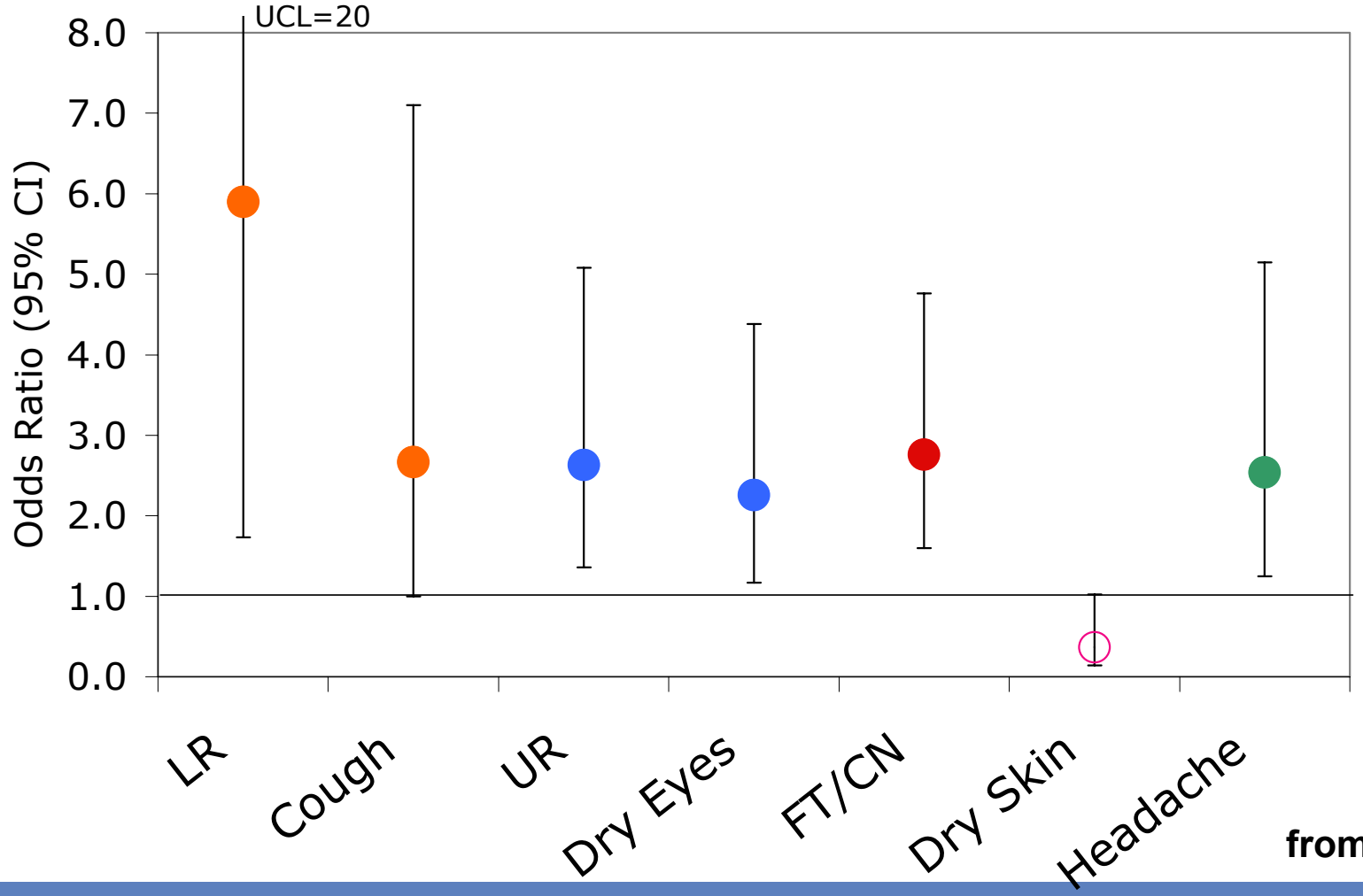
Filters in BASE Buildings

- Most common types of single filter materials
  - fiberglass
  - polyester
  - synthetic
- Most common blends of filter materials
  - cotton-polyester
  - cotton-synthetic
- Final Model
  - polyester/synthetic filter material vs. fiberglass filter - 34 Buildings
  - High and low ozone concentrations

from Apte, 2007

Joint Risk
Ozone >67.6 μg m^{-3} and Poly/Syn Filters



from Apte, 2007

Solid circles statistically significant at 95% confidence level

EPA United States Environmental Protection Agency

Ozone-filter discussion

- Polyester/synthetic filter materials & higher ozone highly, significantly associated with higher BRS
- Suggests that outdoor ozone mitigation and proper filter selection
  - Reduce BRS 30% to 60% in buildings
- Possible mitigation strategies
  - Reduce ambient ozone, e.g., Clean Air Act
  - Outside air cleaning for HVAC systems
  - Appropriate HVAC filter selection –> research needed

from Apte, 2007

EPA United States Environmental Protection Agency

Conclusions

- BASE data strongly suggest IAQ link with BRS
- Sensitive individuals have additional risk
- Increased ventilation rates per person (dCO_2) decreases BRS
- Outdoor ozone increases are associated with increased BRS
- Identified indoor VOC sources ~ BRS
- Ozone-initiated chemistry a likely cause of symptoms
- Ozone interactions with HVAC system materials is a likely factor in causation of BRS (filter example)
- Caution: more research needed to confirm causation

from Apte

EPA United States Environmental Protection Agency

Summary

- Protocol developed for the study of IAQ in large office buildings
- Extensive data on U.S. office buildings are now available
- Data are useful for modeling, analysis and developing policy on buildings and IAQ
- Information, data summaries and publications are available at www.epa.gov/iaq/base