How to interpret indoor pollutant measurements

Hal Levin

Building Ecology Research Group

Where and How and What you Measure
Evolution of IAQ measurements 1978-2013

- **Organic chemicals**
  - **TVOC (non-methane hydrocarbons?)**

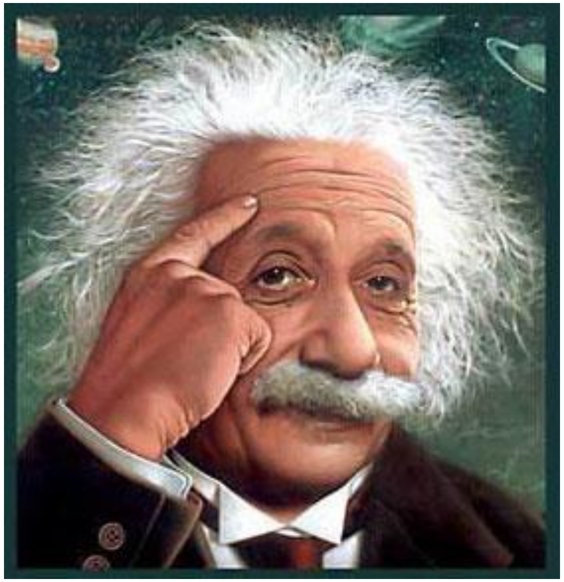
  IVOC

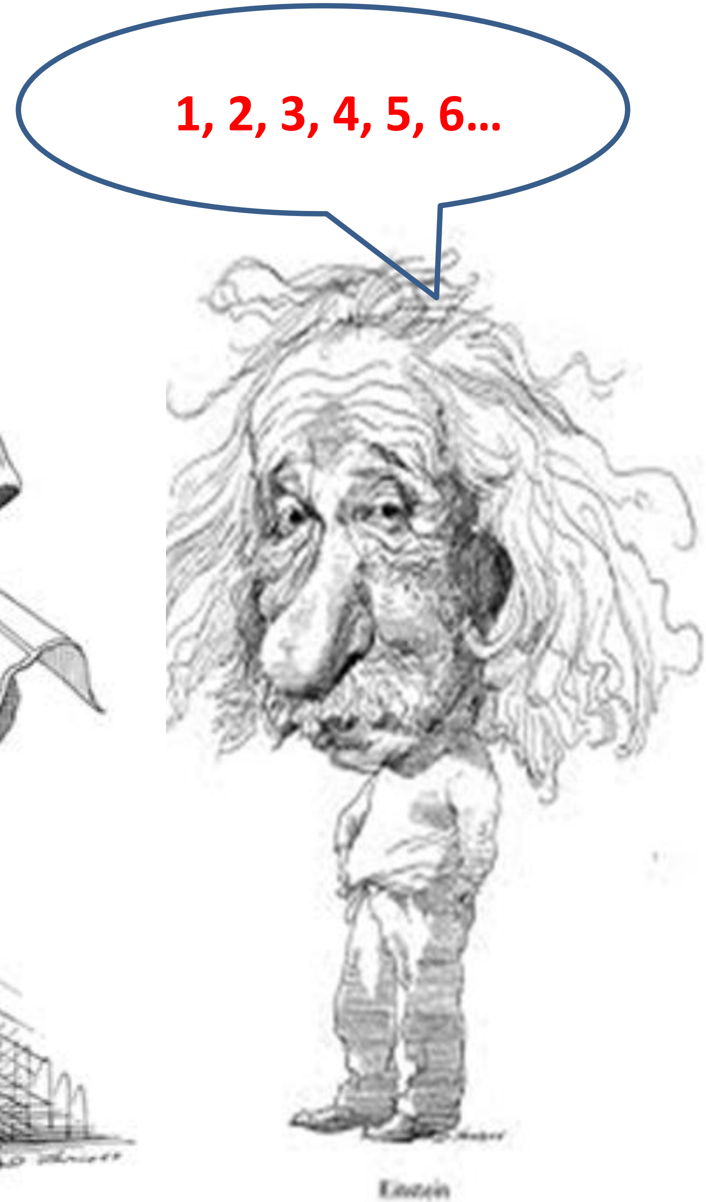
  PAH

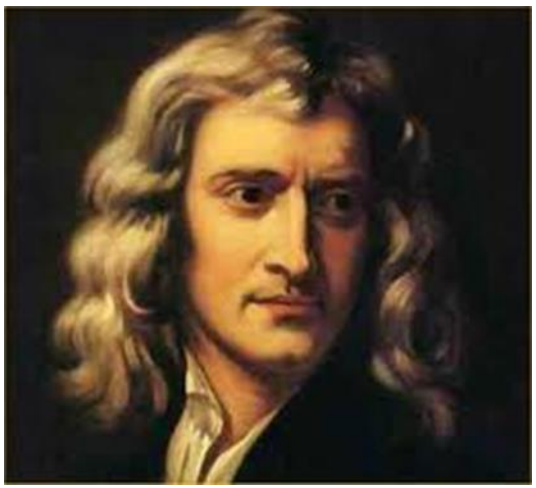
  SVOC

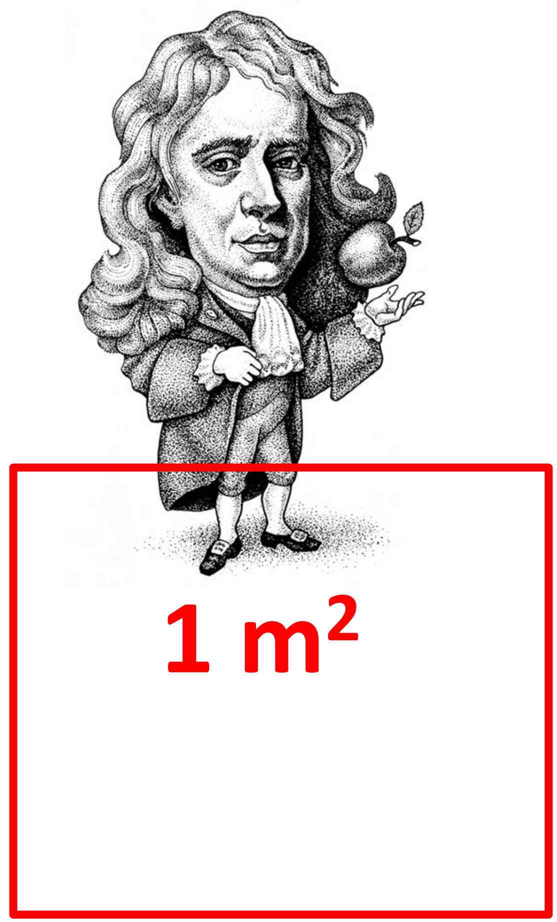
  VVOC
- **Microbes**
  - **CFU/m^3**
  - **OTUs**
  - **Relative abundance**
- **Particles**
  - **Mass/volume**
  - **Number**

Three famous scientists (Einstein, Pascal, and Newton) are playing "hide and go seek"




1, 2, 3, 4, 5, 6…

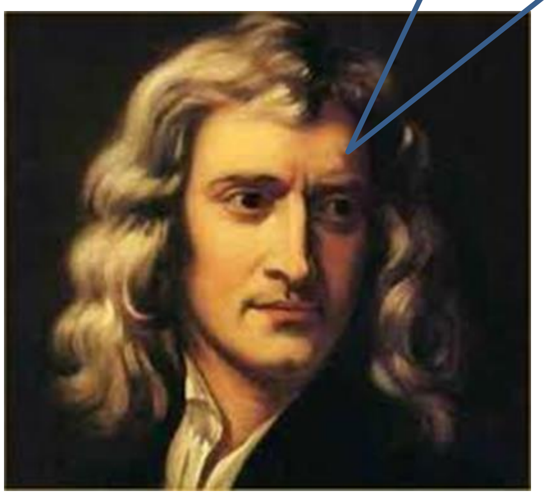


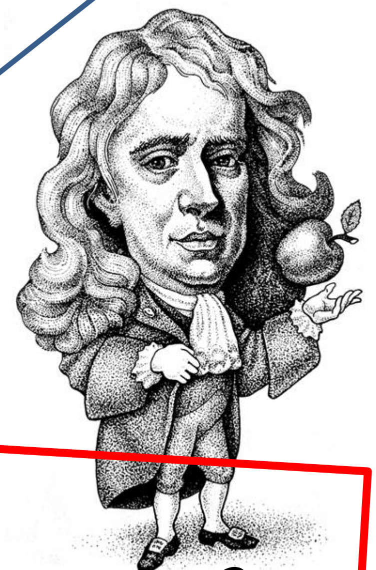

1 m²

I caught you, Newton!

No you didn't. You caught 1 pa.

1 Newton/m^2 = 1 Pascal





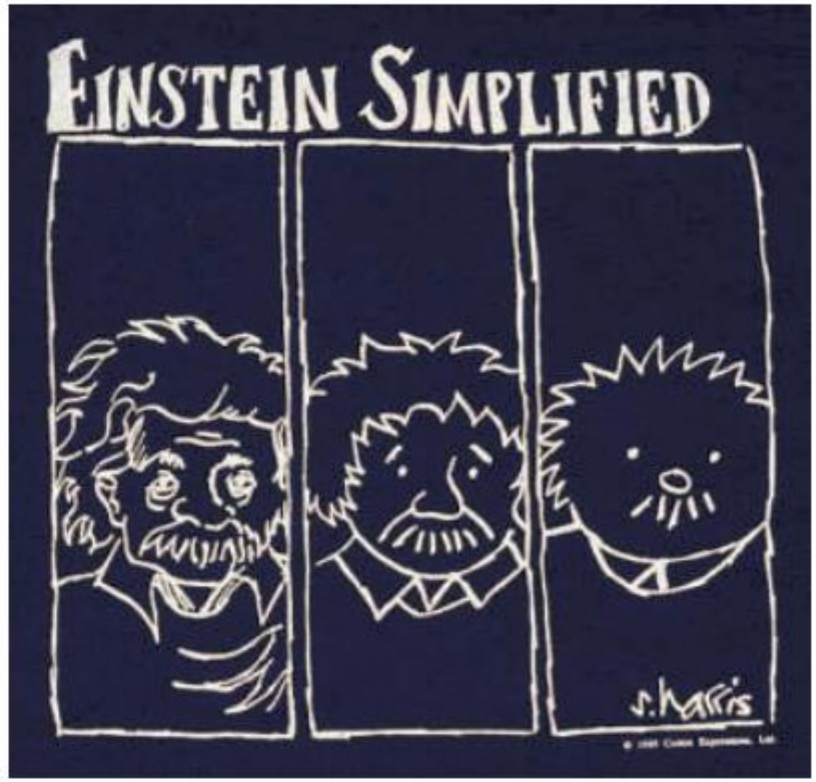
1 m^2

=

A Philosophical Point

"Everything should be made as simple as possible, but not simpler."

— Albert Einstein



Slide courtesy of William W Nazaroff

Inherently complex subject

- People (~ 10^{10})
- Buildings (~ 10^{9})
- Contaminants (~ 10^{5}) (?)
- Environmental conditions

- Many aspects are dynamic and interconnected through natural, technical, and social feedback loops.


Portland, Oregon (2010)

Slide courtesy of William W Nazaroff

What is the purpose of the measurement?

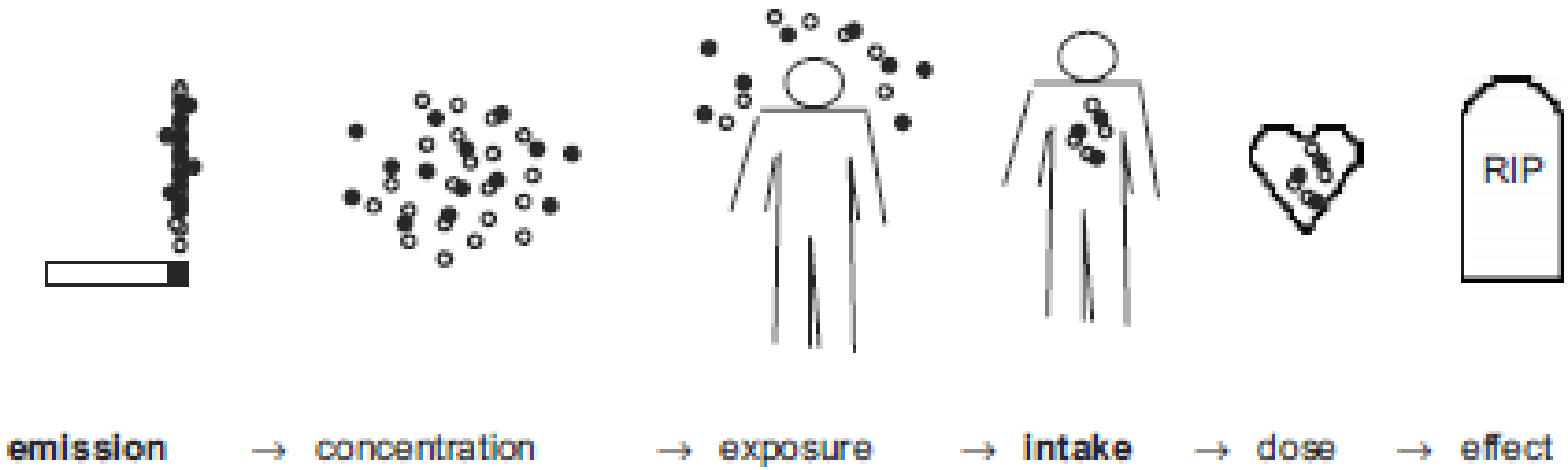
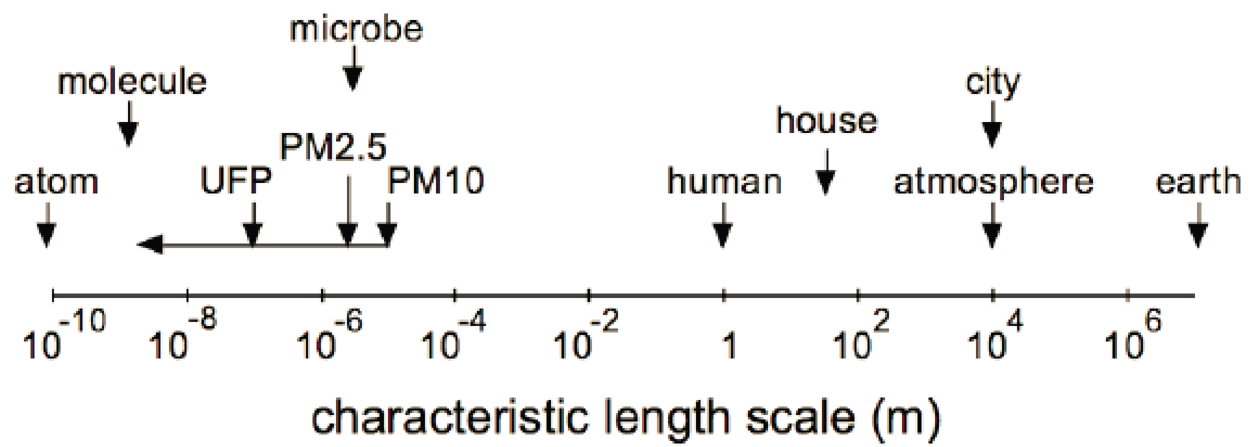


Fig. 1. Source-oriented, air pollution health effects paradigm. After Smith [3,9].

Nazaroff, 2008. *Building and Environment* 43 269–277

Perspectives on scale

- Earth's atmosphere: ~ 5000 Eg
- Humans collectively breathe ~ 0.04 Eg/y (~ 10 ppm/y)
- Humans use ~ 0.1 Eg/y of air to burn fossil fuels
- Buildings are ventilated with ~ 5 Eg/y of air
- Cities (**) are "ventilated" with ~ 600 Eg/y of air



(*) Reminder: E = 10^{18} (exa); (**) 3600 cities with P > 10^5 (2 billion total)

Slide courtesy of William W Nazaroff

[some of the] Important factors that affect indoor air pollutant concentrations

- Sources: - no sources, no pollutants
- Ventilation: dilution and removal of indoor source pollutants as well as introduction of outdoor air with moisture and pollutants.
- Sinks

  (are pollutants on surfaces or in dust part of "indoor air")?
- Reactions

  For reaction products, when do you measure?
- Time (everything changes)

Important factors that affect indoor air pollutant concentrations

- **Source strength – is it constant? what affects its variations? How representative of average, peak, and low strength is it during sample collection. How does temperature affect it and its effect on occupants?**
  - Reactions – gas transformations through reactions with other airborne constituents
  - Deposition – on surfaces of building, contents, occupants, and airborne particles
  - Phase change – solid, liquid, vapor, gas
- **Ventilation – dilution, removal by exhaust, direction of air flow (from or away from occupants)?**
- **Time – "everything changes"**

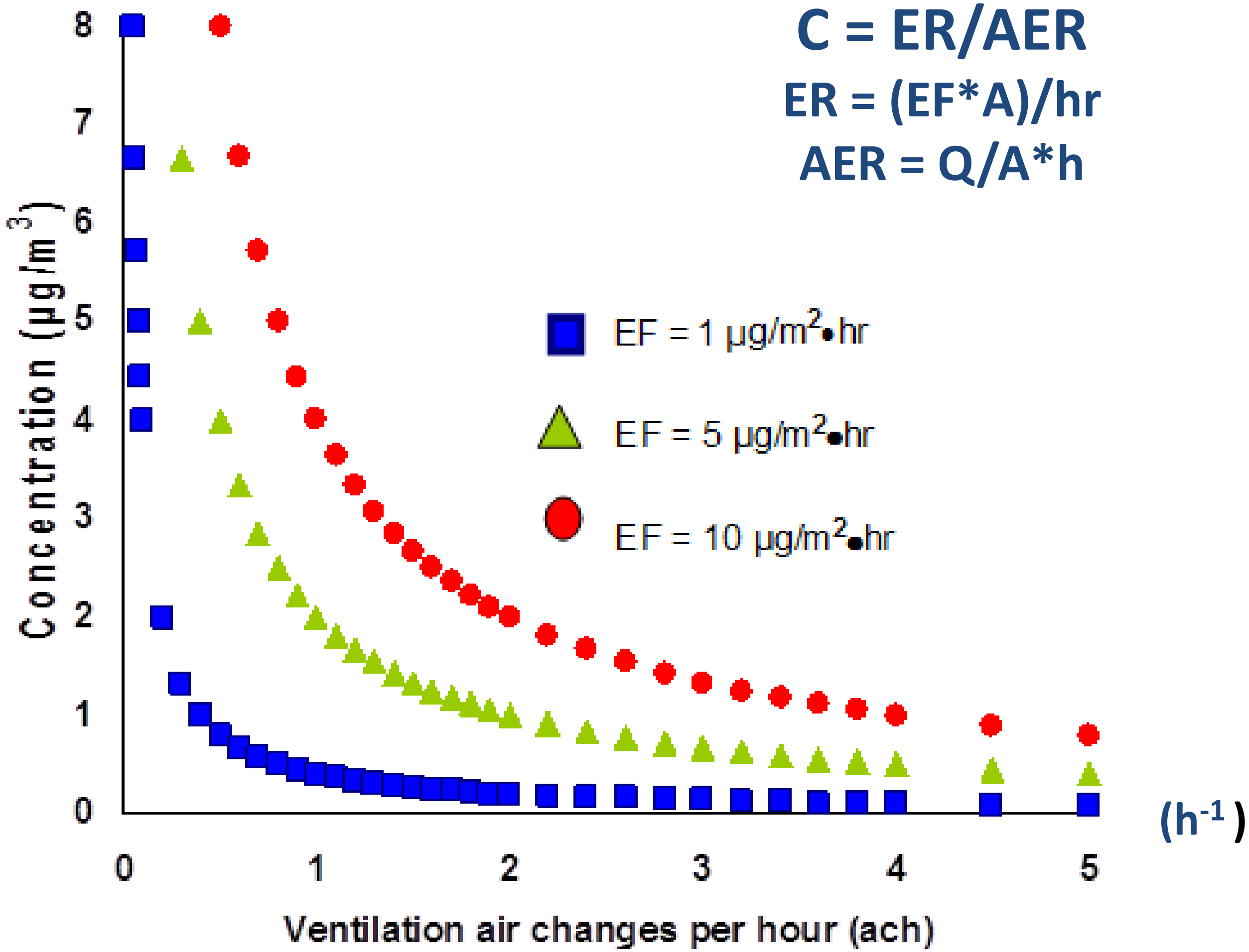
Ventilation rates, source strengths, and concentrations: oversimplified relationships

Oversimplified model:

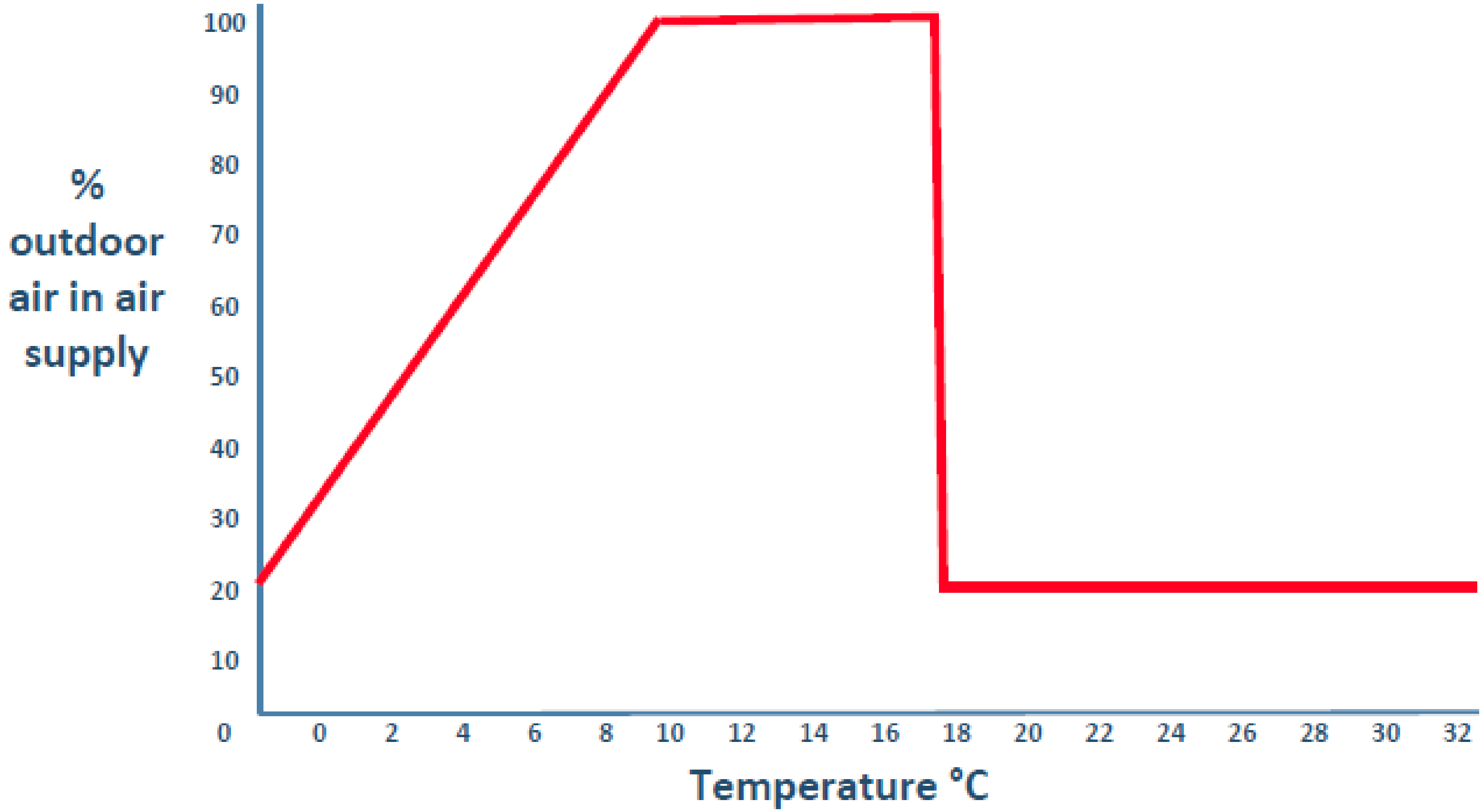
C = ER/AER

ER = (EF*A)/hr

AER = Q/A*h



Variable air volume OA ventilation (mechanical ventilation system)



After Karl Guttmann, 1992

AER (h^{-1}) vs T_{in} - T_{out}

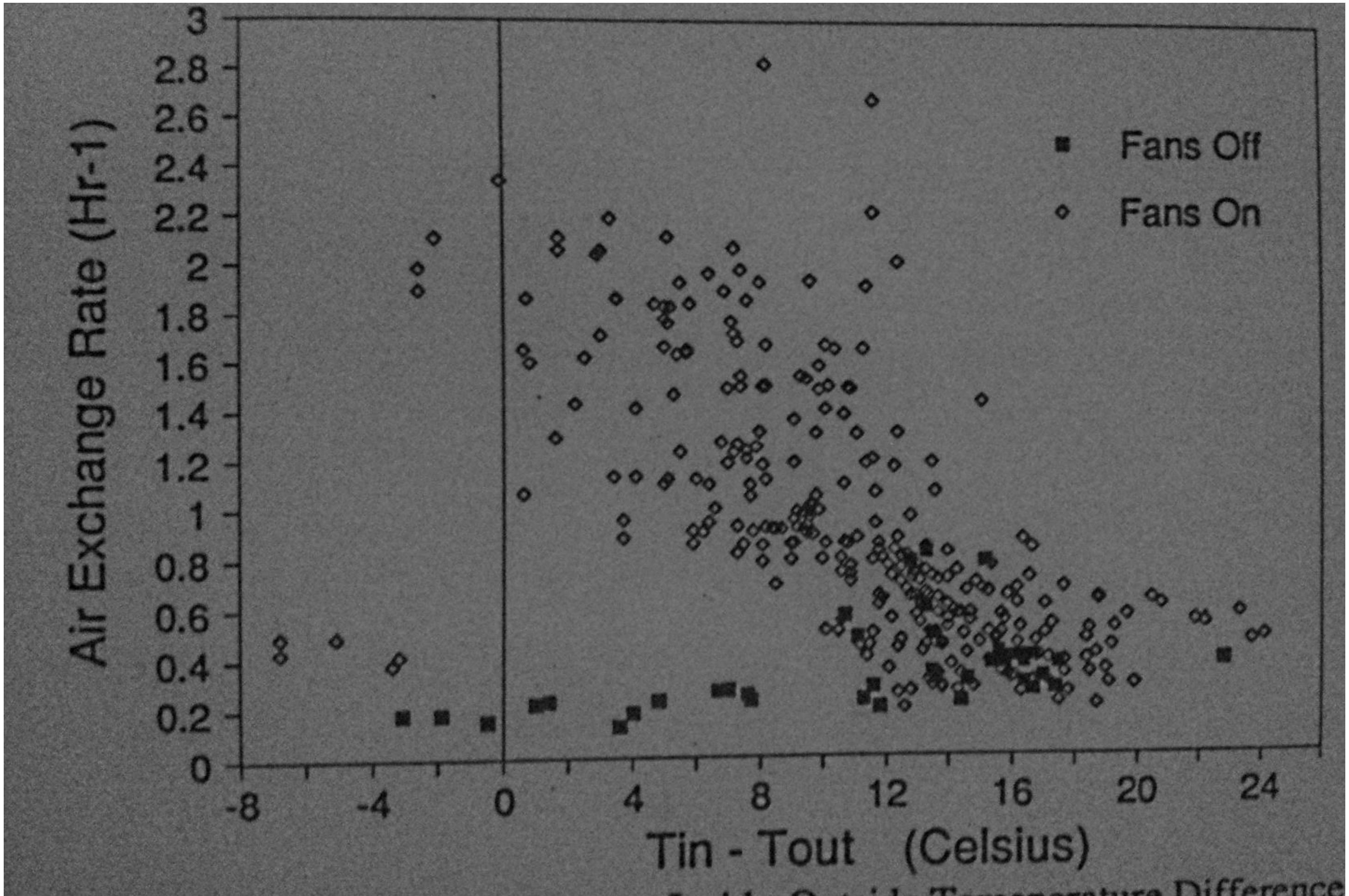


Figure 12. Air Exchange Rate versus Inside-Outside Temeperature Difference

Grot, Persily, Daisey, and Hodgson, 1989, NISTI 89-4066R

AER (h^{-1}) vs T_{in} - T_{out}

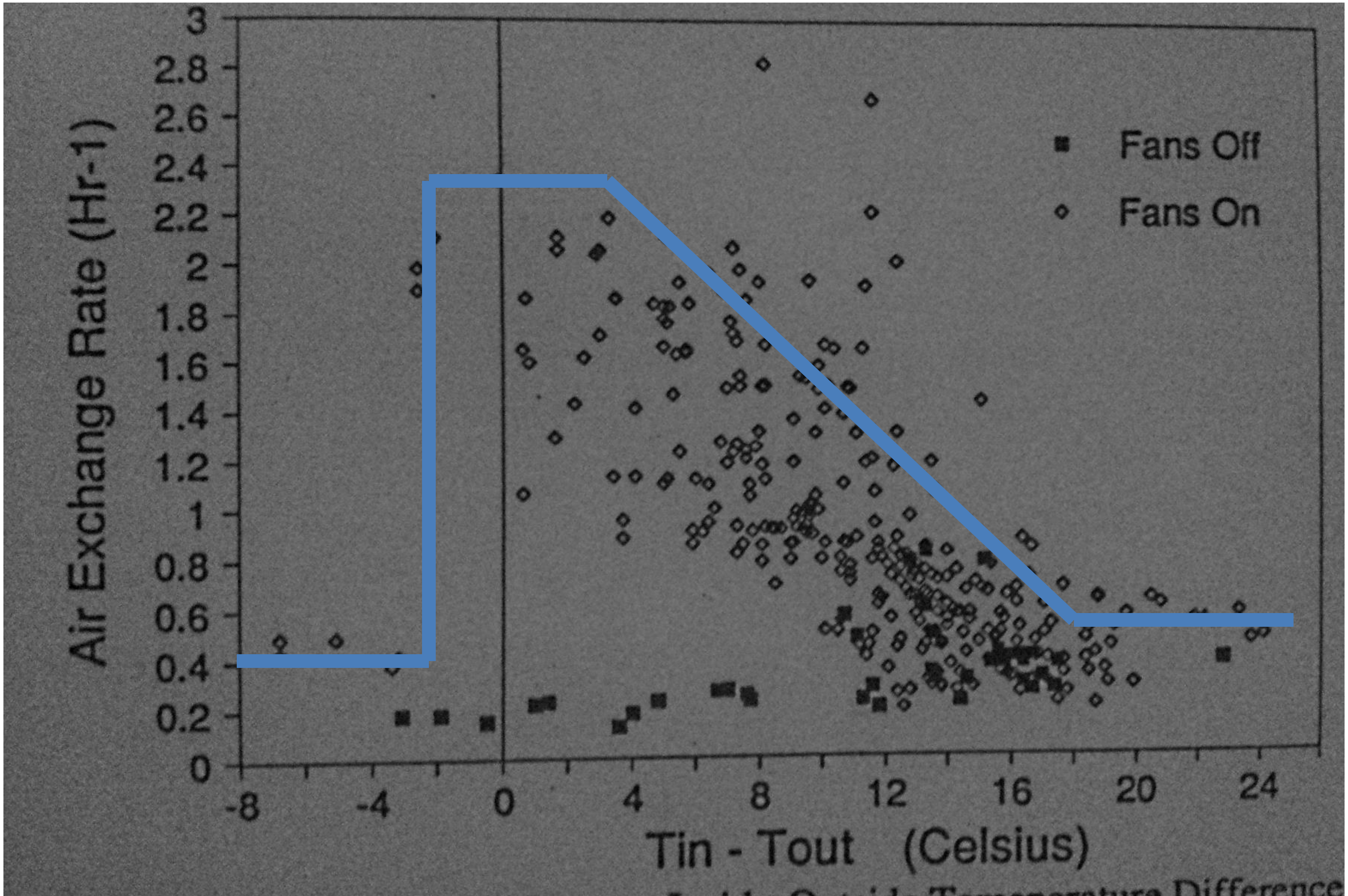
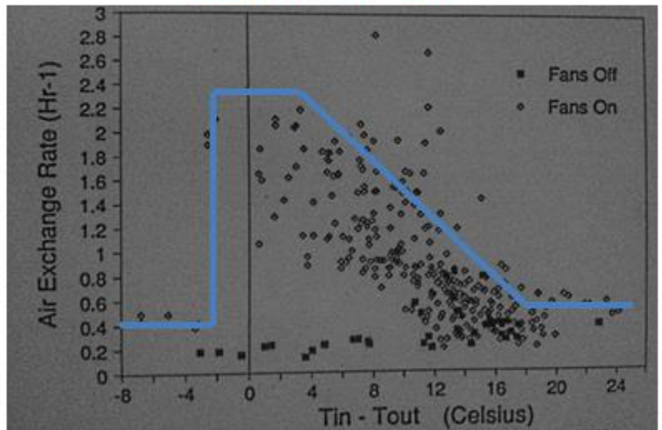


Figure 12. Air Exchange Rate versus Inside-Outside Temeperature Difference

HVAC with VAV operations: % Outdoor Air

AER (h^{-1}) vs T_{in} - T_{out}



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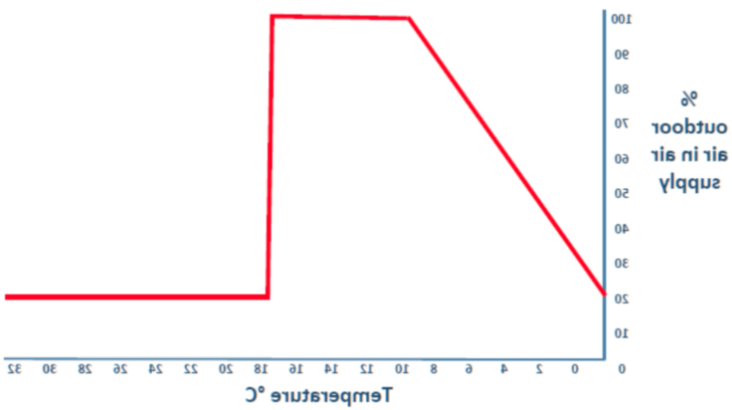

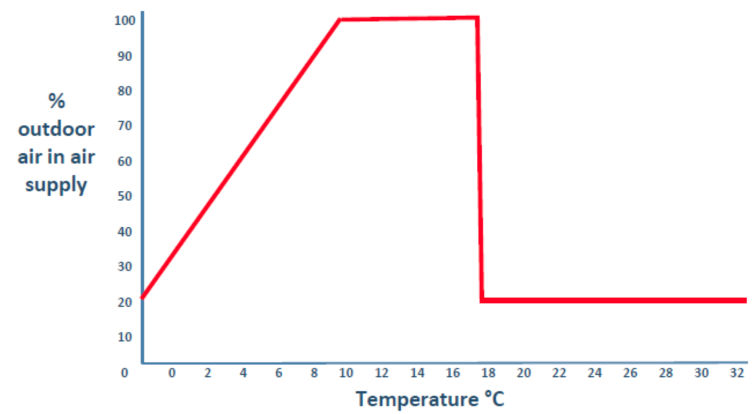

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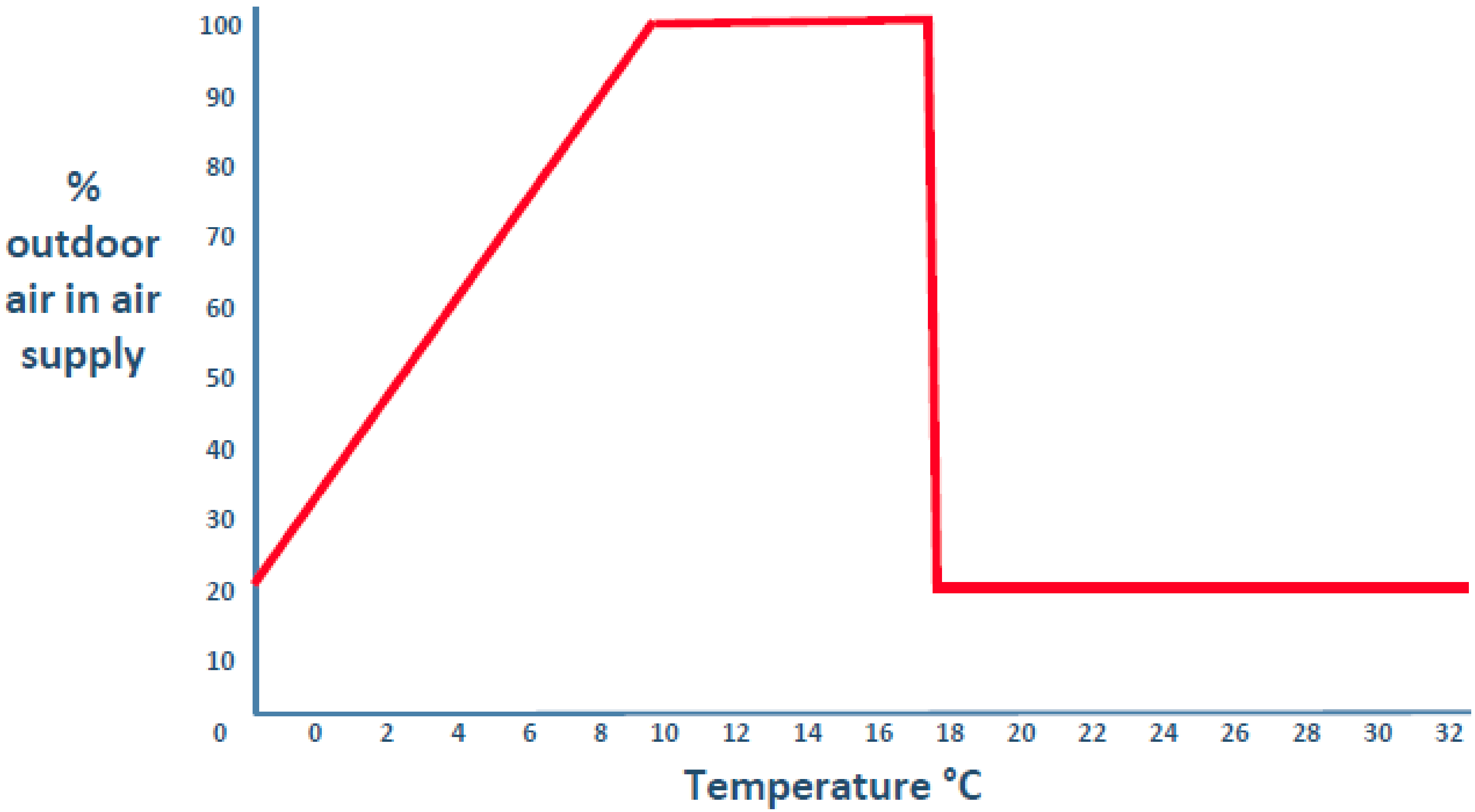


St. Louis office building

(Nabinger, Persily, and Dols, 1994, *ASHRAE Transactions*)

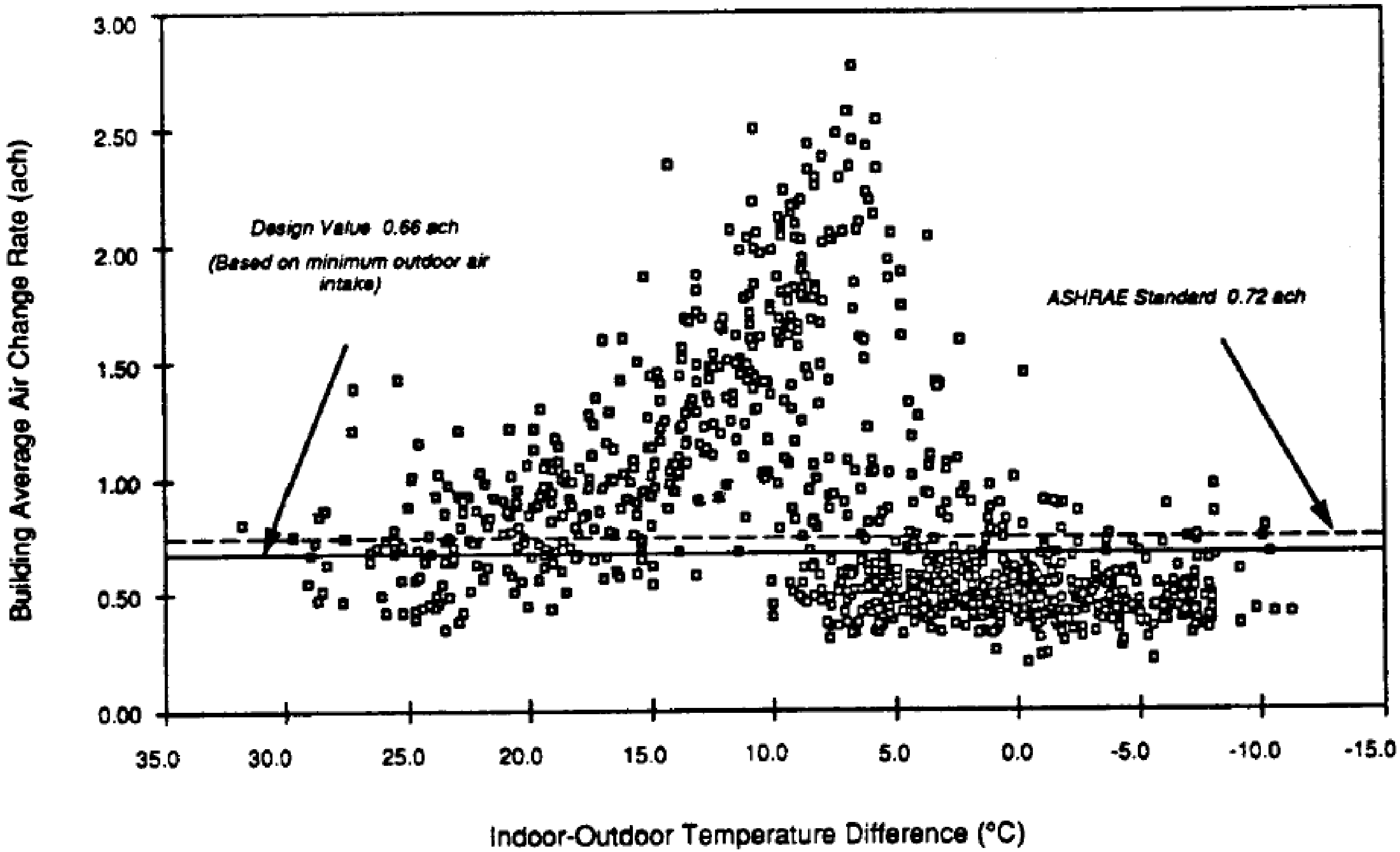


Figure 6 *Building air change rate as a function of indoor-outdoor temperature difference.*

St. Louis office building

(Nabinger, Persily, and Dols, 1994, *ASHRAE Transactions*)

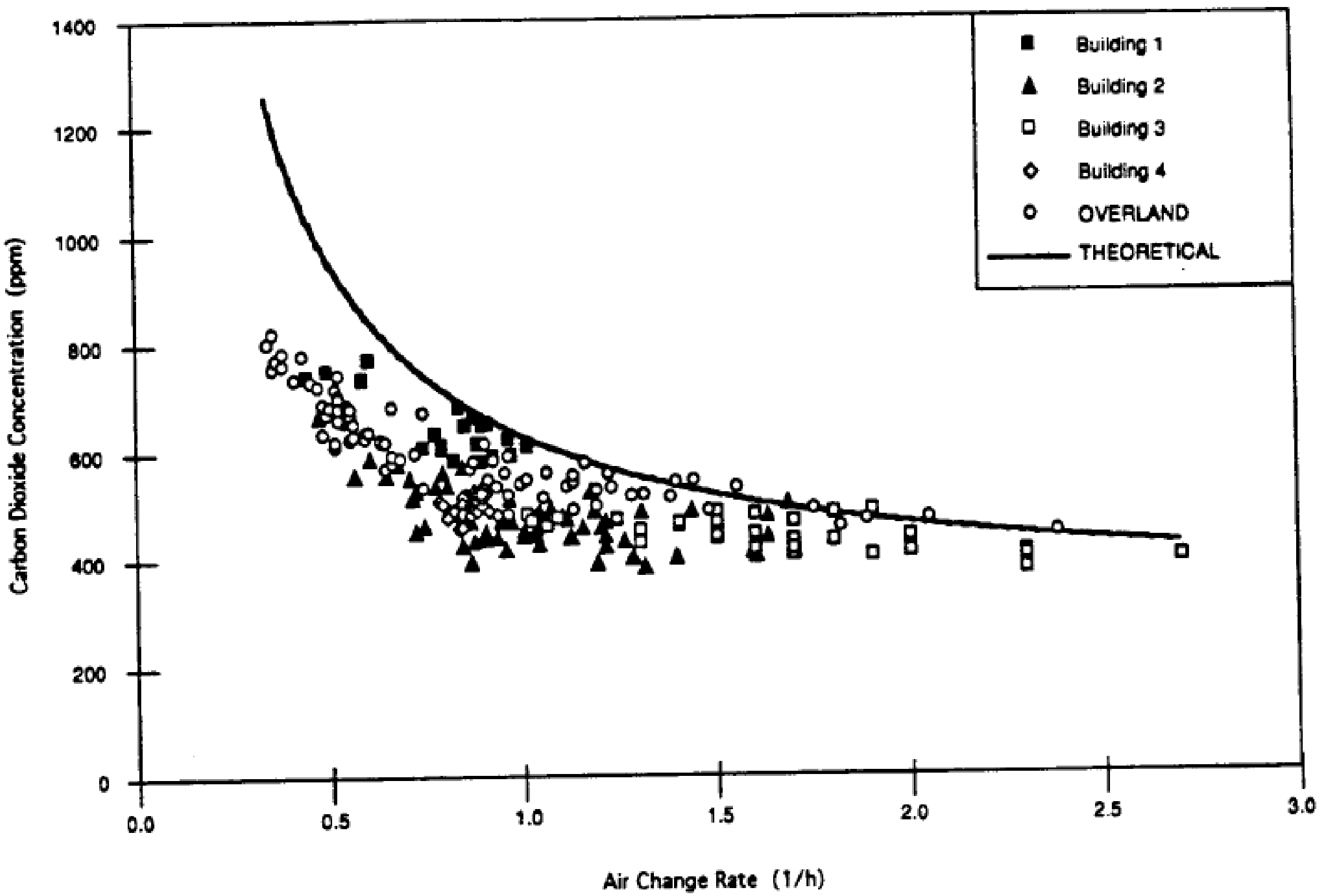


Figure 8 Maximum carbon dioxide concentration vs. air change rate.

Types of natural ventilation

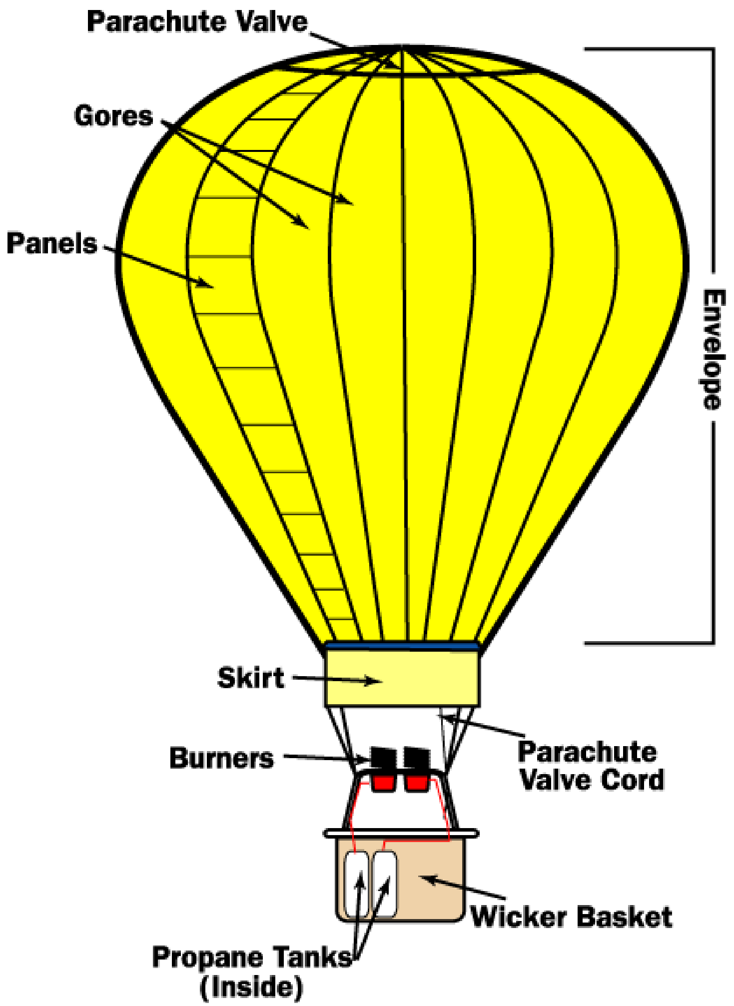
Stack effect (buoyancy)

- Warm air is lighter (less dense) than cold air
- Warm air rises, cold air falls
- Intentional chimneys (stacks) can create larger differences between top and bottom, increasing the air flow rate

Wind-driven (pressure)

- Pressure differences result in air mass movement
- "Packets" of air flow from higher to lower air pressure regimes

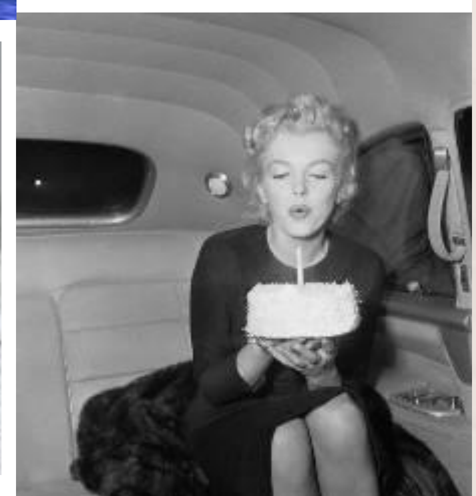
Hot air → buoyancy



Natural Driving Mechanisms – Pressure: Wind-driven air flow






Wind Pressure as a function of angle of incidence on wall

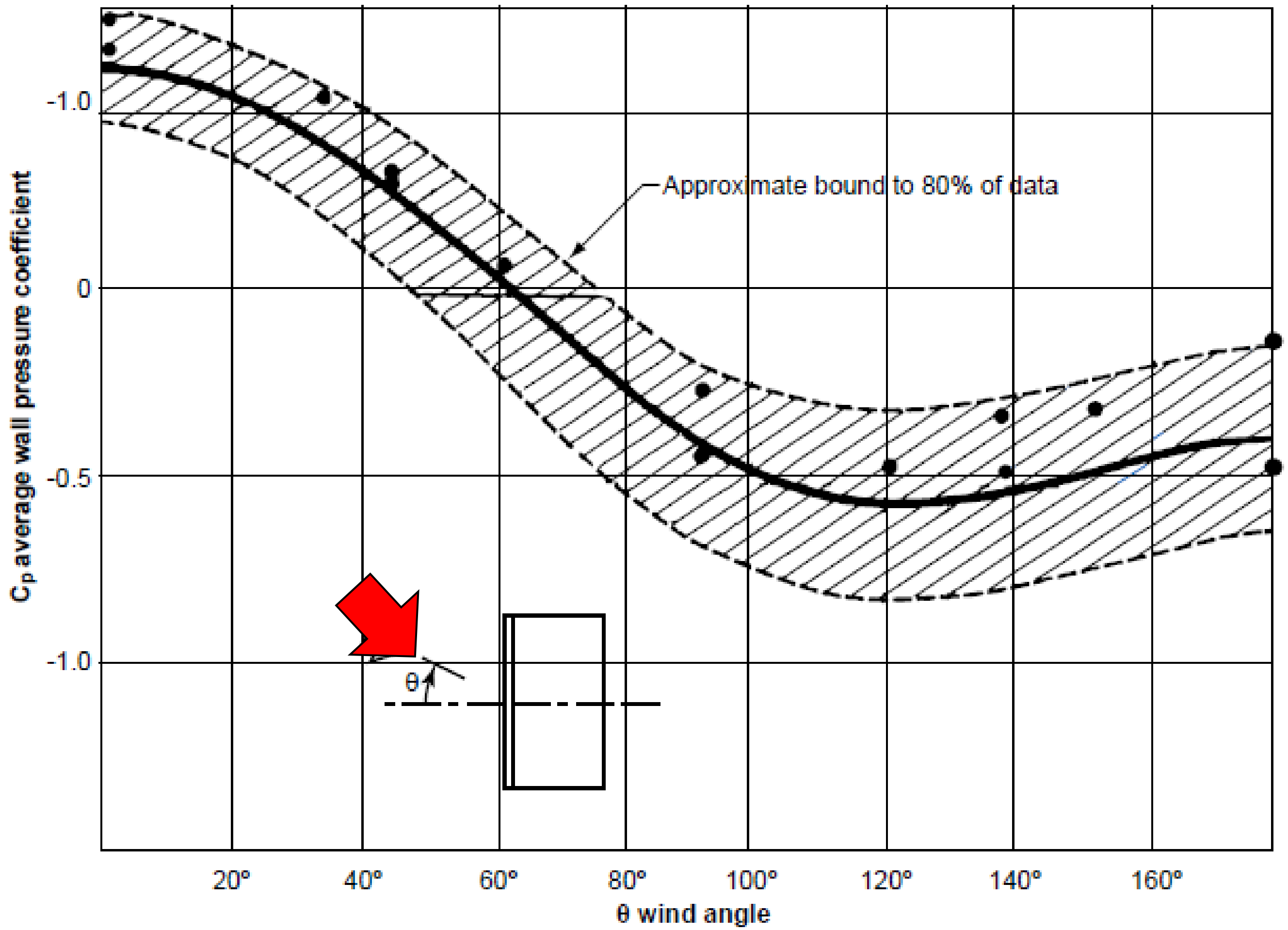
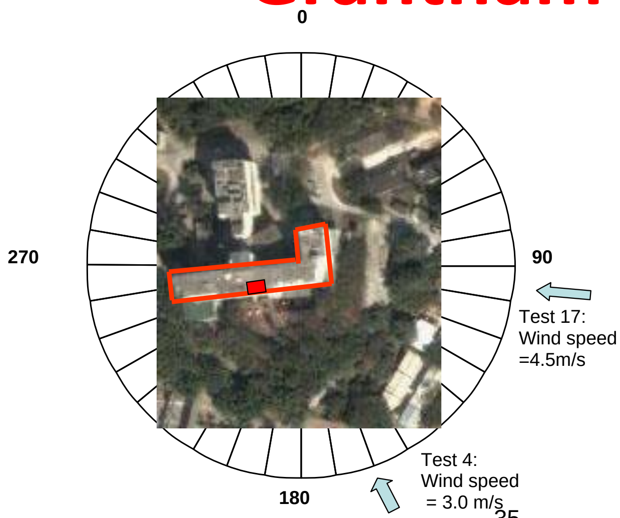
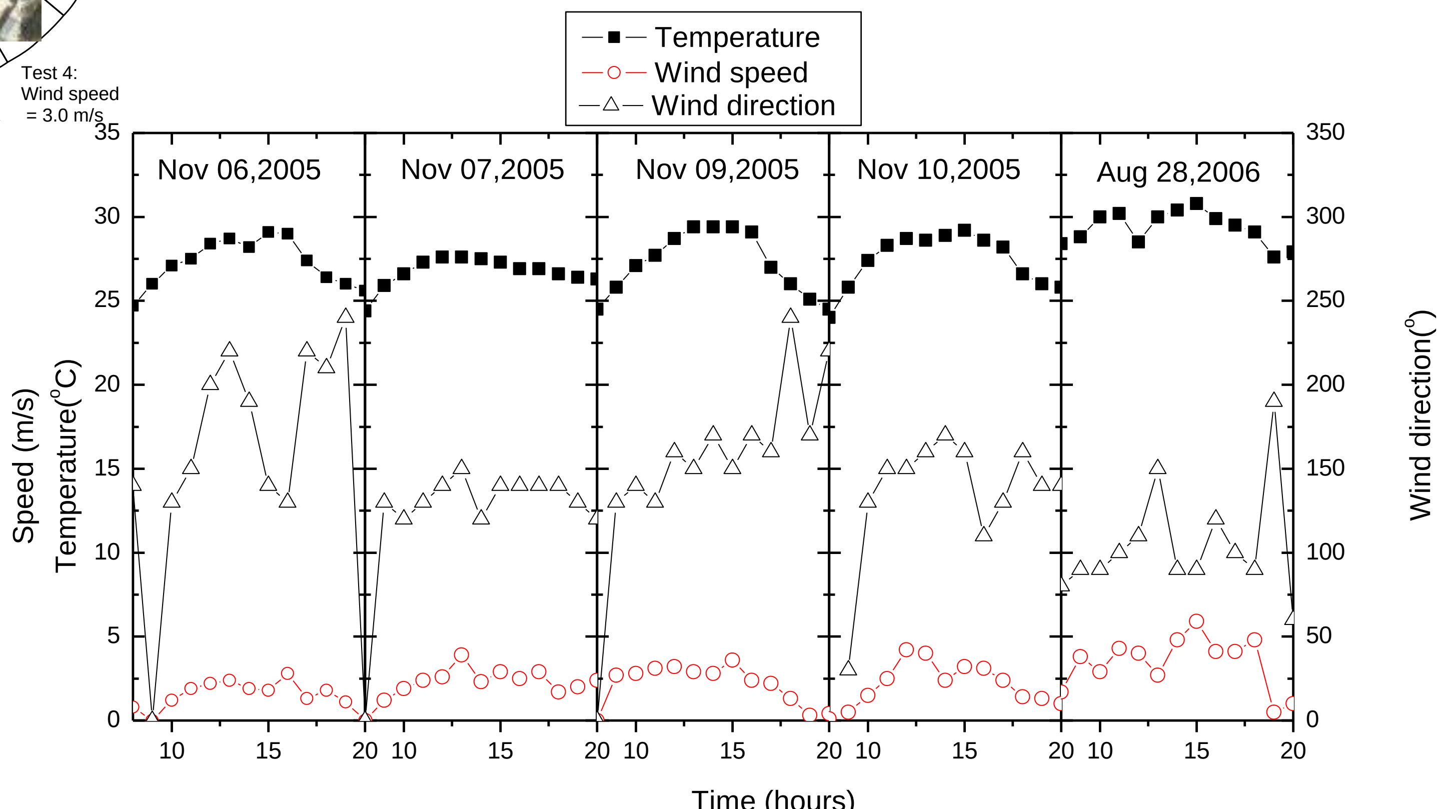


Figure 3. Typical Wall-averaged Wind pressure Coefficients for Low-rise Buildings
(Swami & Chandra, 1987)

Grantham Hospital Study, Hong Kong

Yuguo Li, WHO 2009





Natural ventilation in buildings

Francis Allard, Mat Santamouris, Servando Alvarez, European Commission. Directorate-General for Energy, ALTENER Program

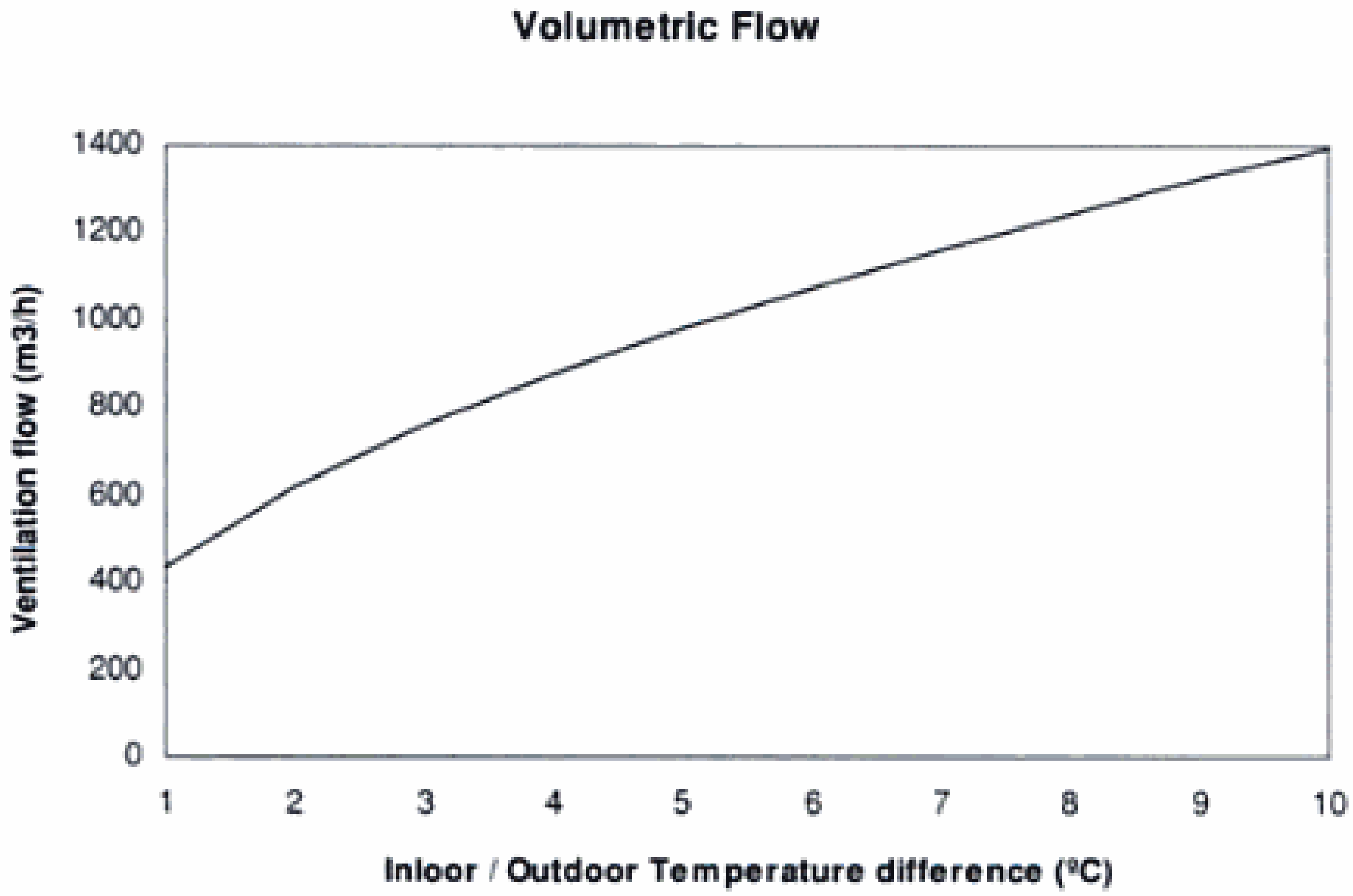
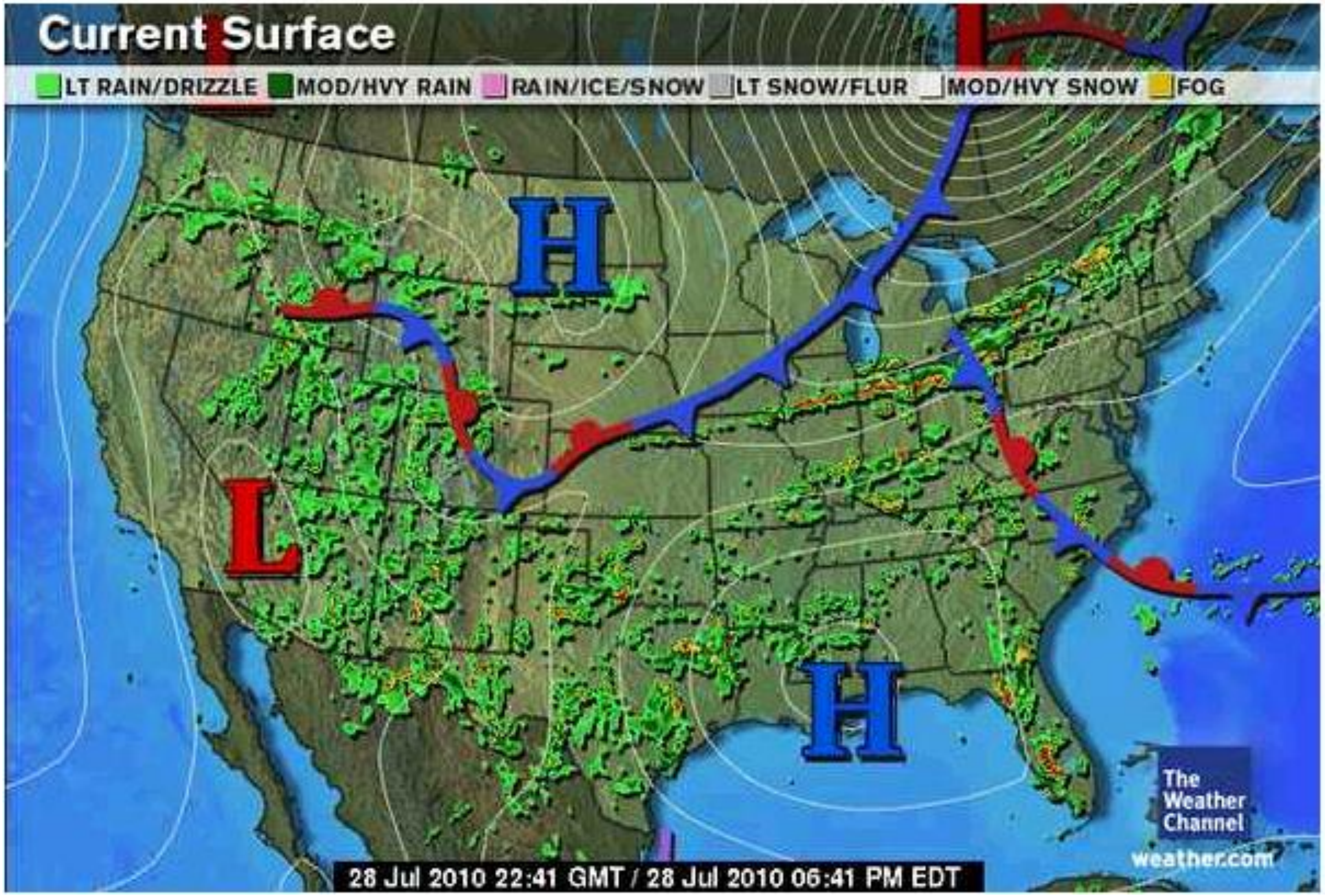


Figure 2.33. Airflow as a function of the temperature difference

Weather – "wait a minute and it will change"



ELSEVIER
Building and Environment 39 (2004) 1157–1170
www.elsevier.com/locat

How to use natural ventilation to cool narrow office buildings

E. Gratia*, I. Bruyère , A. De Herde

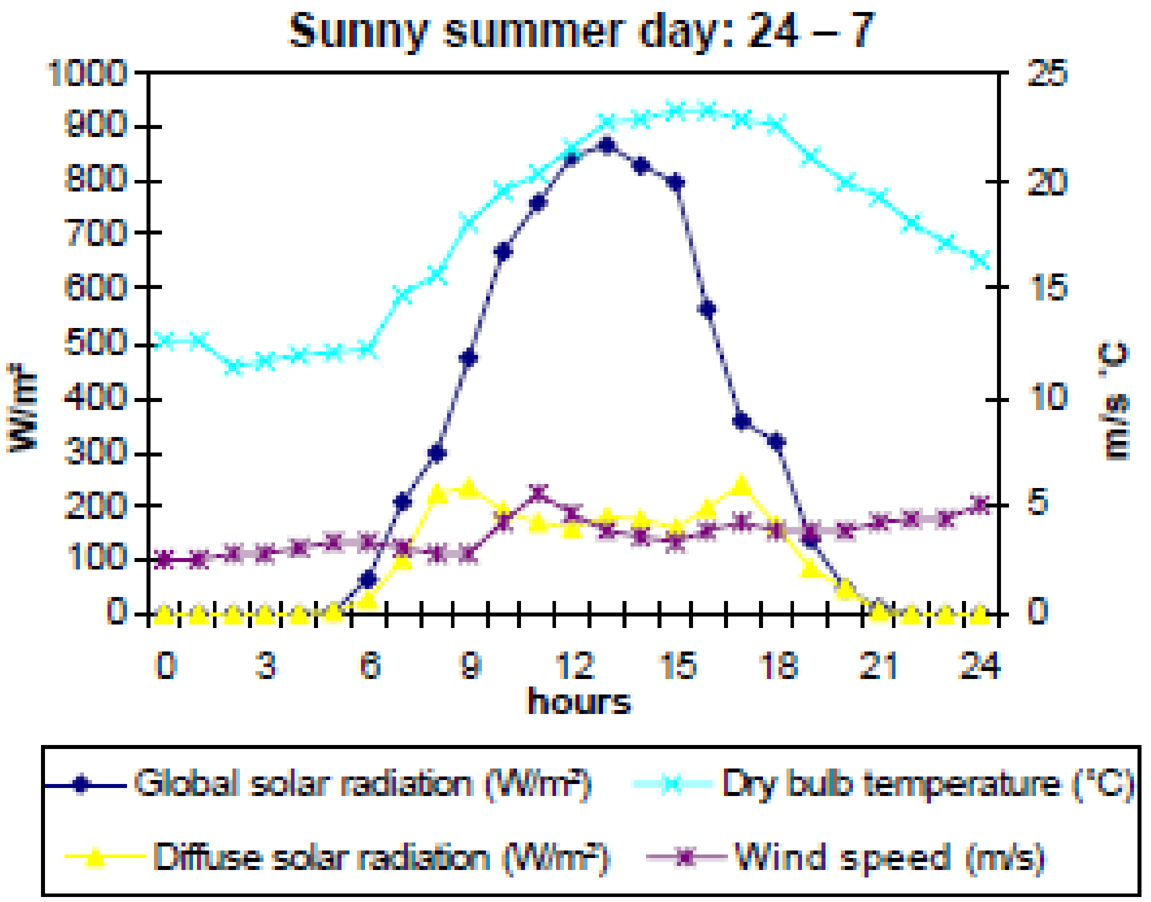
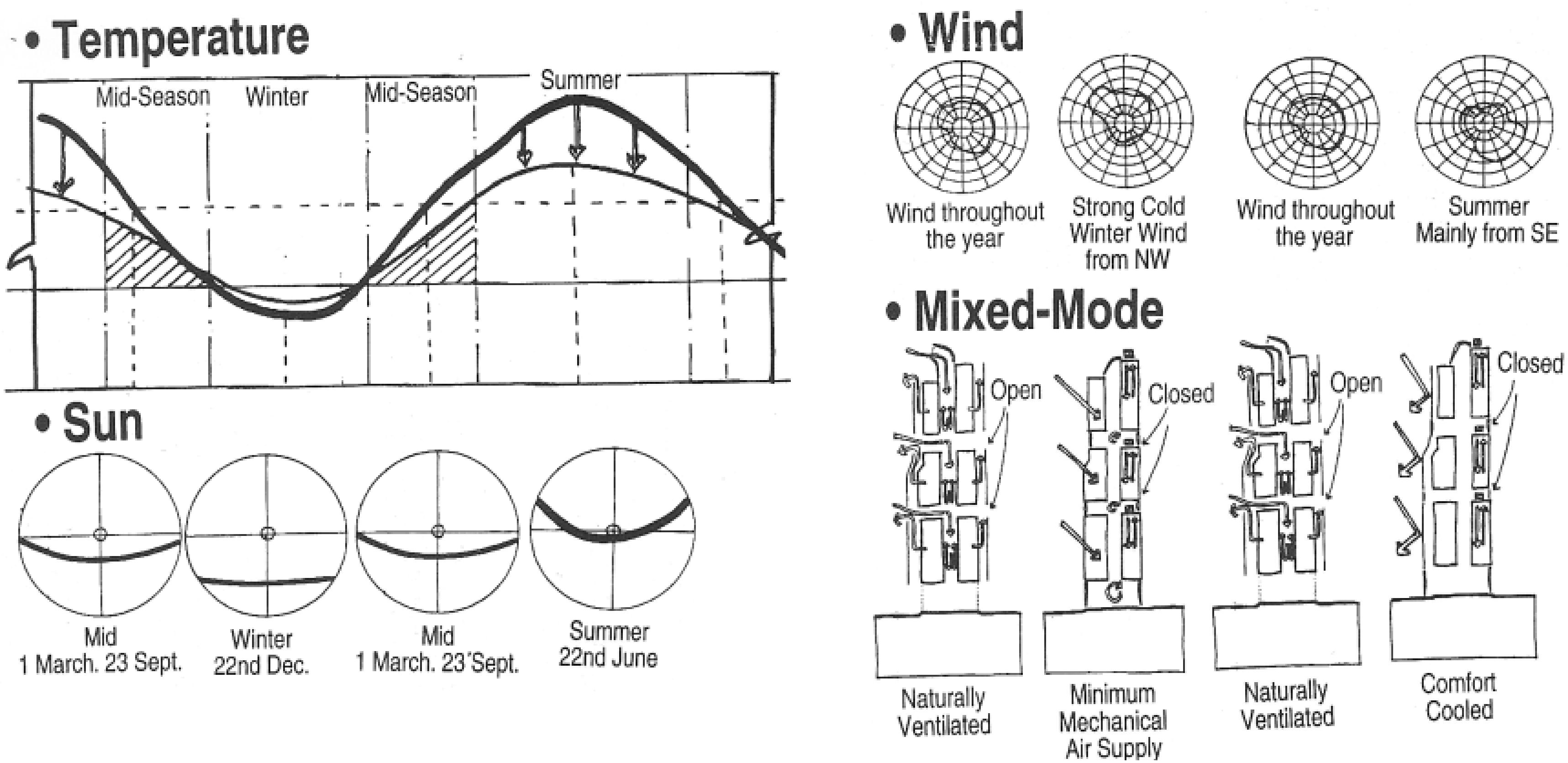


Fig. 7. Climatic data of the sunny summer day.

Weather conditions and ventilation mode

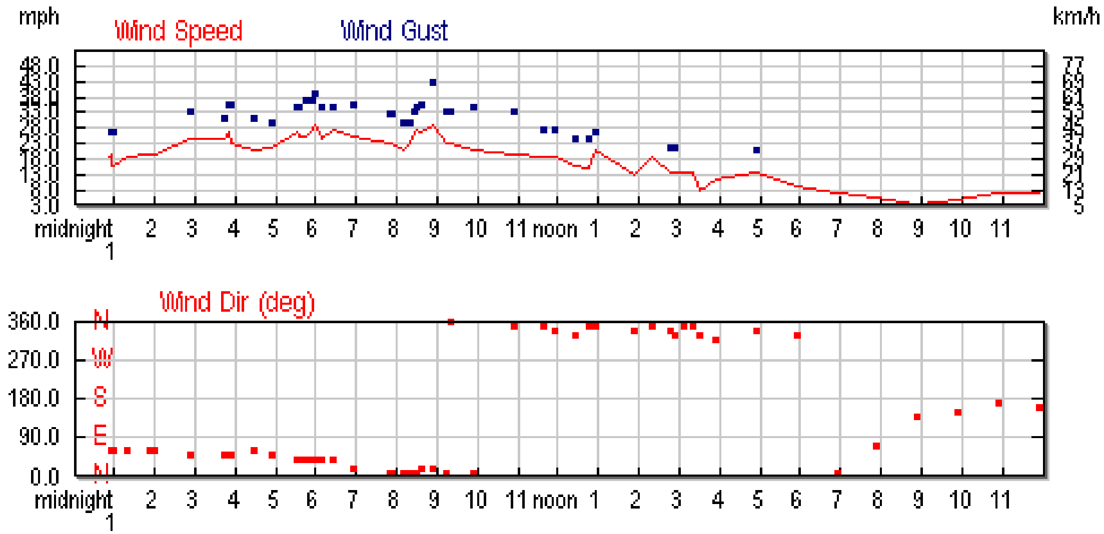
Armoury Tower – Shanghai, China



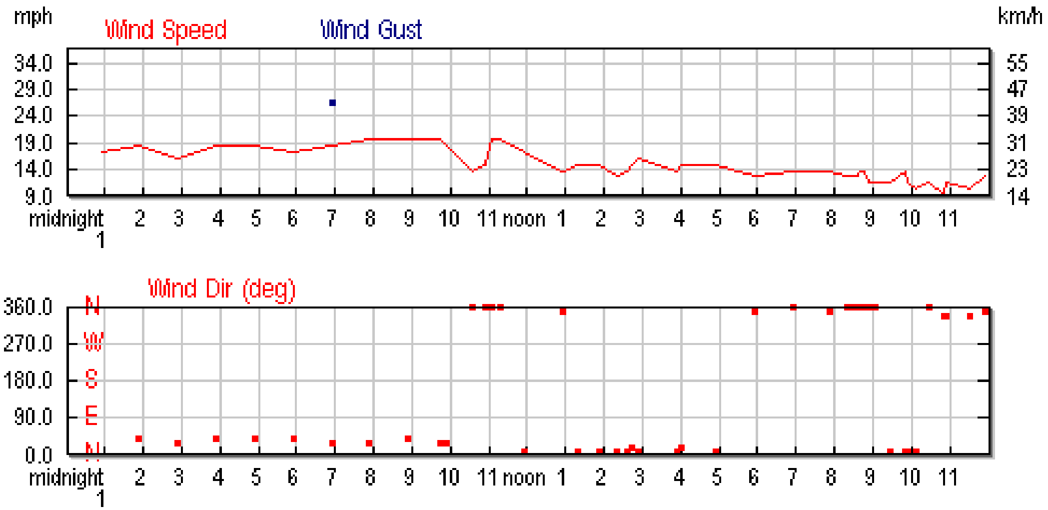
Wind Towers, 1999. Battle McCarthy Consulting Engineers

Boston, MA

July 24, 2009

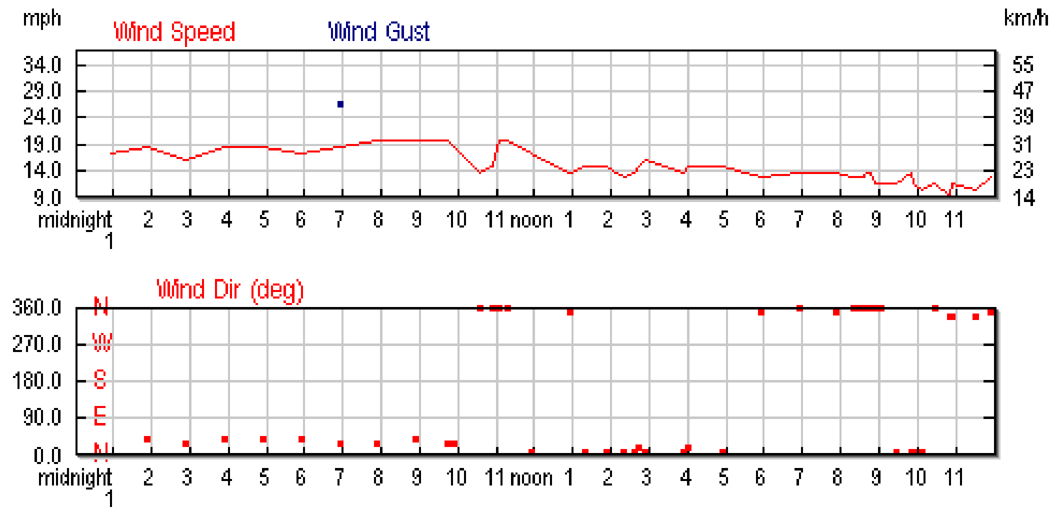


March 1, 2009

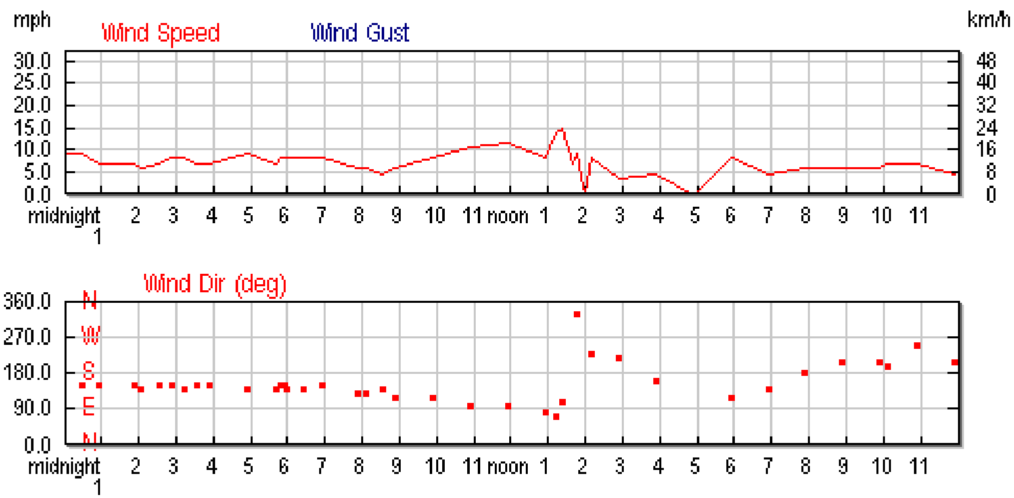


Boston, MA

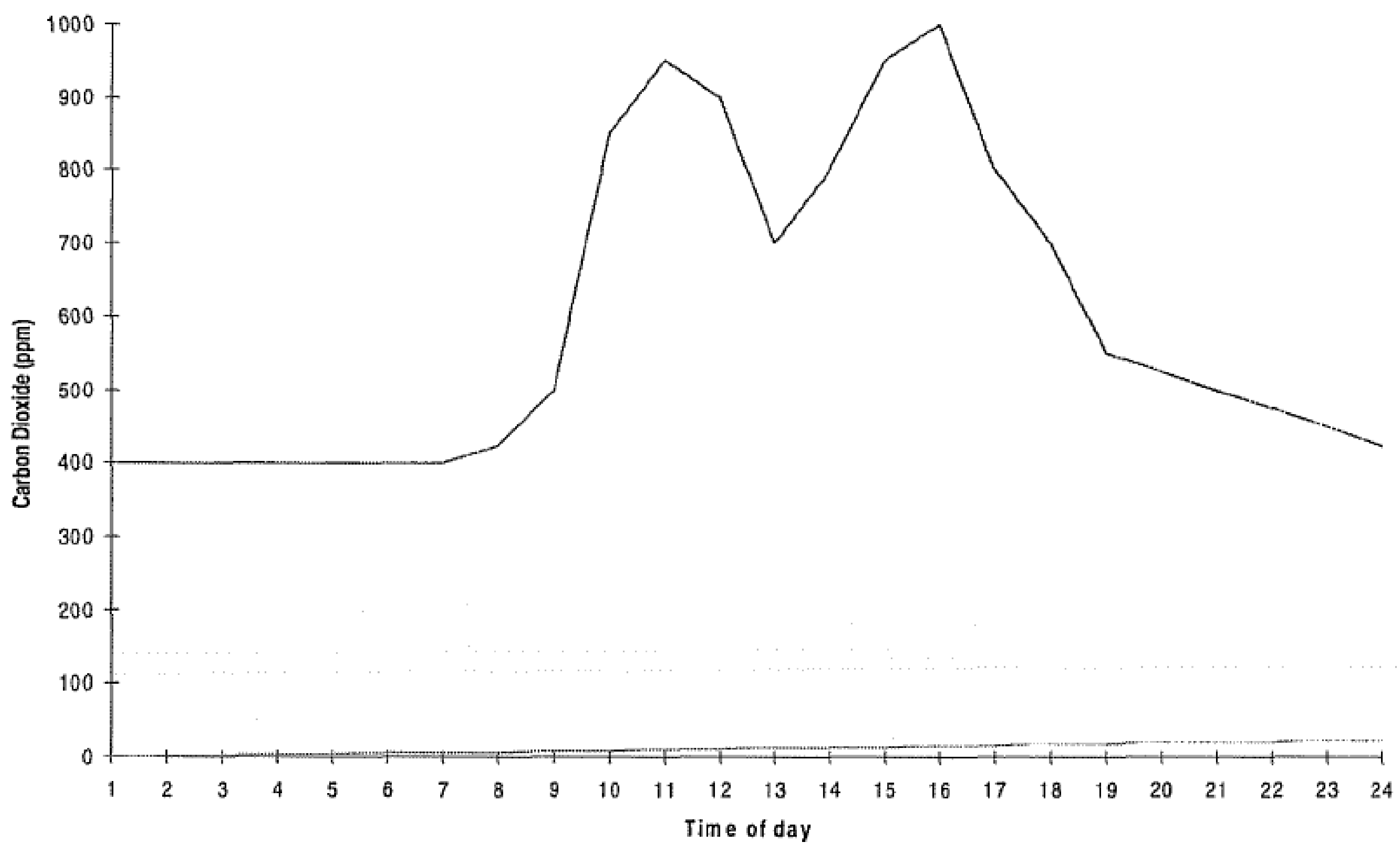
January 1, 2009



October 1, 2008



Lag time: Typical CO_2 concentration in relation to typical office building occupancy



Ventilation rates, source strengths, and concentrations

Need to plot concentrations, source strengths, and ventilation rates for various key compounds using data from Block 225.

Figure 1. 6th floor TVOC source strengths (µg/m² h)

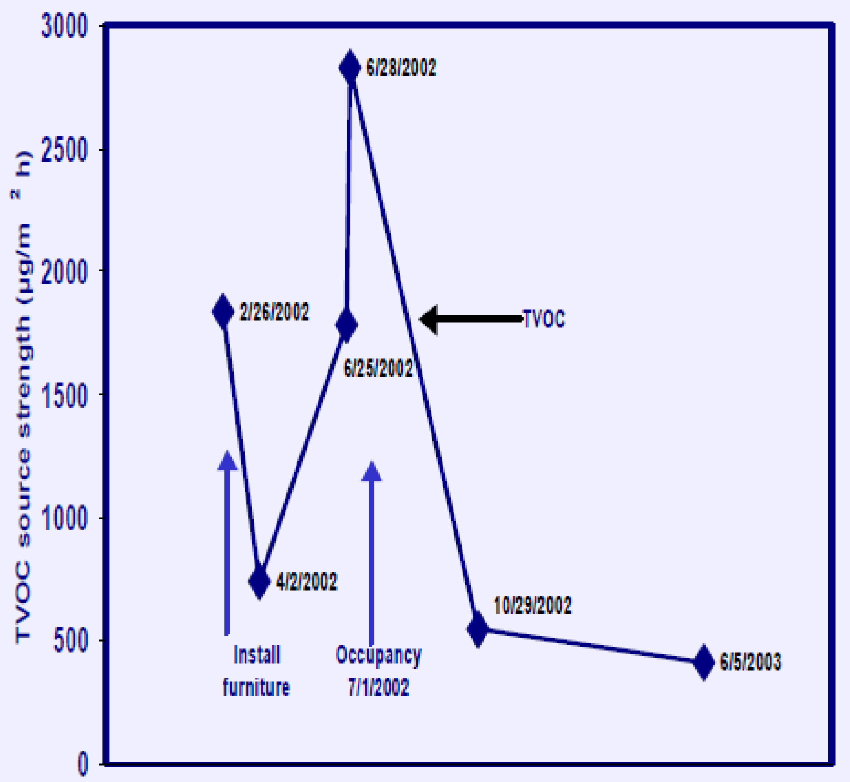
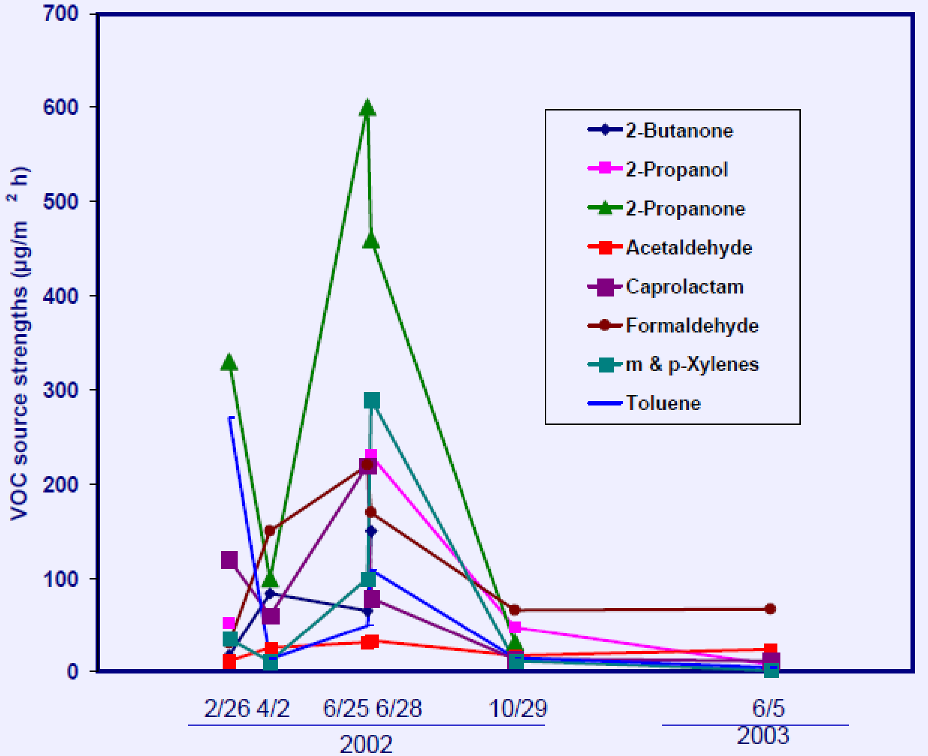


Figure 2. 6th floor VOC source strengths (µg/m² h)

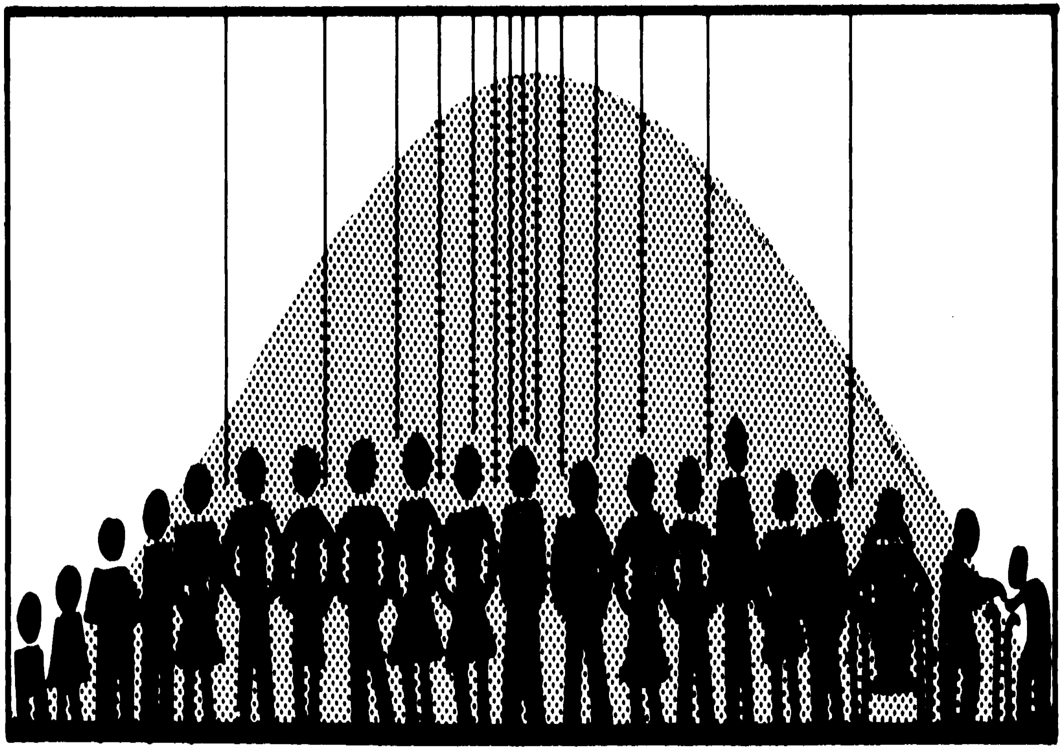


Using CO_2 to estimate ventilation rates: Variations in occupant generation rates

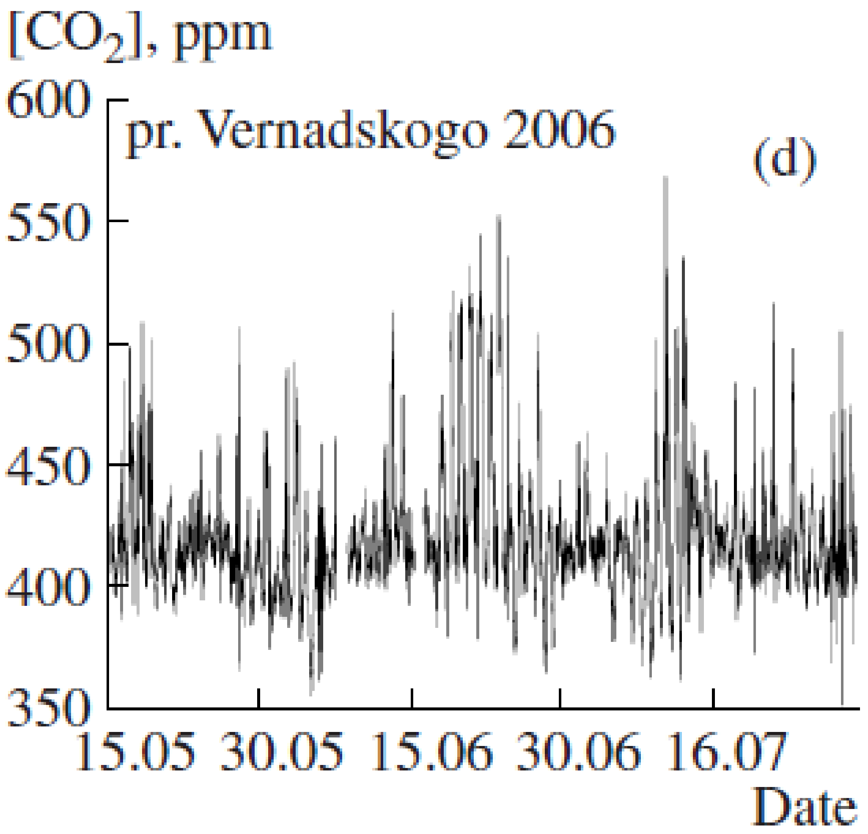
METABOLISM AS A FUNCTION OF…

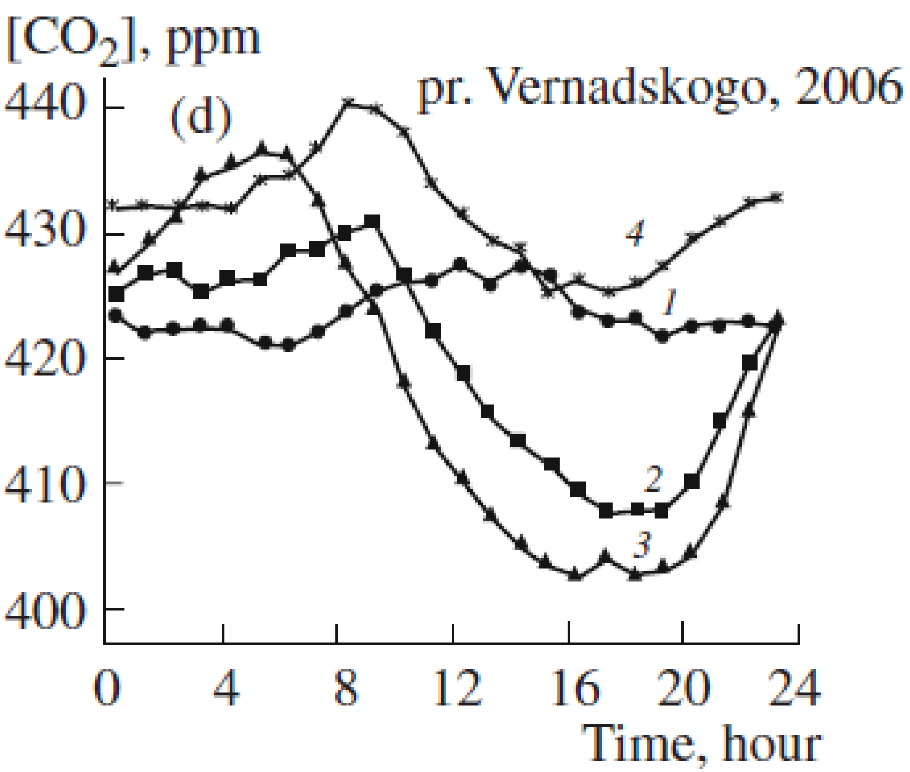
- **Activity level (metabolic rate)***
- **Diet (metabolic rate)***
- **Sex (?) ***
- **Age (size?) ***
- **Obesity? ***
- **Health status**
- **Stress (Wang, 1971, *ASHRAE Transactions*)**

*** EPA Exposure Factors Handbook 2011**



Time-, day-, and Season-dependent variation in outdoor CO_2



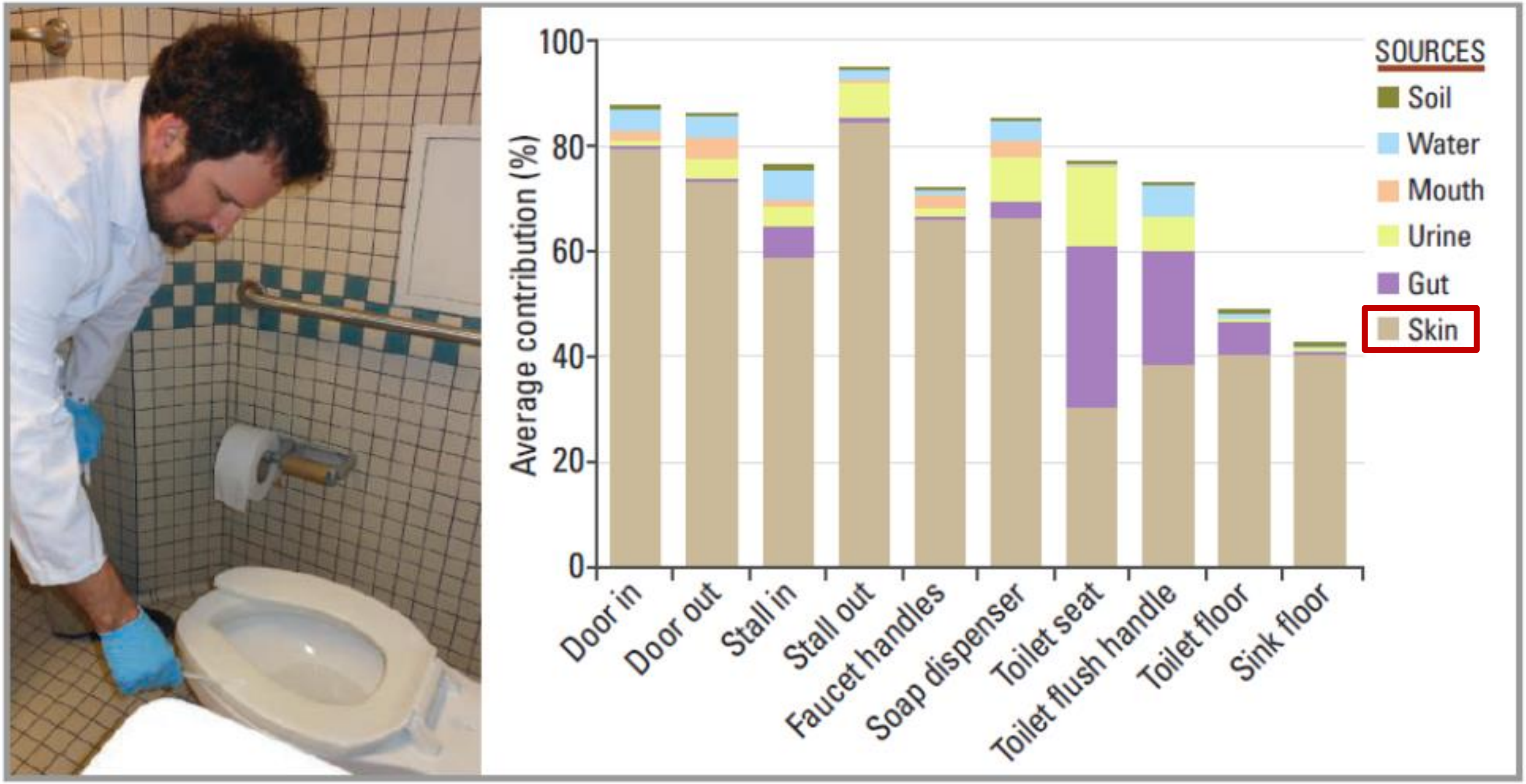


(1) winter, (2) spring,
(3) summer, and (4) fall.

further evidence of microbes on all indoor surfaces – “unidentified complex surface films” - UCSF

Gene sequence analysis: further evidence for soiling by squames

Slide courtesy of Charles J. Weschler from Plenary lecture, 22 Aug 2013



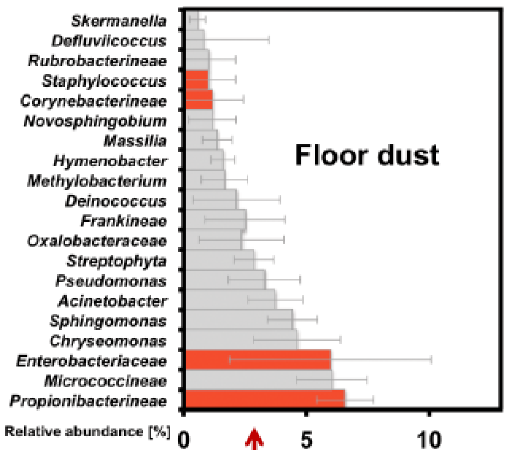
Sources of microbes found on different surfaces in public toilets

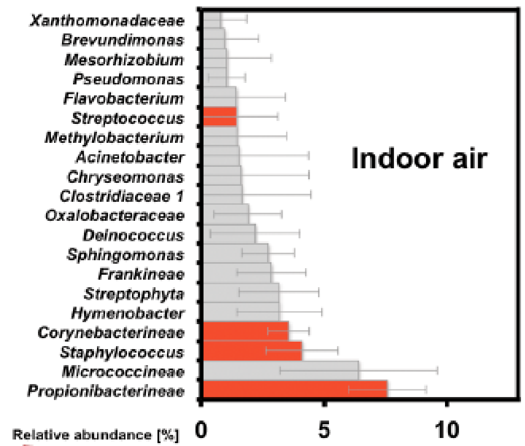
Fierer et al., as reported in Science, Feb 10, 2012

Humans contribute a significant fraction of bacteria found in indoor air and dust

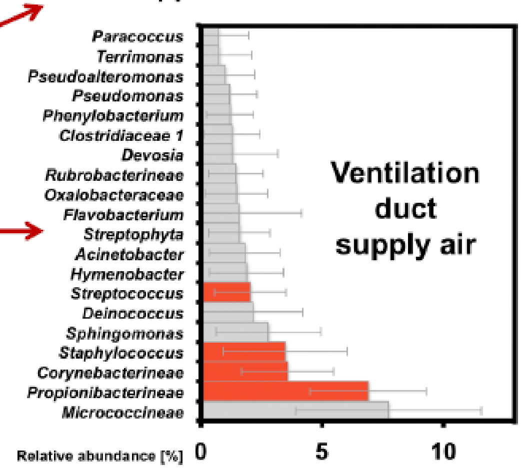
Slide courtesy of Charles J. Weschler from Plenary lecture, 22 Aug 2013

Gene sequence analysis: indoor air & dust





Red bars: bacteria associated with human skin, hair & nostrils – roughly 20% of all bacteria in indoor dust and air



- Shedding of skin cells and subsequent resuspension contribute to airborne bacteria
- Occupants commonly inhale microbes shed by others

Hospodsky, Qian, Nazaroff, et al., PLoS One **7***, e34867, 2012*

Representative samples?

- **Representative of what?**
  - All similar buildings
  - Other (all) buildings for similar uses
  - All local buildings (neighborhood, city, state, socio-cultural type, climate)
  - Exposure or portion of total exposure
- **Purpose of sample collection and analysis?**
  - Health effects risks
  - Building performance
- **Compared to what?**
  - Standards and Guidelines
  - Large population samples
  - Yesterday, today and tomorrow?
- **Sampling biases?**
  - Location of sample collection?
  - Timing: duration, peak, average?

Steady state construct (theory) and real world buildings

In summary

"Everything changes"

- **Suzuki Roshi**

(contemporary Zen master)

Principles of Building Ecology - 1

Building ecology defined:

Building ecology is the study of the behavior of buildings in relationship to their occupants and the larger environment

Principles of Building Ecology - 2

1. **Everything changes**

   (Suzuki Roshi, Zen master [dates:])

2. **Everything is connected to everything**

   (John Muir, Naturalist [dates:])

   (Barry Commoner, Ecologist [dates:])

3. **Every building site and each building is unique**

Everything changes

- Temperature (T)
  - Indoors
  - Outdoors
  - Diurnal cycles
  - Seasonal cycles
- Relative humidity (RH) (% of moisture relative to 100% [saturated] air
  - As T goes up, RH decreases (and the reverse)
  - Cold air holds less absolute moisture than warm air; as we warm the air indoors in the winter, the RH goes down
- I-O Temperature ratio
- I-O RH ratio
- I-O pressure relationships:
  - driving forces for indoor air exchange rate
  - Air moves from warm to cold (gas molecules more active, “energized”

Everything is connected to everything*

- Chaos theory – 'when a butterfly flaps its wings in Basel, the weather changes in Beijing.'
- Ecosystems are complex webs of inter-related and inter-dependent living organisms sharing the same geology, hydrology, climate and weather
- Buildings [for human occupancy] <u>are</u> "ecosystems" (note: plants are optional)
- Building ecology looks at buildings as part of a complex ecosystems: the building, its contents and occupants, and the larger environment

* John Muir, Barry Commoner

Every building site and each building is unique

- **Identical house designs built on different sites will respond differently to their environment – geology, soil, hydrology, microbes, termites, etc.**
- **Studies of houses of identical designs built by the same crew on sequential days had air leakage differences as large as a factor of two.**

Fundamental relationships

- **Simplest model:**
  - **Steady state**
  - **Source, Ventilation, Concentration**
- **Next level model:**
  - **Dynamic**
  - **Sources:**
    - **point, distributed**
    - **Episodic, periodic, continuous, modulating**
  - **Removal mechanisms:**
    - **Ventilation**
    - **Sinks**
    - **Reactions**
    -

Complexity of source characterization

- **Sources change over time**
  - **Natural decay of organic chemicals emitted from building materials, furnishings**
- **New sources introduced**
  - **Consumer products**
  - **Furnishings**
  - **Personal care products**

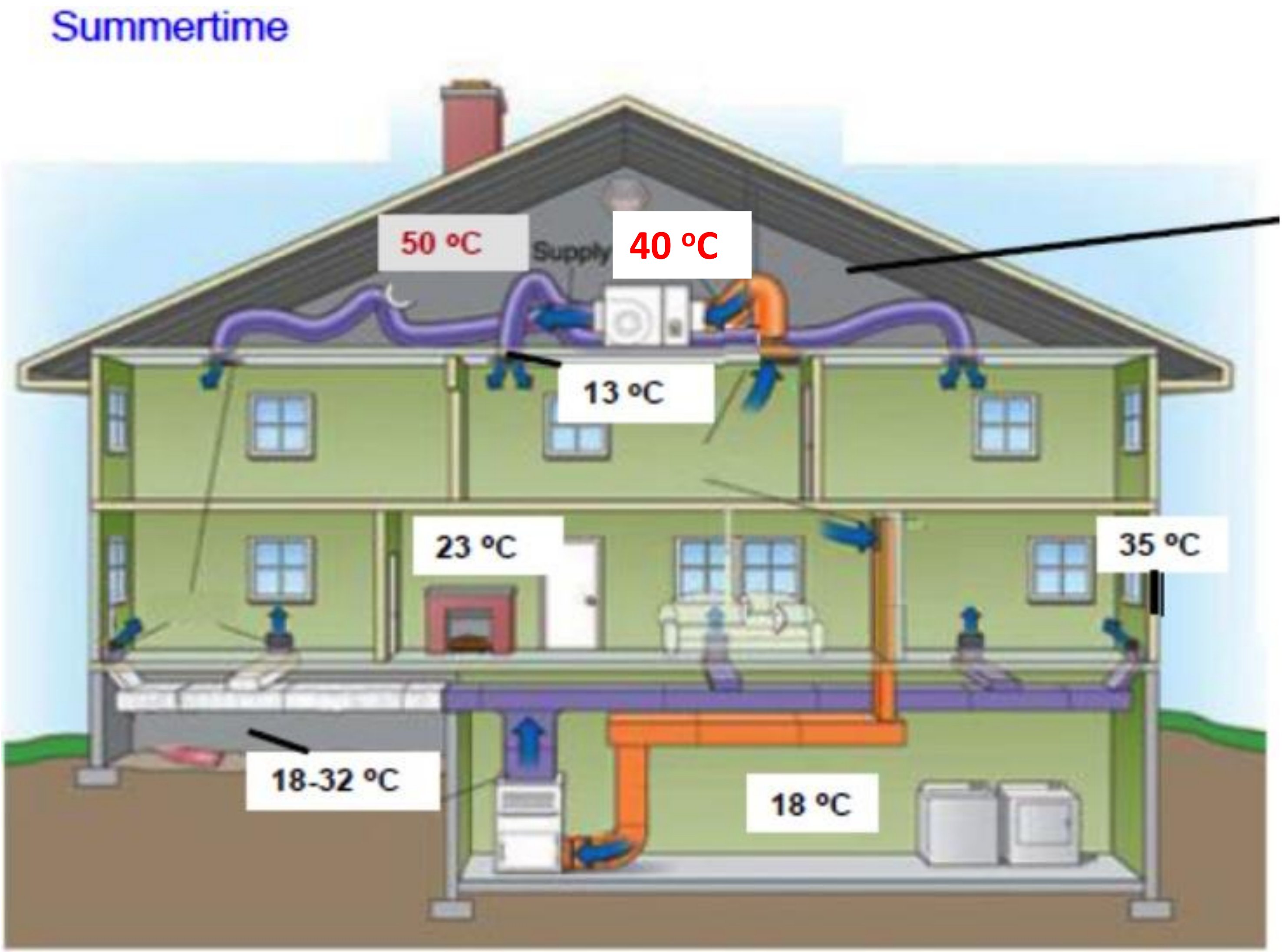
Where does mold grow?

- **Wet surfaces**
- **Moisture**
- **Where and when do these occur**

Environmental Conditions

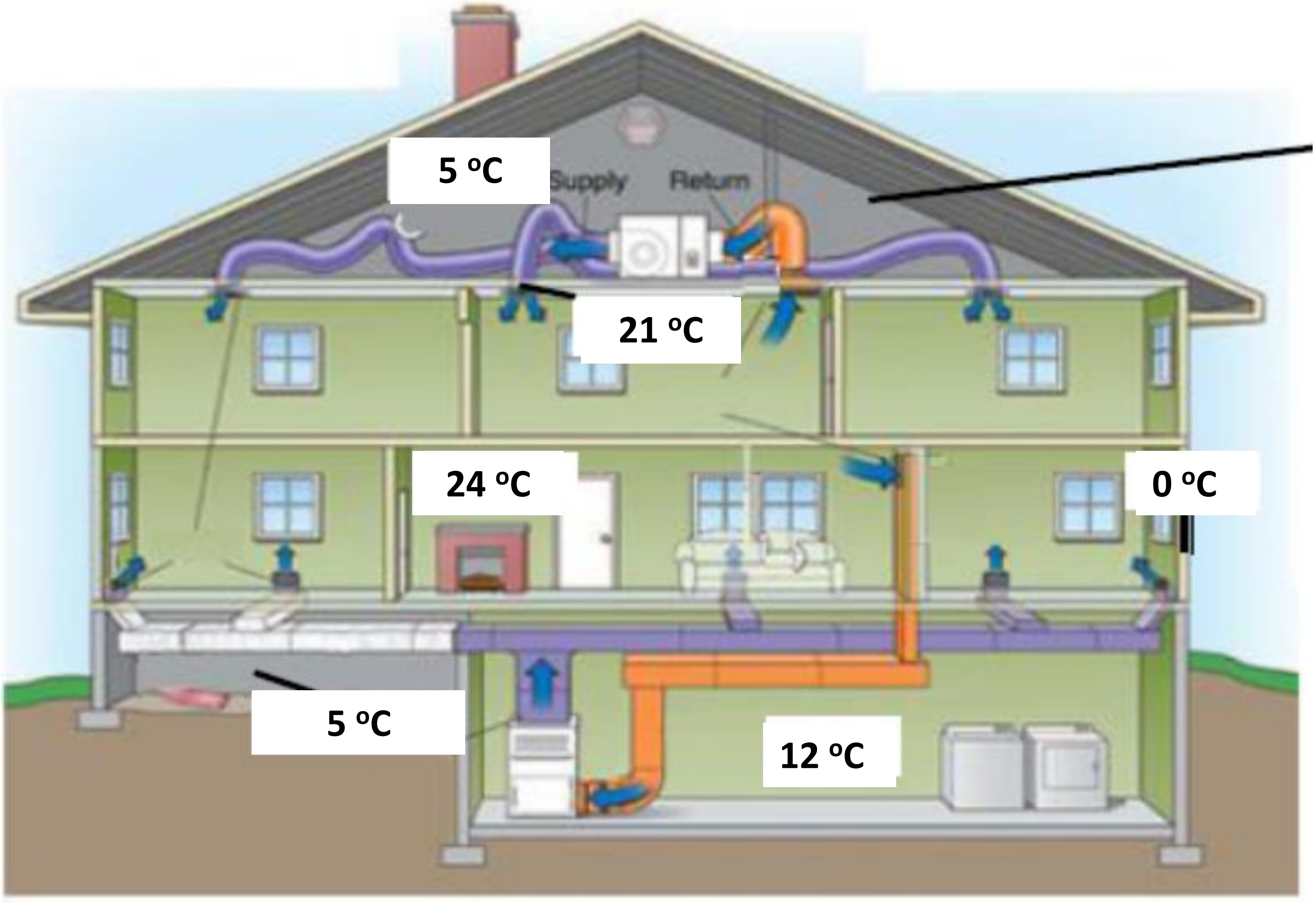
condensation

Where would you look for moist surfaces, mold?



Where would you look for moist surfaces, mold?

Wintertime



New ideas: new challenges
Unidentified complex surface films - UCSF

- **Take Charlie Weschler's description of the surfaces of a human-occupied environment, filled with squames covering every surface.**
- **Add to that the bacteria that hitchhike on those shed skin cells (2000/cm^2 of skin surface)**
- **The bacteria form "biofilms" where they emit chemicals to help themselves survive and to compete with their enemies**
- **So you have the SVOCs, the SOAs, the non-viable particles, and all those bacteria forming communities – bacteria grow on the mold that grows on the wet wood or gypsum board**