Assessing IAQ and Improving Occupant Health in Residences

Weatherization Plus Health

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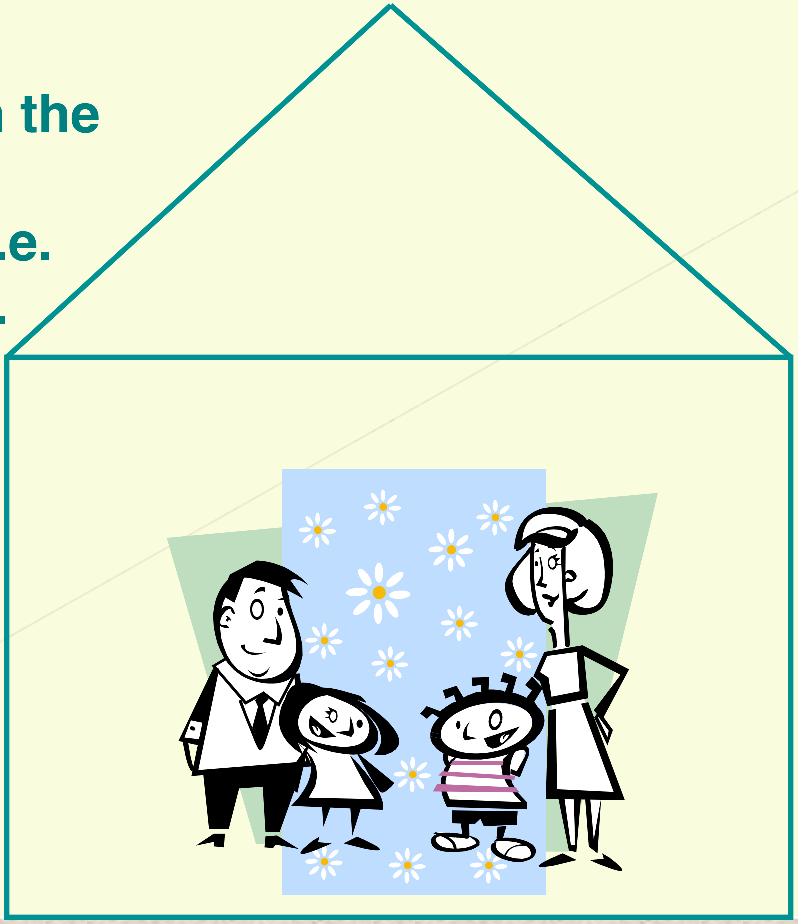
- Certified Industrial Hygienist - ABIH
- B.S. (Rensselaer) and M.S. (Stanford) in Mechanical Engineering
- Staff Scientist: IAQ Program, Lawrence Berkeley Laboratory
- Member of USBGC LEED EQ Technical Advisory Group
- Co-Chair ISIAQ HVAC Hygiene Task Force
- Member of ASHRAE Standard 62 Ventilation for Acceptable IAQ
- Member of ACGIH Bioaerosols Committee
- Member of the Cal-OSHA IAQ Advisory Committee
- Published 30 Peer-Reviewed Studies on Building Air Quality
- IAQ Diagnostics/Mitigation in over 2,000 Buildings (31 years - 2009)

The Problem - Tight Envelopes

Buildings are designed to isolate us from the outdoor environment (i.e. rain, hot, cold).



This isolation allows for air contaminants generated indoors to accumulate to high concentrations.

The Problem - Tight Envelopes

Many people never open their windows for ventilation, relying only on envelope leakage for ventilation.

Weatherization practices that reduce building outdoor air exchange rates cause for increases in the concentrations of indoor generated air contaminants

Tightening up homes to a “limit” as determined by an ACH_{50} blower door test does not guarantee there is adequate outdoor air ventilation.

Homes with significant sources of air contaminants should not be made more air tight without installation of a mechanical outdoor air ventilation system.

The Problem - Tight Envelopes

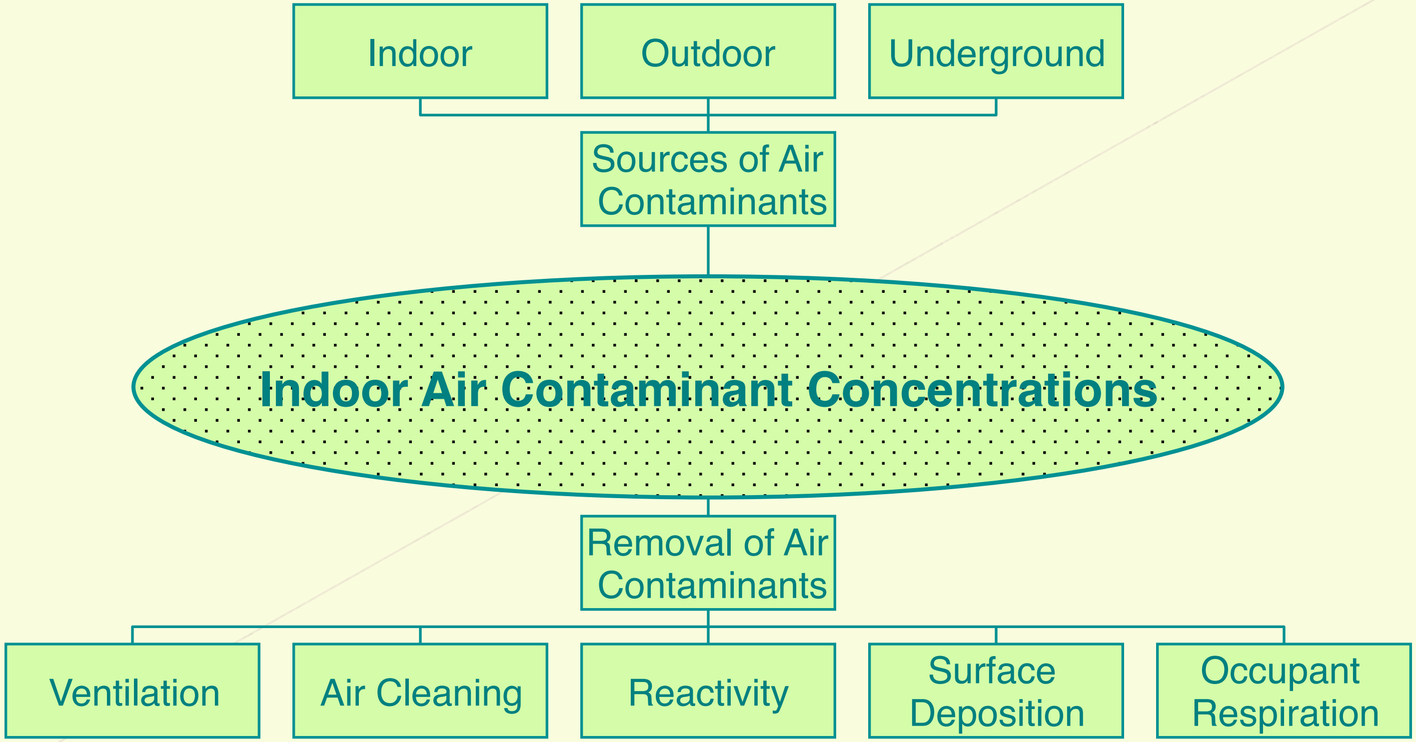
Home Weatherization Indoor Air Quality Concerns

Reducing the building envelope air leakage reduces outdoor air exchange rates which increases the indoor air contaminant concentrations

Potential increase in air contaminant concentrations = Initial ACH_{50} / Final ACH_{50}

For a home that is weatherized from an ACH50 of 15 to an ACH50 of 5, the exposures to indoor generated air contaminants increases by up to a factor of 3, with the windows closed.

Understanding IAQ



Understanding IAQ

Indoor Contaminant Sources

Building Occupants

- Biological emissions
- Infectious disease
- Tobacco smoking
- Personal hygiene products
- Pets

Building Materials

- Adhesives
- Caulking
- Pressed-wood products
- Vinyl wall coverings
- Thermal insulation
- Paint/Finishes

Home Furnishings

- Composite-wood
  - Furniture
  - Cabinetry
  - Flooring
  - Door/window trims

Home Activities

- Cooking
- Hobbies
- Vacuuming

Cleaning Items

- Cleaners
- Deodorizers
- Pesticides

Ventilation Systems

- Condensate pans, coils
- Leaky ducts
- Humidifiers
- Untrapped condensate drains
- Contaminated air filters
- Induced unplanned airflows

Understanding IAQ

Outdoor and Underground Sources

Outdoor Air

- Ozone
- Vehicle Traffic
- Wood Smoke

Exhaust Stacks and Vents

- Furnace
- Hot Water Heaters
- Kitchen
- Toilette
- Sewer vents

Soil Gas

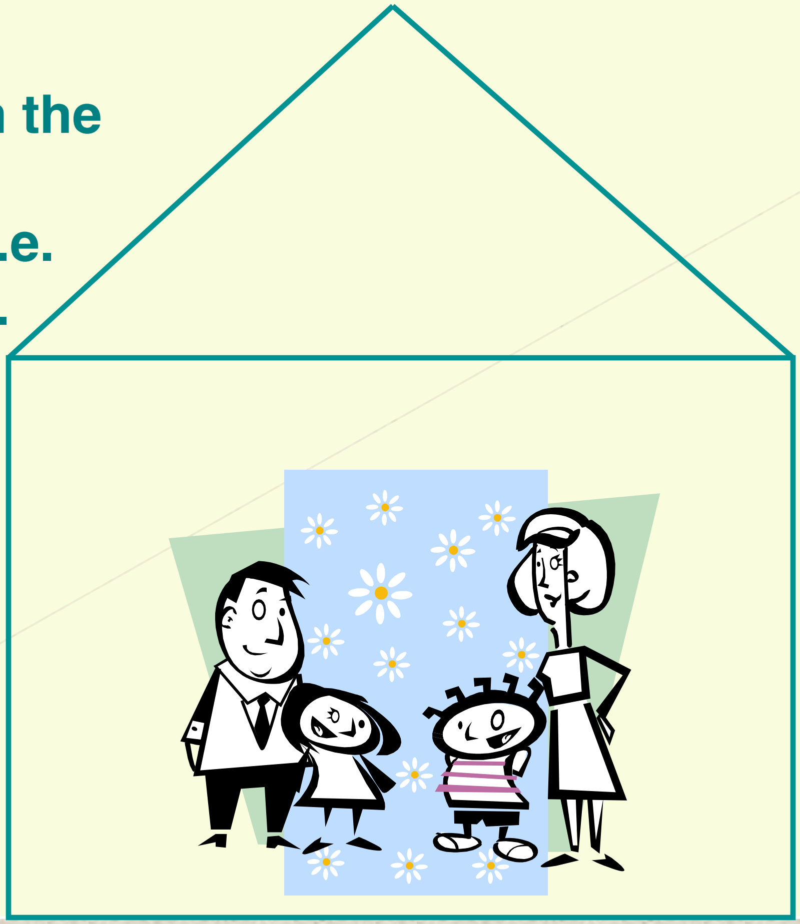
- Radon
- Methane
- Other Soil Contaminants

Some Contaminants Related to Home Weatherization Activities

Asbestos and Lead	- asbestos and lead containing materials that are disturbed
Fiberglass	- fiberglass insulation
Mold	- moldy materials
Isocyanates/amines	- polyurethane spray foam
Ammonia	- cellulose insulation (too wet) and with ammonia sulfate fire retardant
Volatile Organic Compounds (VOCs)	- adhesives, caulks, paints

The Problem - Tight Envelopes

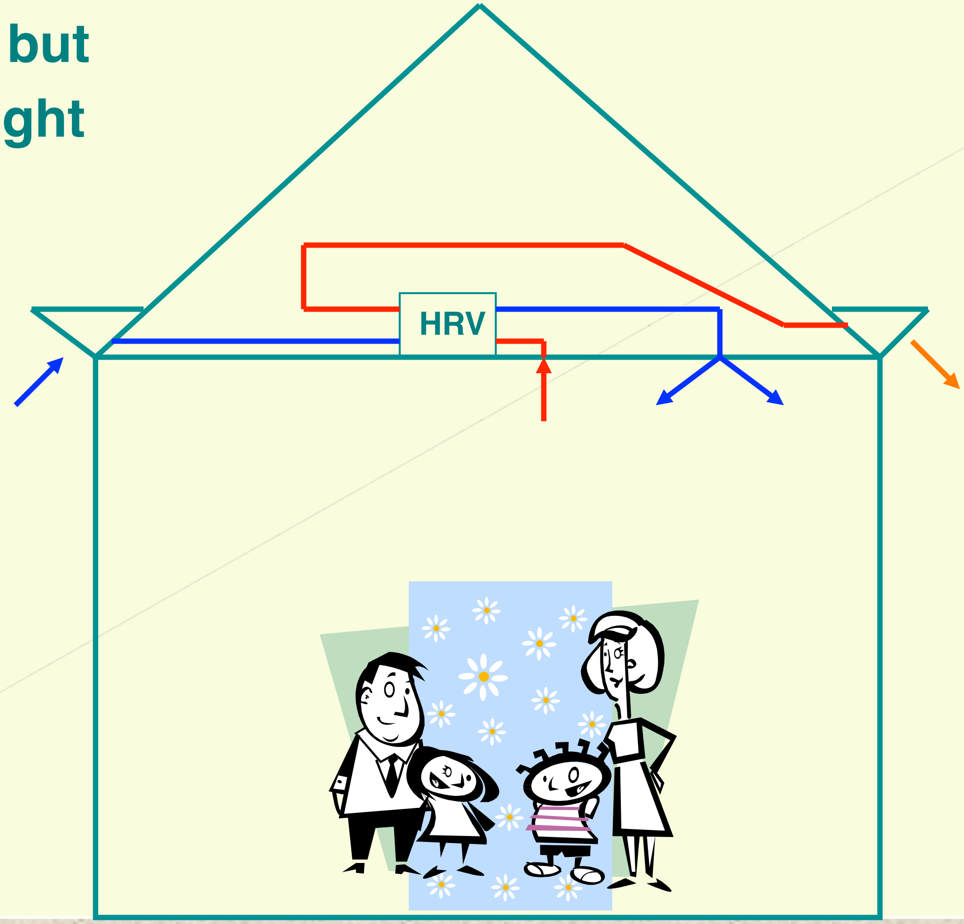
Buildings are designed to isolate us from the outdoor environment (i.e. rain, hot, cold).



This isolation allows for air contaminants generated indoors to accumulate to high concentrations.

The Solution - Energy Efficient Ventilation

Build Tight but Ventilate Right



Ventilation

While air filtration and air cleaners can remove SOME particles and SOME gasses,

Ventilation removes 100% of ALL particles and gasses.

Ventilation

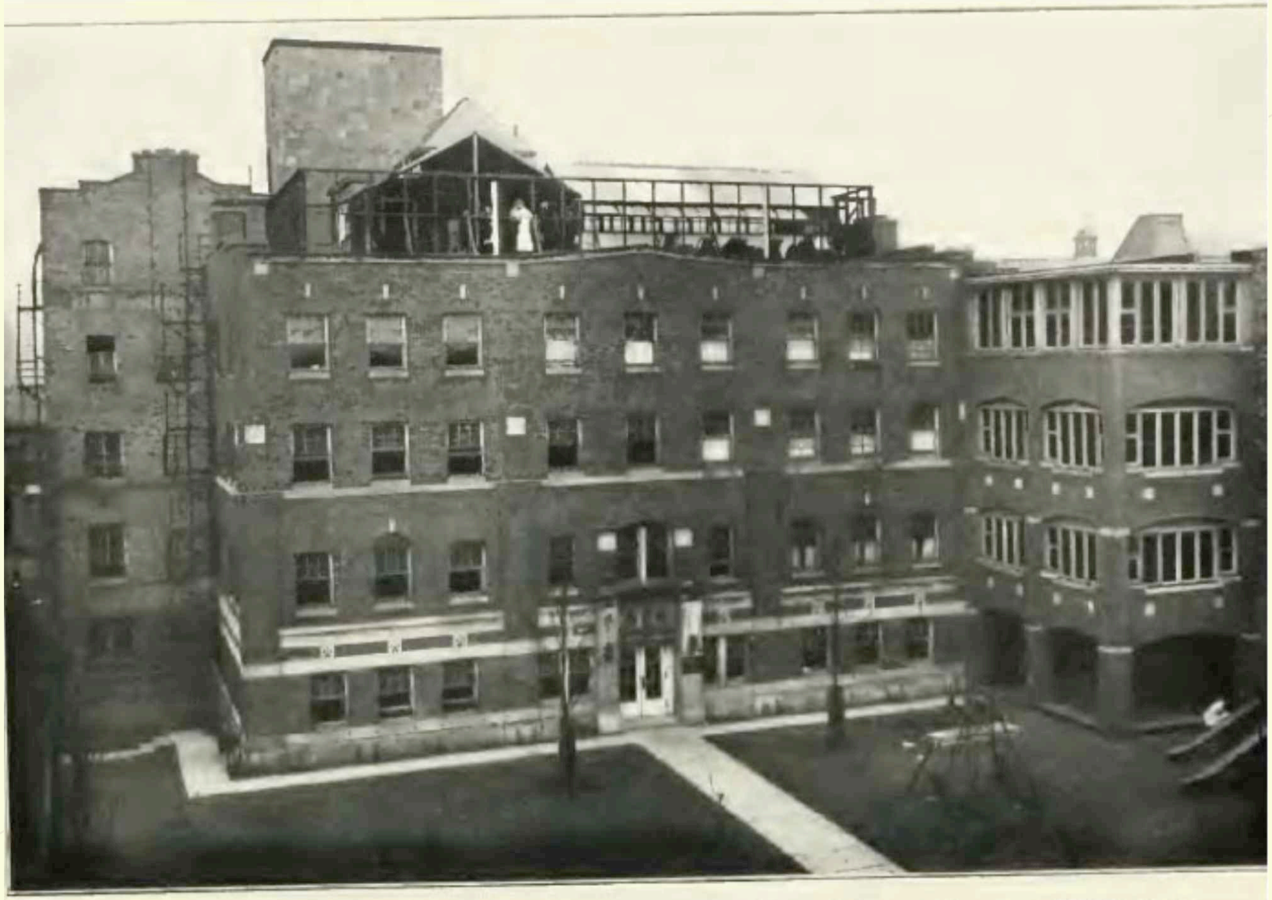
School ventilation and disease 1908 - Chicago ventilation intervention study.

Elizabeth McCormick Open Air School

Published in 1910 by the United Charities of Chicago

City of Chicago
1.6% (4,700) children with TB
5% (14,600) children anemic / weakened

Ventilation

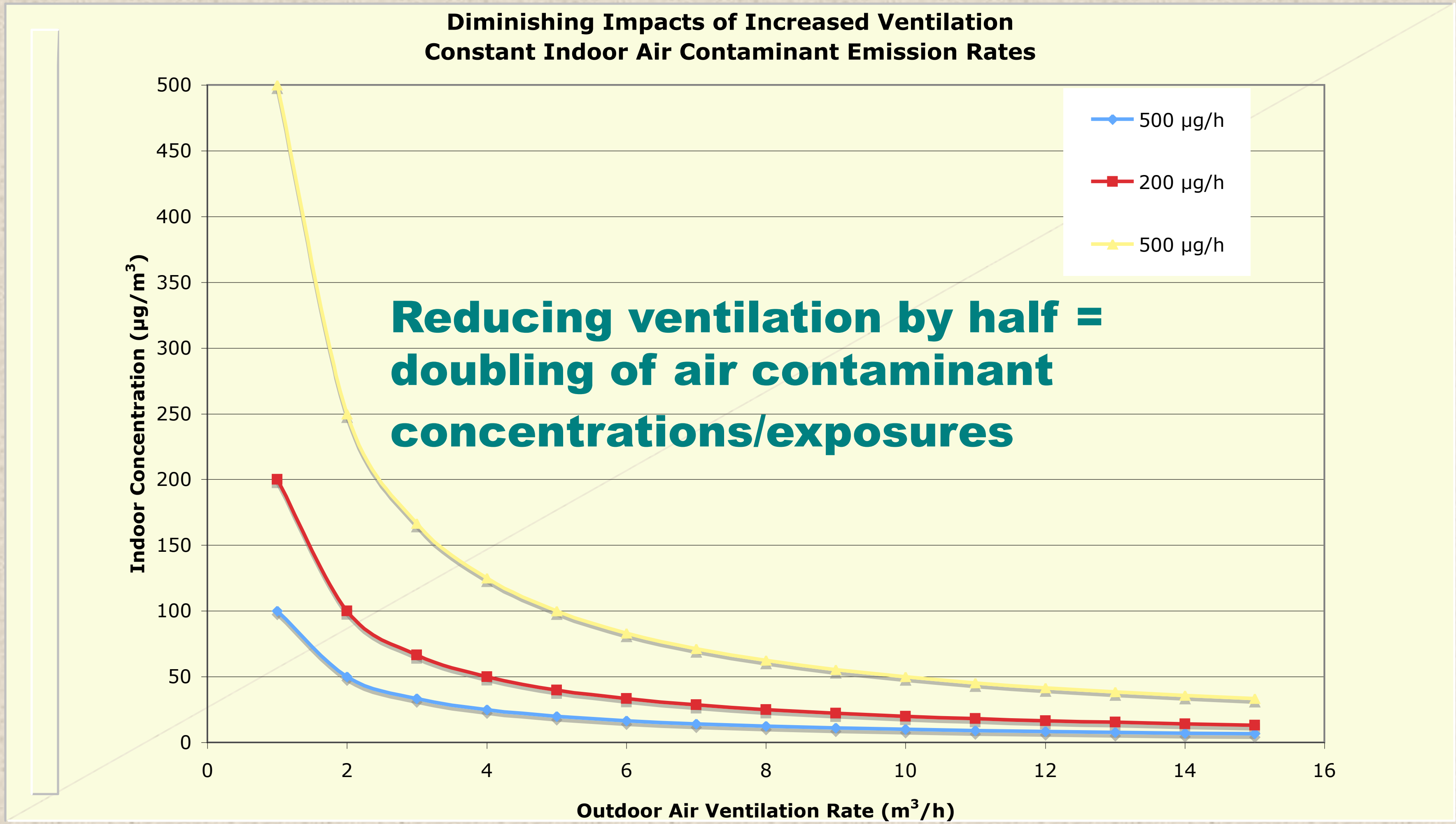


Exterior of Mary Crane Nursery, Showing Tents on Roof, Shelter Tent in Foreground, Study Tent to the Right

Ventilation

Open Air — Open Minds

Ventilation and IAQ



Ventilation

Ventilation *versus* Source Control

Pettenkofer
"If there is a pile of manure in the barn making an odor, do not ventilate the barn remove the manner"

Ventilation is NOT a solution to MOLD contamination in Buildings anymore than it is for ETS.

Ventilation is a GOOD solution for people generated contaminants.

Ventilation and Carbon Dioxide

Ventilation Costs

Annual Cost of Ventilation ($/yr)

	Exhaust	FAU/DOA	HRV/ERV
First Cost	25 - 50 (20 yr)	30 (20 yr)	210 (10 yr)
Heating/Cooling *	150 - 300	150 - 300	50 - 100
Fan Power	15	100 (25% duty)	125
Total Cost	190 - 365	280 - 430	385 - 435

* Boston, Washington, Houston, Phoenix climate zones
"Residential Ventilation Handbook" - Paul Raymer

California New Home Study

In 2005, the California Energy Commission and California Air Resources Board commissioned a large and comprehensive field study of ventilation and IAQ in new homes.

Indoor Environmental Engineering conducted this field study in 2006-2007.

Final Report published November, 2009

Available at www.iee-sf.com.

HYPOTHESIS

- Many homeowners never or rarely open their windows (UC Berkeley 2005 Mail Survey)
- As a result, outdoor air exchange rates in these homes are very low (e.g. 0.1 - 0.2 ach)
- These low air exchange rates result in elevated indoor concentrations of air contaminants such as formaldehyde, which is both a potent irritant and a know human carcinogen.

Study Design - California New Home Study

- Recruit 108 home

 - 54 each from Northern and Southern California

 - 20 homes with mechanical outside air ventilation systems.

- Summer and Winter Field Sessions (20 home seasonal crossover)

- Measure window/door opening, outdoor air exchange rates, air contaminant concentrations, house characteristics, source activities, and occupant perceptions.

Recruitment

- We utilized a 2005 mail survey by UCB on window use in new single family homes (random stratified).
- A total of 965 of the 1,515 UCB Mail Survey respondents indicated an interest in participating in the follow up field study.
- We mailed out recruitment letters to the 965 interested UCB Mail Survey participants, as well as 1,798 additional nearby new homes.

Ventilation Measurements

7 Day Monitoring Period

- **Window/door openings**

  - electronic loggers and occupant logs.

- **Exhaust fan usage**

  - electronic loggers, occupant logs, and flowhood measurements.

- **Mechanical outside air and FAU fan usages**

  - electronic loggers and flowhood measurements.

- **Building envelope air leakage**

  - multi-point fan depressurization

Ventilation Measurements

Window Opening Data Logger

Building Envelope Air Leakage Measurements

Blower Door with Computer Automated Test System

Outdoor Air Exchange Rate Measurements - 24 hour

- **Passive tracer gas technique (PFT)**

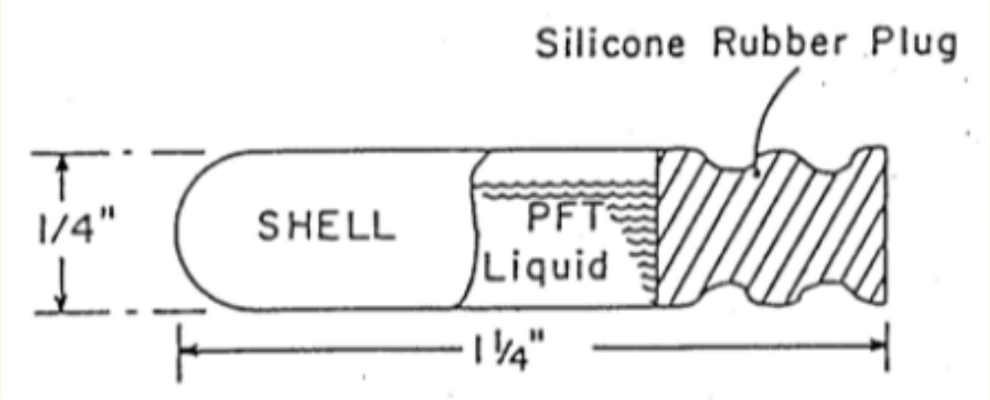
  - 4-8 tracer gas sources deployed one week in advance to allow for the emission rates to equilibrate.

  - tracer sampler deployed in home for 24 hour period

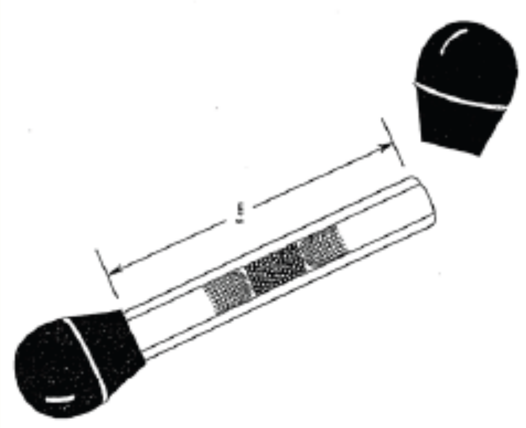
  - a subset of 30 homes also deployed samplers for a 2 week period

Outdoor Air Exchange Rate Tracer Gas Measurements - ASTM E741

Perfluorocarbon Tracer (PFT) Passive Source



PFT Passive Sampler



Quiet Active Indoor Air Sampler

- HCHO
- VOC's
- $PM_{2.5}$
- CO_2
- CO
- T
- RH
- Flow Control
- Power Surveillance

Shielded Outdoor Air Sampler

Rain/Radiation Shield

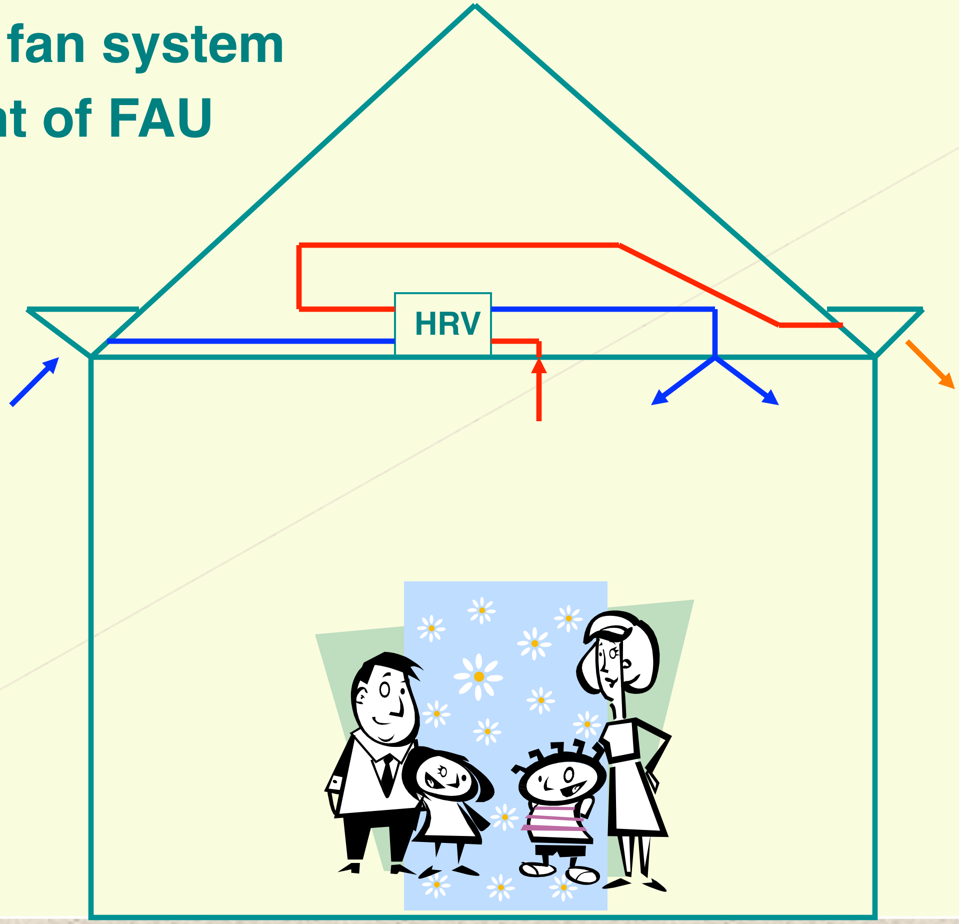
Field Session Recruits

- 108 homes primarily from tract developments
- built 2002 or later, and have been owner-occupied for at least one year (median age 3.4 years)
- typically stucco and slab on grade with attached garages.
- all homes had forced air unit heating systems (94% with AC)
- 35 homes with some type of mechanical outdoor air ventilation system

Heat Recovery Ventilator (HRV) System

Balanced 2 fan system

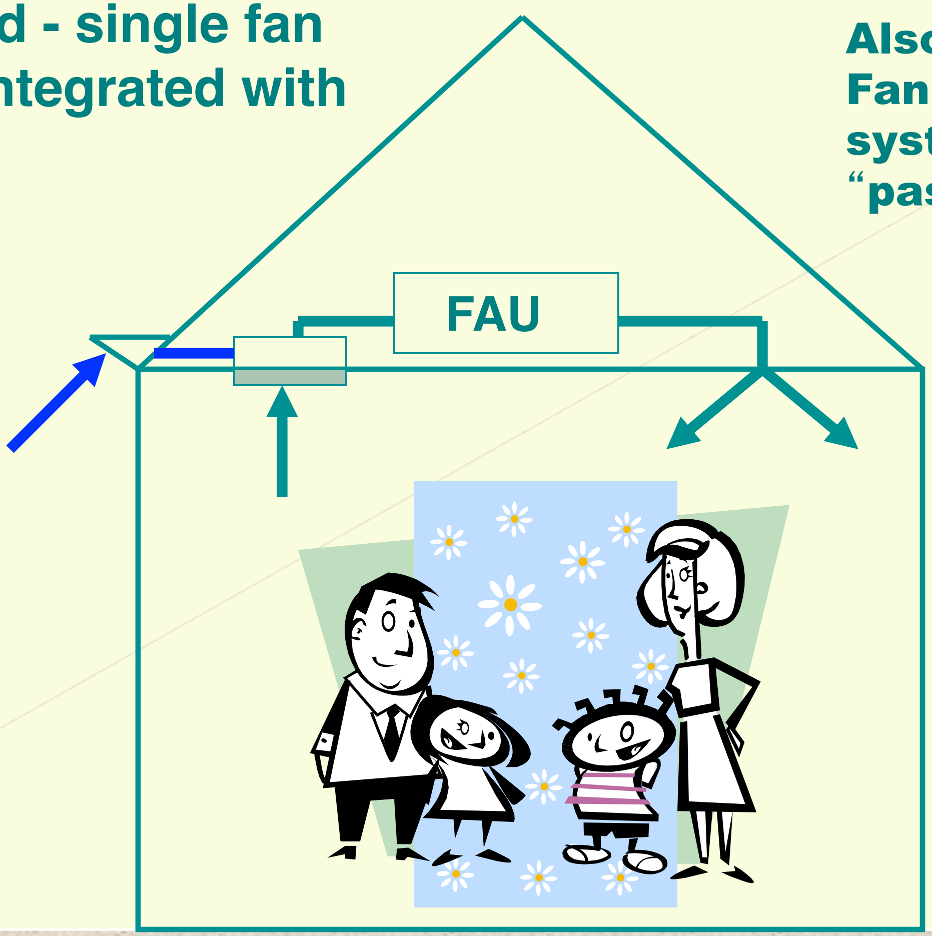
Independent of FAU



Ducted Outdoor Air (DOA) System (17 homes)

Unbalanced - single fan system – integrated with FAU

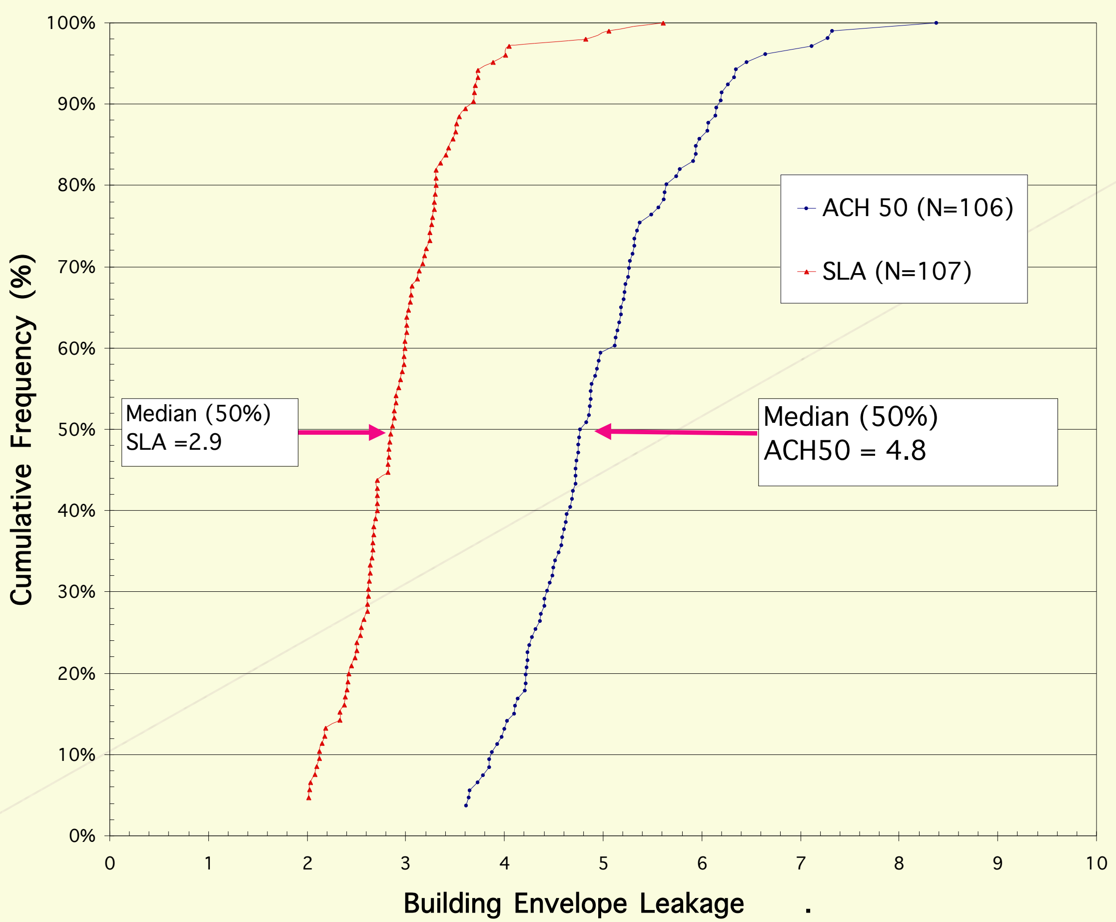
Also called Central Fan Integrated (CFI) systems and "passive inlets".



RESULTS - Window/Door Usage

- 32% of the homes never opened windows or doors during the test day and 15% never during the previous week.
- most of the homes with zero window/door usage were in the Winter field session (85%)

RESULTS - Building Envelope Leakage



RESULTS - Building Envelope Leakage

- Homes are getting more airtight, largely as a result of installation of house wrap.

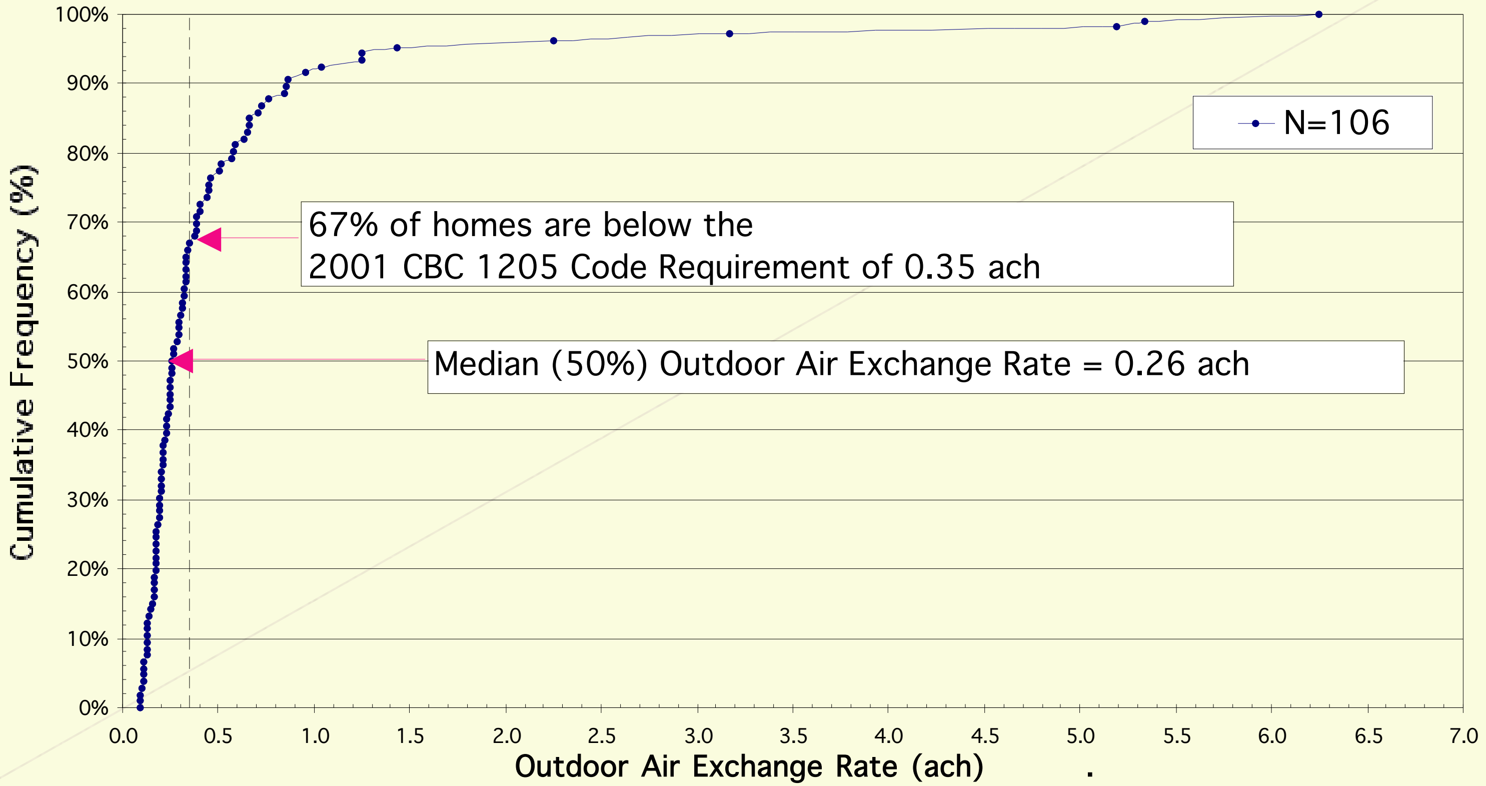
Median ACH50 in California Homes

- built before 1987 (13 homes) - 8.6
- built in 2002 (76 homes) - 5.2
- built 2002 - 2004 (108 homes) - 4.8

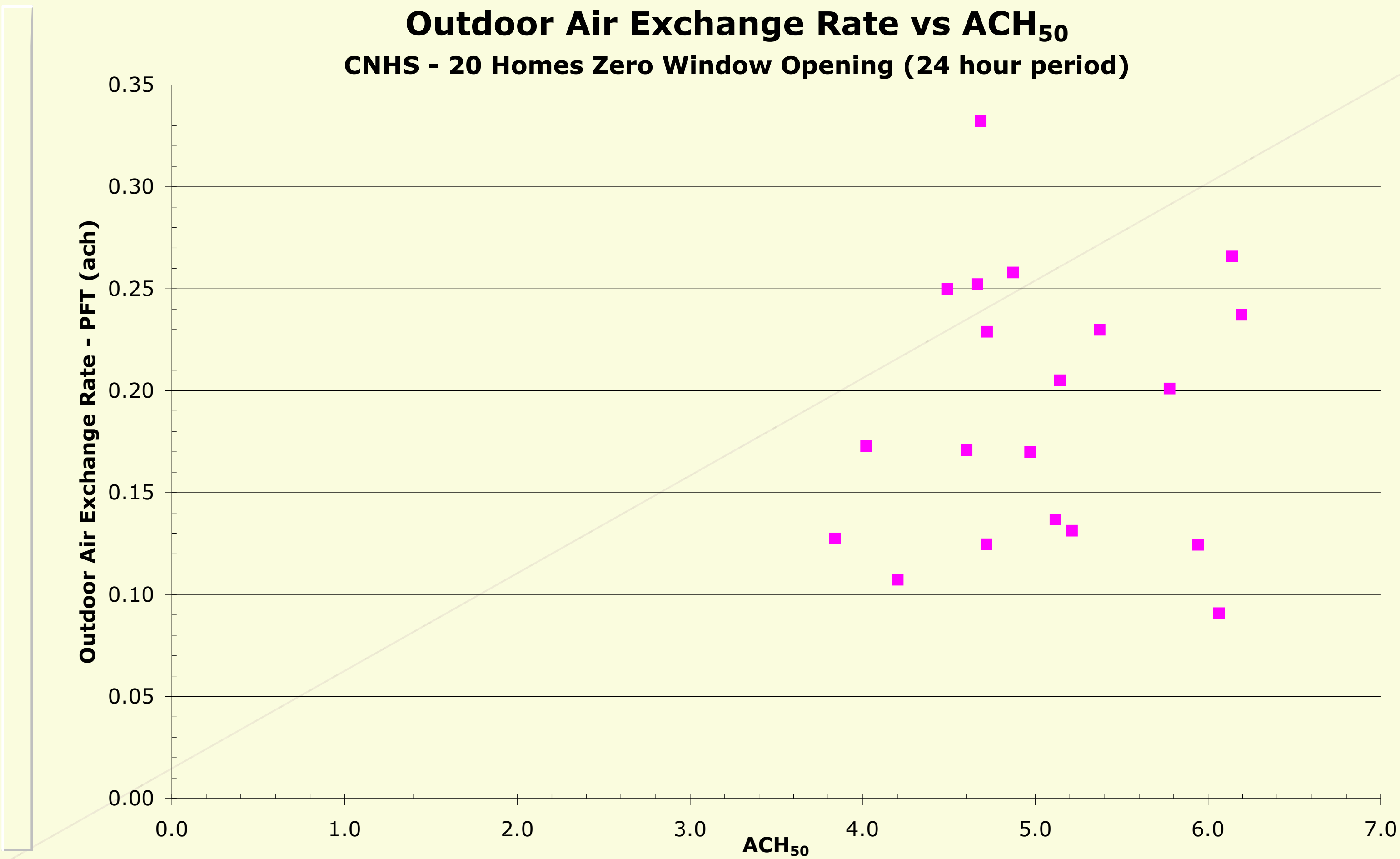
Median Normalized Leakage (70,000 US Homes)

- built before 1950 - 0.67
- built 1950 - 1979 - 0.49
- built 1980 - 1995 - 0.38
- built 1996 - 2002 - 0.31

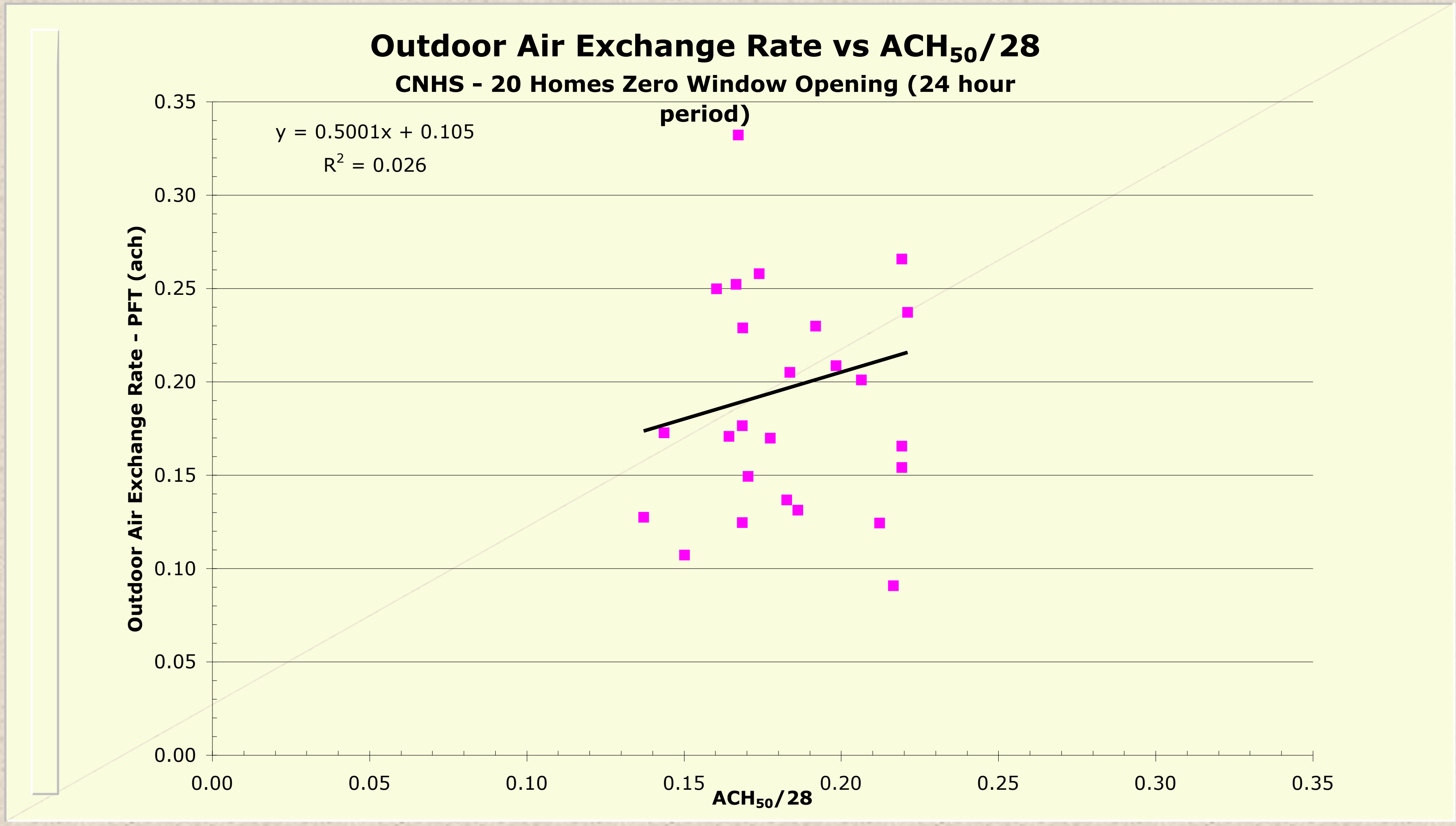
RESULTS - Outdoor Air Exchange Rates - PFT Measurements



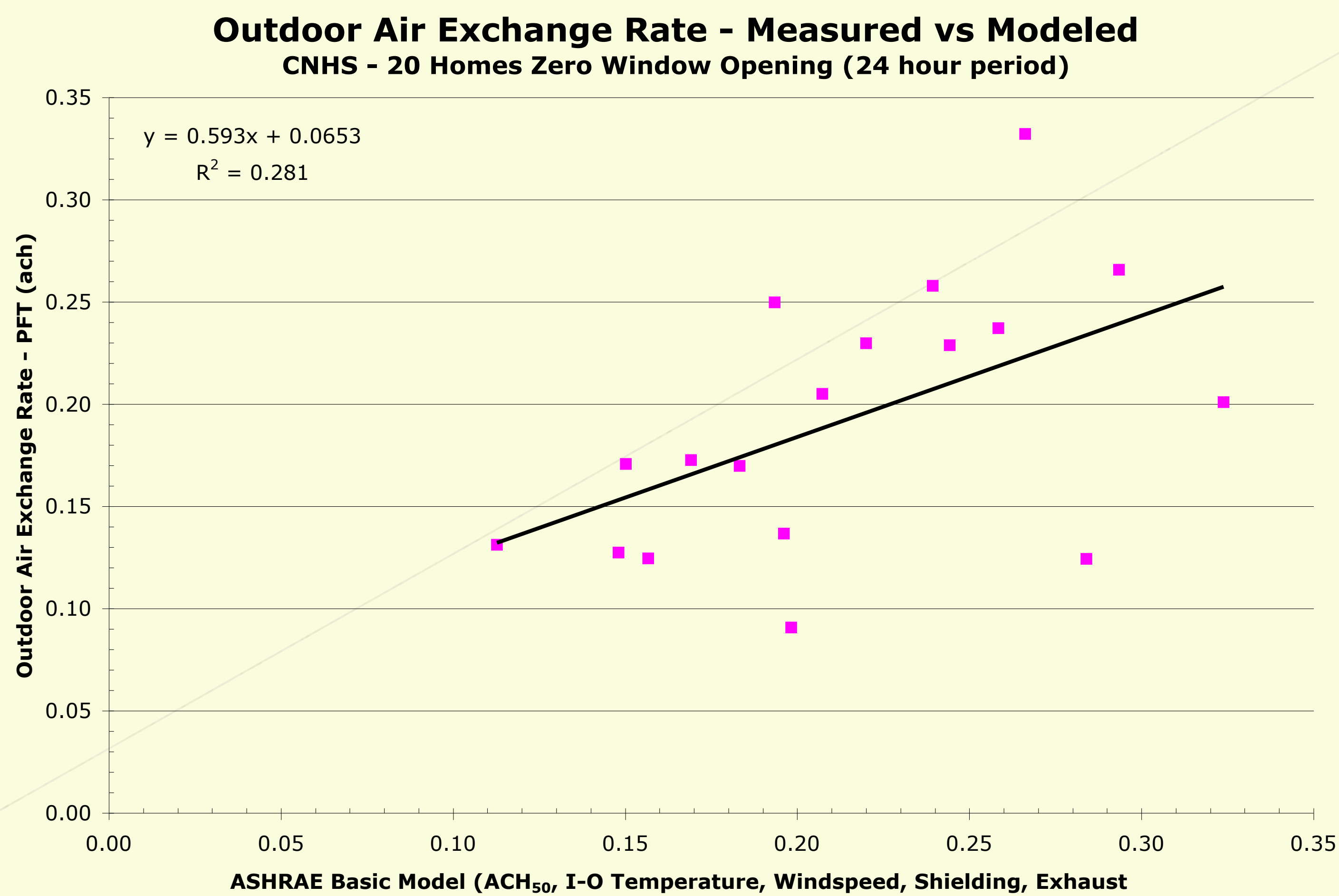
RESULTS - Outdoor Air Exchange Rates - PFT Measurements and ACH_{50}



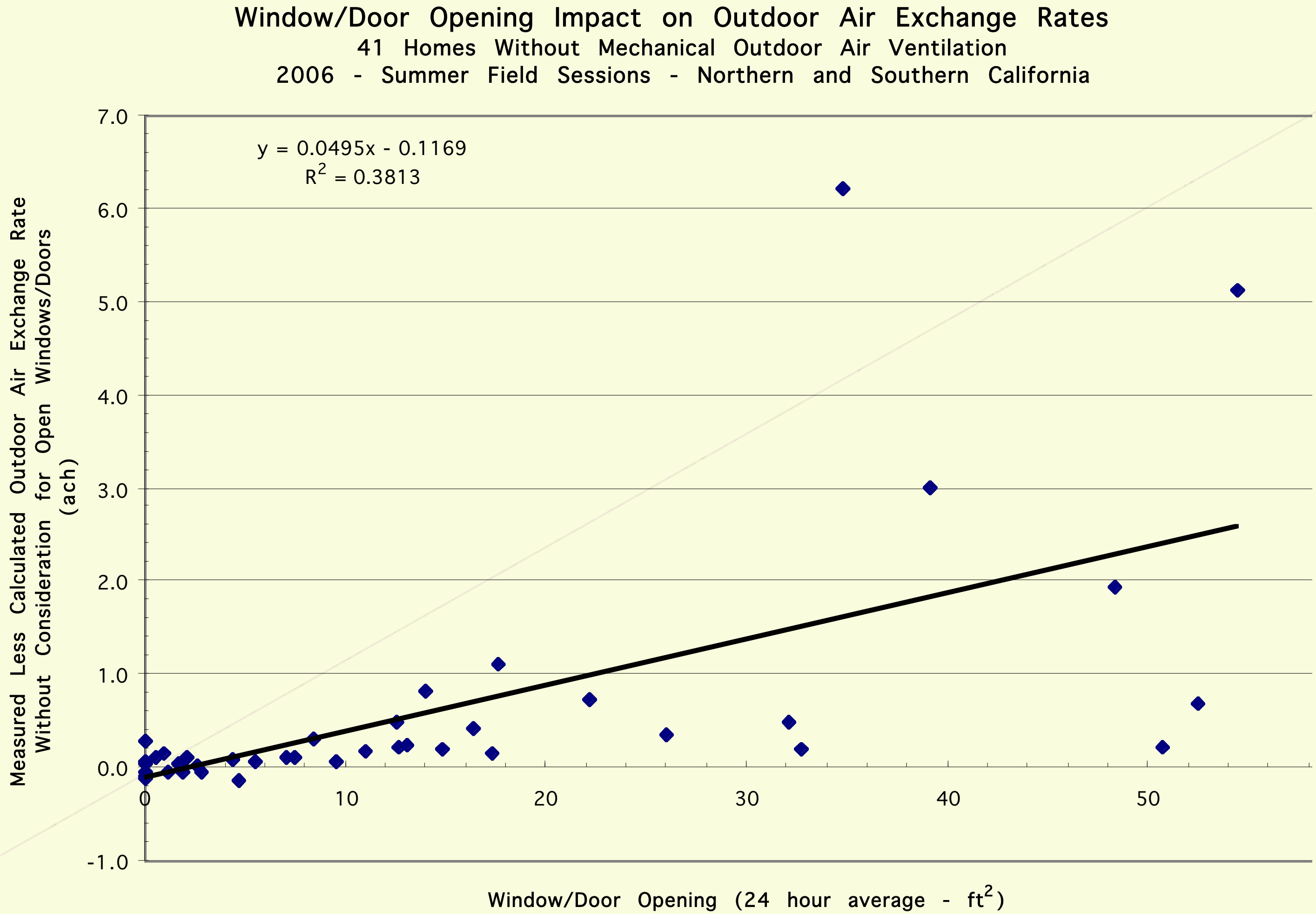
RESULTS - Outdoor Air Exchange Rates - PFT Measurements and ACH_{50}



RESULTS - Outdoor Air Exchange Rates - PFT Measurements and ACH_{50}



RESULTS - Outdoor Air Exchange Rates - PFT Measurements



RESULTS - 24-hour Average Outdoor Air Exchange Rates

	Number of Homes Tested	Minimum (ach)	Median (ach)	Maximum (ach)	Percentage [a] of Homes Below CBC Code Requirement
Non-mechanically Ventilated Homes	73	0.09	0.25	5.3	75
DOA-mechanically Ventilated Homes	14	0.10	0.20	0.60	64
HRV-mechanically Ventilated Homes	5	0.33	0.71 *	4.3	64

- 0.35 ach; 2001 California Building Code (CBC), Appendix Chapter 12, Interior Environment, Division 1-Ventilation, Table A-12-A, Outdoor Air Requirements for Ventilation, Living

* statistically significantly higher mean ach (t-test, $p<0.05$)

RESULTS - Mechanical Outdoor Air System Performance

	DOA Mechanical Outdoor Air Homes (n=14)			HRV Mechanical Outdoor Air Homes (n=8)		
Quartiles	Ach (h^{-1})	% on time	cfm	Ach (h^{-1})	% on time	cfm
Minimum	0	0	9	0.12	32	66
Median	**0.01**	**10**	**38**	**0.30**	**100**	**128**
Maximum	0.08	75	355	0.47	100	159

RESULTS - Formaldehyde Concentration Guidelines

- Proposition 65 (cancer):
  - NSRL (cancer) - 2 $\mu g/m^3$

- OEHHA Reference Exposure Levels (non-cancer, irritant effects)
  - Chronic REL - 9 $\mu g/m^3$
  - 8 hour REL - 9 $\mu g/m^3$
  - Acute REL (1 hr) - 55 $\mu g/m^3$

- California Air Resources Board
  - Indoor Air Guideline - 33 $\mu g/m^3$

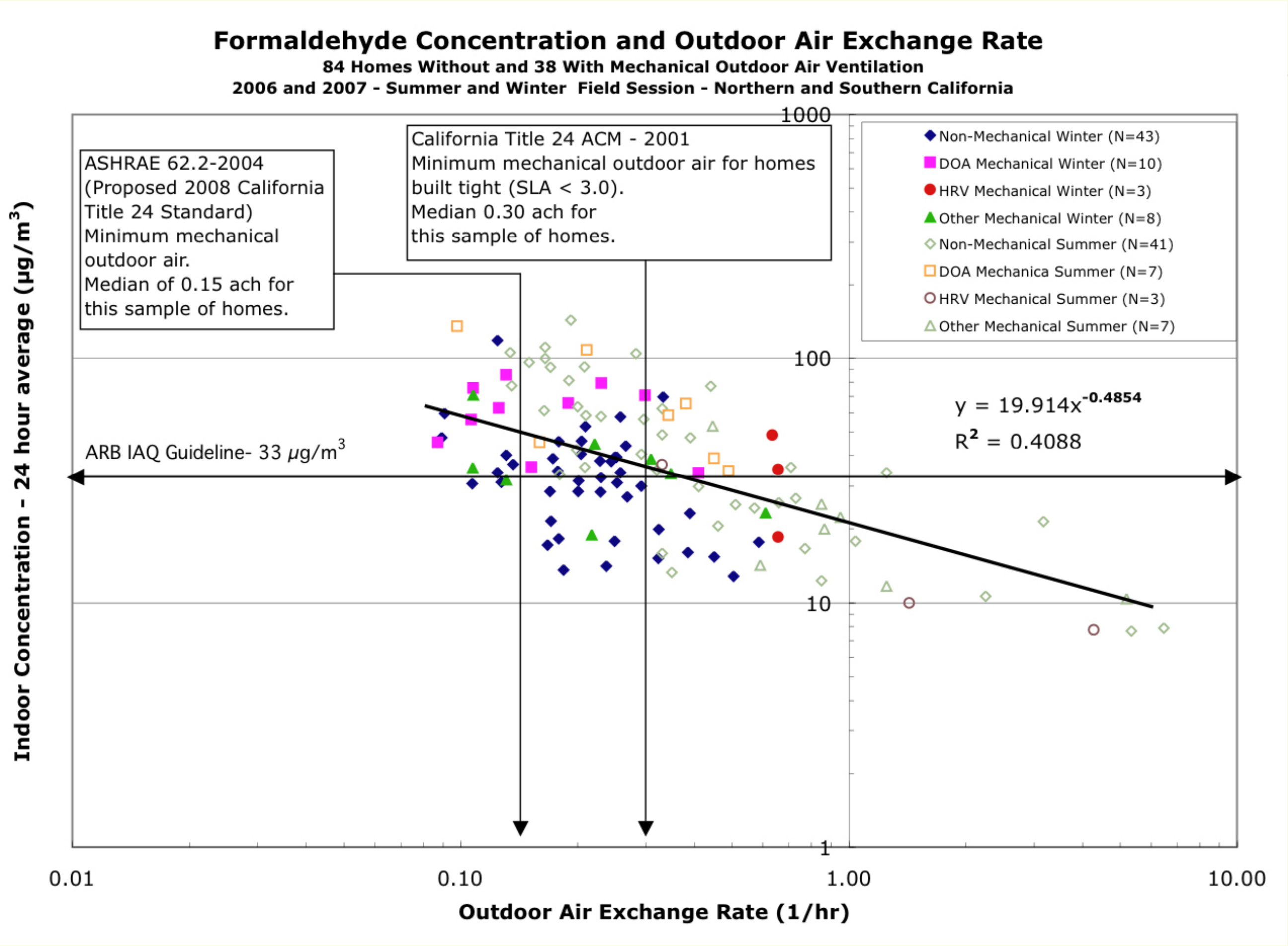
RESULTS – Formaldehyde Concentrations

RESULTS - Indoor Concentrations of Formaldehyde

	Number of Homes Tested	Minimum ($\mu g/m^3$)	Median ($\mu g/m^3$)	Maximum ($\mu g/m^3$)	Percentage [a] of Homes Above ARB Indoor Air Guideline
Non-mechanically Ventilated Homes	72	8	35	126	57
DOA-mechanically Ventilated Homes	14	34	68*	136	93
HRV-mechanically Ventilated Homes	5	8	37	63	60

a.) 2005 California Air Resources Board – 33 $\mu g/m^3$.
* statistically significantly higher mean concentration (t-test, $p<0.05$)

RESULTS - Formaldehyde Concentrations and Ventilation



Hazard Quotient Analyses
"How Bad Is It, Really ?"

- Input measured emission rates into a single zone mass balance model using ASHRAE 62.2 minimum outdoor rates.

  0.16 air changes per hour (ach) mechanical
  + 0.14 ach assumed infiltration = 0.30 ach

- Calculate steady-state indoor concentrations.
- Calculate "Hazard Quotient": concentration/exposure guideline

Exposure Guidelines: OEHHA CRELs or 1% of OSHA PELs

Hazard Quotients - Emission Rates and ASHRAE 62.2 Minimum OA Ventilation Rates

Top 7 Hazard Quotients for the 20 measured VOCs

Compound	Guideline	50%	75%	90%	Max
Formaldehyde	9	4.307	6.159	8.752	24.31
Acetaldehyde	140	0.142	0.182	0.232	0.492
Ethylene glycol	400	0.034	0.067	0.118	0.368
Toluene	300	0.027	0.05	0.097	0.271
Naphthalene	9	0.022	0.033	0.048	0.567
Benzene	60	0.016	0.033	0.061	0.244
Tetrachloroethene	35	0.011	0.025	0.072	0.549

Other Indoor Air Contaminants

Percentage of homes exceeding recommended lifetime cancer risk (i.e. 1 in 100,000)

Formaldehyde -100 (composite wood products)
Acetaldehyde - 93 (composite wood products)
Benzene - 63 (attached garages, paint, caulking)
Naphthalene - 27 (mothballs)
1,4-dichlorobenzene - 12 (mothballs)
Tetrachloroethene - 8 (dry cleaned clothes)
Trichloromethane - 8 (chloroform - chlorinated water)

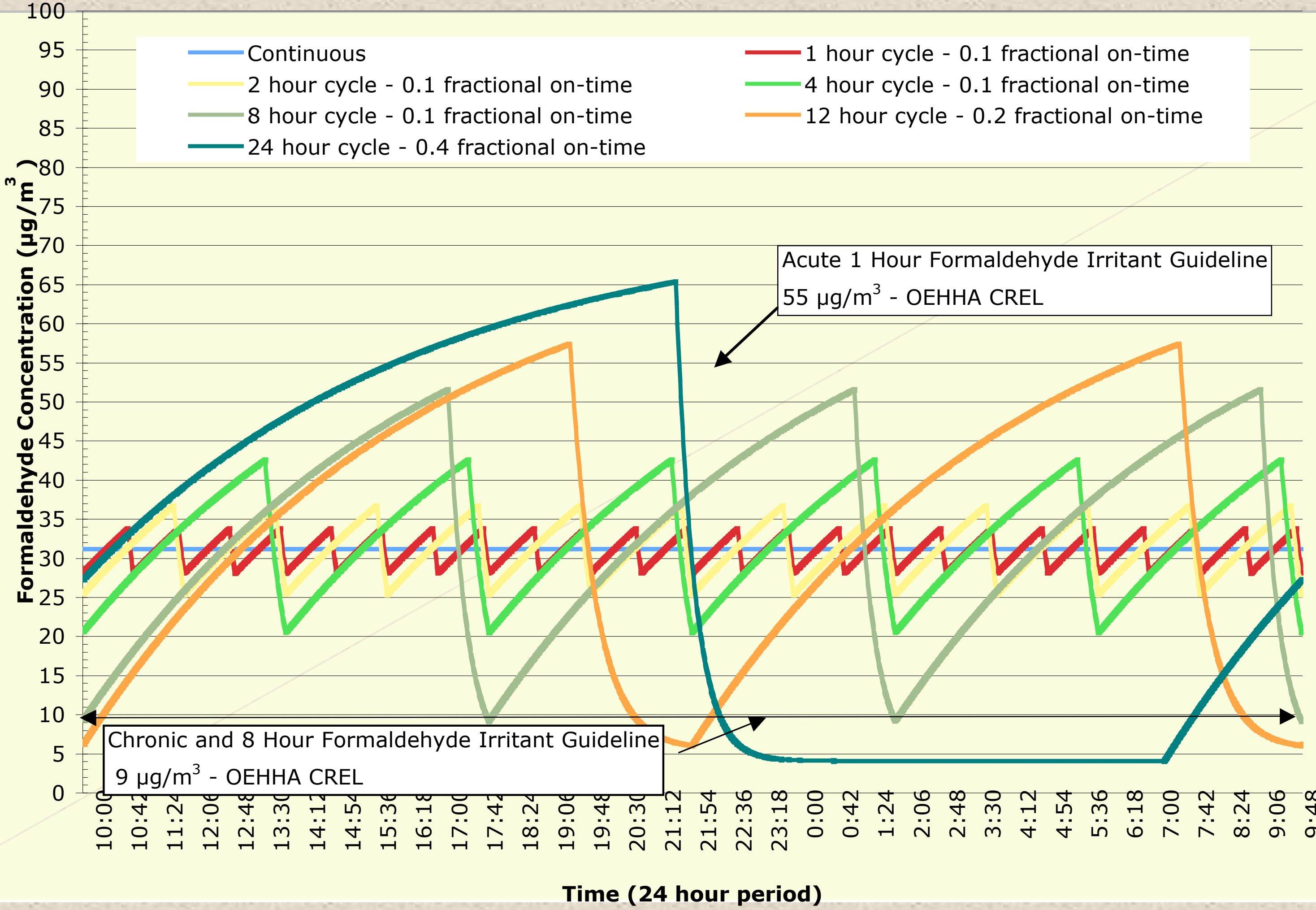
Conclusions

ASHRAE 62.2 ventilation rates are INSUFFICIENT to control formaldehyde. Substantial reductions in emission rates is required.

The emission rates of these 20 VOCs are useful for calculating required outdoor air ventilation rates, BUT the emission rates of other VOCs and other air contaminants are needed.

Research on the impact of ventilation rates on emission rates is needed.

Formaldehyde Concentrations and Intermittent Ventilation



Intermittent Ventilation IAQ Performance

Cycle Time (hrs) Fractional On-Time Ventilation Effectiveness	**24** 0.4 0.20	**12** 0.2 0.56	**8** 0.1 0.79	**4** 0.1 1.0	**2** 0.1 1.0	**1** 0.1 1.0
Outdoor Air Flowrate (L/s)	283	202	287	227	227	227
Hours of Operation	9.6	4.8	2.4	2.4	2.4	2.4
Outdoor Air (m^3 per 24 hours)	9,787	3,495	2,478	1,957	1,957	1,957
Formaldehyde Hours exceeding one hour irritant guideline: 55 $\mu g/m^3$)	5.6	1.9	0	0	0	0
Carbon Dioxide (Hours exceeding visitor body odor guideline: 700 ppm over outdoors)	9.4	9.7	8.0	1.6	0	0

Intermittent Ventilation IAQ Performance - Relative to Continuous

Cycle Time (hrs) Fractional On-Time Ventilation Effectiveness	24 0.4 0.20	12 0.2 0.56	8 0.1 0.79	4 0.1 1.0	2 0.1 1.0	1 0.1 1.0
Average (24 hr) Concentration	0.95	1.07	1.07	1.03	1.00	0.99
Maximum Concentration	2.1	1.8	1.7	1.4	1.2	1.1
Visitor New Cases of Airborne Infectious Disease	2.0	1.7	1.4	1.1	1.0	0.99
Occupant New Cases of Airborne Infectious Disease	0.95	1.07	1.07	1.03	1.00	0.99

Conclusions

- We conclude that new single-family detached homes in California are built relatively tight (i.e. 50% of the homes had an $ACH_{50} < 4.8$).

- Many homeowners never open their windows (e.g. 32% in the Winter).

Conclusions

- Homes where the windows/doors are not opened, have low outdoor air exchange rates (e.g. 0.1 - 0.2 ach), and indoor concentrations of air contaminants, such as formaldehyde, can be significantly elevated.

- 67% of the homes had outdoor air exchange rates below 0.35 ach (2001 CBC 1205 code requirement).

- 59% of the homes had indoor formaldehyde concentrations above 33 $\mu g/m^3$ (27 ppb), the California ARB indoor guideline.

Conclusions

- The HRV mechanical outdoor air systems performed well in increasing the home outdoor air exchange rates and reducing indoor formaldehyde concentrations.

- The DOA systems did NOT perform well as a result of a combination of the low outdoor air flow rates and low fan operation times.

Conclusions

- Intermittent mechanical outdoor air systems, as operated according to ASHRAE 62.2-2010, do NOT provide IAQ that is equivalent to a continuous systems.

- Cycle times greater than 2 hours, can result in exceedences of short term exposure guidelines causing irritation, odors, and increased exposure to airborne infectious disease organisms.

Pursuing Safe Indoor Air in Net Zero Energy Buildings

Saving Energy Through Reducing Outdoor Air Ventilation Rates

Increased interest in defining “Safe Indoor Air” for the purpose of reducing outdoor air ventilation rates, while preserving acceptable indoor air quality.

Pursuing Safe Indoor Air in Net Zero Energy Buildings

Engineers routinely size HVAC systems for thermal comfort based upon:

- anticipated heating and cooling loads
- desired indoor air temperature and humidity

Engineers SHOULD be able to size mechanical outdoor air ventilation rates based upon:

- anticipated indoor contaminant emission rates
- desired indoor air contaminant concentrations

Pursuing Safe Indoor Air in Net Zero Energy Buildings

???

Can we adequately assess indoor air exposures such that we may confidently reduce outdoor air ventilation rates without compromising health ?

and

How tight is too tight ?

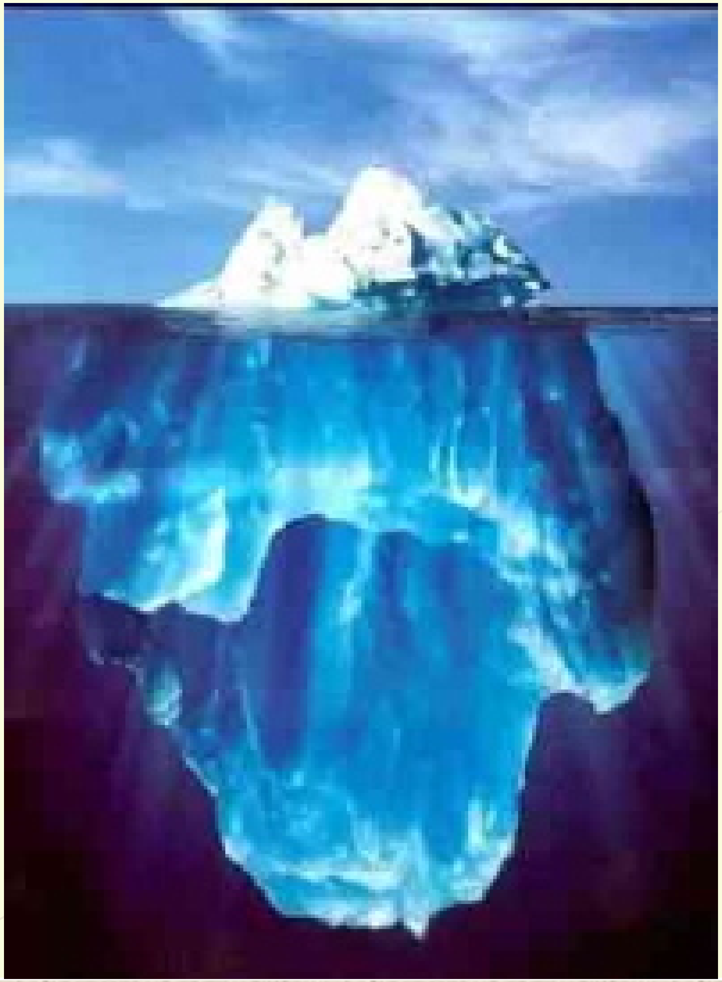
Measuring IAQ - Defining Safe Indoor Air

Current Limitations to an Air Contaminant Approach of Assessing Healthy Indoor Air

Insufficient measurement capabilities for determining indoor air is safe (i.e. not unhealthy)

- Analytical capabilities to assess exposures to ALL indoor air contaminants
- Exposure criteria for interpreting acceptability of ALL measured air contaminants.

Measuring IAQ - Defining Safe Indoor Air



Tip of the Iceberg Capabilities
Measurable and have health based exposure data.

Measurable and have NO health based exposure data.

Not Measurable

Measuring IAQ - Defining Safe Indoor Air

Additional Limitations

Only single contaminant exposures considered.

Insufficient current knowledge to assess combinations of contaminant exposures which can result in health effects that are:

- independent
- additive
- antagonistic
- synergistic

Measuring IAQ - Defining Safe Indoor Air

ASHRAE 62.2 Ventilation and Acceptable Indoor Air Quality, defines "**acceptable indoor air quality**" as air with contaminant concentrations that:

1.) are below health based exposure criteria

2.) do not cause odor or irritation to a substantial majority of the occupants (e.g. 80%)

Limitations of IAQ Problem Diagnostics by Air Testing

Example of unhealthy air NOT diagnosable by air testing.

Indoor Environment: Laser printer test lab.

Occupant Symptoms: Respiratory irritation/chest tightness (some employees wear disposable respirators and achieve some relief)

Air Test Results: VOC's (MS-TD-GCMS), Aldehydes (DNPH-HPLC), $PM_{2.5}$ and PM_{10} (SSI-Gravimetric), Ozone (UV-Spectrometry), all BELOW non-industrial health guidelines and LESS than the median concentrations in the EPA BASE study of office buildings.

Limitations of IAQ Problem Diagnostics by Air Testing

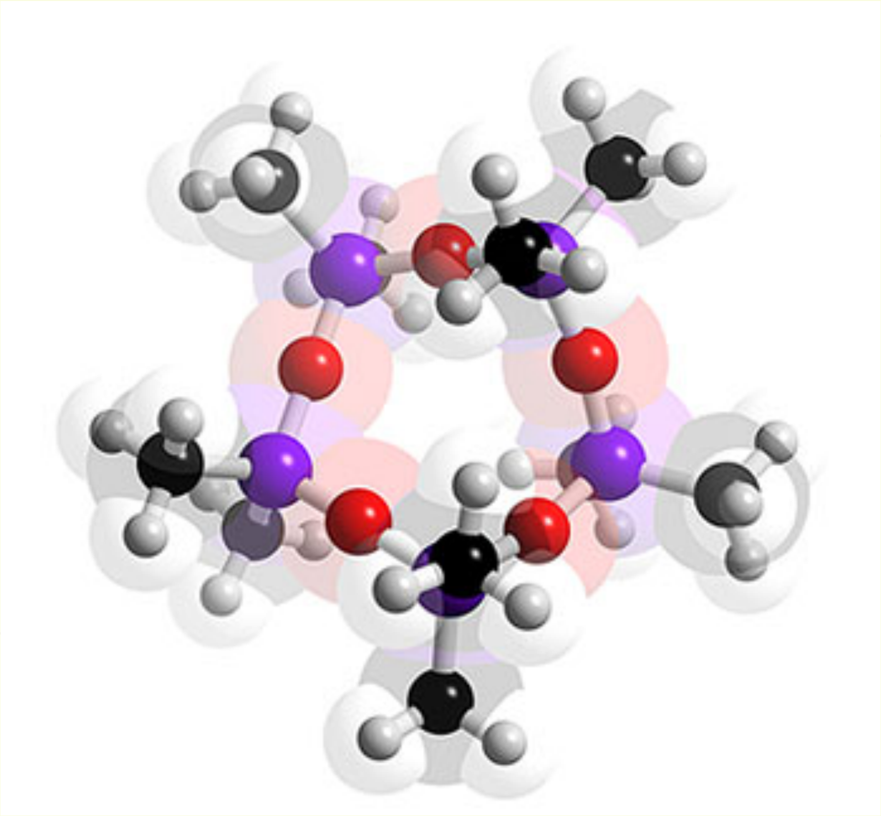
Example of unhealthy air not diagnosable by air testing.

Hypothesis: respiratory irritation caused by exposure to ultra-fine (i.e. 0.06 to 0.1 μm) particles of cyclic siloxanes, oily substance vaporized in printing process and then condensed into particles.

Currently, NO health exposure guidelines exist for these silicone compounds.

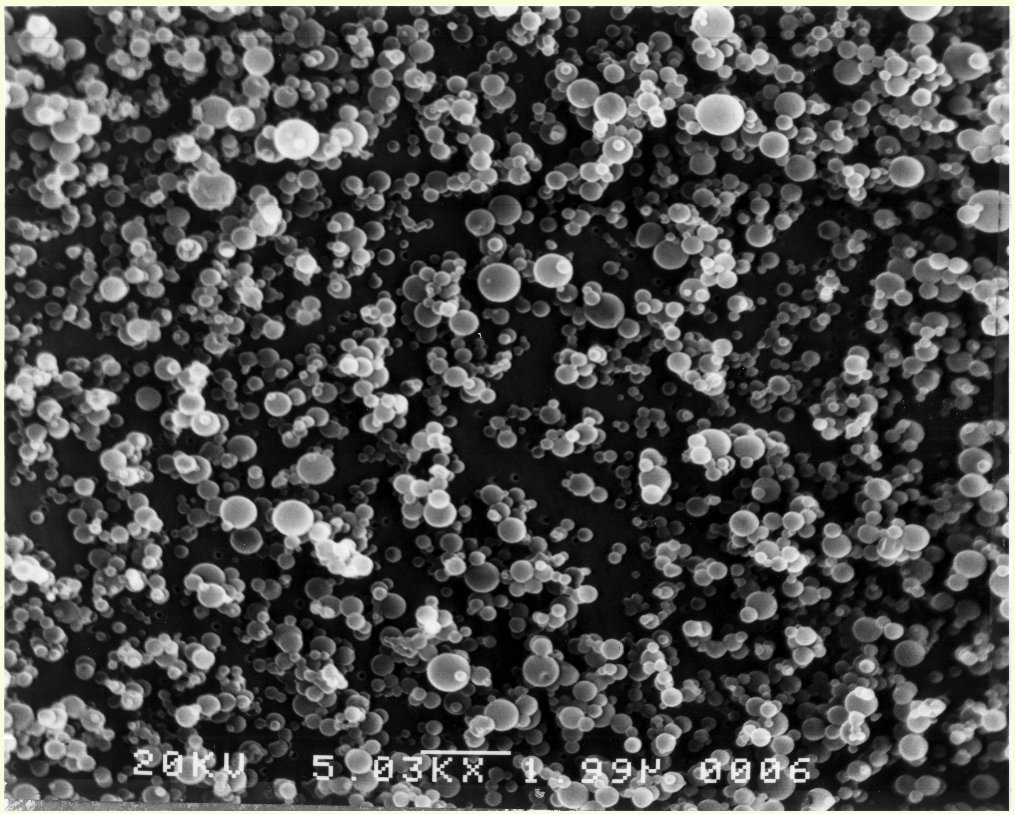
Limitations of IAQ Problem Diagnostics by Air Testing

Decamethylcyclopentasiloxane (D5)
MW 370.77



Safe Building Air - Limitations

Electron microscope photo of sub-micron particles formed by condensation.



Safe Building Air - Limitations

We can determine if the air is unhealthy for specific air contaminants that are:

- measurable
- have health based exposure criteria

Air contaminant concentrations below established health based exposure criteria constitute **"necessary but insufficient"** criteria for declaring the air in a building is safe.

Measuring IAQ - Defining Safe Indoor Air

Starfleet Tricorder
circa 2268

TR-590 Tricorder
circa 2370

Measuring IAQ - Defining Safe Indoor Air

At this time, we can best reduce the probability of "Unsafe Air" is not through air contaminant measurements.

Fortunately, there is another way.

Measuring IAQ - Defining Safe Indoor Air

At this time, we can best reduce the probability of "Unsafe Air" through <u>minimization</u> of known IAQ "Risk Factors".

IAQ Risk Factors

IAQ Risk Factors by themselves:

- do not constitute evidence that the building air is NOT safe.

- are known to increase the risk of unsafe building air.

IAQ Risk Factors

Some IAQ Risk Factors

- inadequate supply of outdoor air

- visible moisture condensation (e.g. mold)

- odors (e.g. mold, ETS, chemicals)

- concentrations of mold spores higher indoors than outdoors

- concentrations of carbon monoxide less than exposure guidelines (i.e. 9 ppm), but higher indoors that outdoors

- surface accumulations of dust (especially glass fibers)

- evidence of pest infestations

Building Risk Factors

Some IAQ Risk Factors

- elevated carbon dioxide concentrations (>1,000 ppm)

- adverse air pressure relationships : Negative indoor pressure to outdoors - positive pressure of spaces with high air contaminant concentrations to adjacent spaces.

- elevated concentrations of total volatile organic compounds (TVOC) - greater than 1,000 µg/m^3.

Health versus Energy

- Homes need to be, first and foremost, built to provide healthy environments, while striving for energy efficiency and sustainability.

Bottom line: health trumps energy.

We can have BOTH healthy and energy efficient sustainable homes, through use of energy efficient heat recovery ventilation systems recovery ventilation systems and selection of low emitting building materials.

- Build TIGHT - Ventilate RIGHT.

??? QUESTIONS ???

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