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U.S. DEPARTMENT OF ENERGY

Backdrafting Overblown!

Rethinking Combustion Appliance Safety

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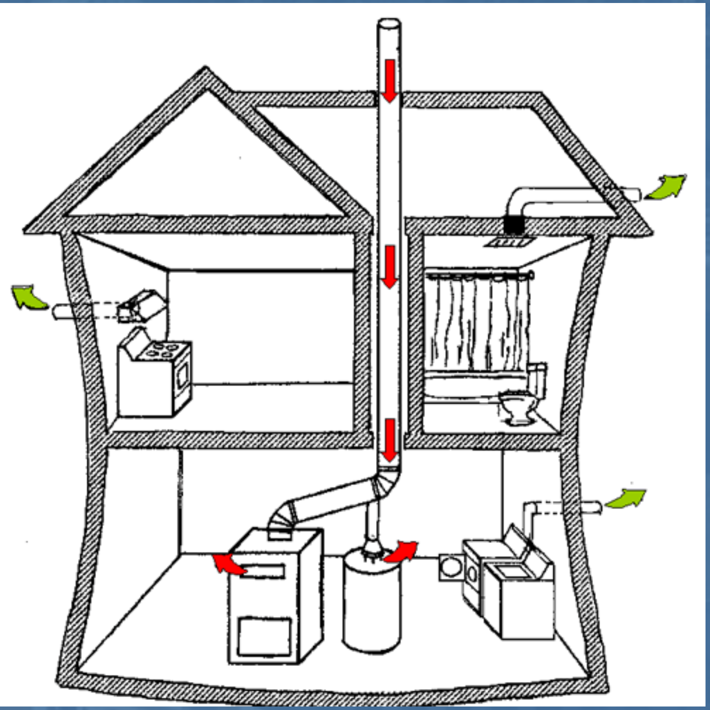


February 26, 2014

RESNET, Atlanta, GA

Why do we conduct combustion safety tests?

What are we worried about?

What are we trying to prevent?

What are the most severe combustion appliance hazards?

What are the most common combustion appliance hazards?

What level of health risk are we willing to tolerate?

Key Point: Objectives

Critical: Identify appliances and venting systems that are broken or likely to break.

Critical: Identify gas leaks and other life-safety hazards.

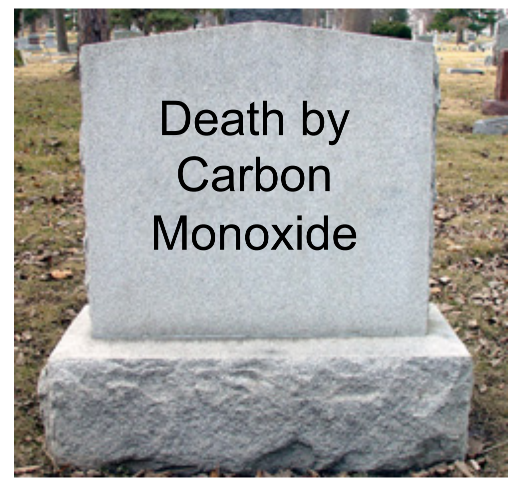
Important: Identify appliances that cannot reliably establish draft under conditions that are likely to be encountered.

Natural draft appliance + airtight home = DANGER

IS THIS TRUE?

+

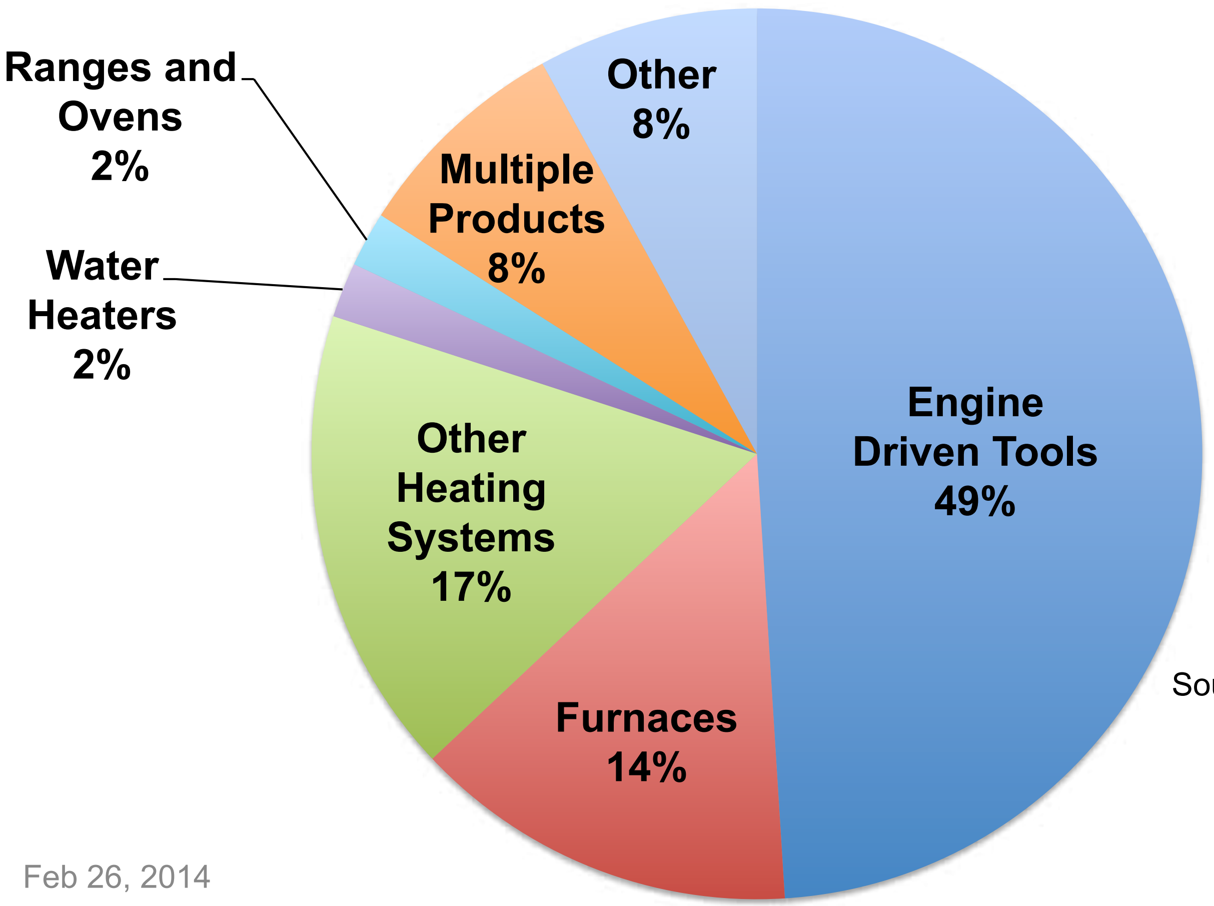
=



Source: Moore, Rich (2011). CAZ Pressure Testing. ACI Presentation, March, Denver, CO.

Reality: more deaths by lightning than by furnace or water heater CO

U.S. average 2005-2007:
184 deaths / year from unintentional CO poisoning



< 32 deaths / year from water heaters and furnaces

2002-2011 average: 37 deaths / year from lightning (NOAA)

Source: Hnatov, M.V., Non-Fire Carbon Monoxide Deaths Associated with the Use of consumer Products: 2007 Annual Estimates (2011)

Health hazards associated with combustion appliances

Life-Safety

- CO at level that impairs judgment, creates risk of more severe effects including death (100+ ppm CO)

Acute

- Impacts sensitive individuals when CO & NO_2 exceed outdoor air quality standards

  (10-50 ppm CO; 100-200 ppb NO_2)

Chronic

- Low-level exposures over periods of weeks or more (5-10 ppm CO)

Acute ambient CO levels that could result in hospitalization or death

Ambient Concentration	Exposure	Symptoms
100 ppm	2-3 hours	Slight Headache
200 ppm	2-3 hours	Headache, Nausea
400 ppm	2-3 hours	Life threatening
800 ppm	2 hours	Death

GOLDSTEIN,M.Carbonmonoxidepoisoning.*JournalofEmergencyNursing34*,6(December2008), 538–542.

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CO standards to protect sensitive sub-populations of general population

Organization	1 hour average (ppm)	8 hour average (ppm)
National Ambient Air Quality Stds	35	9
California Ambient Air Quality Stds	20	9
Health Canada	25	10**
Consumer Product Safety Commission	25	15

** 24 hour time-weighted average

Health hazards associated with combustion appliances

Life-Safety: Must NEVER happen

- Requires extreme failure of burner and venting; not just depressurization-induced spillage

Acute: Costly to eliminate; must manage

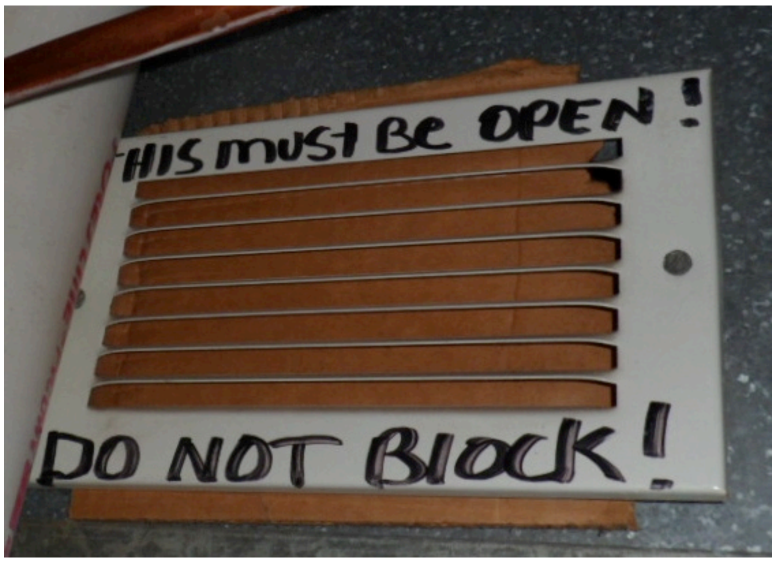
- Sustained spillage + problem with combustion

Chronic: Minimal risk achievable

- Requires routine spillage + compromised combustion
- Moisture can can still be a problem even if CO low

What are the practiced procedures?

- Visual inspection



http://blog.greenhomesamerica.com/2009/12/22/dont-mess-around-with-appliance-venting/

What are the practiced procedures?

- Visual inspection
- Spillage Test

http://www.metrohome.us/

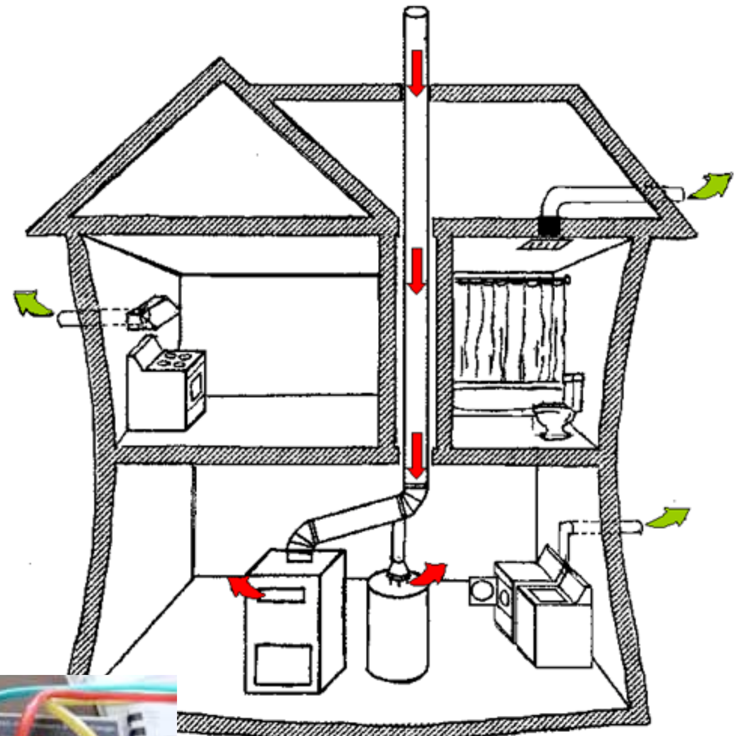
What are the practiced procedures?

- Visual inspection
- Spillage Test
- Flue CO Test

http://www.htownhomeinspector.com/node/56
http://www.plumbtechnj.com/wp-content/uploads/2012/09/Carbon-monoxide-awareness.jpg

What are the practiced procedures?

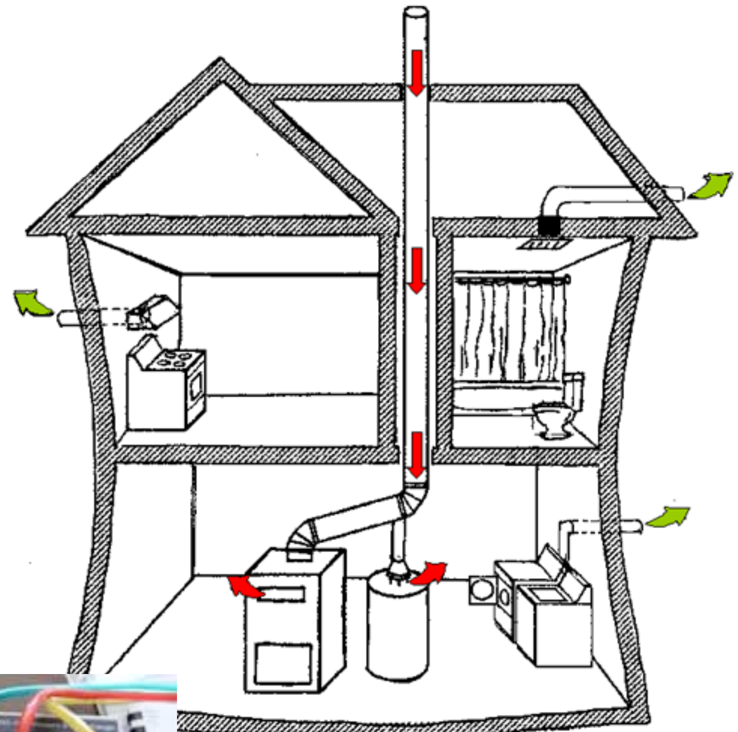
- Visual inspection
- Spillage Test
- Flue CO Test
- Worst-case Depressurization



What are the practiced procedures?

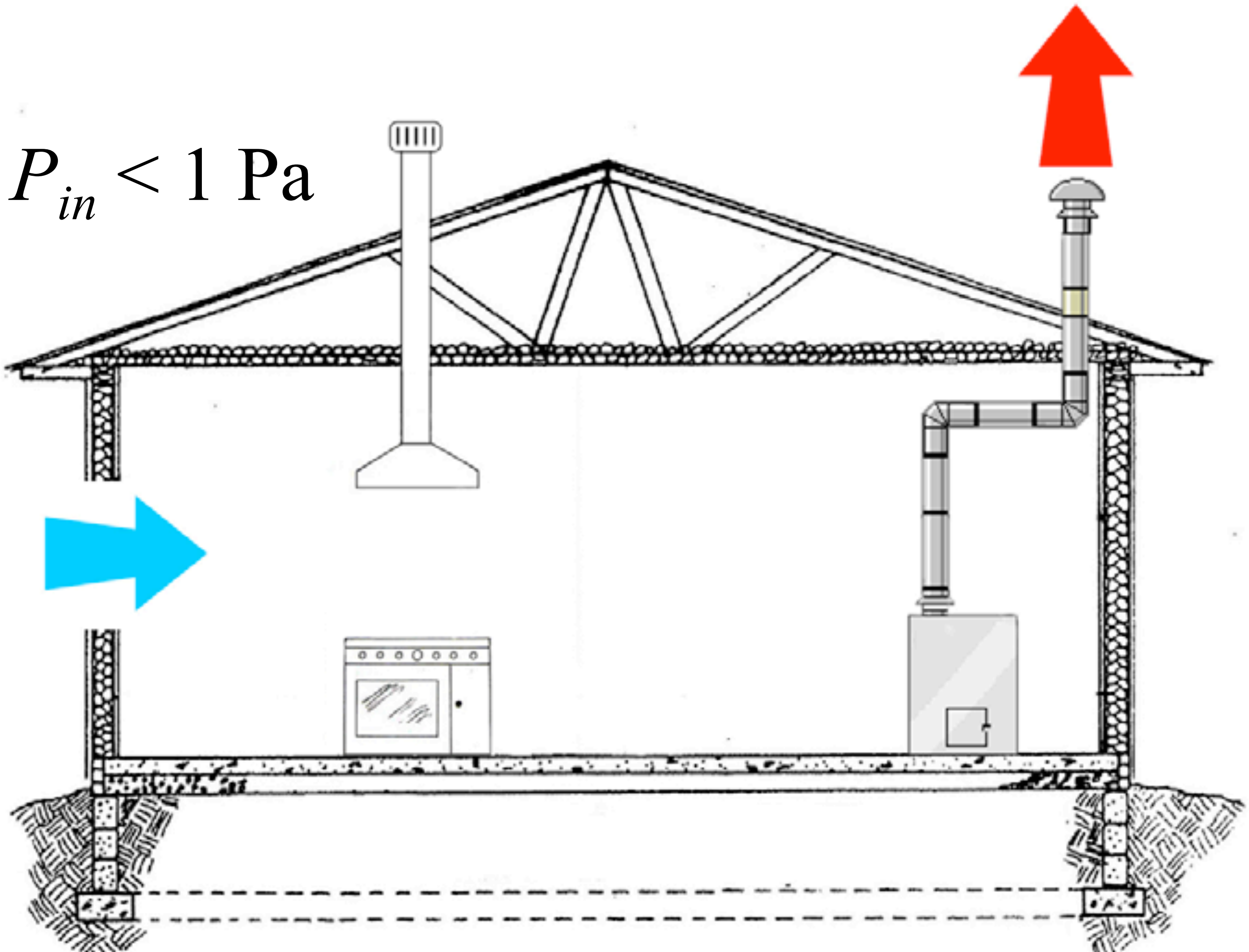
- Visual inspection
- Spillage Test
- Flue CO Test
- Worst-case Depressurization

What do the results mean?



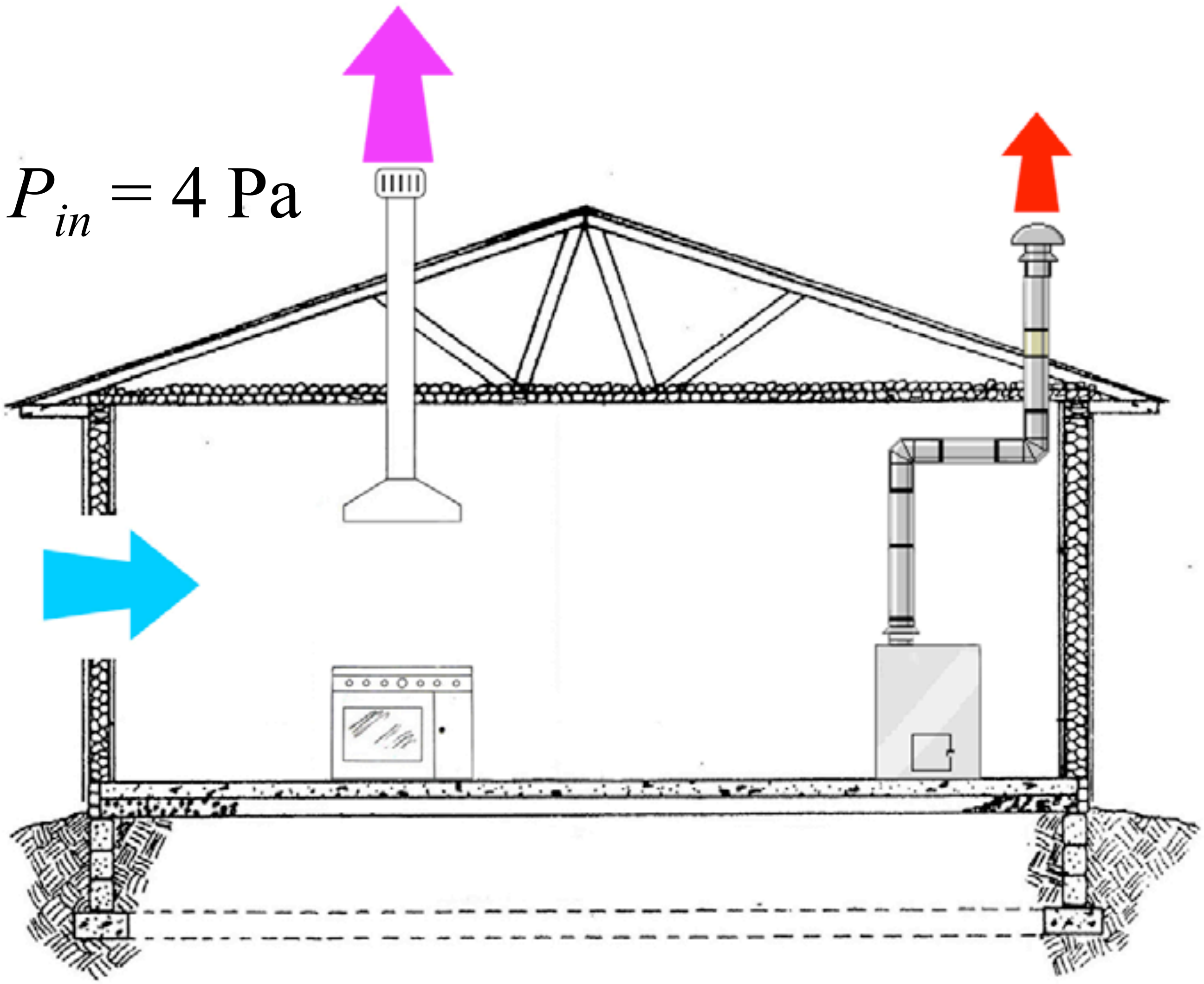
Backdraft Intro: consider a 6 ACH50 house with a natural draft furnace…

$$D_p = P_o - P_{in} < 1 \text{ Pa}$$



Operate a 375 cfm range hood… No problem

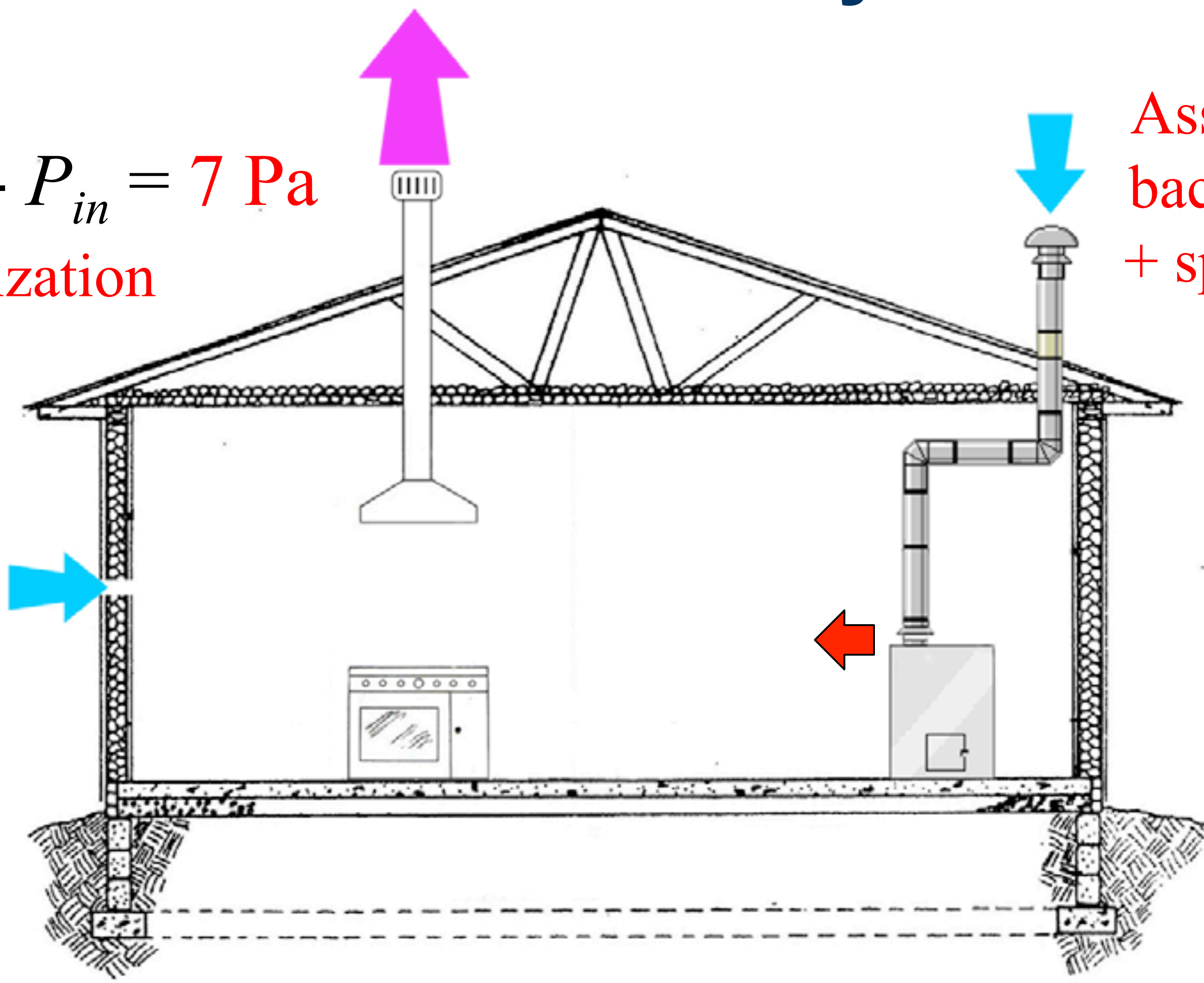
$$D_p = P_o - P_{in} = 4 \text{ Pa}$$



Air-seal to 4 ACH50 and you are likely to fail a combustion safety test

$D_p = P_o - P_{in} = 7\ Pa$

Depressurization



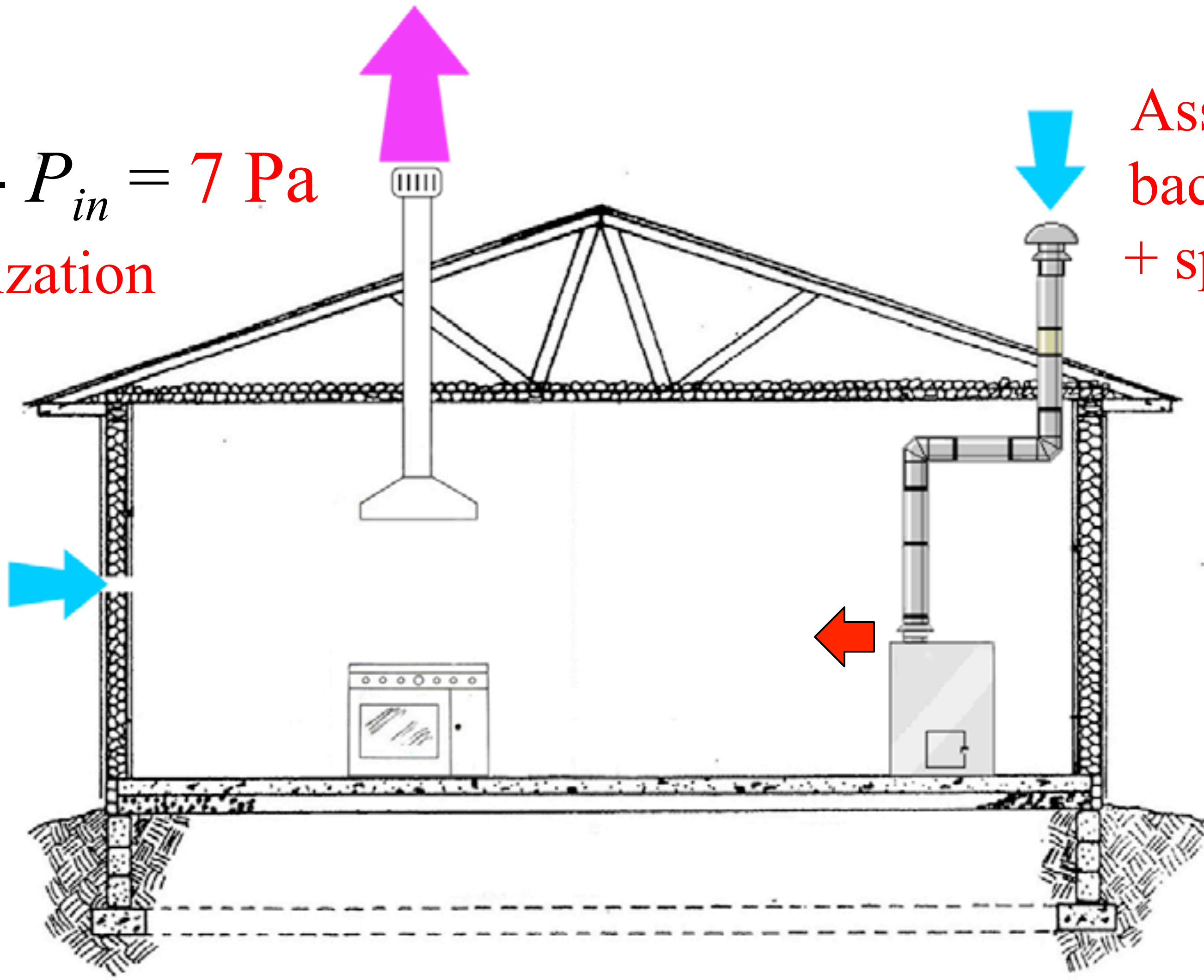
Assumed backdraft + spillage

Is this really a problem?

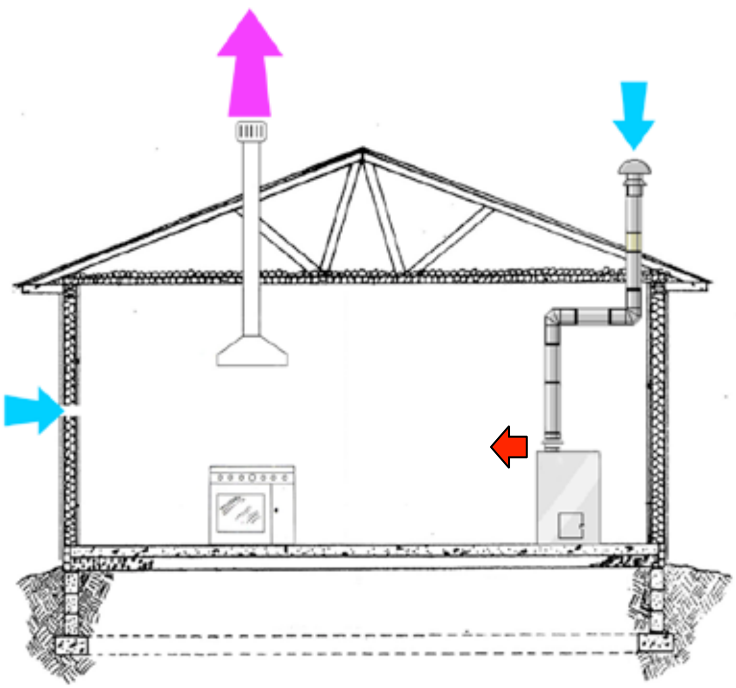
$D_p = P_o - P_{in} = 7\ \mathrm{Pa}$

Depressurization

Assumed backdraft + spillage

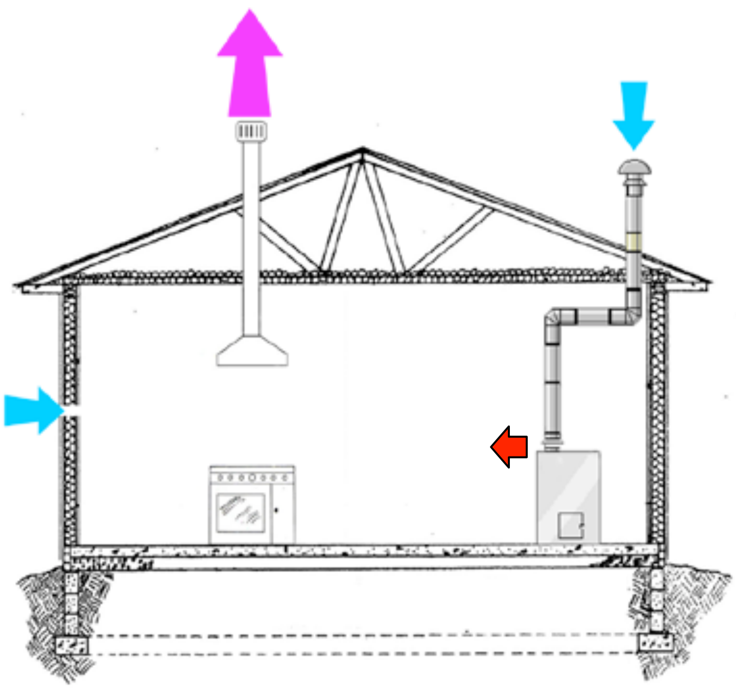


What determines if there is a problem?



- Is appliance really not able to establish draft at -7 Pa?
- How often is there 375 cfm of exhaust with burner on?
- Does spillage occur long enough to create a hazard?
- How does exhaust flow impact buildup of exhaust gases and pollutants?

Combustion hazards depend on both physics and statistics



- Is appliance really not able to establish draft at -7 Pa?
  - Vent configuration
  - Atmospheric conditions
- How often is there 375 cfm of exhaust with burner on?
- Does spillage occur long enough to create a hazard?
- How does exhaust flow impact buildup of exhaust gases and pollutants?
- How much CO emitted?

Worst-Case Depressurization Test

Threshold Test: Compare to depressurization limit

Draft Test: Does the appliance draft under WCD?

Depressurization limits

BPI

Orphan natural draft water heater	-2 Pa
Natural draft boiler or furnace commonly vented with water heater	-3 Pa
Individual natural draft boiler or furnace Induced draft boiler Furnace commonly vented with a water heater	-5 Pa
Power vented or induced draft boiler or furnace along, or fan assisted DHW alone	-15 Pa

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Atmospheric vented oil or gas system	-5 Pa
Pellet stoves with exhaust fans and sealed vents	-15 Pa

What is the basis of these limits?

BPI

Orphan natural draft water heater	-2 Pa
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The physics of draft

Depressurization just one part of the equation

$$D_a = D_t - \Delta p_{Loss} - D_p$$

Available Draft (D_a)

Theoretical Draft (D_t)

Flow Losses (Δp_{Loss})

Depressurization (D_p)

2008 ASHRAE Handbook – HVAC Systems and Equipment, Chapter 34

The physics of drafting

Depressurization just one part of the equation

$$D_a = D_t - \Delta p_{Loss} - D_p$$

Burner Size

Appliance Efficiency

Vent Dimension

Weather

Theoretical draft

$$D_a = D_t - \Delta p_{Loss} - D_p$$

Heat Output Rate

Burner Size

Appliance Efficiency

Vent Dimension

Weather

Theoretical draft

$$D_a = D_t - \Delta p_{Loss} - D_p$$

Burner Size

Appliance Efficiency

Buoyancy

Vent Dimension

Weather

Friction losses in vent

$$D_a = D_t - \Delta p_{Loss} - D_p$$

Vent Design (Bends)

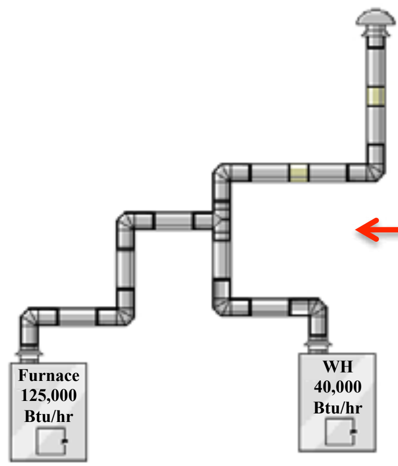
Vent Location & Material

Weather

Bird Nest

Friction losses in vent

$$D_a = D_t - \Delta p_{Loss} - D_p$$



Vent Design (Bends)

Vent Location & Material

Weather

Bird Nest

Friction losses in vent

$$D_a = D_t - \Delta p_{Loss} - D_p$$

Vent Design (Bends)

Heat Loss

Vent Location & Material

Weather

Bird Nest

Depressurization

$$D_a = D_t - \Delta p_{Loss} - D_p$$

- Exhaust Fans
- CAZ Location
- Envelope Tightness
- Other Appliances
- Usage Patterns
- Weather

Worst-Case Depressurization

Threshold Test: Compare to depressurization limit

Draft Test: Does the appliance draft under WCD?

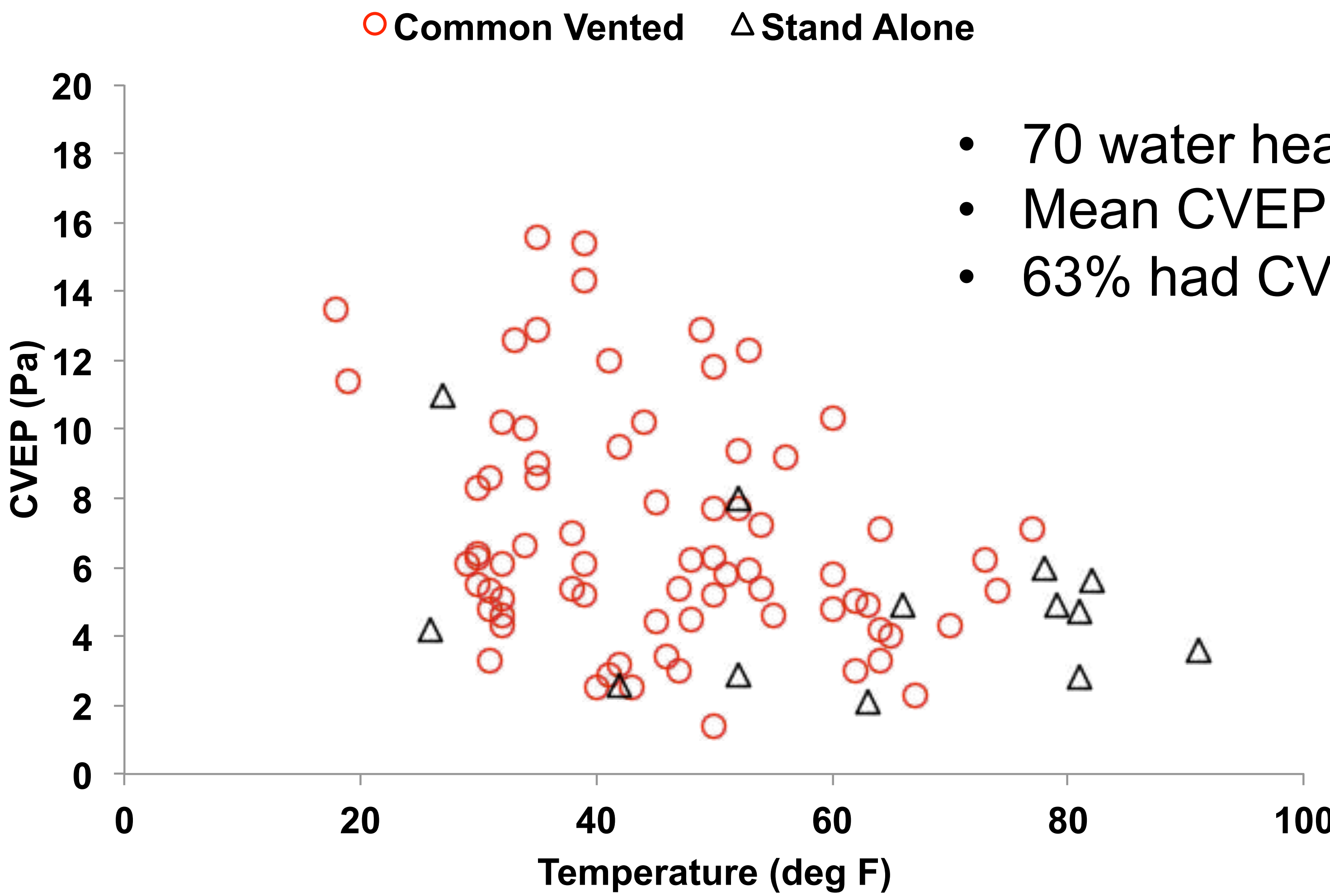
CVEP is the maximum depressurization an appliance can overcome

Cold Vent Establishment Pressure (CVEP)

1. Measure diff. pressure between CAZ and outdoors
2. Depressurize house using blower door
3. Turn on the appliance (should be spilling)*
4. Lower house depressurization until appliance establishes draft
5. Record the differential pressure when the appliance established draft

*Measure downdraft CO at this point if not before

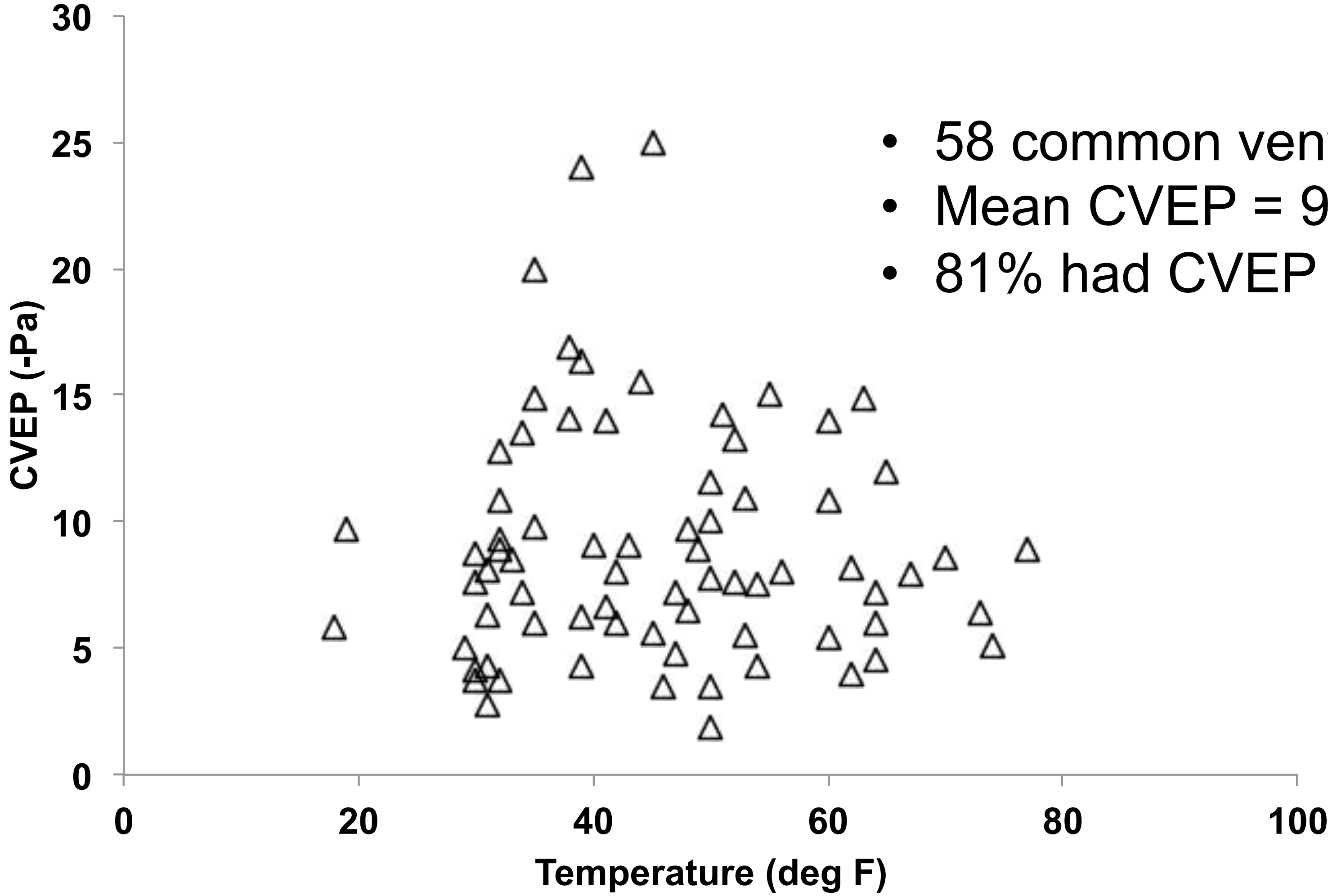
How much depressurization can water heaters overcome?



- 70 water heaters
- Mean CVEP = 6.9 Pa
- 63% had CVEP > 5 Pa

Data taken from Koontz et al., 1999; Grimsrud and Hadlich, 1999

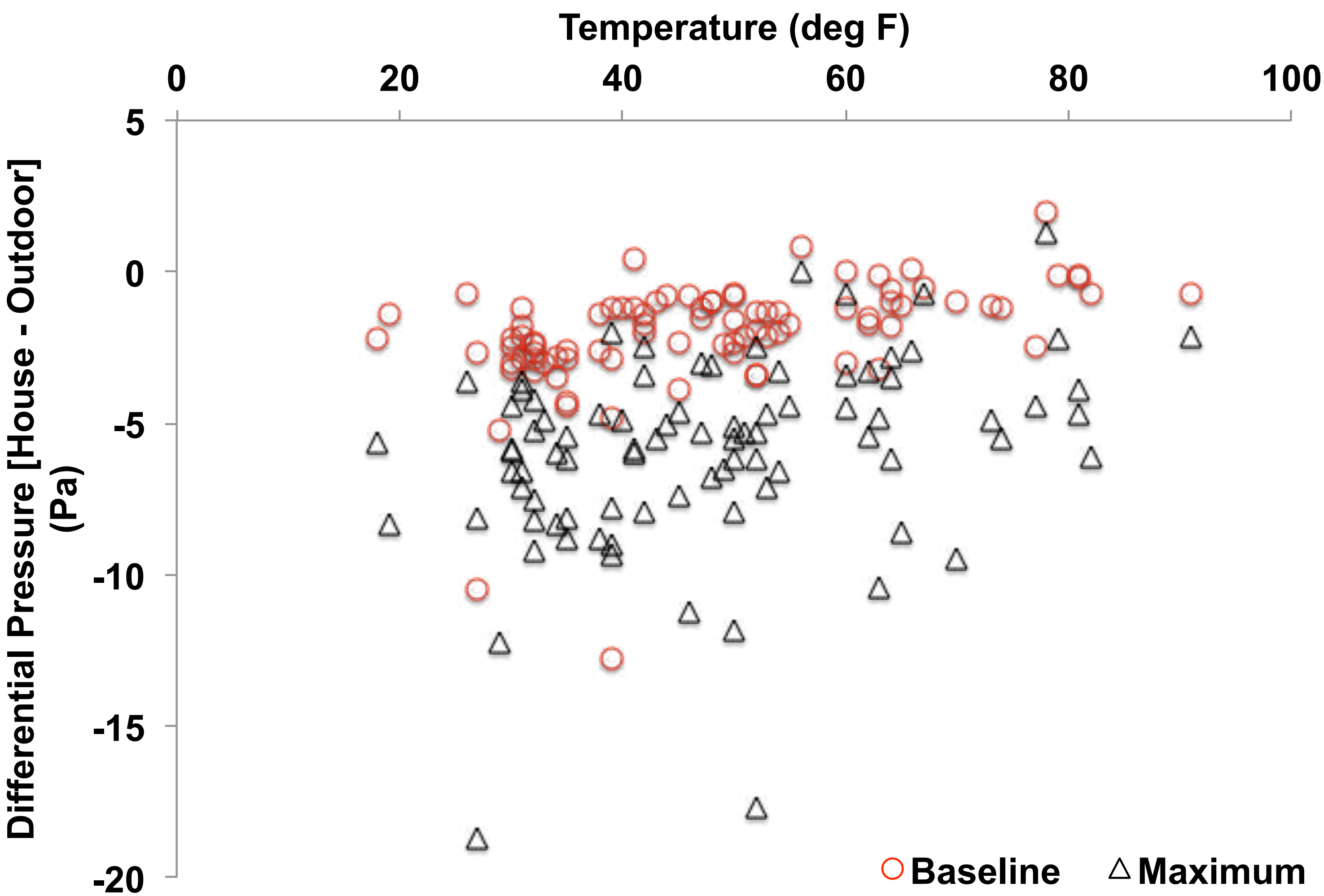
How much depressurization can furnaces overcome?



- 58 common vented furnaces
- Mean CVEP = 9.4 Pa
- 81% had CVEP > 5 Pa

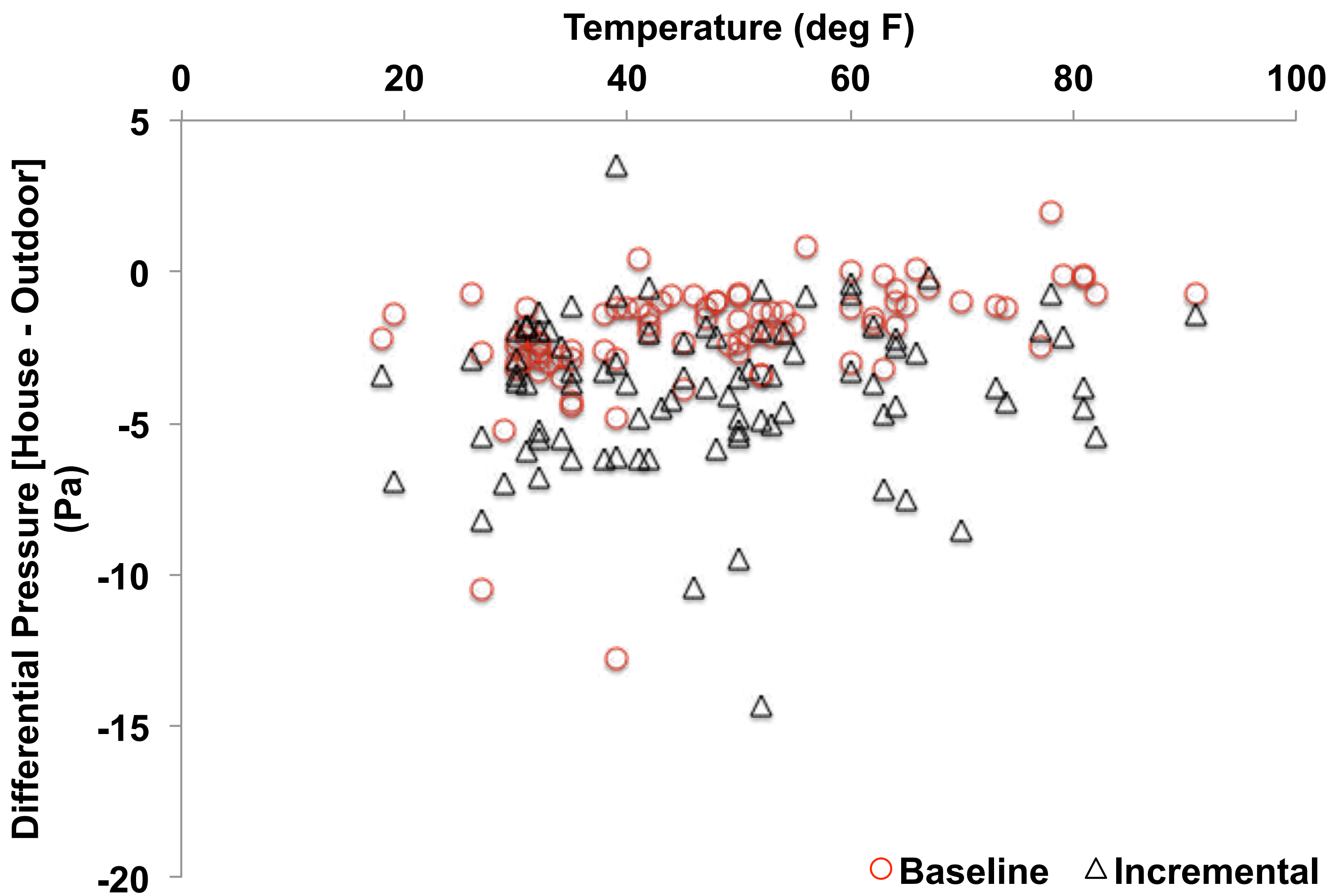
Data taken from Koontz et al., 1999; Grimsrud and Hadlich, 1999

Weather affects depressurization



Data taken from Koontz et al., 1999; Grimsrud and Hadlich, 1999

Should we subtract “baseline”?



Data taken from Koontz et al., 1999; Grimsrud and Hadlich, 1999

Are the thresholds saving lives or only limiting tightness?

What is the risk of depressurization induced spillage?

$$Risk = P_1 \times P_2 \times P_3$$

P_1 = probability that conditions exist to cause backdrafting and spillage if the appliance operates

P_2 = probability that the appliance will operate during the time that the conditions of P_1 persist

P_3 = probability that the appliance emits pollutants at a sufficient rate to cause an IAQ problem if P_1 and P_2 occur

Data and calculations are needed…

$$\text{Risk} = \boxed{P_1} \times P_2 \times P_3$$

The probability that conditions exist to cause backdrafting and spillage if the appliance operates depend on:

- Weather conditions throughout the year
- Existing fans and usage patterns
- Appliance location

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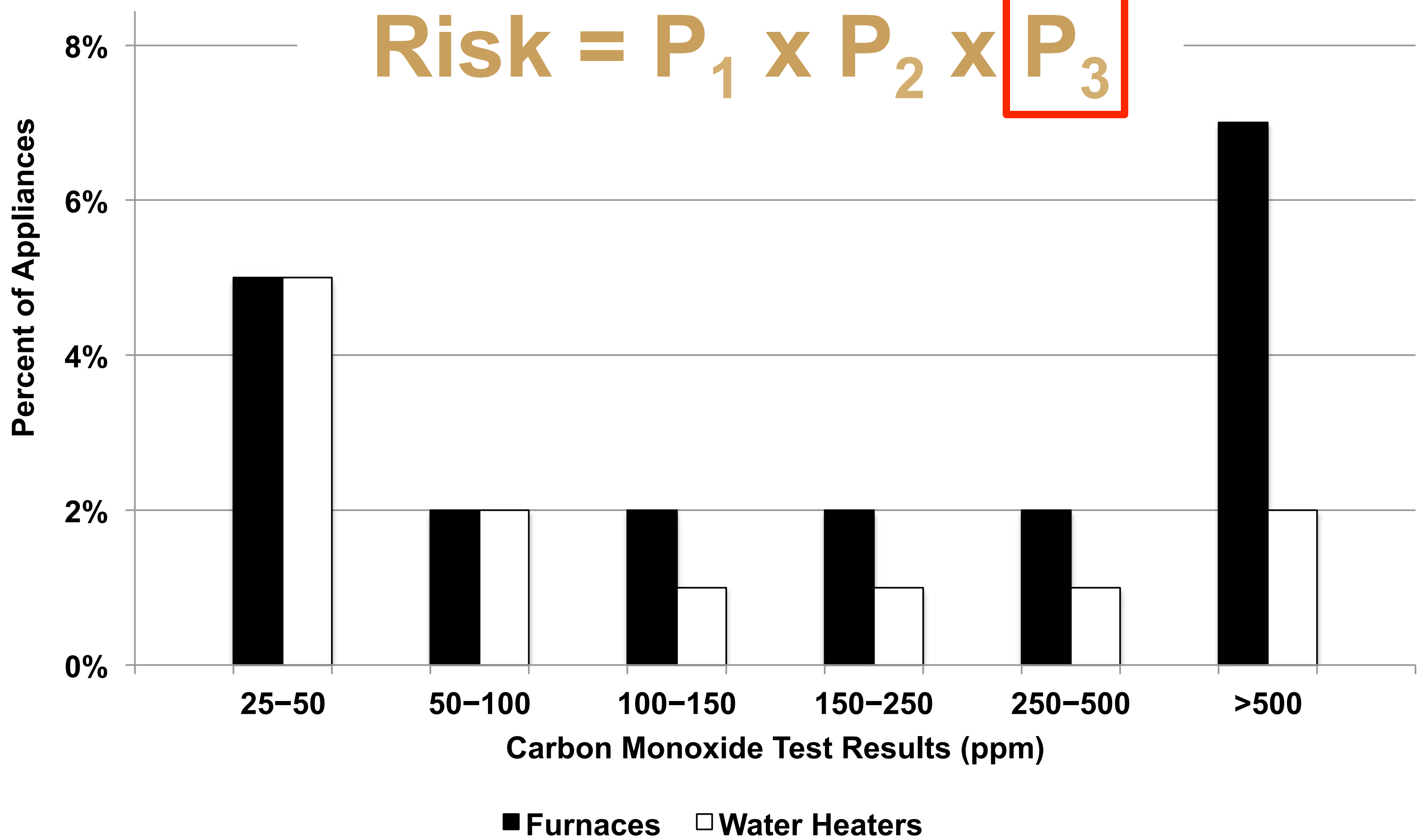
Data can provide probability an appliance will be operating

$$\text{Risk} = P_1 \times P_2 \times P_3$$

- 143 California homes showed a maximum continuous on-time of 139 minutes in 8 hours for water heaters
- Wall furnace could operate continuously
- Data for central furnaces & boilers?

Data can provide probability of appliance pollutant emission rates

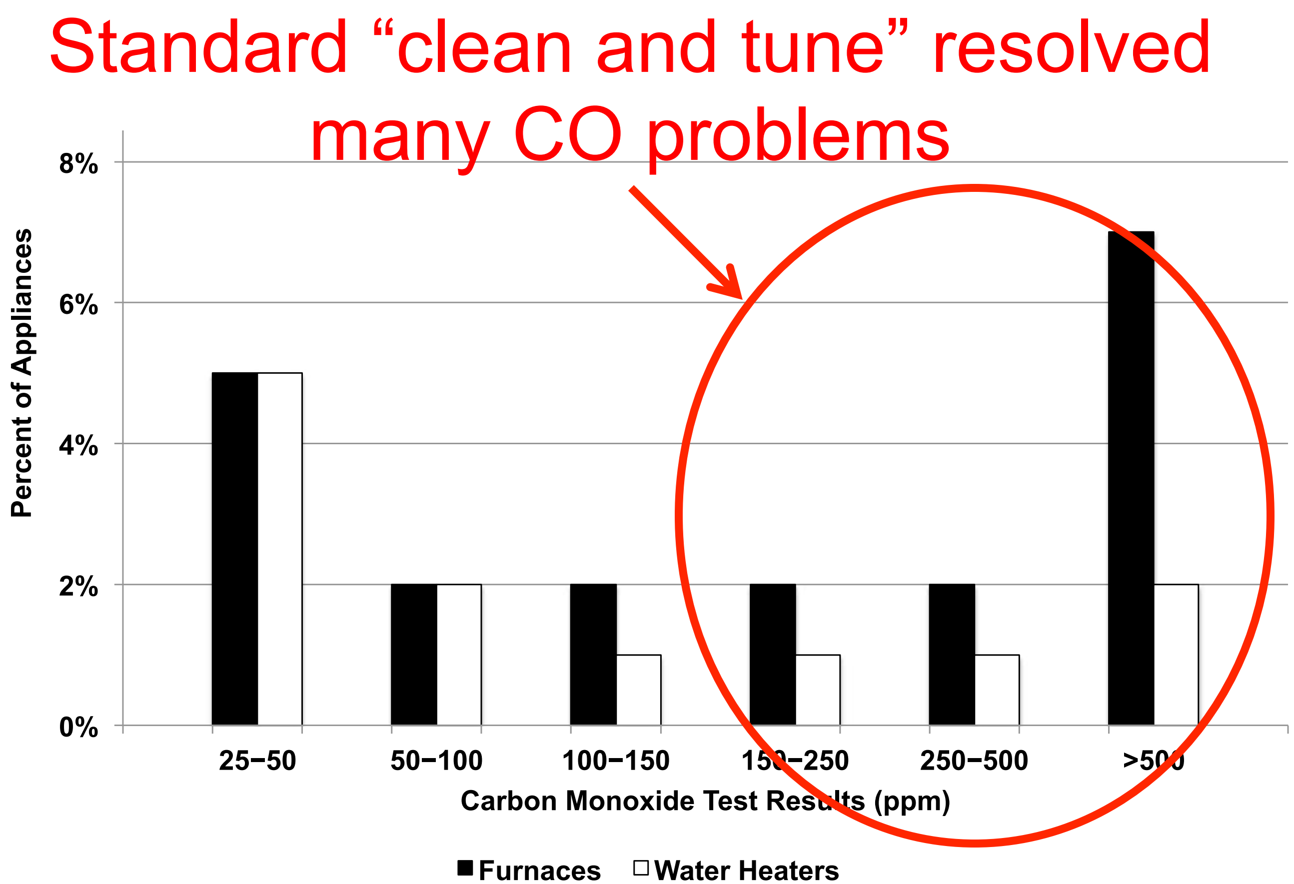
$$Risk = P_1 \times P_2 \times P_3$$



1,427 homes in Twin Cities, MN

Bohac, D., et al., Ventilation and Depressurization Information for Houses Undergoing Remodeling (2002)

Data can provide probability of appliance pollutant emission rates



1,427 homes in Twin Cities, MN

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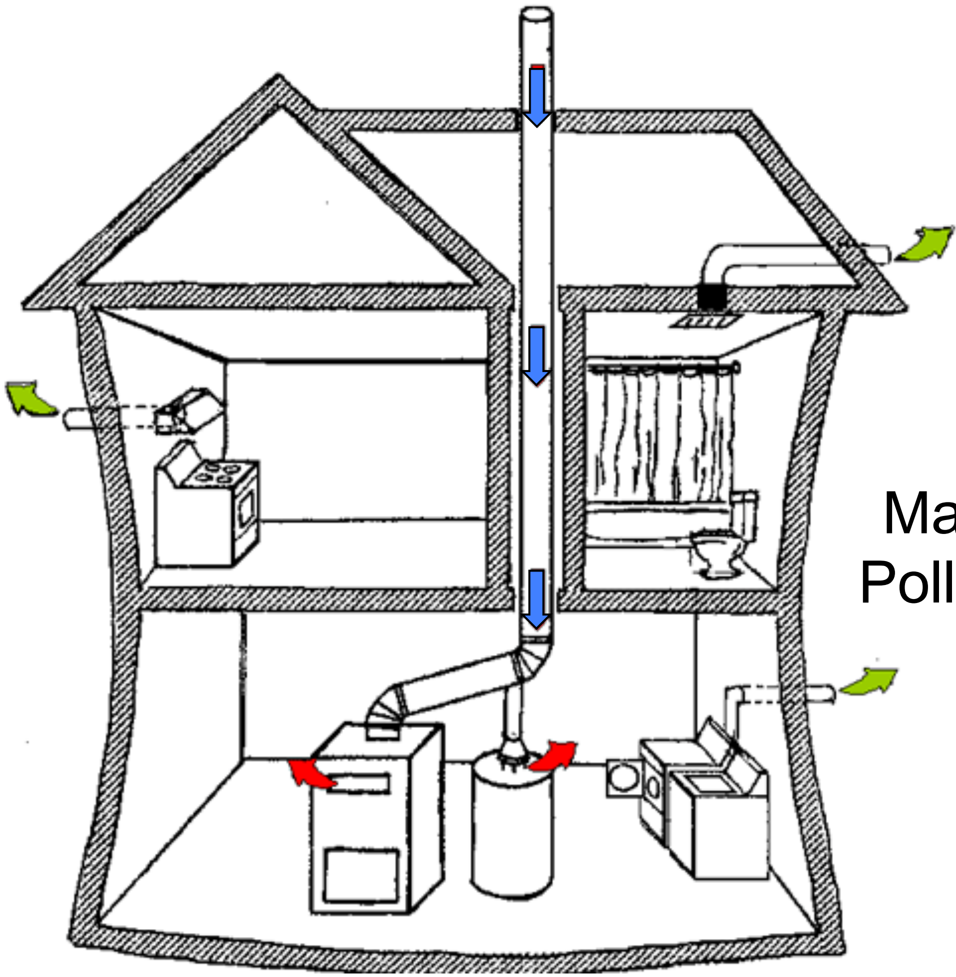
Calculating pollutant concentrations and risk



Mass Balance

Mass of Pollutants = Pollutants removed + Pollutants added

What are ppm anyway?

$$100\ ppm\ CO = \frac{100\ parts\ CO}{1{,}000{,}000\ parts\ Air}$$

$$10\ ppm\ CO = \frac{10\ parts\ CO}{1{,}000{,}000\ parts\ Air}$$

How do we get to danger?

Given:

40,000 btuh water heater -> 40 ft^3 fuel / h

Need roughly 10 ft^3 air per ft^3 fuel

-> 400 ft^3 exhaust per hour

Assume:

1000 ppm CO in exhaust

10,000 ft^3 home (1250 sf x 8 ft ceiling)

1 h of spillage with no ventilation

$$\frac{1000\,ppm\,CO \times 400\ ft^3}{10{,}000\ ft^3} = 40\,ppm\,CO$$

This is a health hazard but not a life-safety hazard

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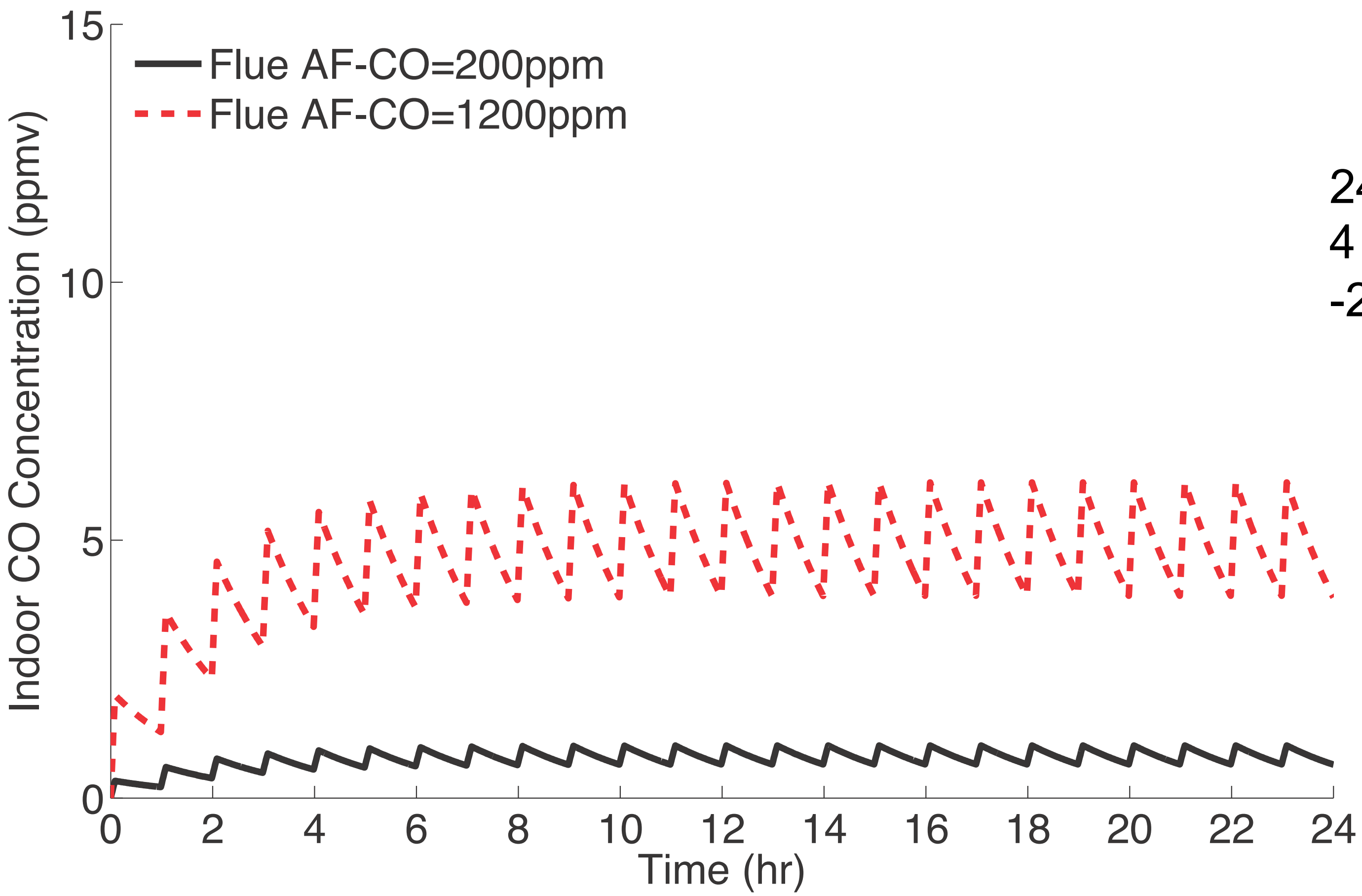
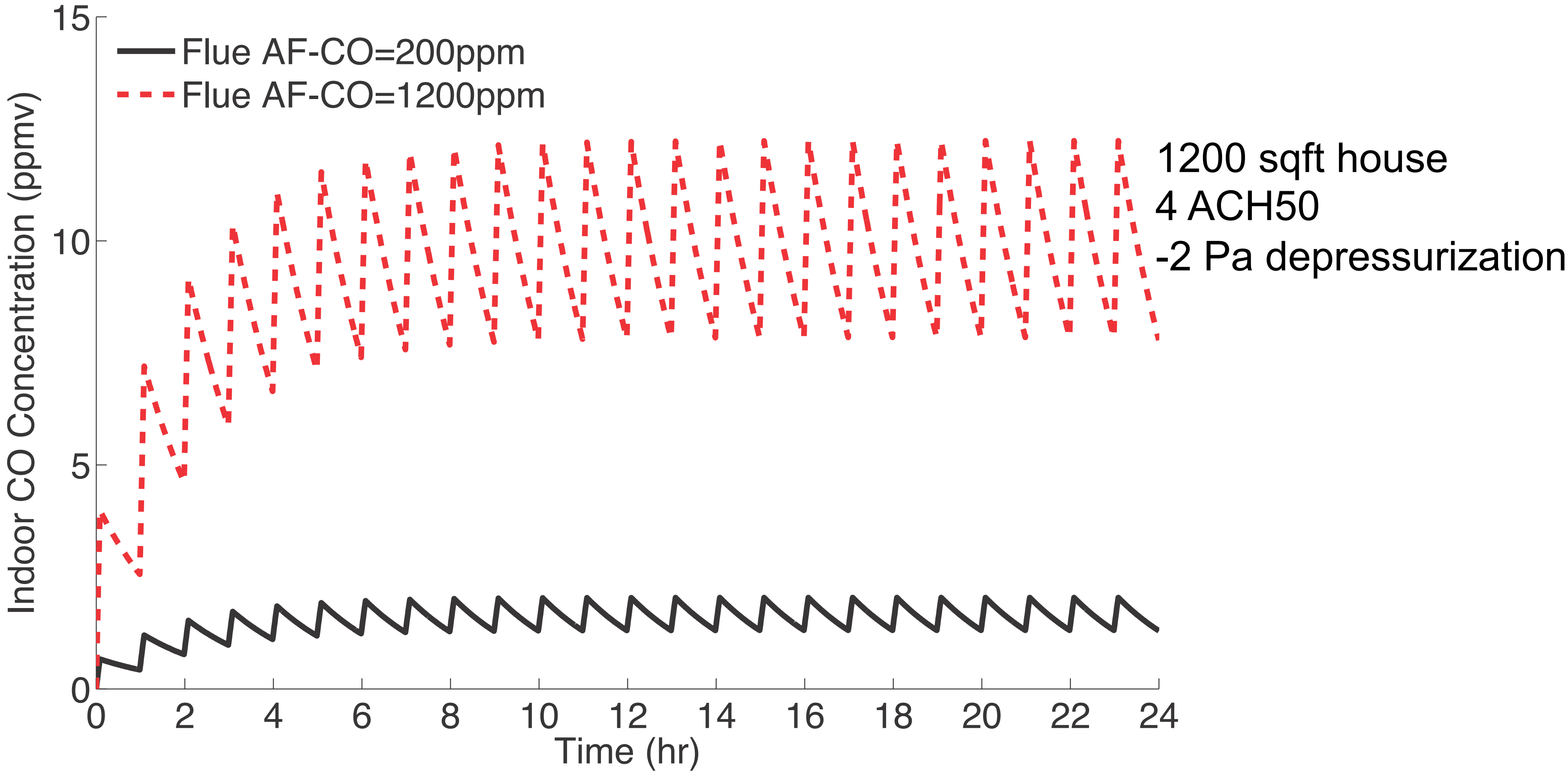
But we can’t assume no ventilation…
That’s how we get depressurization!

40,000 btuh appliance spilling for five minutes of every hour



2400 sqft house
4 ACH50
-2 Pa depressurization

For a house half the size, pollutant levels would be twice as high



What do simulations and data tell us?

- Greatest hazard is when flow just reverses (lowest dilution)
- Increasing depressurization increases exhaust airflow, which dilutes any emitted CO
- Halving the house size, ACH50, or doubling the appliance size, doubles ambient CO
- BPI and RESNET CO and depressurizations limits are overly conservative
- Recommend use of range hood when cooking
- Advise against unvented heaters and fireplaces

Unvented combustion appliances pose the highest health risk

Appliance	Pollutant Exposure Risk
Induced Draft	Very Low: Unlikely to backdraft and spill
Water heater	Low: non-continuous operation; vented
Vented furnace	Medium-Low: Possible long-term operation; vented; wall furnaces can have lower draft
Range & Ovens	Medium-high: 100% spillage in living space; some venting through range hood, higher CO
Unvented heater	High: 100% spillage in living space; possible long-term operation; higher CO and NO_2

Recommendations: Combustion Safety Diagnostics

Focus first on basic safety

- Proactively check for unvented heating. Primary appliance has to work. Ask about other heaters including oven
- Inspect for gas leaks; check appliance burner, flue, combustion air to CAZ
- Check vent sizing and horizontal runs

Focus on finding appliances that could backdraft often

- Depressurization draft test with exhaust fans that can run for extended periods (dryer, bathroom; no range hood on high).

Add safety by checking CO during induced downdraft

Confirm range hood is venting & advise it be used

Other Random Thoughts

At <2 ACH50, most likely need sealed combustion

At >5 ACH50, required exhaust flows high enough to protect

We should not try to use WCD diagnostics to find the one in a million hazard scenario

May be able to develop rule of thumb by comparing sum of exhaust fans to cfm50

Combustion safety best ensured with direct-vent combustion

Challenges

Are there CAZ configurations that can become dangerous under rare conditions?

Example: backdraft in poorly ventilated space depletes oxygen, creates combustion problem.

Is this a real problem or too rare to be a concern?

How do we diagnose this potential hazard?

Effective kitchen exhaust combined with a dryer produces substantial depressurization in a tight house

Take Home Points

Life-safety hazards almost always result from broken appliances and venting

Depressurization-induced spillage is a problem when it happens frequently

High flows to cause depressurization are safety feature

Unvented combustion appliances require particular attention as they are effectively “spilling” 100% of the time

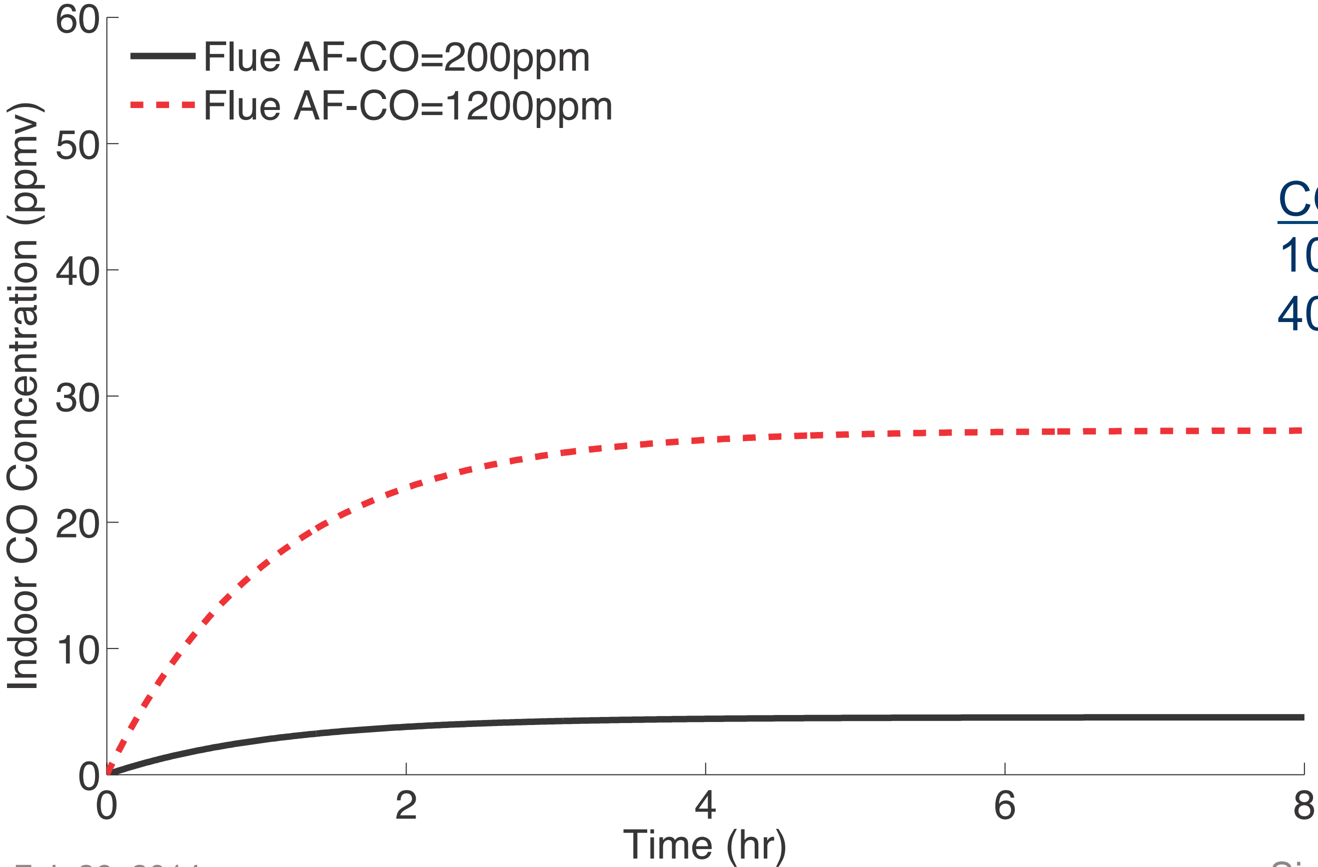
If time permits…

(It didn't. Reader is cautioned to not refer to information in these extra slides without contacting presenter to confirm accurate understanding.)

Furnaces

Continuous spillage for 8-hours reaches a steady-state concentration

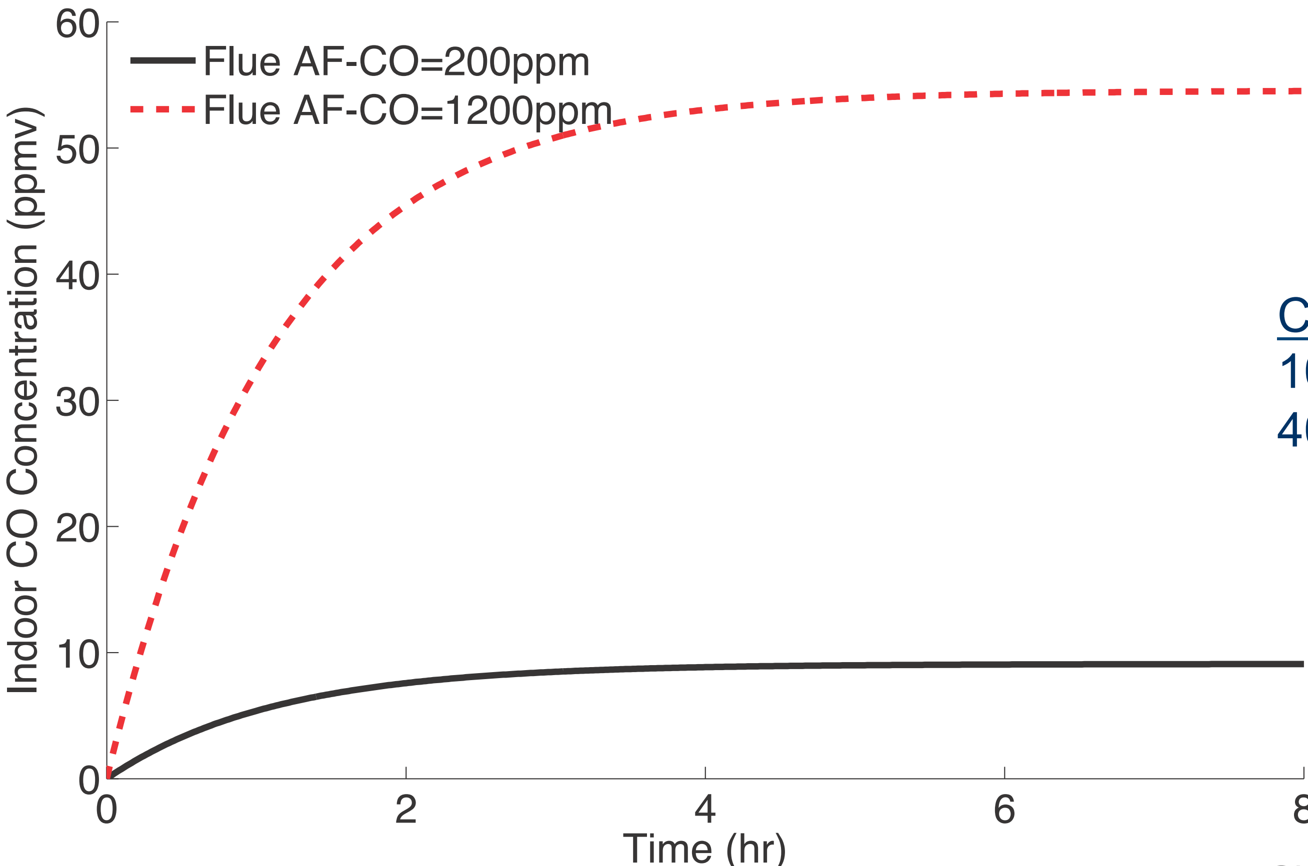
- 1200 sqft home; ACH50=4; 20 kBTU/hr appliance
- **8-hours of spillage**; -5 Pa depressurization



CO Poisoning (2-3 h)
100 ppm: headache
400 ppm: life threatening

What about a larger furnace? Doubling size doubles indoor CO concentrations

- 1200 sqft home; ACH50=4; 40 kBTU/hr appliance
- **8-hours of spillage**; -5 Pa depressurization



CO Poisoning (2-3 h)
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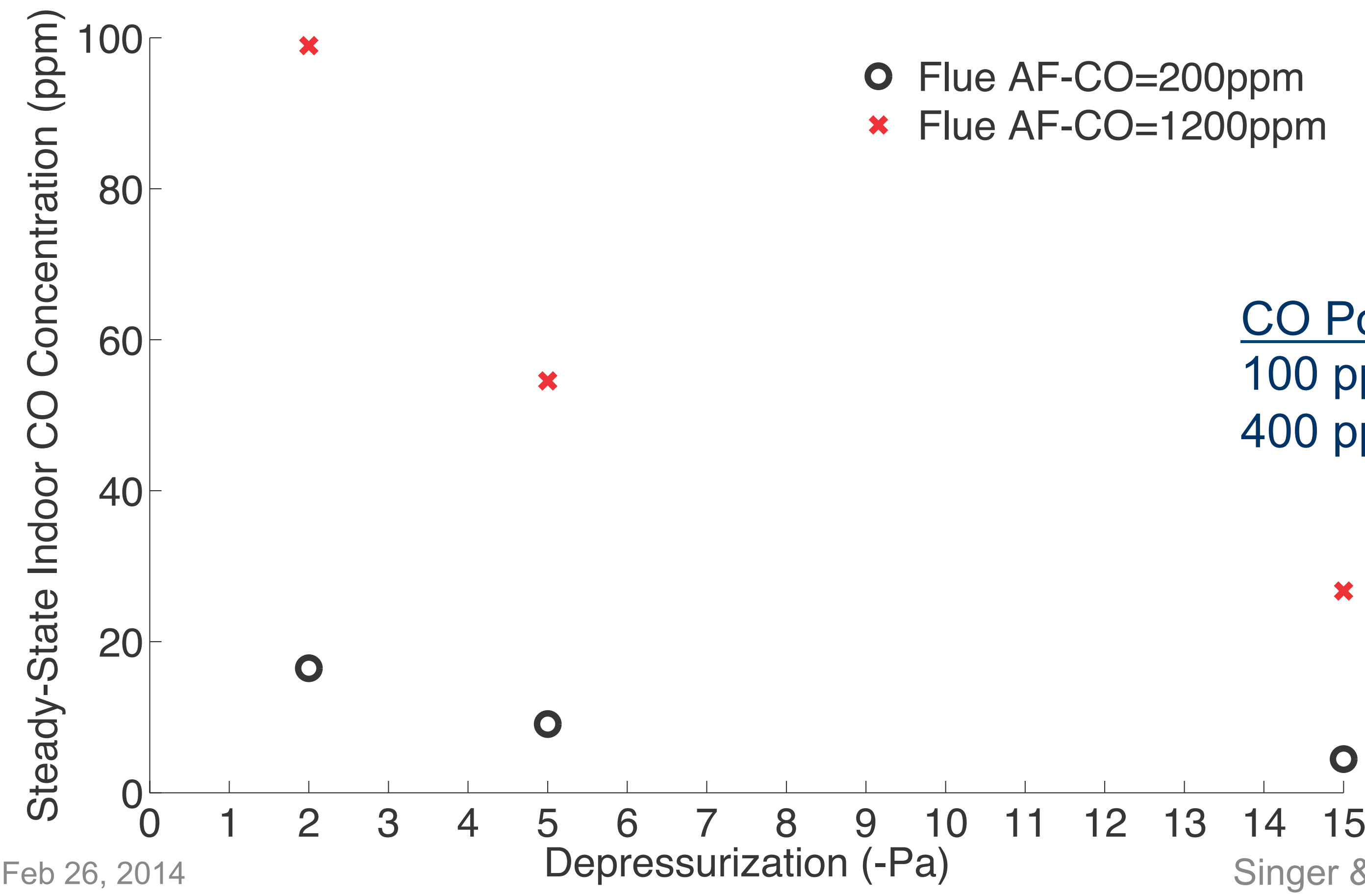
Larger depressurization reduces ambient CO concentrations

- 1200 sqft home; ACH50=4; 40 kBTU/hr appliance
- **Continuous Spillage** (Steady-state concentrations)



CO Poisoning (2-3 h)
100 ppm: headache
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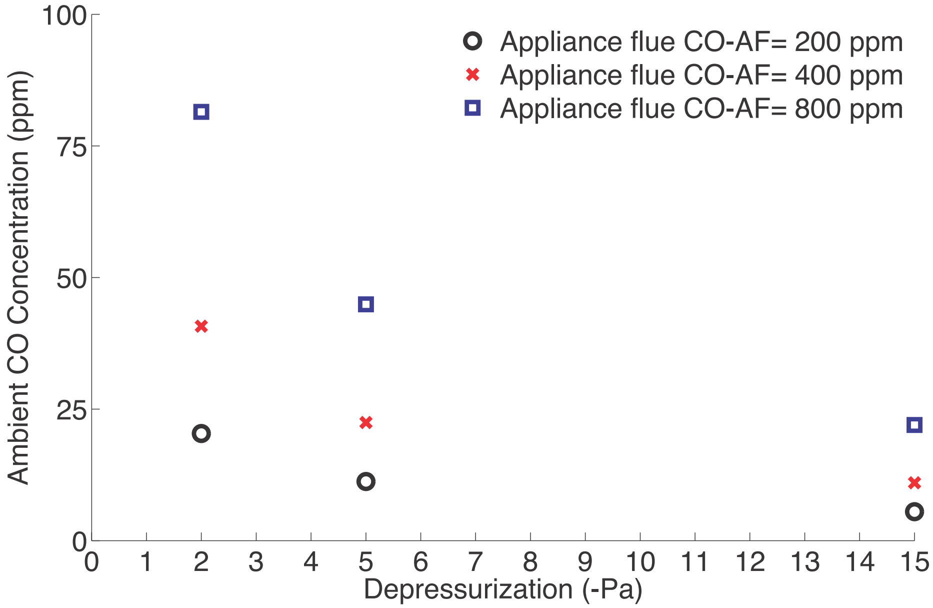
A wall furnace has less effect on ambient CO in larger homes than smaller homes

- ACH50=4; 20 kBTU/hr wall furnace
- **Spilling continuously** (Steady-state concentrations)



500 sq. ft.

CO Poisoning (2-3 h)
100 ppm: headache
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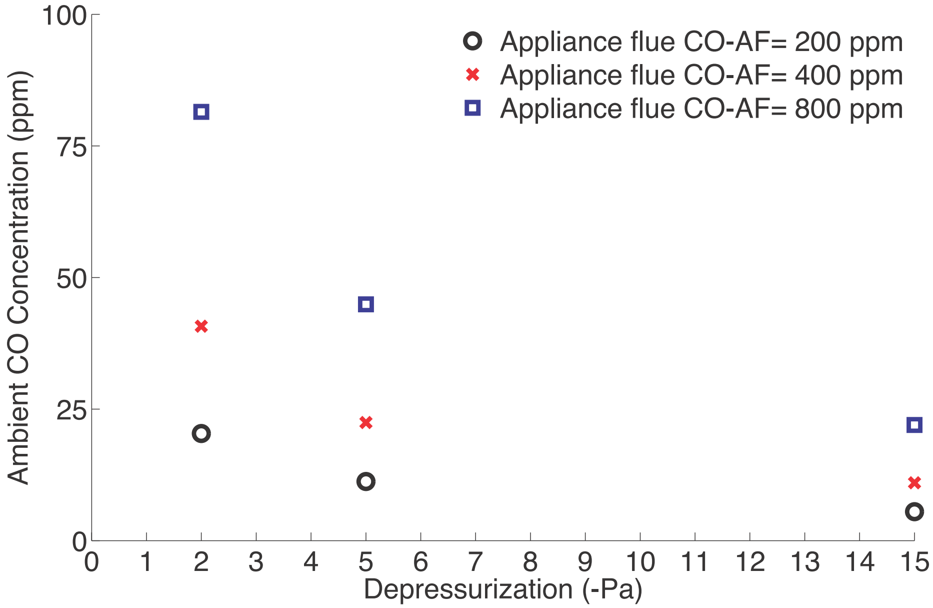
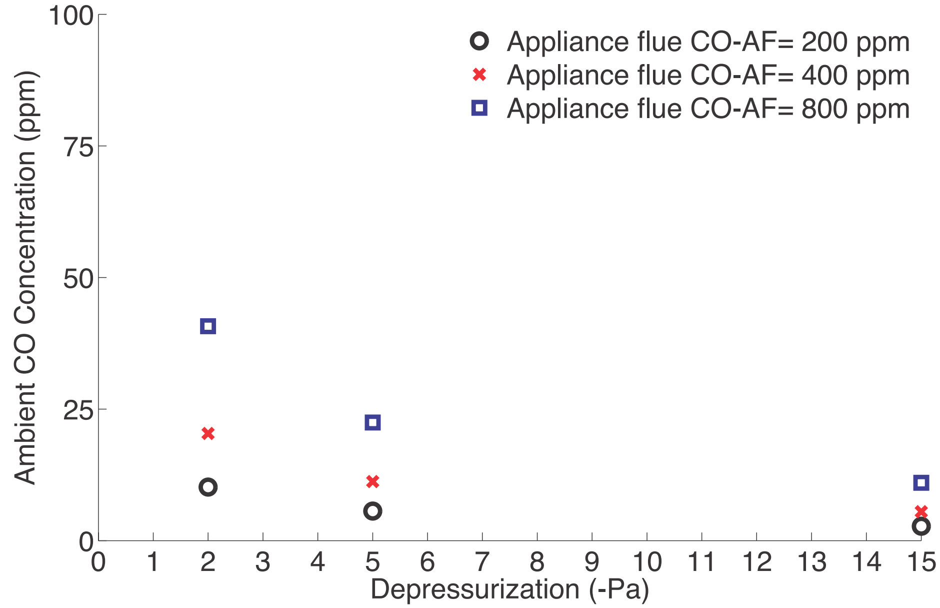
A wall furnace has less effect on ambient CO in larger homes than smaller homes

- ACH50=4; 20 kBTU/hr wall furnace
- **Spilling continuously** (Steady-state concentrations)



500 sq. ft.

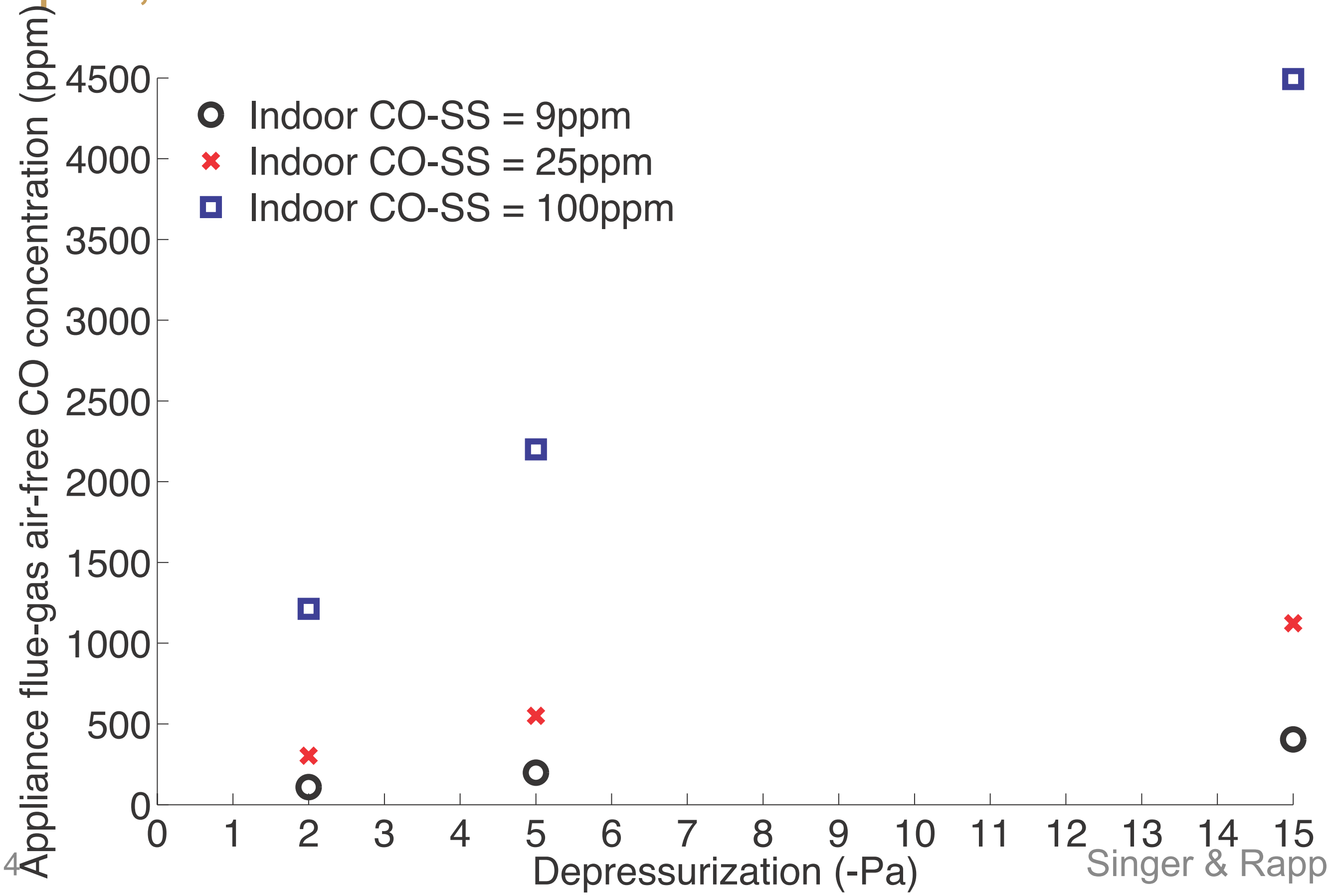


1000 sq. ft.

CO Poisoning (2-3 h)
100 ppm: headache
400 ppm: life threatening

Simulations can be used as a screening tool to identify problematic conditions

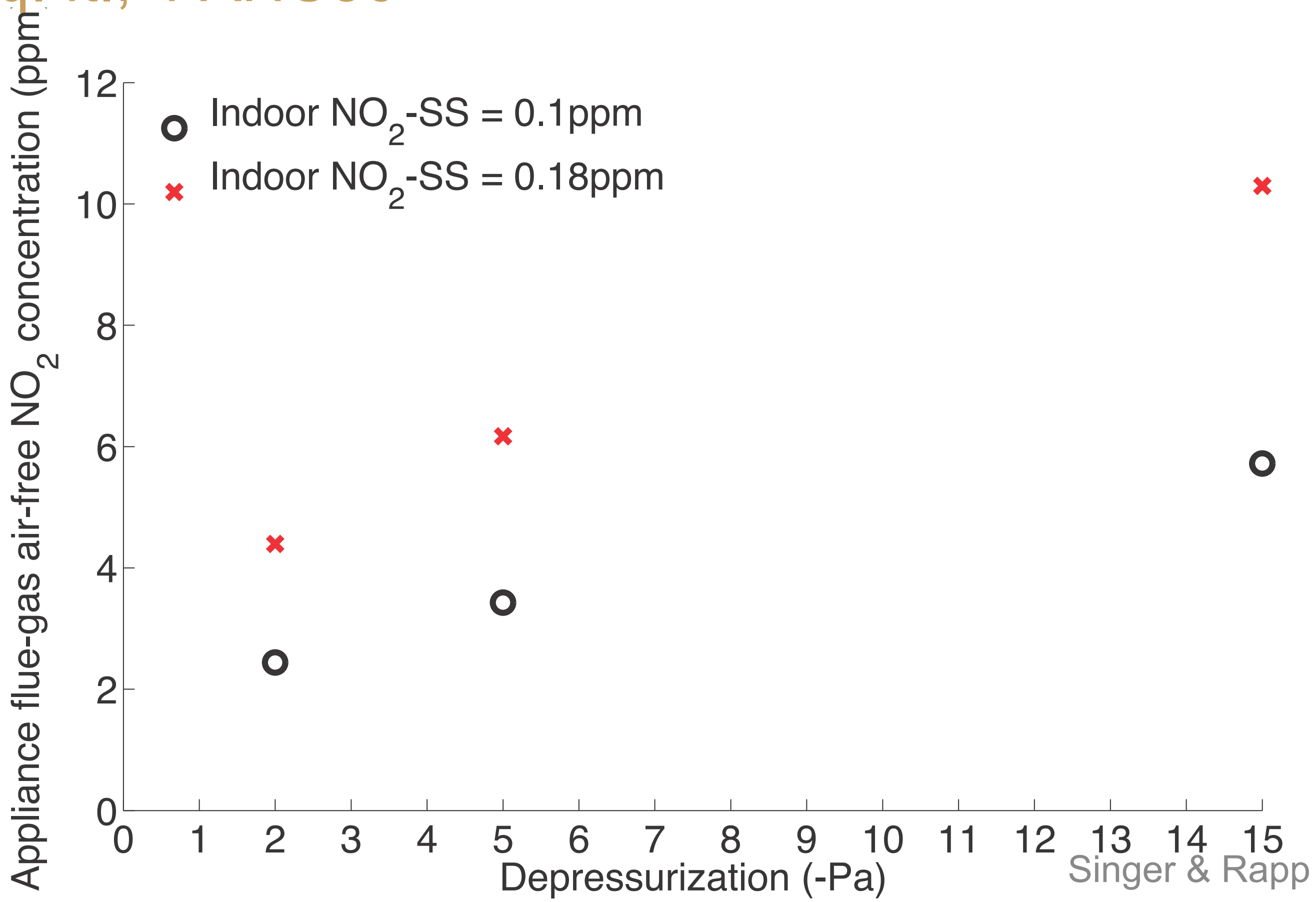
Appliance flue air-free CO in 40 kBTU/hr appliance **spilling continuously** to maintain specified concentrations (steady-state) 1200 sq. ft., 4 AHC50



Simulations can be used as a screening tool to identify problematic conditions

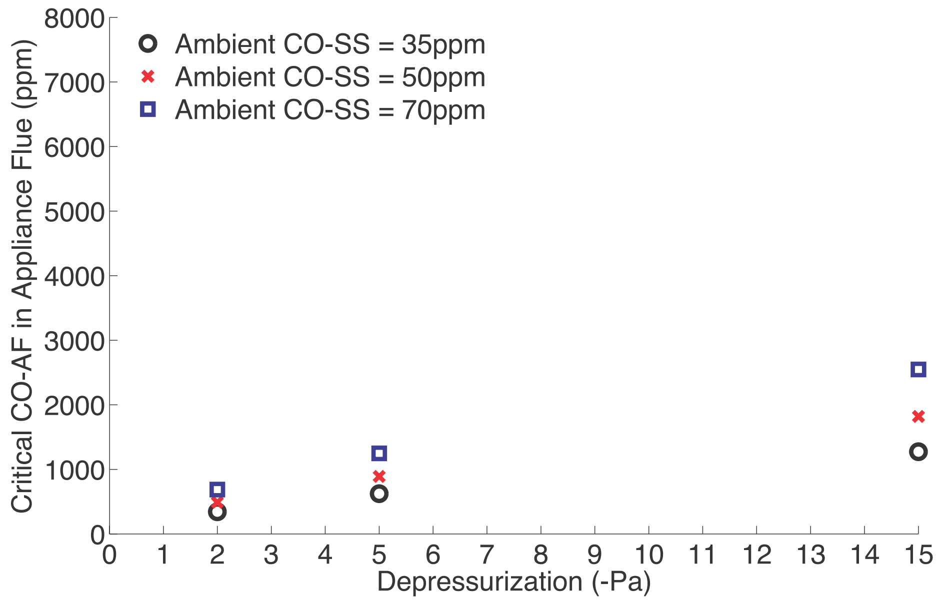
Appliance flue air-free NO_2 in 40 kBTU/hr appliance **spilling continuously** to maintain specified concentrations (steady-state)

1200 sq. ft., 4 AHC50

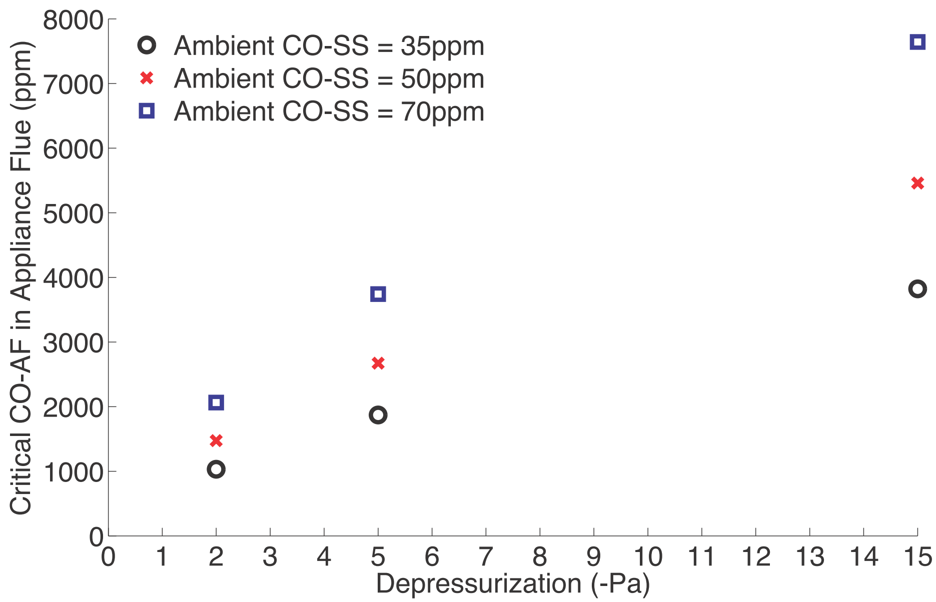


Simulations can be used as a screening tool to identify problematic conditions

Appliance flue air-free CO in 20 kBTU/hr wall furnace **spilling continuously** to maintain specified concentrations (steady-state)



- 500 sq. ft., ACH50=4
- Possible risk at low depressurization spillage



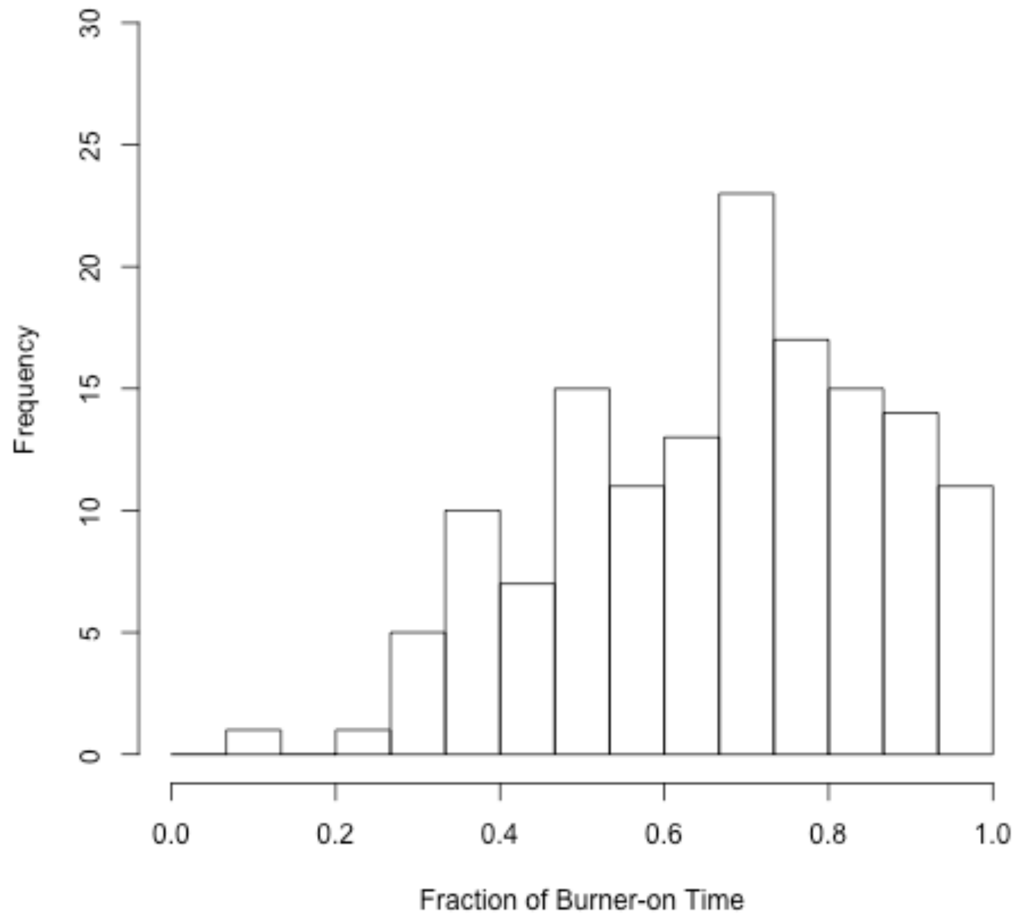
- 1500 sq. ft., ACH50=4
- Minimal risk

Water Heaters

Water heaters sometimes operate continuously over 1h

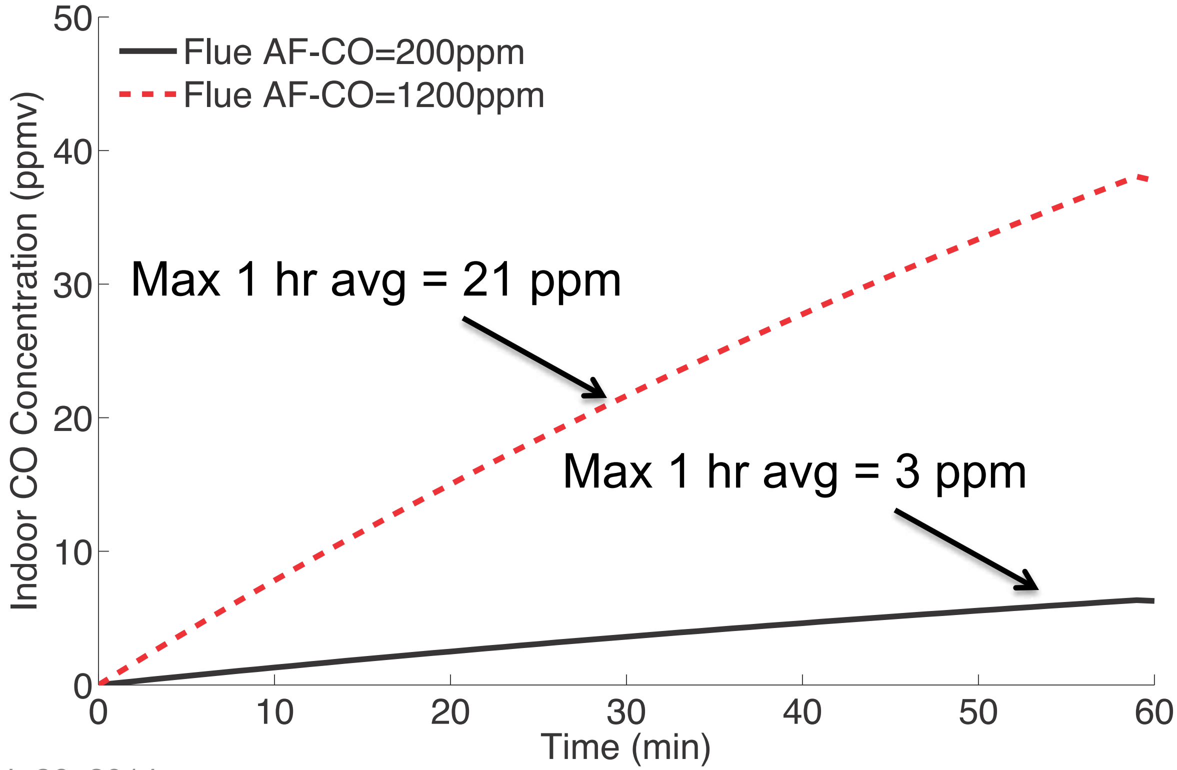
Water heater operation in 143 California homes

- 95^{th} percentile: 59 min
- 75^{th} percentile: 50 min
- Mean: 40 min



Simulation shows 1h of WH backdraft-induced spillage is not a life-safety issue

- 1200 sqft home; ACH50=4; 40 kBTU/hr appliance;
- **59 minutes of spillage**; -2 Pa depuressurization

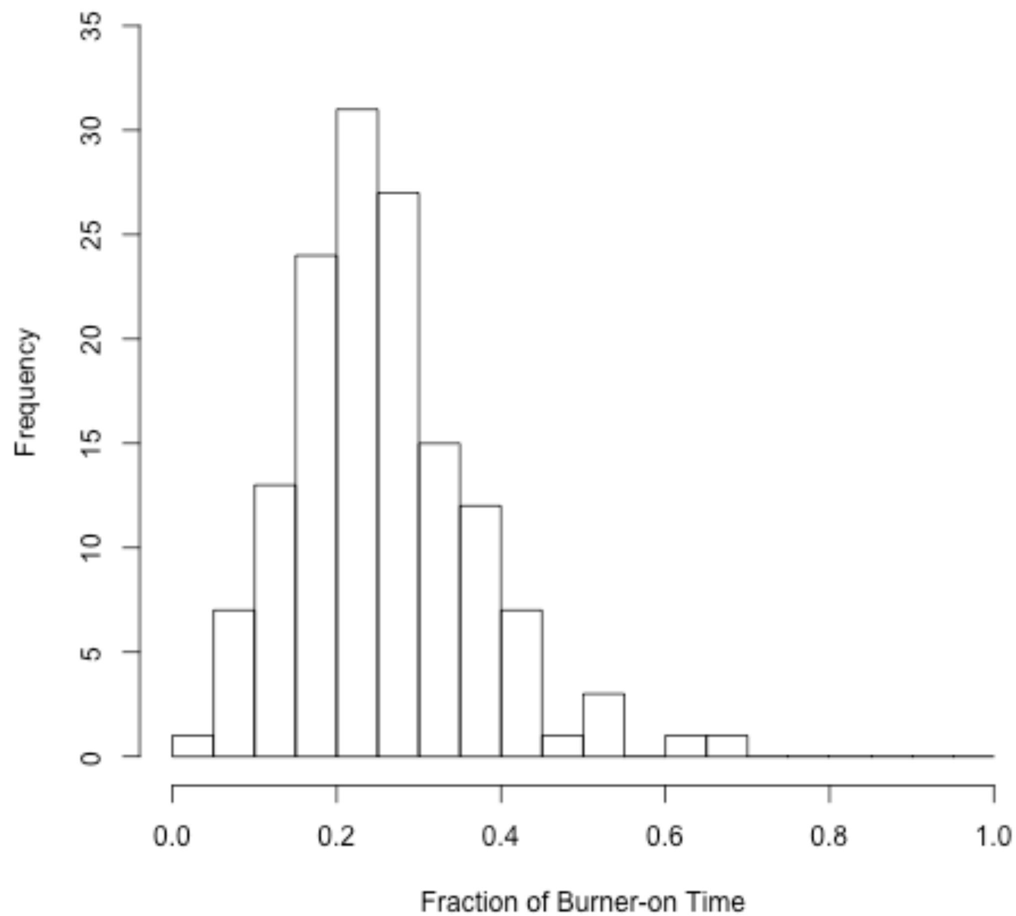


CO Poisoning (2-3 hrs)
100 ppm: headache
400 ppm: life threatening

Water heaters don't operate continuously over longer periods: data over 4h period

Water heater operation in 143 California homes

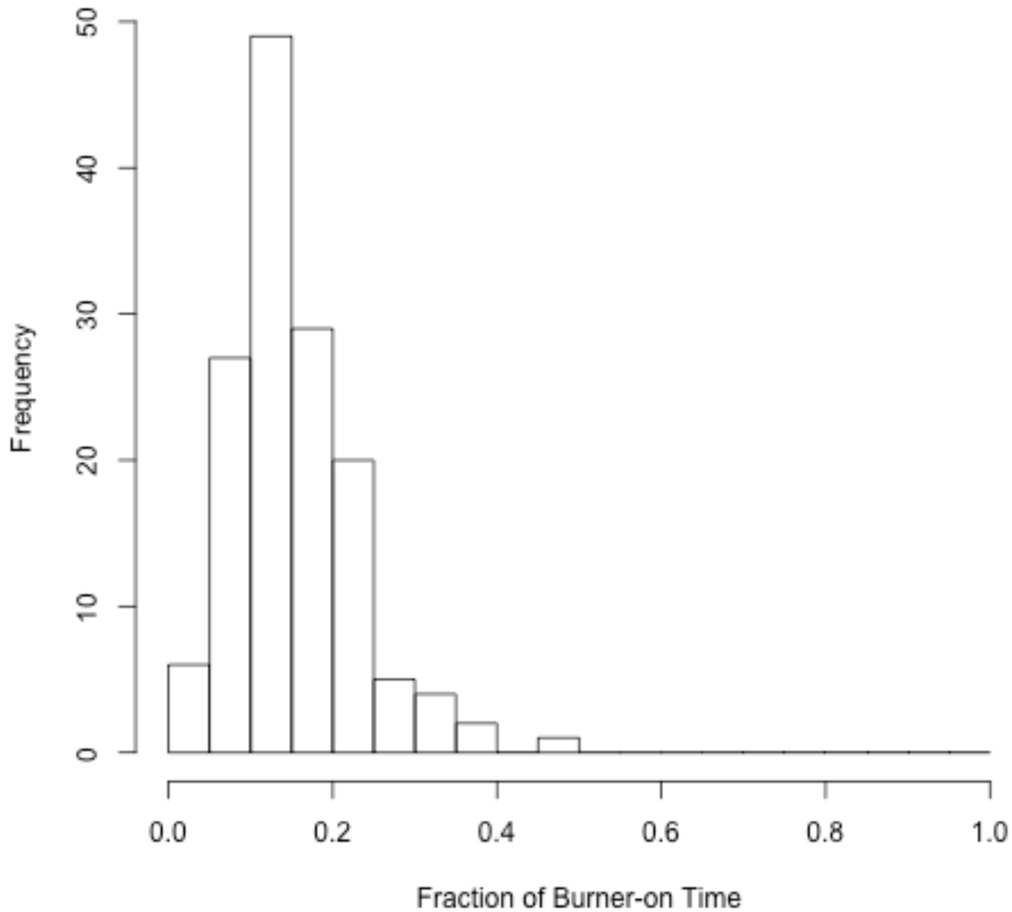
- 95th percentile: 105 min
- 75th percentile: 76 min
- Mean: 63 min



Water heaters don't operate continuously over longer periods: data over 8h period

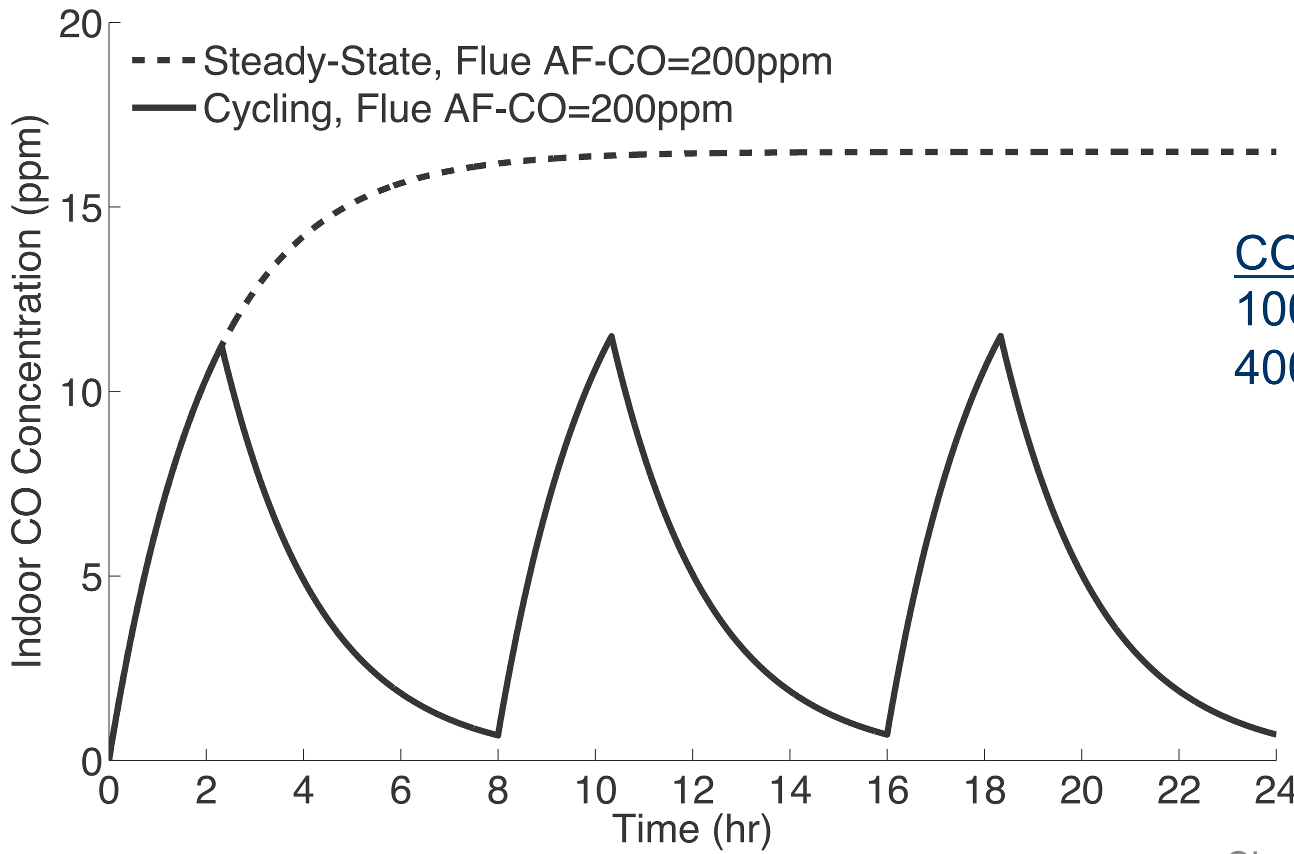
Water heater operation in 143 California homes

- 95th:139 min
- 75th percentile: 96 min
- Mean: 76 min



Simulation shows 8h of WH backdraft-induced spillage is not a life-safety issue

- 1000 sqft home; ACH50=4; 40 kBTU/hr appliance, 400 ppm CO-AF
- **139 minutes of spillage**, -2 Pa depressurization



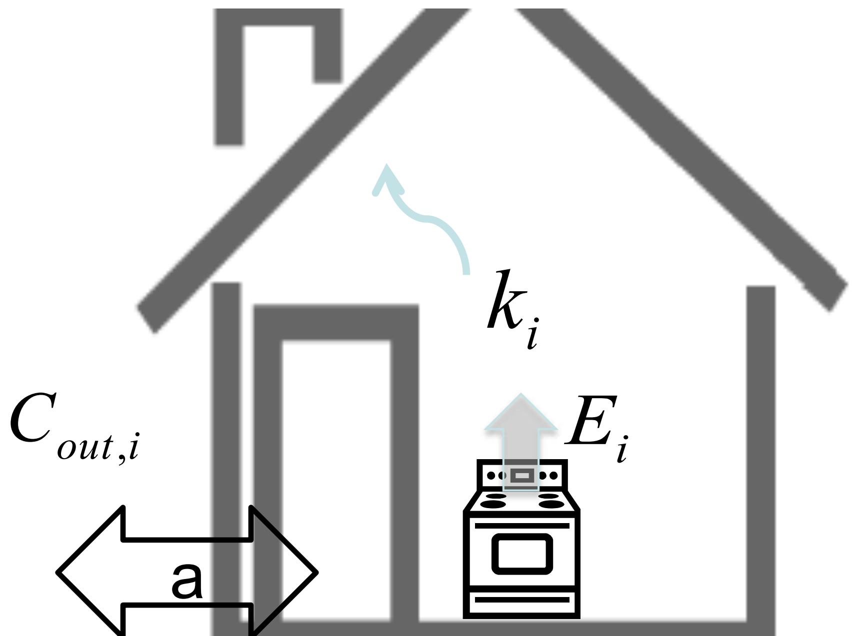
CO Poisoning (2-3 h)
100 ppm: headache
400 ppm: life threatening

Cooking

Estimated exposures to pollutants from natural gas cooking burners in SoCal

Using LBNL's Population Impact Assessment Model

Physics-based simulation of each home



$$V\frac{\partial C_i}{dt} = E_i + aVP_iC_{out,i} - k_iVC_i - aVC_i - LR_i$$

Apply to large sample of homes that cook with gas

Data from RASS:

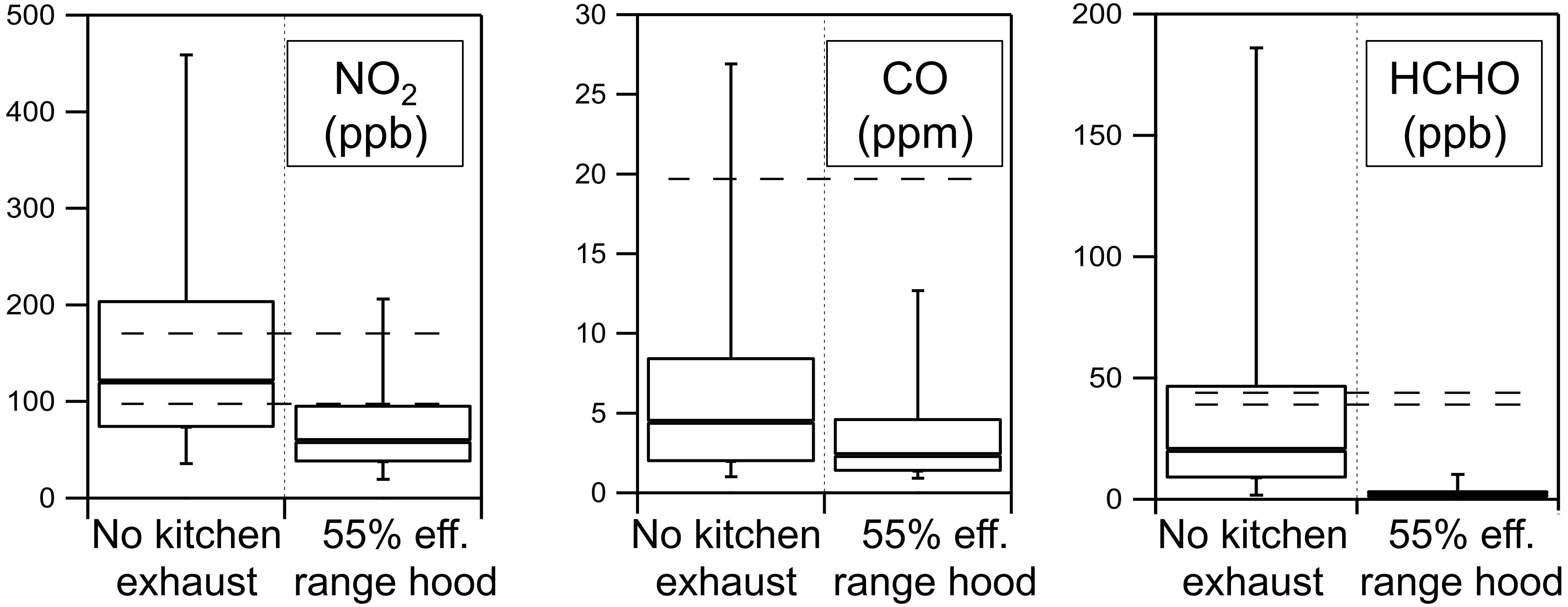
- *Data on age, size*
- *Demographics*
- *Cooking frequency*

- *NHAPS occupancy patterns*
- *Emissions measured from used stoves.*
- *Cooking times from surveys*

Simulations show many homes exceeding air quality standards when no range hood is used

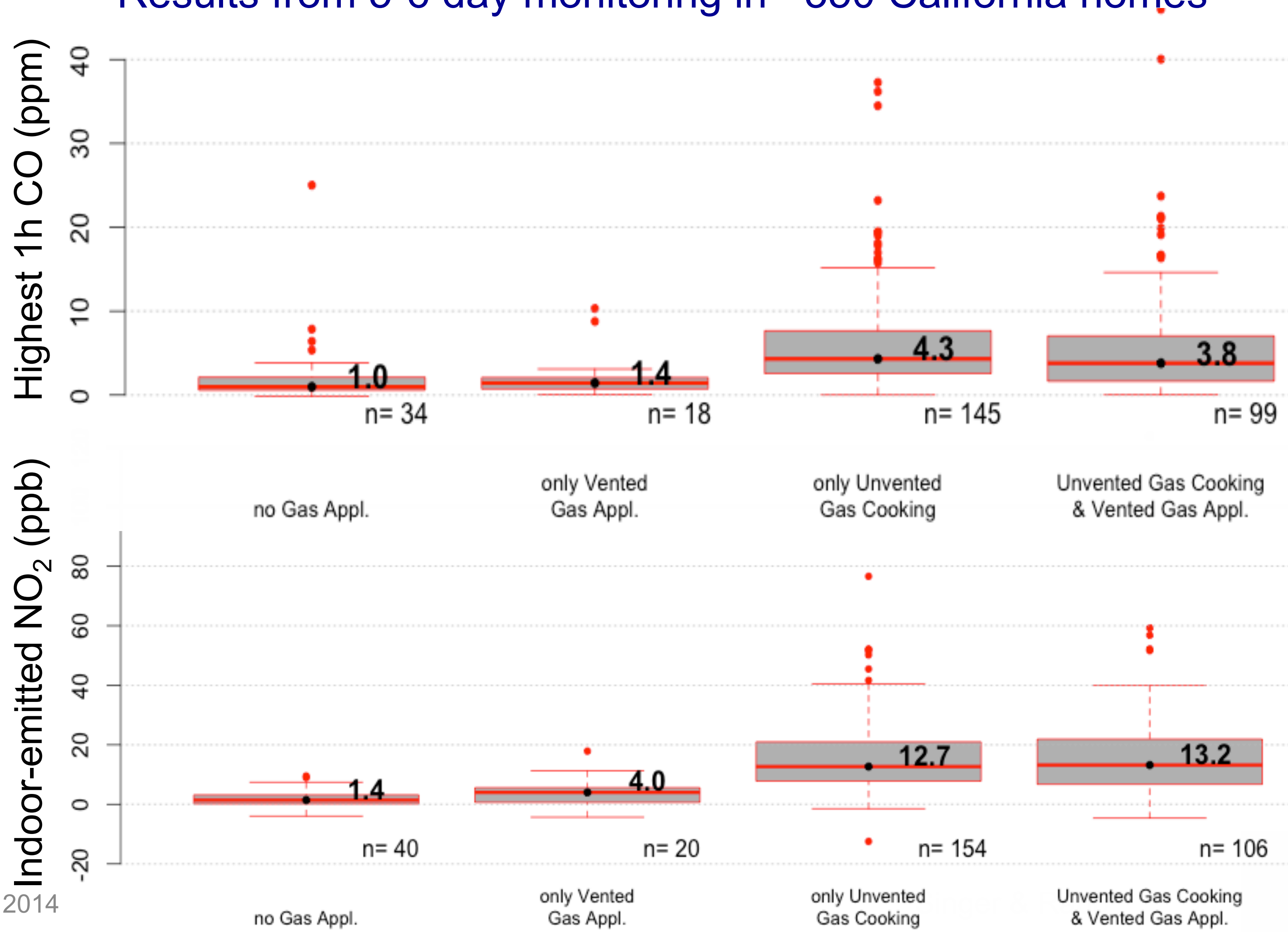
Use of 55% efficient range hood reduces exceedances

Highest 1h concentrations during typical week in winter



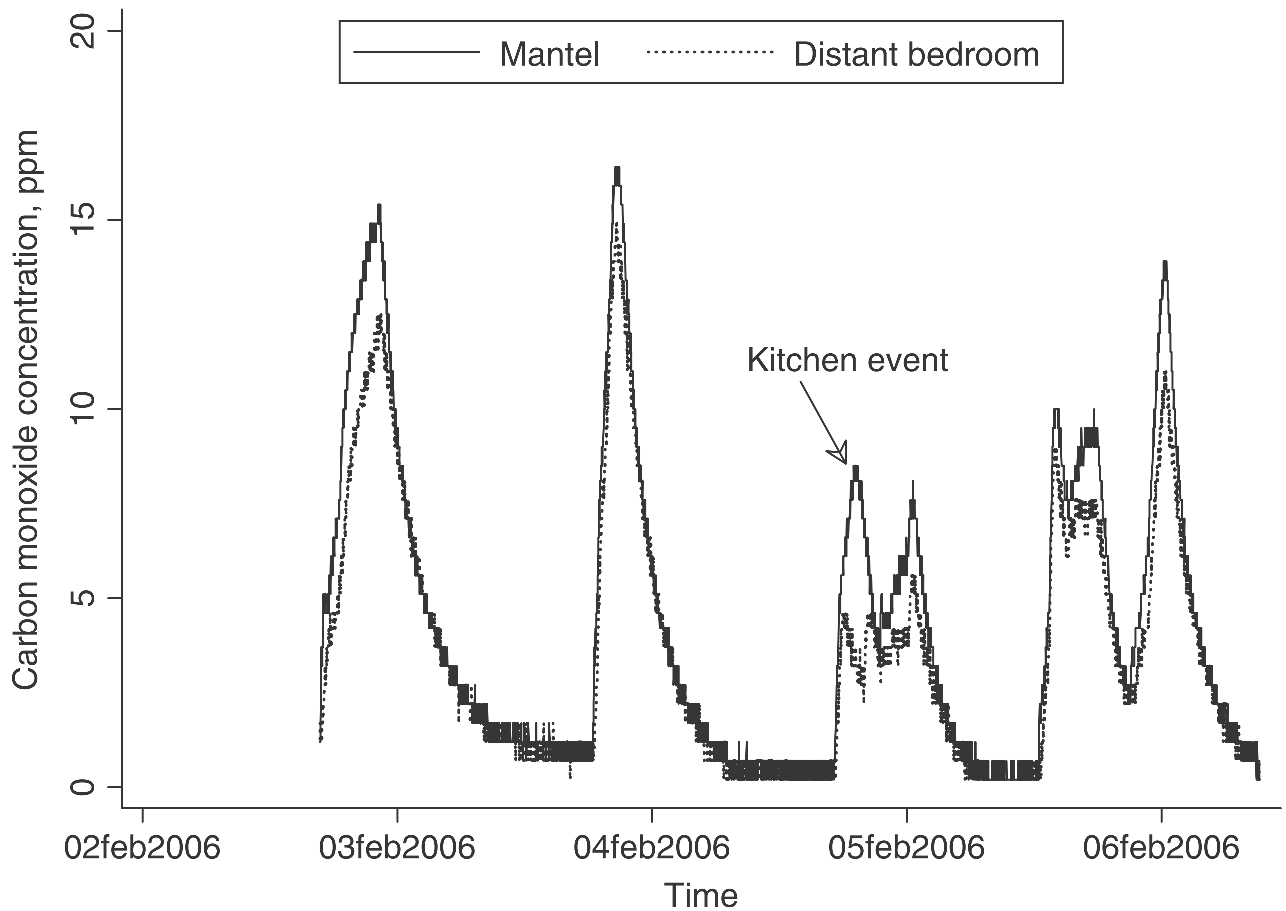
Measurements show that cooktops are most common problem in California

Results from 5-6 day monitoring in ~350 California homes



Unvented Heaters and Fireplaces

Room concentrations follow CO concentrations from unvented fireplaces (also see notes for % failures)



Francisco, D., et al., Measured concentrations of combustion gases from the use of unvented gas fireplaces (2010)

Prevent use of unvented heaters and fireplaces

- Located in the living space and continuously spill combustion gases
- Increase risk CO, NO_2, and moisture problems
- Produce 1qt/hr of water vapor
- Canada and many U.S. states ban the use of unvented heaters

http://ventyes.org/