California Air Quality Impacts of Liquefied Natural Gas (LNG)

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Presented to

Stakeholder and Project Advisory Committee Meeting

California Energy Commission

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Motivation for PIER Project

- **Concern about LNG impact on burners**
  - LNG composition and physical properties differ from recent supplies
  - Focus on Wobbe Number (WN)
    - Proportional to energy delivery rate through orifice
    - Higher WN can shift air-fuel ratio, impact operating temperature and pollutant formation
- **Higher emissions could impact air quality**
  - Outdoors:
    - Higher NO_X can impact ozone and PM
    - CO, NO_2, Formaldehyde direct effects + ozone impacts
    - Focus on South Coast Air Basin
  - Indoors:
    - CO, NO_2, Formaldehyde, Ultrafine particle direct effects

LBNL Research Goals

- **Effects of higher WN fuel on appliances**
  - Controlled experiments in lab and residences
  - Residential burner model simulations
- **Outdoor air quality impacts**
- **Indoor air quality and exposure impacts**
- **Range hoods as mitigation for indoor exposures**

Thank you to Project Advisory Committee

- Alfonso Baez, *SCAQMD*
- Charles Baukal, *John Zinc LLC*
- Leon Brathwaite, *CEC*
- Meredith Colket, *United Technologies Research Center*
- David Collier, *Eclipse Inc.*
- Donald Dabdub, *UC-Irvine*
- Jorge Gutierrez, *SoCalGas*
- Ben Ho, *BP American Inc.*
- Peggy Jenkins, *CARB*
- Marty Kay, *SCAQMD*
- Kimberly Kemp, *PG&E Co.*
- *Edgar Kuipers, Shell Trading*
- Steve Moore, *San Diego APCD*
- Glenn Morrison, *Missouri Institute of Science and Technology*
- Adriano Pangelinan, *Shell Trading*
- Kevin Shea, *Sempra Utilities*
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- Jed Waldman, *CA Dept of Public Health*
- Bob Wilson, *KeySpan Energy*
- Floyd Vergara, *CARB*
- Gary Yee, *CARB*
- Steve Ziman, *Air Quality Consultant*
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Thank you to Project Technical Team

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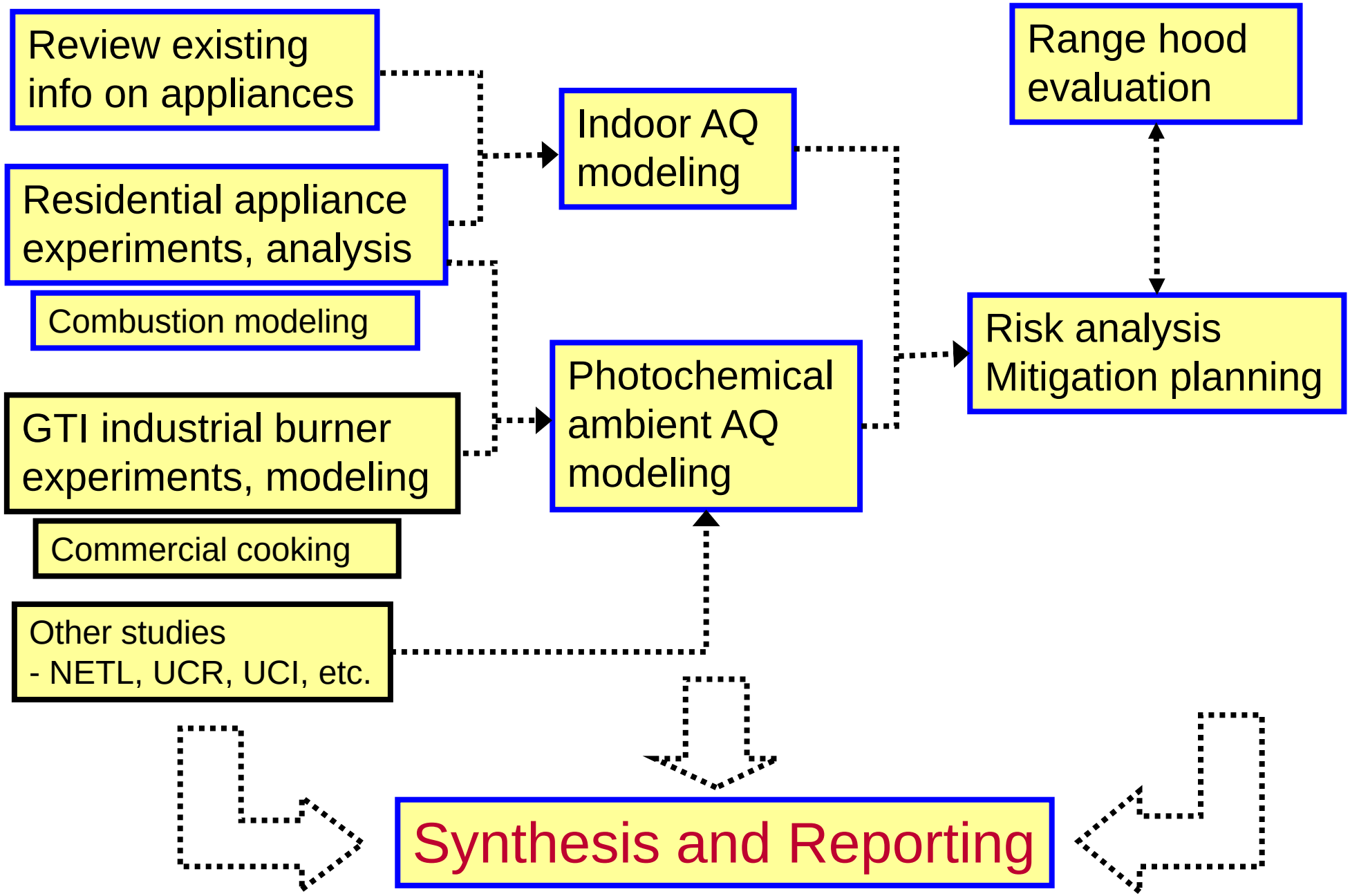
Integrated Research Plan

LBNL tasks in blue boxes



Air Quality Concerns

- **Pollutants with direct health effects**
  - Carbon monoxide (CO)
  - Nitrogen dioxide ($NO_2 = NO_X - NO$)
  - Particle number (PN) as indicator of ultrafine particles
  - Formaldehyde (HCHO)
- **Contribution to ambient air pollution**
  - Nitrogen oxides (NO_X) contributes to ozone, PM
  - Also CO, HCHO, NO_2
- **Emission metrics**
  - Emission factors normalized to fuel energy (ng/J)
  - Air-free concentrations (ppm)
  - Calculated for stable and full-burn conditions

Findings: Appliance Operation

- **Consistent with other studies, we found no substantial operational issues related to LNG use in residential appliances**

Findings: Pollutant Emissions

- Small, if any increase in emissions from forced air furnaces and storage water heaters
- Tankless water heaters have higher emissions and LNG impacts compared to storage WHs
- Cooking burners can have substantial baseline emissions and sensitivity to LNG

Findings:
Air Quality in South Coast Air Basin

- **Baseline inventory likely overstates NO_X from residential appliances**
  - LBNL experimental results suggest that basin-wide NO_X may be 1.2% lower than official inventory
- **Negligible change in ambient PM and ozone with any realistic LNG distribution at current capacity**
- **Hypothetical case of 100% LNG – which is not feasible with current or planned infrastructure – would cause 0.4 ppb increase in 8-h ozone**

Findings: Indoor Air Quality

- **Emissions from cooking burners frequently yield hazardous pollutant levels indoors**
  - Among homes that cook with gas,
    - ~40% exceed NO_2 1-h standards
    - ~20% exceed formaldehyde 1-h guidelines
    - ~5% exceed CO 1-h and 8-h standards
  - LNG can make this incrementally worse; but does not dramatically change the equation
- **Range hoods can mitigate exposures to pollutants from cooking, but issues exist**
  - Not used regularly in most homes; noisy
  - Inadequate airflow rates given inefficient designs
  - Much better performance for back burners

Reporting

- **Published CEC reports (Available on web site)**
  - Search for all reports: "Natural Gas Variability in California" or by author name (Singer)
  - Literature Review and Evaluation for Residential Appliances. CEC-500-2006-110
  - Experimental Evaluation of Pollutant Emissions from Residential Appliances. CEC-500-2009-099
  - Air Quality Impacts of Liquefied Natural Gas Use in the South Coast Air Basin of California. CEC-500-2011-041
- **Reports submitted to CEC**
  - Evaluation of installed range hood performance
  - Cooktop burner combustion modeling
  - Indoor exposure modeling
- **Reports also available via LBL publications database**

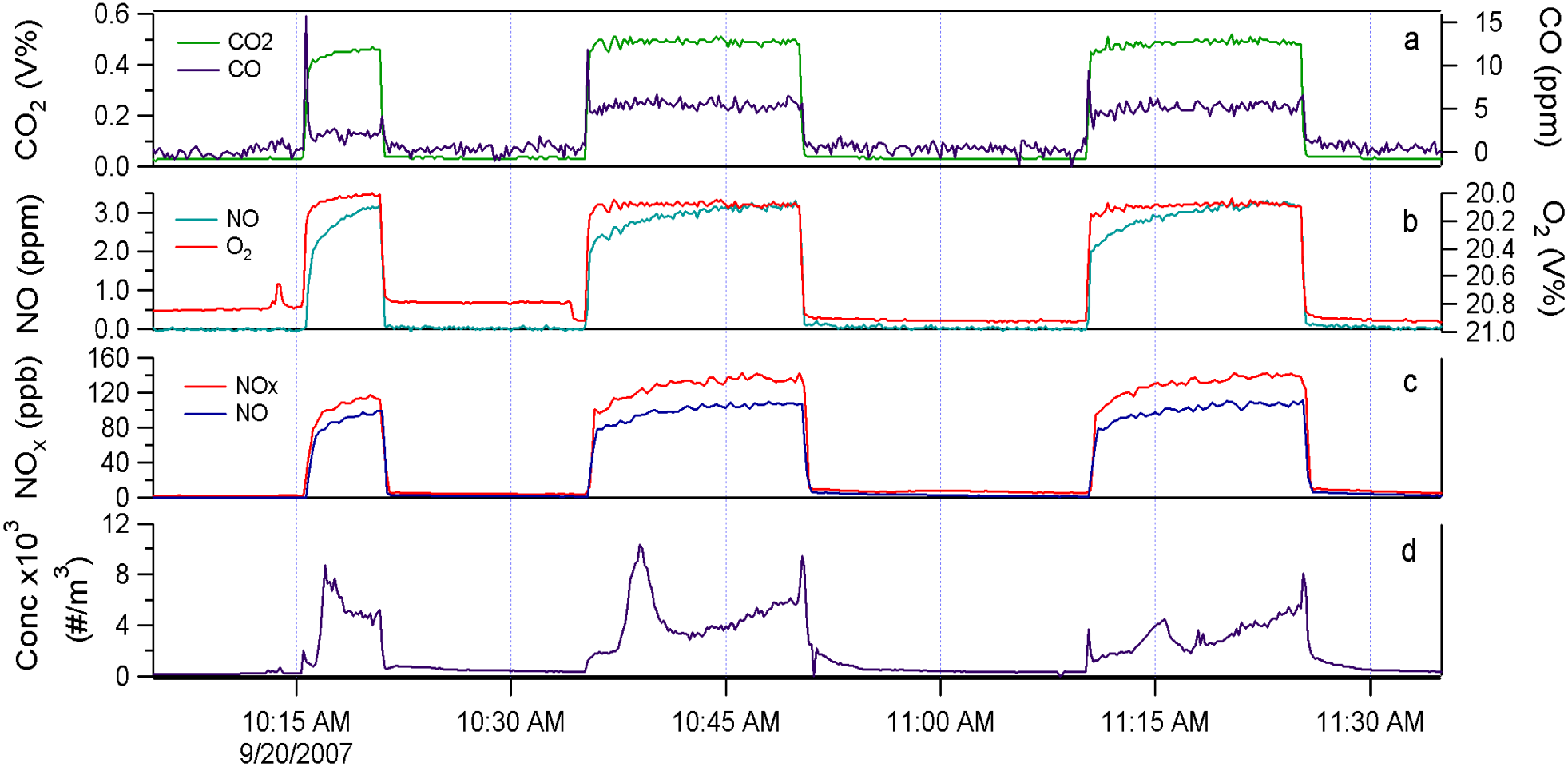
Reporting II

- **Archival journal papers**
  - Range hood paper published online in 2011 (Indoor Air)
  - Appliance emissions paper in preparation
- **Indoor Air conference papers**
  - Range hood evaluation
  - Indoor exposures
- **Other conferences**
  - Affordable Comfort Institute
  - HUD Healthy Homes
  - DOE Building America

Appliance Burner Experiments

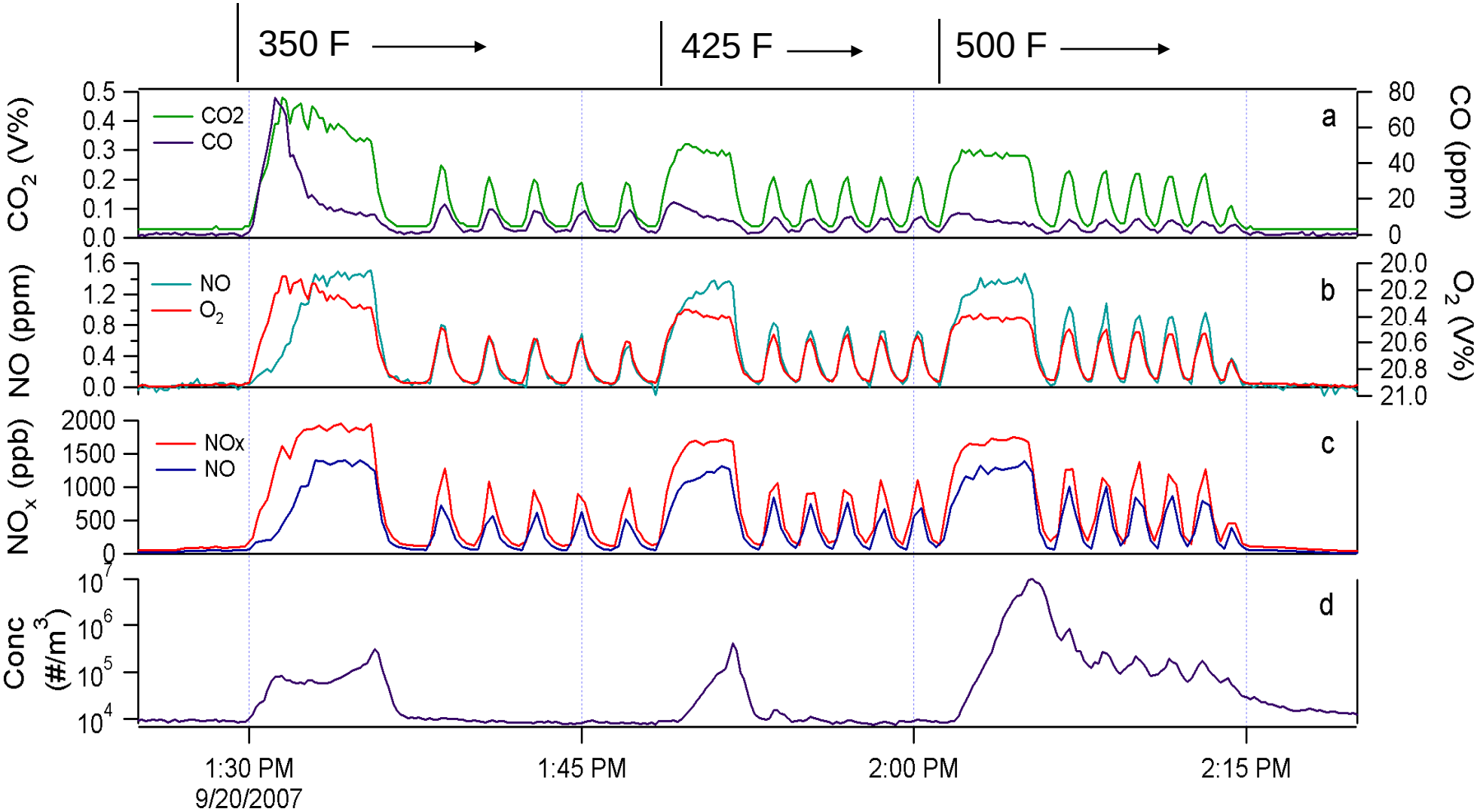
- **Burners**
  - Cooking: 13 cooktops, 12 ovens, 5 broilers
  - Vented: 5 storage water heaters, 6 tankless , 5 furnaces
- **Fuels**
  - Northern CA line gas: 1330-1340 WN
  - Simulated LNG: 1390, 1420 WN (some 1360 WN)
- **Experimental approach**
  - Operating *cycles* to capture transient emission events
  - Duplicate burns for cooktops, ovens, furnaces, storage WHs
  - Varied operation for oven (temp) and tankless (flow)

Example data: cooktop experiment



Pot + 4 L H_2O on each corner burner, all at highest firing rates; 15-min burns. Cooling period varied in early expts, then consistent at 15 min. (CT02, fuel 3A+N_2)

Example data from oven experiment



Subsequent experiments used 2-3 maintenance cycles per T setting
(OV02, fuel 3A)

Emission rates: gaseous pollutants*

$$E_i\left[\frac{\mu g}{KJ}\right]=\frac{\left(\frac{10^{-6}\,mol\ i}{mol\ air}\right)}{\left(\frac{10^{-2}\,mol\ CO_2}{mol\ air}\right)}\left(\frac{mol\ CO_2}{MJ\ \ fuel}\right)\left(\frac{g\ i}{mol\ i}\right)\left(\frac{MJ}{10^3\,KJ}\right)\left(\frac{10^6\,\mu g}{g}\right)$$

$$\boxed{E_i\left[\frac{\mu g}{KJ}\right]=\left(10^{-1}\right)\frac{C_{i,AIR-FREE}\left[ppm\right]}{Theor.CO_2\left[\%\right]}\left(\frac{mol\ CO_2}{MJ\ \ fuel}\right)M_i}$$

*Obligatory math slide

Data Analysis

- Calculate emission factors for full-burn, end-of-burn
- Experimental repeatability
- Univariate: emissions by burner and fuel
- Bivariate: emissions related to fuel WN
- Multivariate: include other effects
- Relate change in emission factor to increase in WN
- Executive Summary presents change for 50 WN difference (1335 →1385 WN)

Interpretation of Results

Cooking / Unvented Burners

- Indoor exposures
- Concern: impacts for individual burners
- Focus on primary pollutants
  - CO, NO_2, PN, HCHO
  - Small contribution to ambient air quality
- Sample includes common technologies, varied ages
- Sample not large enough to reliably assess outliers

Vented Burners

- Ambient air quality
- Concern: impacts on total emissions from population
- Focus on regulated pollutants
  - NO_X effect on O_3, $PM_{2.5}$
  - CO small effect on ozone
  - HCHO is Hazardous Air Pollutant
  - NO_2 primary pollutant
- Most common technologies sampled; results consistent with other studies

Baseline Emissions* by Appliance Group

	CO (ng J^{-1})	NO_2 (ng J^{-1})	HCHO (ng J^{-1})	PN* (10_4 J^{-1})	NO_X (ng J^{-1})
Cooktops	7 – 823	5.0 – 17.7	0.1 – 4.7	183 – 9200	25 – 47
Ovens	16 – 528	3.8 – 13.9	0.3 – 5.5	10 – 6300	27 – 41
Broilers	29 – 178	2.8 – 13.0	0.1 – 0.9	107 – 2650	17 – 37
Furnaces	<1 – 31	<1 – 9.7	0.2 , 0.4	<1 – 46	22 – 34
Storage WH	<0 – 2	0.3 – 2.2	<0.1	3 – 51	24 – 32
Tankless WH	19 – 434	4.0 – 8.9	0.2 – 2.4	<1 – 27	9 – 31

* Range of mean emissions across burners; PN is range of maxima across burners.

Key Findings: Cooktops

Effects are change in emission factors (ng/J) per 50 Btu/scf increase in WN

- **CO: Increases in most cooktops**
  - Significant increases in 11 of 13 cooktops
  - ↑6-40% for 4 cooktops with CO > 100 ng/J
- **NO_2: Increases in half of the cooktops**
  - Significant increases in 7 of 13 cooktops; ↑5-20%
  - All had NO_2 > 5 ng/J
- **HCHO: Important impacts for some cooktops**
  - No change for most burners including highest emitter
  - Next two highest had one increase 62%, one decrease 28%
- **PN varies much more with operation than fuel**

Key Findings: Ovens and Broilers

Effects are change in emission factors (ng/J) per 50 Btu/scf increase in WN

- **CO: Increases in most**
  - Increases in 16 of 17 burners
  - ↑5-40% for 7 of 9 with CO ≥ 100 ng/J
  - ↓5-14% for 2 of 9 with CO ≥ 100 ng/J
- **NO_2: Increase in half of the burners**
  - Increases in 9 burners: ↑10-38% for NO_2 > 5 ng/J
  - Decrease of 7% in 1 burner:
- **HCHO: Some impacts**
  - Increases of 8-20% in 6 burners; decrease of 21% in 1 burner
  - No change in 8; no data for 2 burners
- **PN varies much more with operation than fuel**

Key Findings: Water Heaters I

Effects are change in emission factors (ng/J) per 50 Btu/scf increase in WN

- **Standard storage WHs have low CO and NO_2, appear to have low HCHO; negligible fuel effects**
- **Tankless had higher CO, NO_2, HCHO, PN**
- **Tankless:**
  - CO increase for group dominated by unit w/bad regulator
  - Frequency of this problem in population is unknown!
  - NO_2 ↑3-19% for 5 burners; ↓3% for 1 burner
  - HCHO ↓2-11% for 5 burners; no change for 1 burner

Key Findings: Water Heaters II

- **Storage to tankless switch has much larger impact than LNG on CO, NO_2, HCHO!**
  - Baseline emissions much higher
  - CO and NO_2 increase with LNG
  - HCHO decreases with LNG (but still higher than storage)
- **Baseline NO_X lower in tankless water heaters, but more sensitive to fuel WN!**
  - With LNG, NO_X from tankless likely still lower than from conventional storage WHs
  - Given variability of tankless NO_X, market analysis needed
- **Effect of fuel WN on ultra-low-NO_X storage WHs and next generation tankless?**
  - TBD in CEC-funded Healthy Homes study

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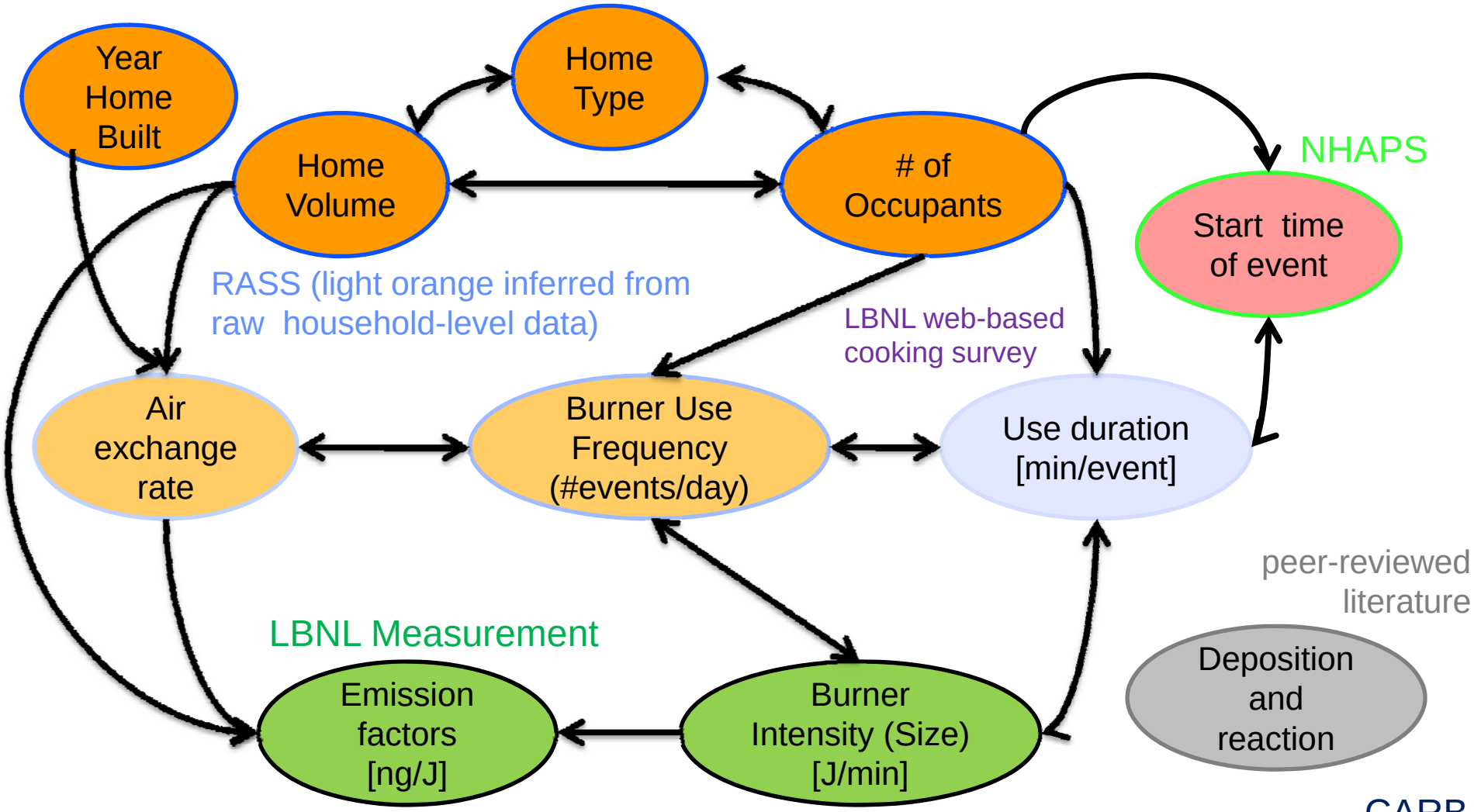
Cooking Burner Pollutant Exposures

- Apply physics-based model of emissions and removal processes to individual homes
  - Time-resolved concentrations in each home
- Apply to cohort of representative homes
- Key inputs from surveys, measurements
  - Building & household, Cooking activity, etc.
- Assigned parameters from data
  - Air exchange rate, Emission factors, Cooking duration
- Focus on burners, not cooking
  - CO, NO_2, Formaldehyde (HCHO)

Exposure Model Influence Diagram



Correlations are shown by double arrows

CARB

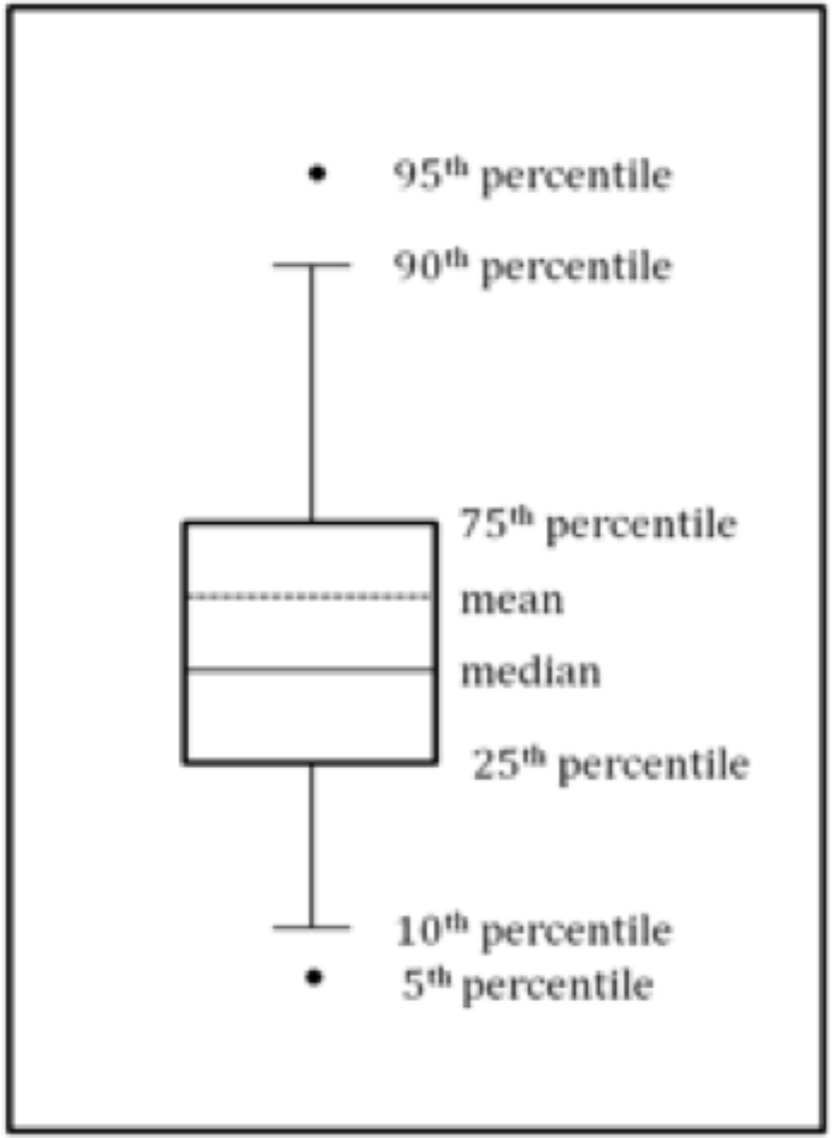
Hourly outdoor concentrations (NO and NO_2)

Data Sources

- **Household characteristics and cooking-activity**
  - Residential Appliance and Saturation Survey (RASS)
  - 21,000 homes representing population of California
- **Cooking-activity details**
  - Web-based cooking survey
- **Time-activity patterns**
  - National Human Activity Pattern Survey (NHAPS)
- **Emission factors**
  - LBNL measurements: 13 cooktops, 12 ovens
- **Air Exchange Rate (AER)**
  - Infiltration based on leakage database
  - Measurements in California by season

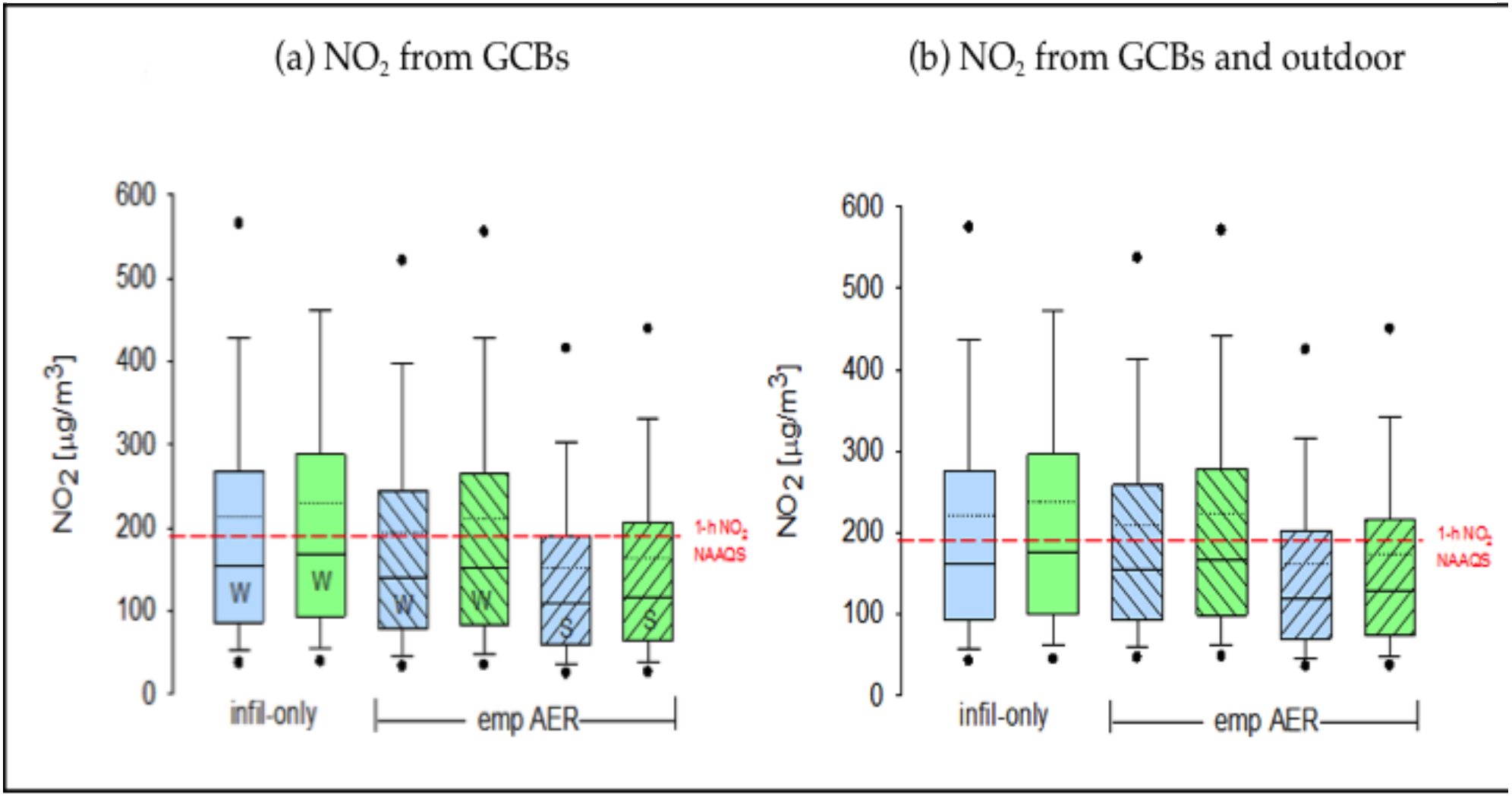
Exposure Impact Metrics

- **Summary statistics:**
  - Average over 1-week
  - Highest 1-h, 8-h
- **Distributions across population**
- **Number of homes or individuals exposed at a level that exceeds a health-based standard**
- **Cancer risk from incremental change to formaldehyde exposures**



Exposure Model Example Results

Highest 1-h NO_2 in Southern California Homes that Cook with Gas
Blue is baseline fuel, Green is LNG; Each Pair is a Scenario



Findings of Indoor Exposure Modeling

- **Emissions from cooking burners frequently yield hazardous pollutant levels indoors**
  - Among homes that cook with gas,
    - ~40% exceed NO_2 1-h standards
    - ~20% exceed formaldehyde 1-h guidelines
    - ~5% exceed CO 1-h and 8-h standards
  - LNG can make this incrementally worse; but does not dramatically change the equation

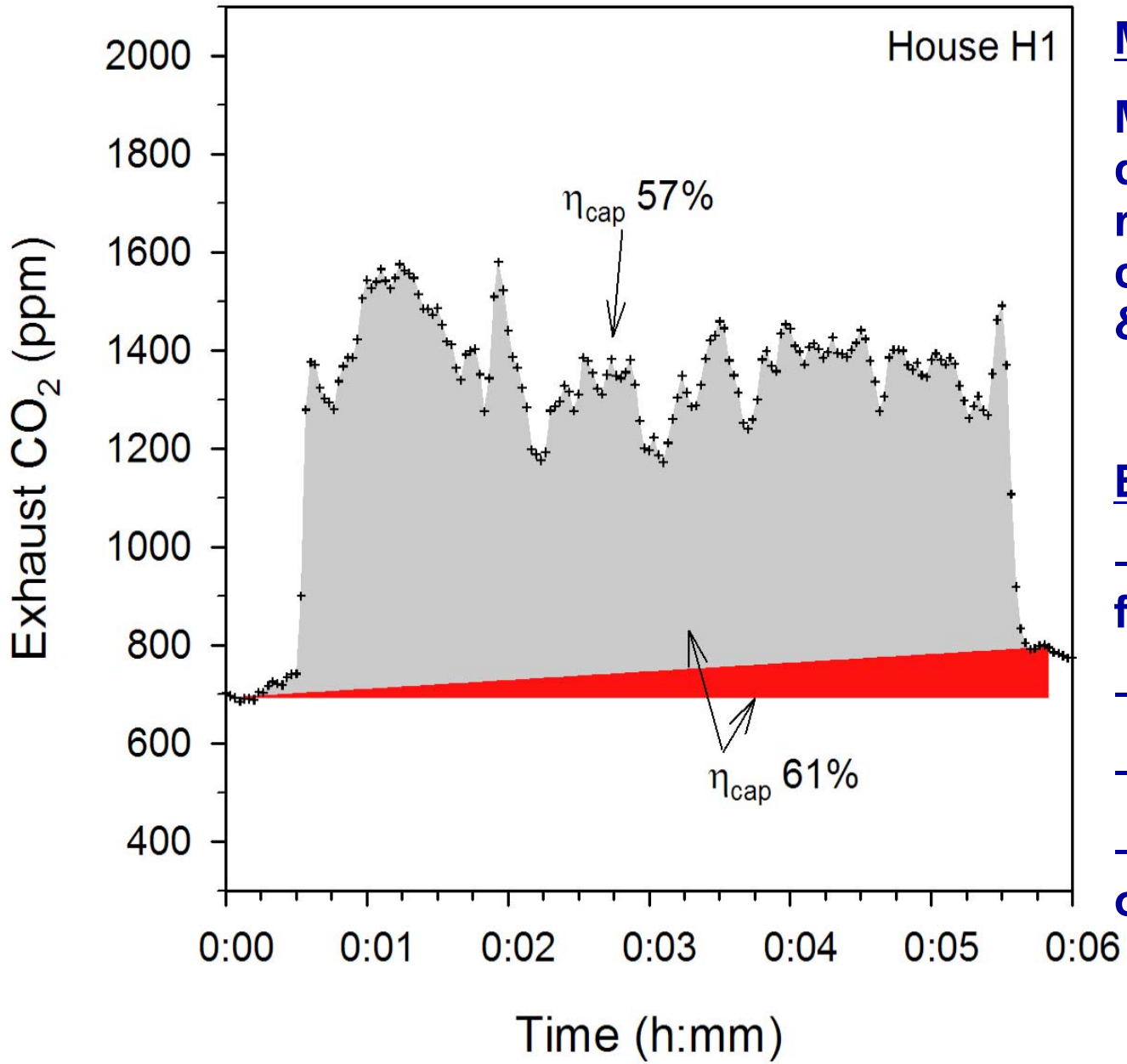
Cooking Exhaust Fan Evaluation

- **Objective**
  - Evaluate in-use performance of venting kitchen range hoods to assess potential for mitigation
- **Background**
  - Results from previous studies
    - Airflow well below rated values for many installed hoods
    - Inconsistent and limited use; primarily for smoke removal
    - Reasons: too loud, not needed, don't think of it
- **Evaluation metrics**
  - Airflow rates
  - Sound / noise levels (dB-A)
  - Capture efficiency

Range Hood Performance Metrics

- Airflow (cubic feet per minute, CFM)
  - ASHRAE 62.2 minimum: 100 cfm
- Capture efficiency (%)
  - Fraction of emitted pollutants removed via hood
  - No standard test – so we developed one!
    - Separate tests for front, back burners
- Sound (Sone)
  - ASHRAE 62.2 maximum: 3 sone
- Fan efficiency (CFM / Watt)
  - Energy Star standard

Capture Efficiency Evaluation



Mass Balance:

Measure CO_2 in exhaust duct; compare emission rate based on fuel use to calculated mass from flow & concentration msts.

Experimental Conditions

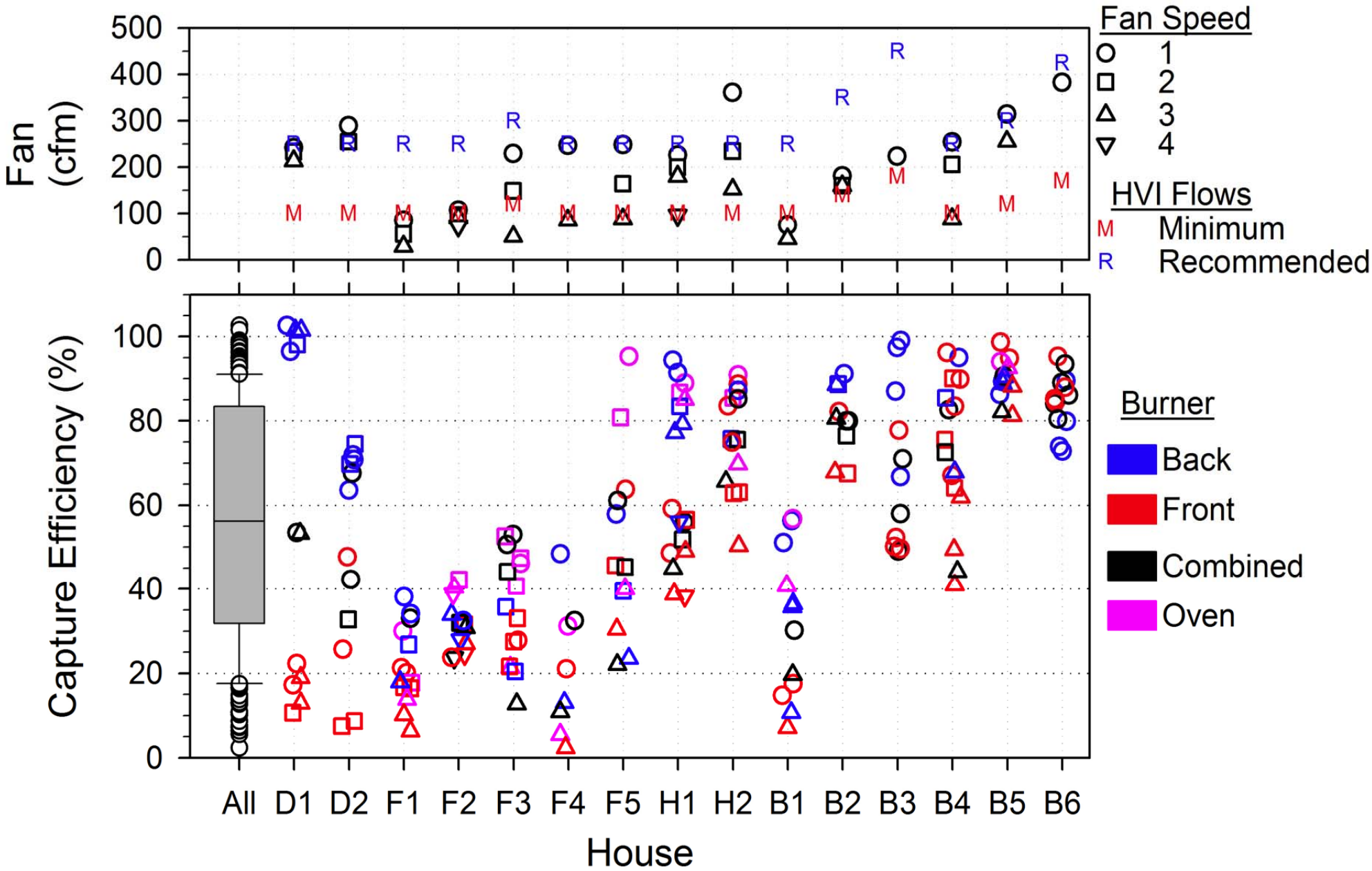
-Covered pot of water on front or back burner

-Oven burner

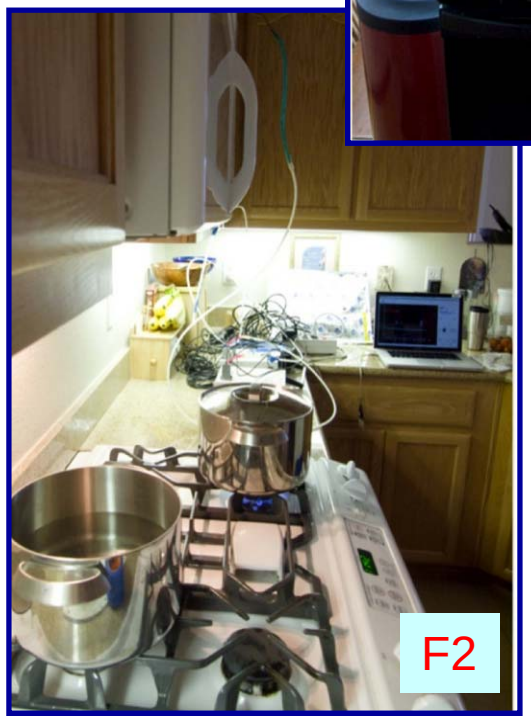
-Vary fan settings

-No person at stove or other airflow interference

Cooking Exhaust Fan Performance



Exhaust systems with low capture efficiency for some or all conditions



Exhaust systems with higher capture efficiency

~50-90%

~70-90%

~80-100%

Ambient Air Quality Impacts in South Coast Air Basin

- At start of project, concern focused on SoCAB; Ultimately, more intensive LNG use in San Diego
- Key metrics
  - Basin-wide emissions (inventory)
  - Ambient ozone
  - Ambient particulate matter (PM2.5)

Ambient Air Quality Impacts; Approach

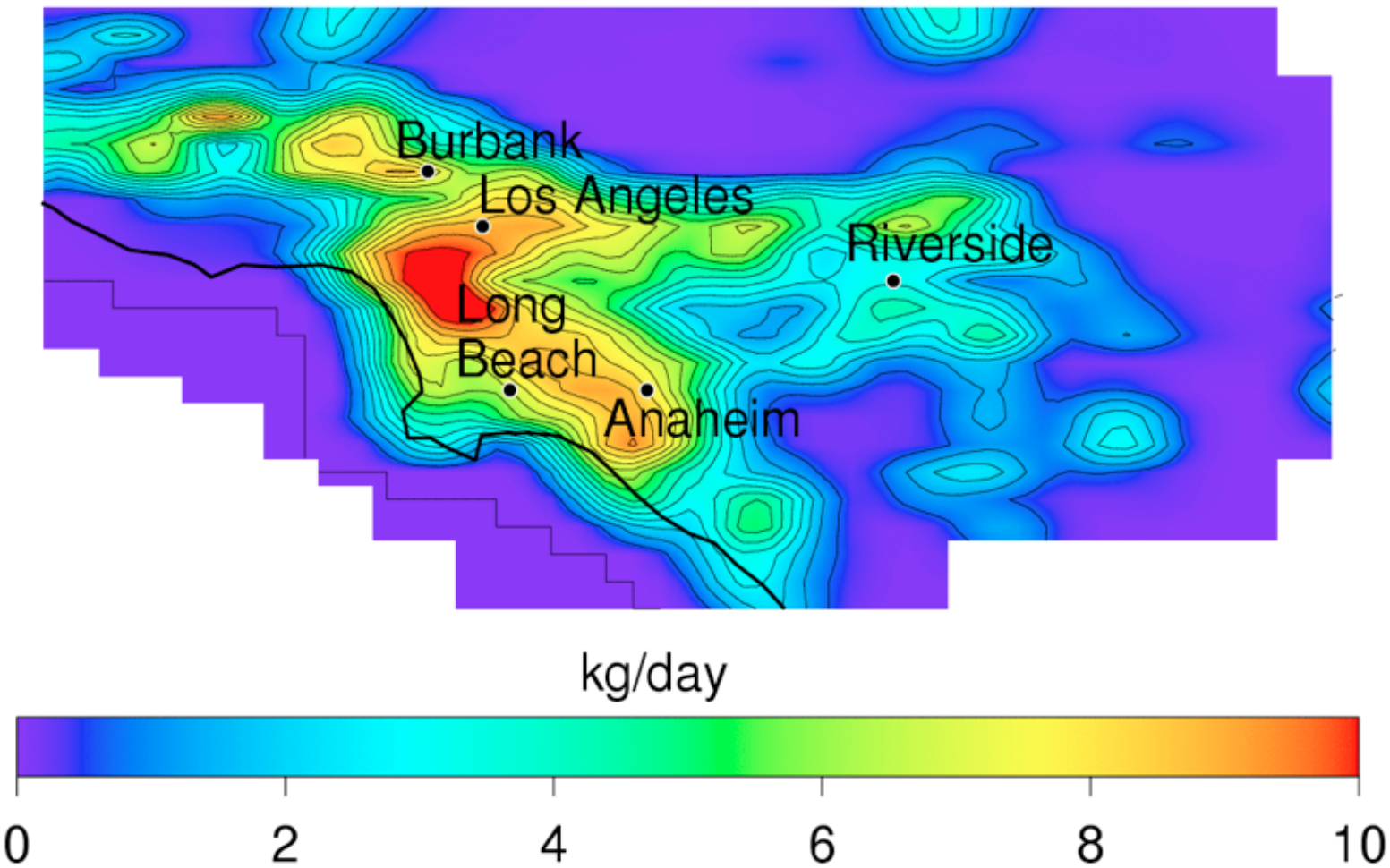
- Start with planning emission inventory
- Revise appliance emissions with data from LBNL
- Stakeholder process to develop range of realistic LNG distribution scenarios in SoCAB
- Hypothetical scenarios of expanded LNG use and higher WN fuels
- Technology-based LNG emission factor impacts
- Develop LNG-impacted emission inventories
- Photochemical modeling of baseline and LNG scenarios

Basin-wide NO_X inventory

LBNL data ➔ baseline NO_X reduced by **2.4 tons per day** or 1.2%

Realistic LNG scenarios ➔ NO_X increase of **0.02 – 0.09 tpd**

100% LNG (currently impossible in SoCAB) ➔ NO_X increase of **2.8 tpd**



Ambient AQ Results

- **Realistic scenarios**
  - No change in highest 8-h ozone or 24-h PM for air basin
  - For individual monitoring sites:
    - 8-h ozone changes of -0.3 to 0.5 ppb
    - 24-h PM changes of -0.6 to +0.6 $\mu g\ m^{-3}$
- **Hypothetical scenario of 100% LNG**
  - Highest 8-h ozone across air basin increases by 0.36 ppb
  - Average 24-h PM increase of 0.07 $\mu g\ m^{-3}$
  - Relevance to San Diego is unclear because of differences in mix of ozone precursors and technologies