Appliance Emissions and Air Quality Impacts of LNG

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Presented to

LNG Stakeholders

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LBNL Research Areas

- Fill gaps in experimental study of interchangeability in residential appliances
- Advance interchangeability modeling
- Outdoor air quality impacts
- Indoor air quality and exposure impacts
- Risk evaluation and mitigation

LBNL Research Tasks

Task	Budget
Administration, reporting & advisory committee	$100K
Technical work with GTI; Stakeholders	35K
Review existing information	94K
Plan for lab & field appliance experiments	60K
Conduct lab & field appliance IX expts	625K
Modeling to predict IX effects	130K
Outdoor AQ evaluation (modeling)	330K
Field study of range hood effectiveness	180K
Indoor modeling of pollutant exposure impacts	315K
Synthesis, risk analysis & mitigation planning	117K
Other research	15K
Total	$2.0M

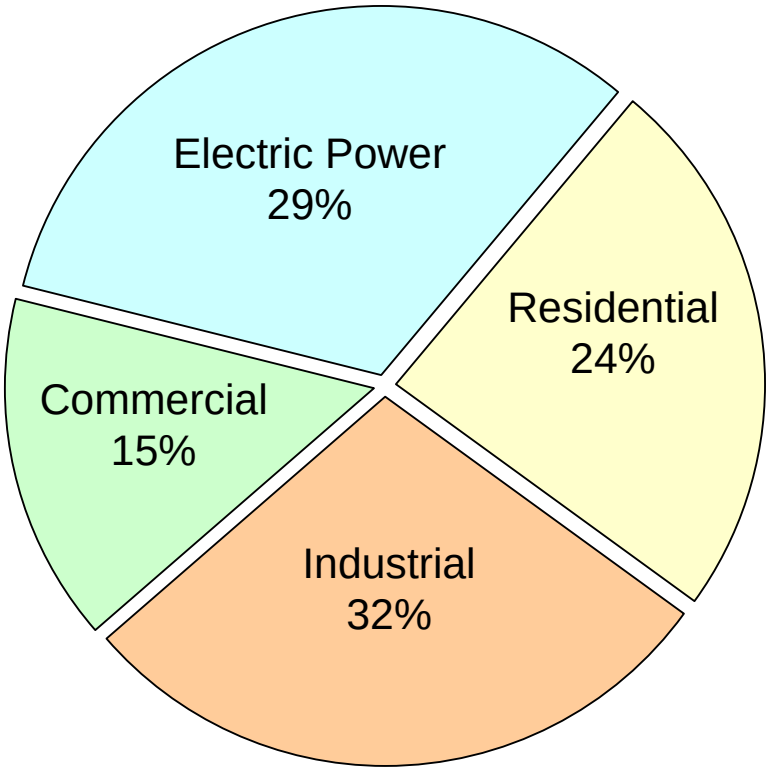
Focus on Appliances

- **Majority of burners and customers**
- **Diverse technologies and design characteristics**
  - Longevity keeps older technologies in service
  - Population includes low quality models
  - Influx of new technologies, devices
- **Diverse operational conditions**
  - Not regularly inspected or serviced
  - Includes maladjusted, misused, improperly installed units
- **Proximity magnifies safety and emissions risks**
  - Users unlikely to detect problems early
  - Pollutants emitted into indoor spaces!

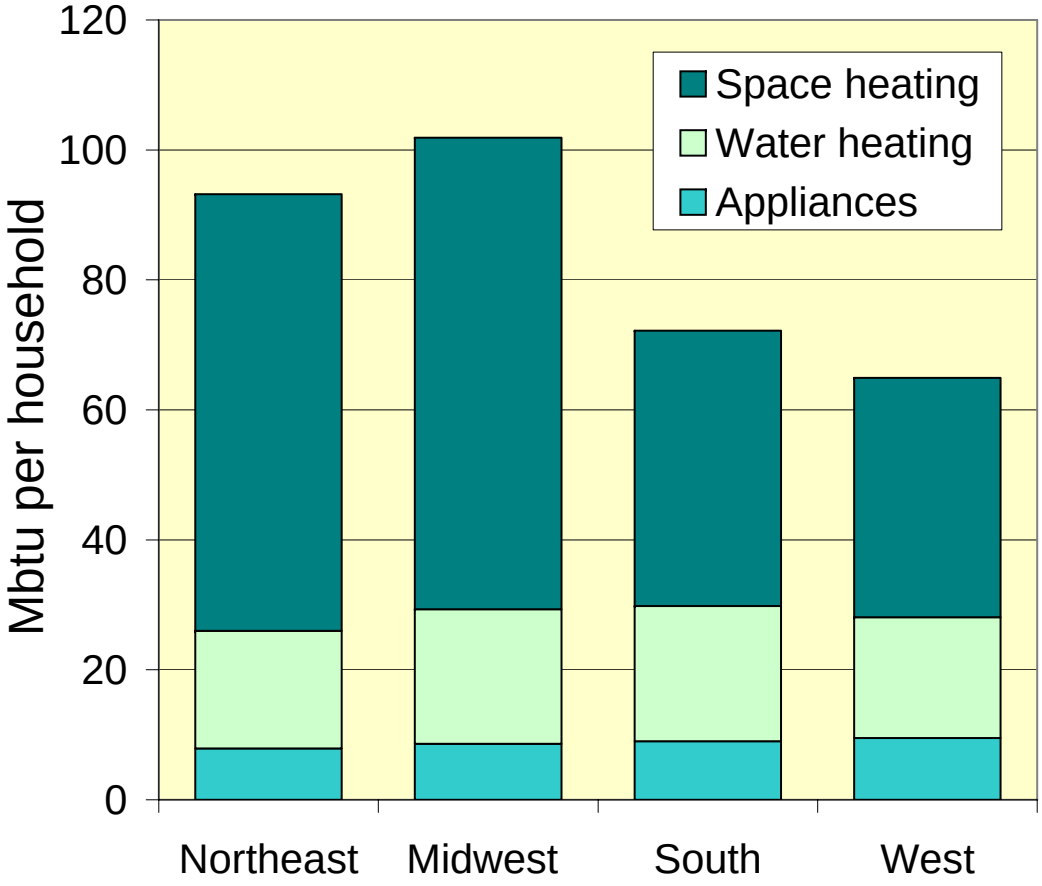
(Adapted in part from TA Williams, AGA Staff Paper 2006)

U.S. Natural Gas Use in Appliances

NG Use by Sector



Residential Use



Source: U.S. Energy Information Administration

Appliance burners and technologies

APPLIANCES

Furnace: forced air, wall, floor

Water heaters: storage, tankless

Basic cooking: cooktop, oven

Other cooking: broiler, fryer, grill

Boilers: commercial, residential

Clothes dryers; Pool heaters

Hearth & space heating

FUEL-AIR MIXING

Partial, Lean, or Non-premix; Excess air

BURNER TYPE

Single-port, Multi-port (circular, tube), Radiant

BURNER CONTROL

On/off, Modulating, Manual adjustment

SAFETY FEATURES

FVIR, ODS, Thermal cut-off, etc.

HEAT EXCHANGE

Section, tube, serpentine, central flue, etc.

VENTING

Natural draft

Mechanical

Direct

Unvented

IGNITION

Permanent pilot

Electronic

Electric glo

Light by hand

Appliance End Use Concerns

SAFETY PERFORMANCE DURABILITY EMISSIONS

- *Flame stability: lifting*
- *Pilot light stability, ignition delay*
- *Safety feature performance*
- *Yellow tipping, incomplete comb.*
- *Flame lengthening / impingement*
- *Fluid & equipment temperatures*
- *Energy efficiency*
- *Specific performance issues*

- *Carbon monoxide (CO)*
- *Soot*
- *Nitrogen oxides (NO_x)*
- *Nitrogen dioxide (NO_2)*
- *Methane*
- *Formaldehyde*
- *Ultrafine particles*
- *Acrolein, nitro-PAH, other*

Factors affecting interchangeability

1. *Device technology and design characteristics*
2. *Device operational condition*
   - *Current adjustment (gas & air)*
   - *Adjust gas properties and composition*
   - *Age, state of repair*
3. *Substitute gas properties & composition*
4. *Device use patterns*
   - *Transient vs. steady operation; possible misuse*
5. *Gas supply pressure, variability, etc.*
6. *Environmental variables*

Interchangeability equation NOT limited to gas quality!

Interchangeability Studies I

- **Initial focus on operability & safety with diverse fuels**
  - AGA and Weaver indices based on fundamentals, experiments with test burners and real appliances
- **Intervening studies of local issues**
  - Index calculations, appliance testing
  - Examined peak shaving, new supplies, local limits
    - PSE&G (NJ) 1978: oil gas, refinery gas, propane-air
    - PSC (CO) 1979: use of higher HV WY pipeline gas
    - PG&E and SCG (CA) in mid-1990s
- **LNG introduction in 1970s**
  - Studies by LNG providers, utilities receiving LNG
    - Elba Island (GA), Cove Point (MD), Everett (MA)
  - Index calculations, appliance testing, field evaluation
  - Focus on operability, safety, carbon monoxide

Interchangeability Studies II

- **LNG re-introduction (Benson/TIAX)**
  - Washington Gas Light (Cove Pt.), Southern LNG (Elba Is.)
  - Focus on CO, safe operation, sensitive conditions
  - Analysis of historic gas variability; appliance testing
  - Set gas quality limits, N_2-dilution needed
- **Recent major U.S. studies of LNG**
  - GTI 2003, Southern California Gas 2005
  - SCG examined NO_X, new technology devices
- **U.K. Dept of Trade & Industry 2004-05**
  - Extensive testing with used devices, range of gases
  - Measured CO, NO_X, NO_2, Soot, CH_4 slip, Efficiency, Temps
- **Gasunie and other studies**

LNG Interchangeability Summary

MINOR

- Lifting*
- Efficiency
- Ignition
- Safety features
  - FVIR, ODS
- Pilot stability

MODERATE

- CO & NO_X increase with Wobbe in some partial premix burners
- Output temperatures increase with Wobbe
- Wobbe increase → flame lengthening → more impingement
- Unclear effect on NO_2

MAJOR

- Steep CO increase with Wobbe in some devices, burners
- Steep NO_X increase for lean premix, low-NO_X burners
- Maladjusted burners & in-use equipment more sensitive
- Temp, soot, flame lengthening could affect device longevity
- Incomplete combust. may increase ultrafine particles, formaldehyde

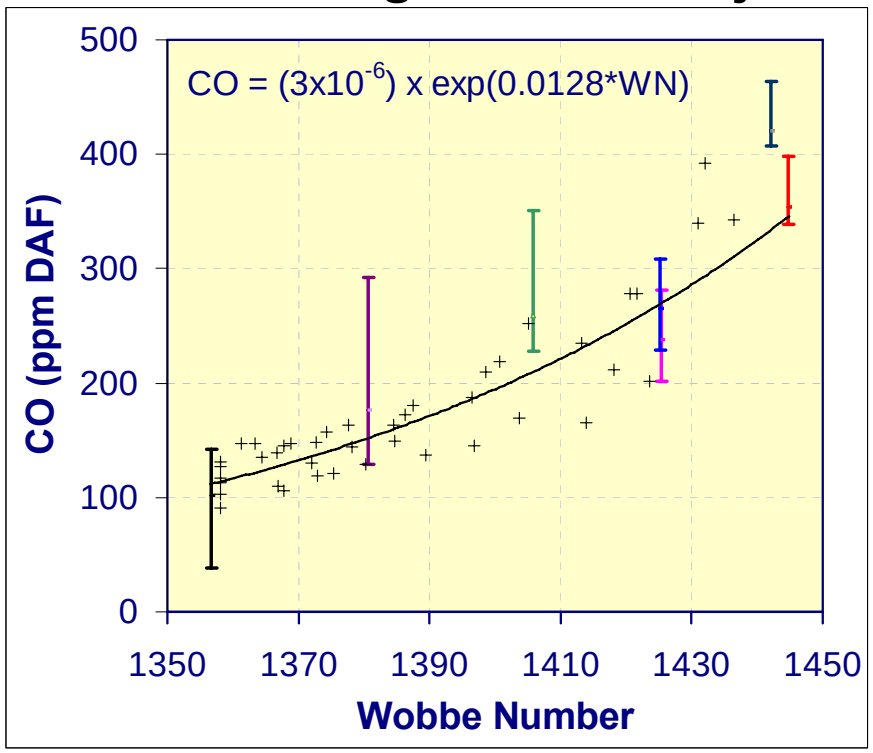
Based on review of existing and available information

CO Impacts of LNG / Higher Wobbe

- **Exponential CO increase in 1 of 11 new appliances in GTI 2003 (Oven 2)**
  - Bottom plate important (Oven 1)
- **Sharp CO increase in 14 of 25 mostly used appliances in DTI/UK 2004-05**
  - 10 of 12 boilers (pre or post service)
  - Increase at Wobbe > 1370 (methane)
- **CO increase in 4 of 13 appliances in SCG 2005; highest Wobbe gas only**
  - Deep fat fryer: CO up by >1200 ppm

GTI 2003

Oven 2: 6 Sub gases with Adjust 1



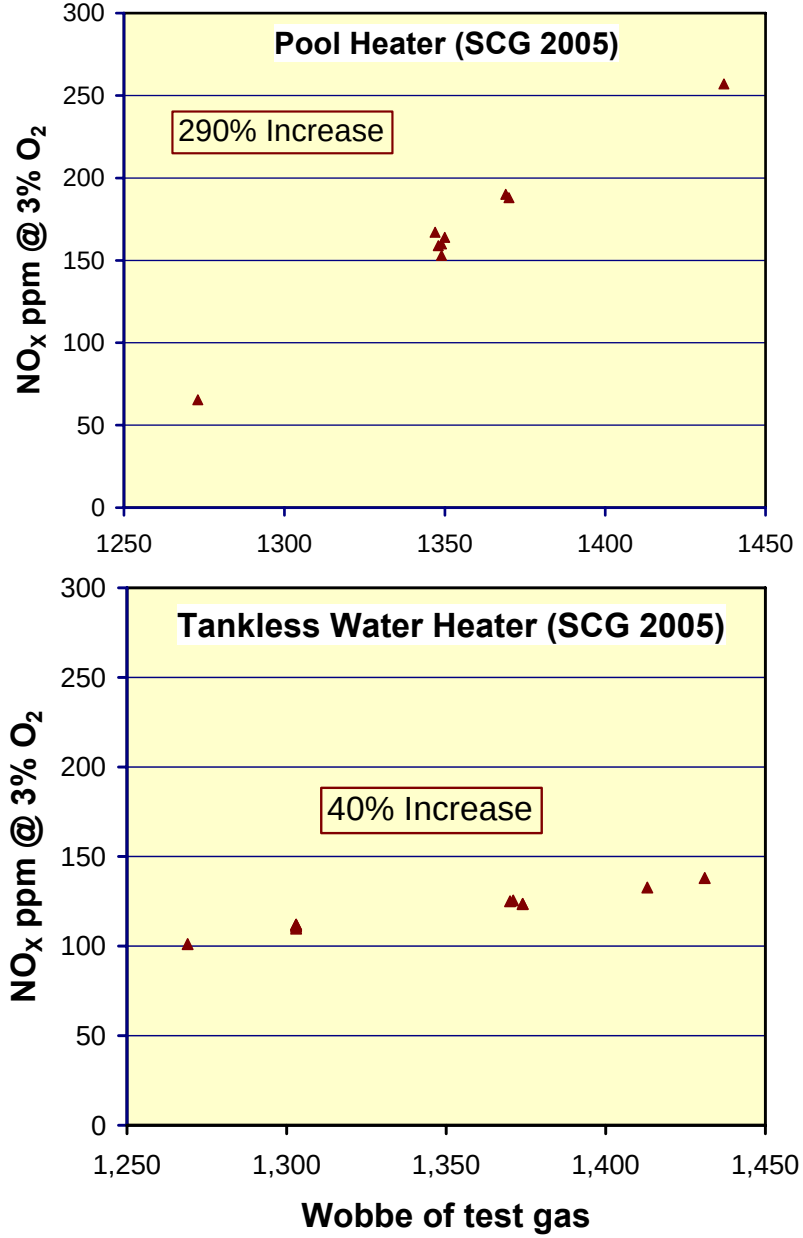
- **CO sensitivity to LNG in 13 of 24 apps in TIAX 2003 (Cove Pt.)**
- **BG&E Phase III (1978): CO up in ovens, WH conversion burners**

N_2 dilution to reduce Wobbe appears to effectively reduce CO

NO_X Impacts of LNG / Higher Wobbe

- **Detailed results reported for SCG 2005 and DTI/UK 2004-05 studies**
- **NO_X increases sharply with Wobbe for premix low-NO_X burners**
  - Increase by factor of 6-10 across wide Wobbe range in UK study
  - Increase by factor of 2.5 to 4 across more narrow Wobbe range in SCG
- **Moderate NO_X changes with Wobbe for partial premix burners**
  - UK: ±2X across wide Wobbe range
  - General trend is gradual increase

N_2 dilution to reduce Wobbe appears to effectively reduce NO_X



Research Gaps: Major points

- **Pollutant Emissions**
  - Ultrafine particles
    - Known to be emitted by gas appliances
    - Growing interest and concern for health effects
  - Formaldehyde
    - Product of incomplete combustion; related to quenching, CO
    - Chronic exposure concerns at relatively low levels
    - Calculations suggest any increase could be important to health
- **Operating Cycles**
  - Previous work focused on steady operation, yet transient emissions may dominate for some devices
- **Installed In-Use Devices**
  - Appear more sensitive; limited relevant and documented work

Experimental Sub-Tasks

✓ 1. Assemble and verify experimental testing apparatus and procedures

✓ 2. Baseline data collection:

- Ultrafine particles & formaldehyde
- Common appliances, line gas

✓ 3. Pilot field study

4. Laboratory testing for interchangeabilty

5. Field testing for interchangeabilty

6. Report preparation

Custom Sampling System for Residences

Preliminary Experiments

Field testing of condensing furnace

Conducted experiments on 18 burners

Lab test of modern range

Interchangeability Experiments Completed

- 2 oven bottom burners
- 1 waist-high (broiler)
- 2 cooktop burner sets

PG&E: WN = 1330-1340

Sim. LNG: WN = 1425

LNG + N_2: WN = 1385

Legacy technology

"Open" burner with pilot

Current standard

Sealed burner, electronic ignition

Configuration for Broiler 02 Expts.

Blower not in view

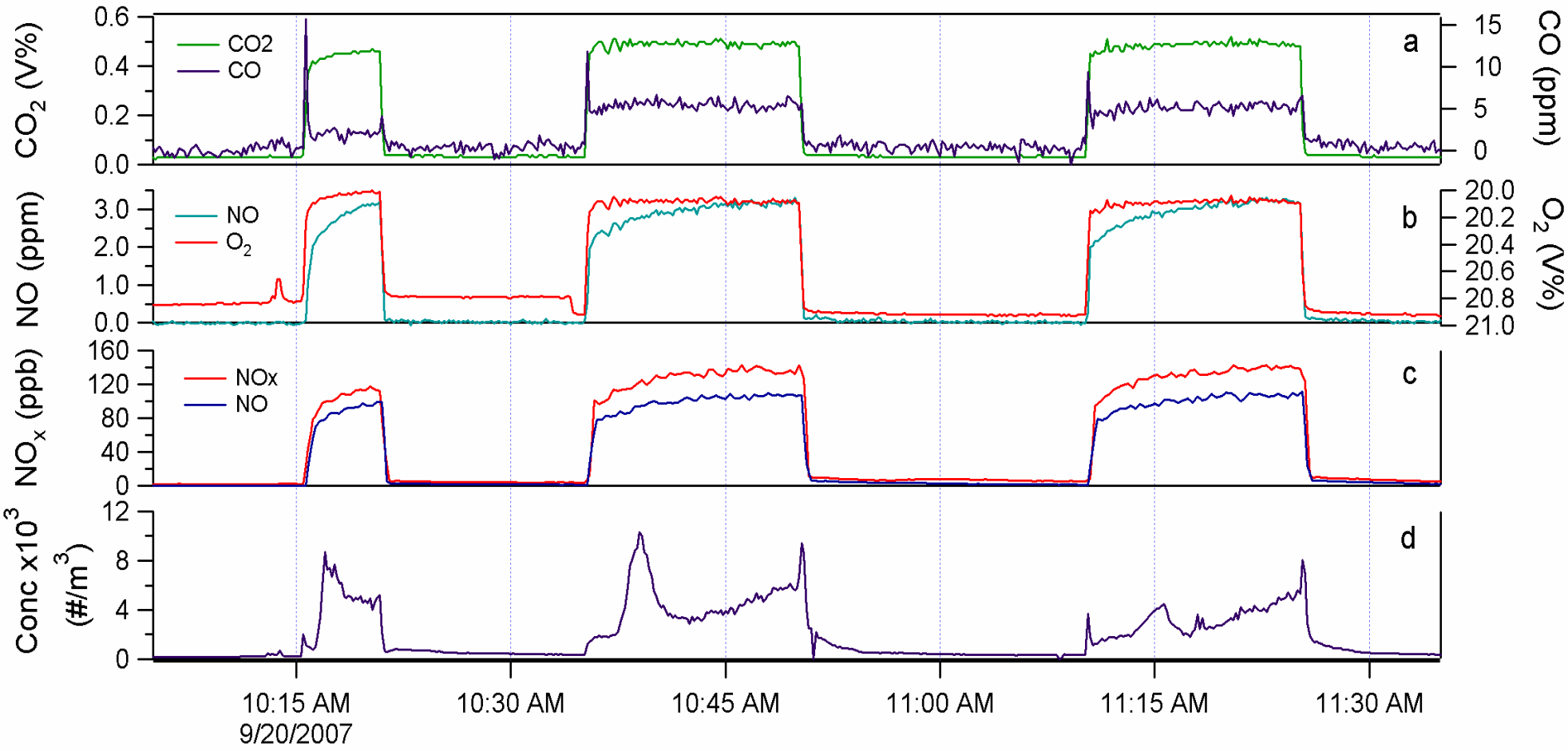
Flex duct from hood to blower (6”)

Efficient mounting of dilution tube

Collection hood:
- below cooktop for broiler and oven expts.
- adjust height for cooktop expts

Note:
Dilution tube not used for oven 02 expts; bottom burner also tested at broil setting

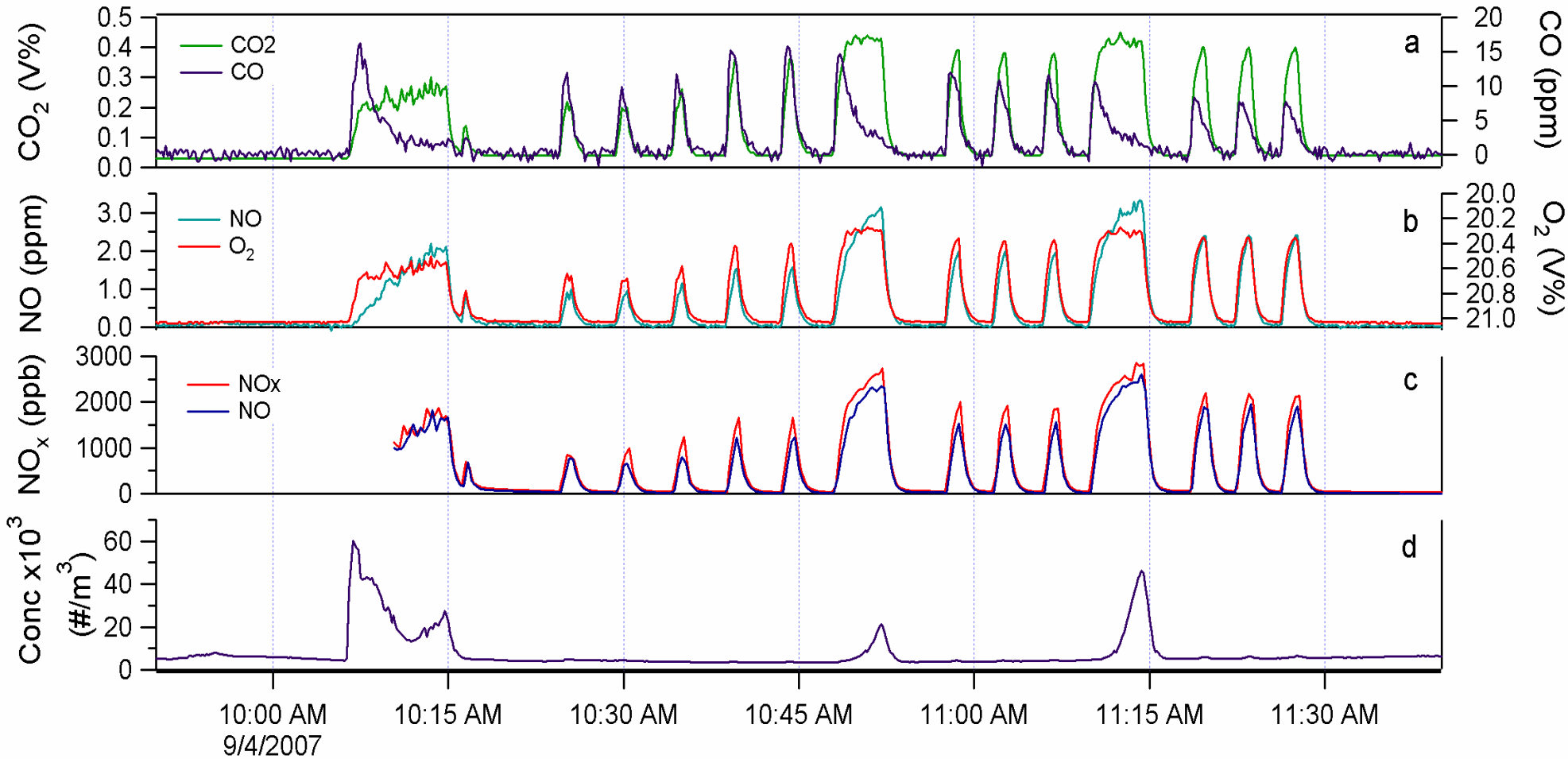
Cooktop 02: LNG + N_2 (W = 1386)



Oven 03

Oven bottom plate with spreader removed and shown at right

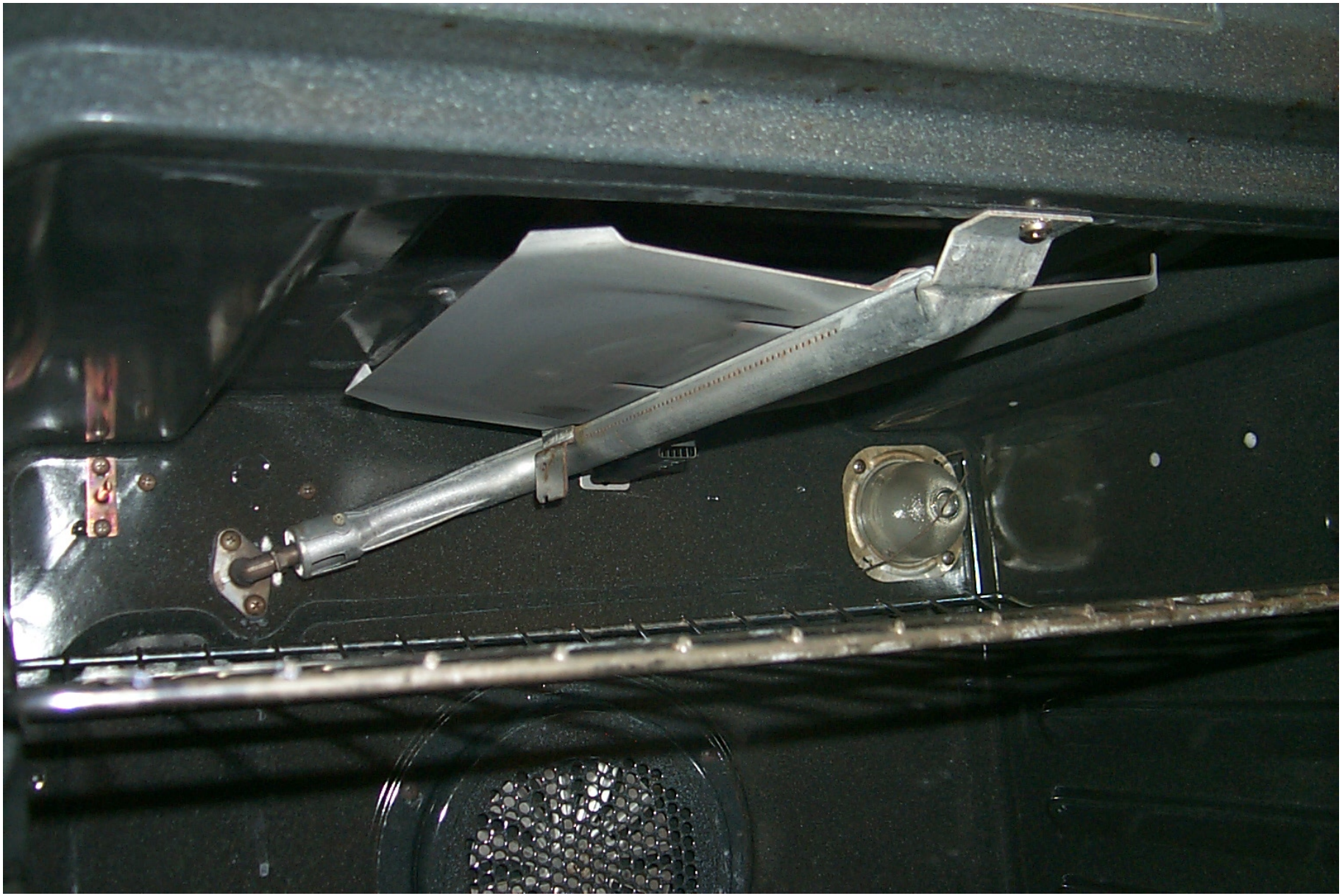
Oven 03 with PG&E gas (W = 1332)



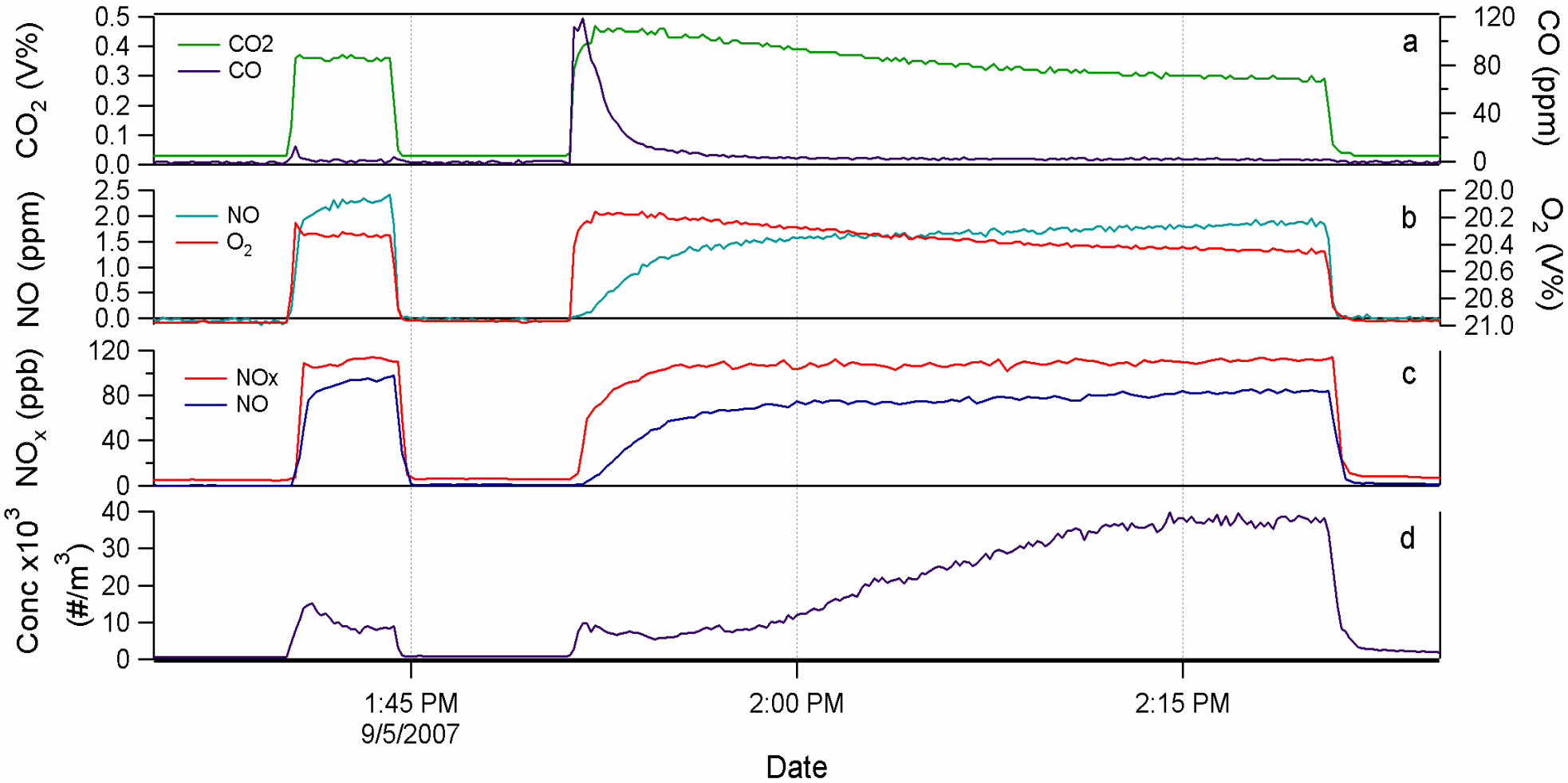
NO_X analyzer communication problem
Mid-expt adjustment of blower speed

Data valid for initial burns at 425, 500 F
Analyze last min of initial burn at 350 F

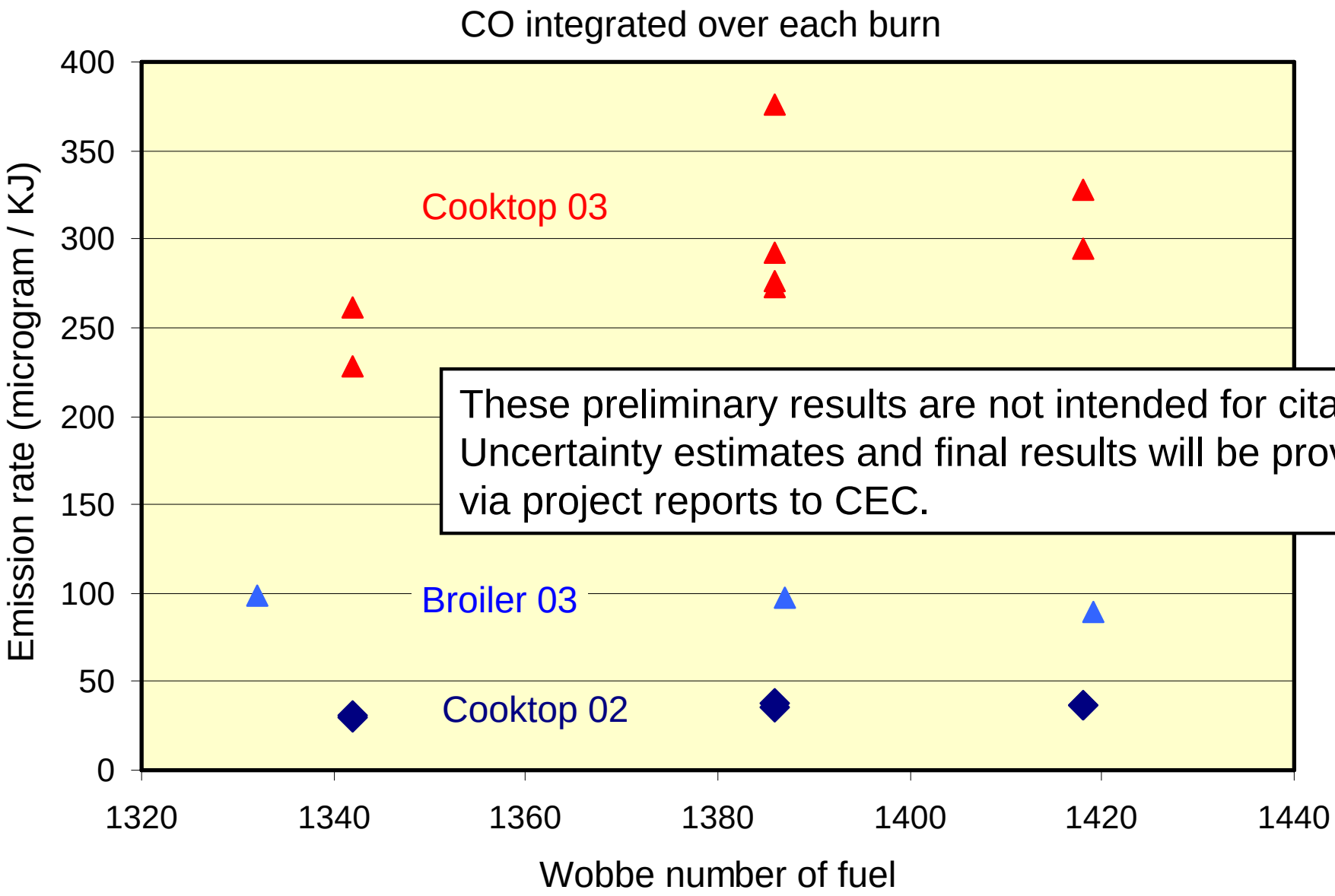
BR03 ('waist-high' burner)



Broiler 03 with LNG (W = 1419)

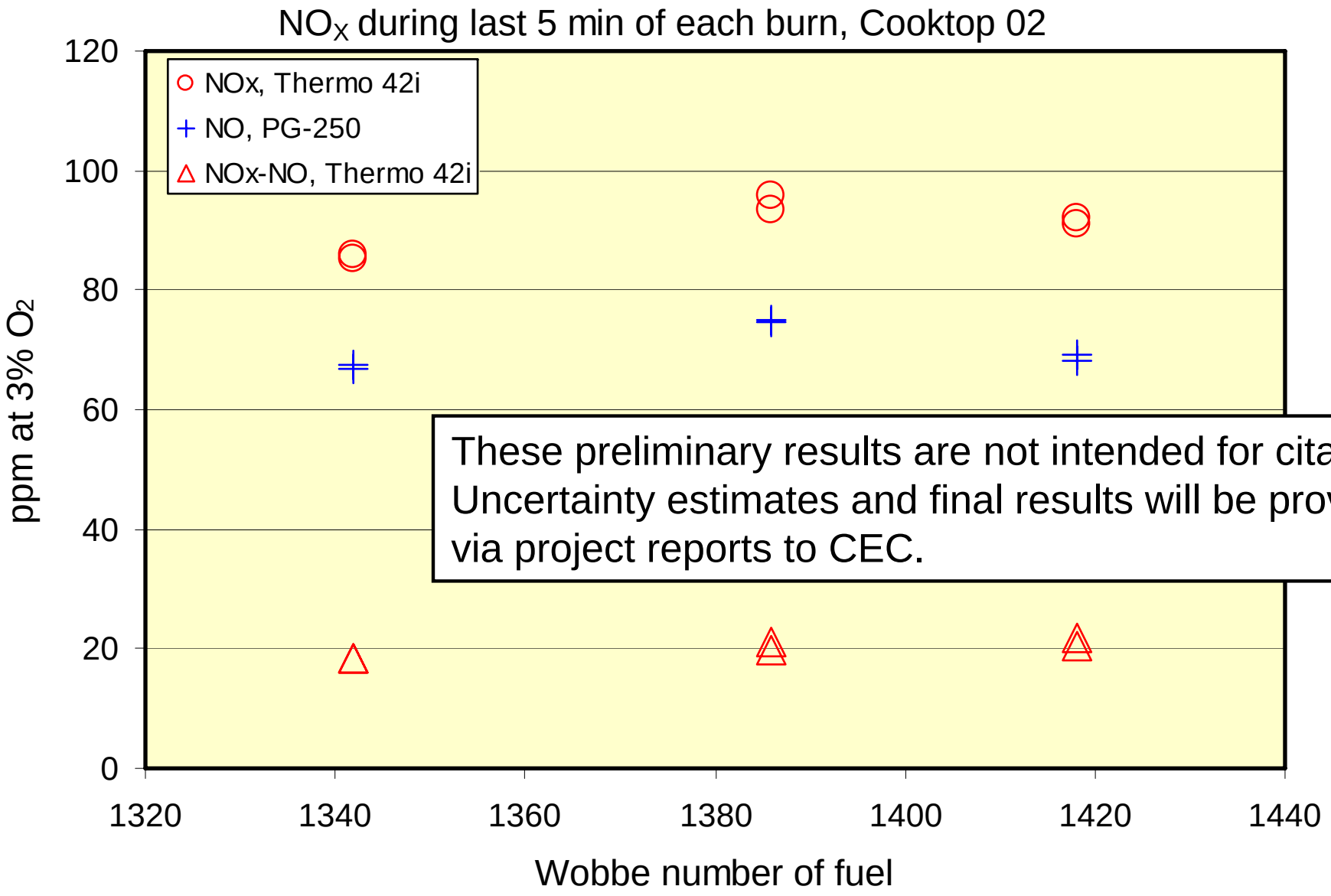


CO results for cooktops and broiler



These preliminary results are not intended for citation. Uncertainty estimates and final results will be provided via project reports to CEC.

NO_X results for Cooktop 02



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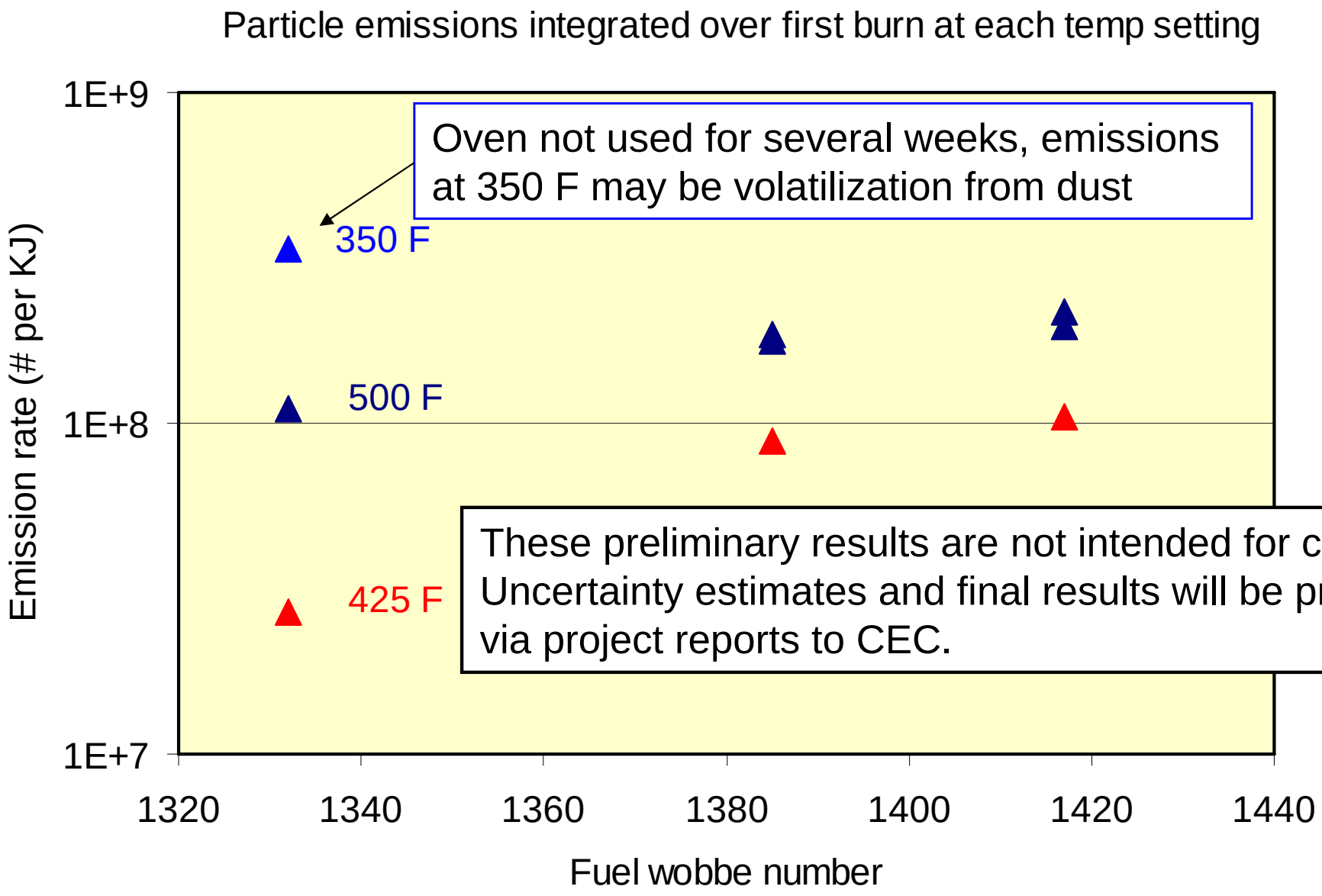
Particle results for Oven 03



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Interim Interchangeability Results

- To date: 2 cooktops, 2 oven burners, 1 broiler
- No substantial sensitivity for NO_X or HCHO
  - NO_2 20-50% of total NO_X for these burners
- CO sensitivity for oven 03
  - Absolute levels moderate
- Particle number
  - Emissions increase with Wobbe for one cooktop, decrease with Wobbe for the other
  - For oven 02, emissions much higher at higher temp setting

Plan to Complete IX Experiments

- **Conduct some IX testing in field**
  - Benefits:
    - Test appliances as installed
    - Access new technologies not available second-hand
    - Save cost of purchasing
    - Save time managing inventory w/space limits, installation
  - Focus on furnaces, tankless & storage WHs, cooktops
  - Resolved cylinder transport and use issues; volunteers willing
  - Set operating cycles to allow 3 expts per day (line + 2 sim. LNG)
- **Continue IX testing in lab**
  - Ovens/broilers: important to precondition
  - New technologies with limited saturation to date:
    - Low-NO_X & power-vent WHs
    - Other?

Target Experimental Schedule

- **Through mid-Jan:**
  - Complete IX expts on 5 burners in residences
  - Complete lab IX expts (PG&E, 3A, 3A+N_2) for 7 burners in hand
  - Compile comprehensive report on methods
  - Present at late Jan or Feb PAC meeting (some draft reports)
- **Mid-Jan through Feb:**
  - Compile reports on burners tested through mid-Jan
  - Procure additional appliances for lab testing (PAC advice)
  - Complete IX expts on 10-20 more burners in residences
  - Complete lab IX expts on additional appliances
- **March:**
  - Complete any remaining expts
  - Compile reports on all field and lab IX expts

Range Hood Evaluation

Range Hood Effectiveness

- Pollutants are generated by natural gas flames and by cooking
- Range hoods can reduce exposure in two ways:
  - Remove pollutants before they mix into room
  - Remove polluted air from kitchen and bring cleaner air in through other parts of house
- Likely determinants
  - Airflow though hood (multi-speed fans)
  - Hood physical design
  - Placement of hood relative to range or cooktop

Range Hood Metrics

- Airflow – measure tracer concentration in duct
  - Compared to rated value
- Energy consumption
- Sound levels in kitchen with fan on
- Single-pass capture efficiency
  - What percentage of emitted pollutants get captured in hood before mixing in room
- Pollutant removal efficiency
  - Measure concentrations in room, not just in duct

Airflow measurements

Range Hood Experimental Schedule

- Completed pilot experiments and method development at 3 sites, testing at 4th site
- Identified next 5-7 homes for evaluation
- Temporary break to advance field testing for interchangeability
- Complete 15-20 hood evaluations by mid-March

Scales of Air Pollutant Impacts

Our analysis focuses on incremental effects of gas quality changes. Incremental changes of interest only if baseline contribution is important.

Scale	Impacts & Issues	Sources
Indoors	Direct exposure to CO, NO_2, ultrafine particles, air toxics; Acute and chronic effects	All Unvented apps; Maladjusted, broken, improperly vented apps
Neighbor-hood	Limited atmospheric mixing + max. appliance activity → chronic exposure to air toxics	All residential sources (incl. vented), some industrial/commercial
Urban and Regional	NG emissions may comprise growing fraction of total NO_X → impact ozone control plans	Industrial, commercial, residential, power generation
Regional	NO_X converts to nitrate, adds to visibility degradation	All

Pollutant Emission in Homes

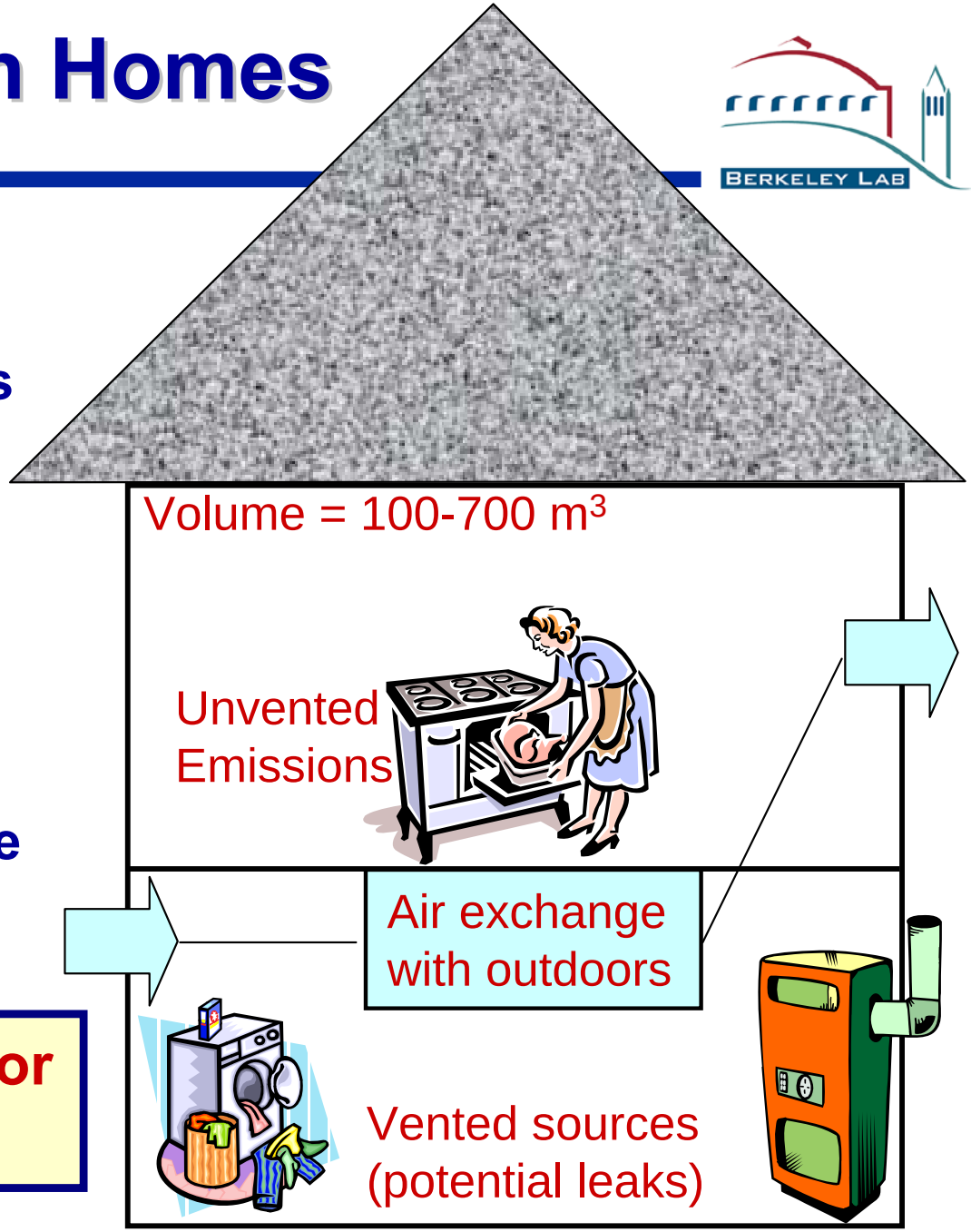
Concentrations depend on:

- Unvented appliance emissions
- Vented appliance leakage
- Home volume
- Air exchange rate
- Pollutant deposition

Exposures also depend on:

- Air mixing & proximity in home
- Occupancy patters

Intake fraction* 1000x higher for indoor vs. outdoor emissions



*Fraction of pollutant mass emitted that is breathed in by humans

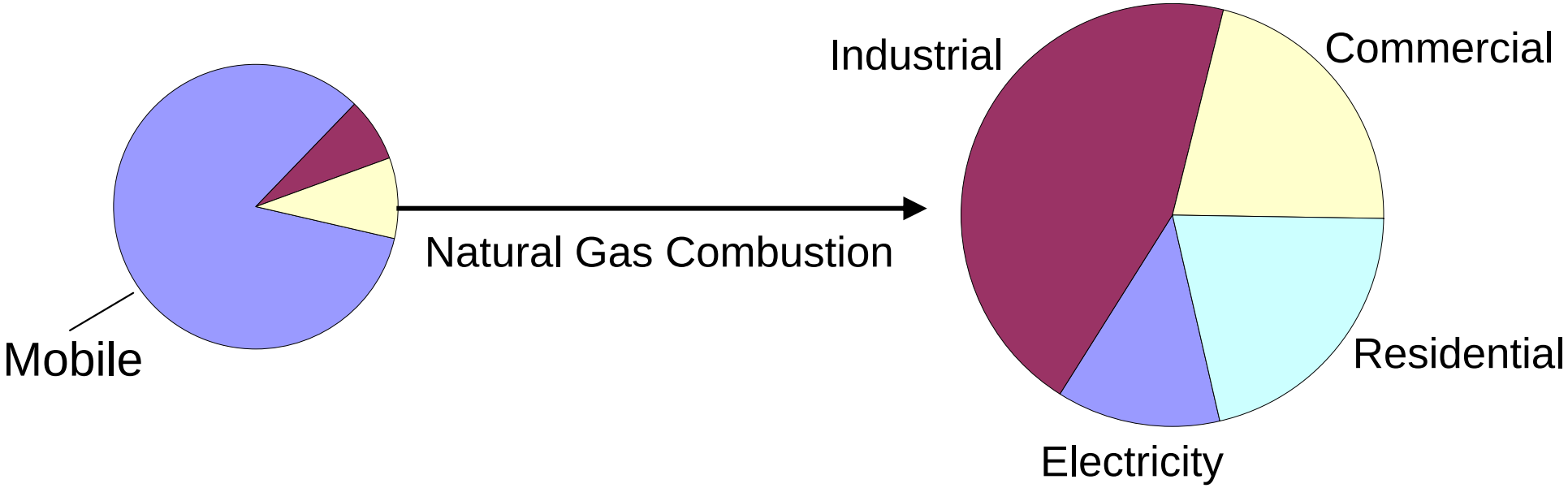
Indoor & Exposure Modeling

- Utilize CARB's California population indoor exposure model (CPIEM) & LBNL "macro-model" of pollutant emissions and indoor dynamics
- Update distributional information on housing, ventilation rates, etc.
- Consider technology-specific effects of gas quality on pollutant emissions
- Model set-up will start in late 2007, early 2008
- Model will use results from appliance lab and field experiments

Outdoor Concern: Impact on Ozone

Ozone produced by NO_X + VOC + Sunlight

Estimated NG contribution to California NO_X



As mobile source NO_X decreases, NG becomes more important.

Impact on ozone not linear with emissions → assess via modeling?

Outdoor Air Quality Impacts

- First step is careful review of baseline inventory and estimates of potential LNG impacts
- Work collaboratively with ARB, SCAQMD, PAC
- If overall change in NO_X is very small, air quality models may not be able to reliably resolve change in ozone.
- Work just started; emissions review completion target of Jan.

Appendix

- **The following slides provide some additional material that may be of interest to some stakeholders.**

Ultrafine Particles (UFPs)

- Ultrafine particles have diameters < 100 nm
  - Large numbers, moderate surface area, small mass
- Growing concern about health effects
  - Epidemiology links UFP levels to cardiovascular effects
  - Effects may result from large number, surface area, ability of smallest particles to cross biological barriers
- Natural gas appliances produce UFPs
  - Dennekamp et al., 2001: cooktop, oven, grill
  - Wallace, 2005: UFPs in home from vented gas dryer
- UFPs can increase w/o discernible mass increase
- No study to date of gas quality impact on UFPs

Formaldehyde

- **Product of incomplete combustion, quenching**
  - Increases sharply with more flame contact with cold surfaces, e.g. pot on cooktop (Ashman & Haynes, 1996)
  - Decrease with higher temps, increase with lifting
  - Emissions much higher for inverted radiant grill
- **Low chronic reference exposure limit (REL) based on cancer concerns**
  - 1 h/day use of 1.2 ng/J cooktop burner in 300 m^3 home yields daily exposure above chronic REL
- **Effect of higher Wobbe LNGs not yet examined**
  - Effect may vary by appliance type, burner technology
  - If increases correlate with CO, formaldehyde effect could be most important health concern

Transient Operation

- **Existing emission data focused on steady operation**
  - Use of standard methods, e.g. ANSI
  - Desire to compare fuels with device at temperature
- **Emissions spike at start of burner cycle**
  - Quenching on cold surfaces -> CO, formaldehyde
  - Transient effects on lifting tendency, fuel-air, mixing
- **Gas quality changes may affect transient emissions**
  - Higher input may reduce warm-up time
  - Longer flames may increase impingement
- **Transient emissions may dominate in some devices**
  - Depends on timing of burner cycles, warm-up time
  - Examples: instant water heaters, cooktop burners

Installed In-Use Appliances

- In-use appliances expected to be more sensitive
  - Age, use lead to component wear
  - Misalignment, maladjustment, improper installation
- Field studies confirm in-use device issues
  - BG&E 1978 study for LNG implementation
  - Southern California studies in 1980s and 1990s
  - Xcel energy studies in Colorado (rating at elevation)
- Past studies of as-installed devices limited
  - Evaluation of flame quality and CO
  - Few studies of response to actual gas quality changes
    - Limited documentation
    - Need data relevant to proposed gas limits, current stock

IX Experiments Completed

Appliance info	Burner	Technology	Heat input (kbtu/h)
Frigidaire 24" range Age: 12 y	Cooktop	Open burners , pilot	9(x4)
	Oven	Tube under bottom/spreader	18
Jenn-Air 30" range Age: 10-15 y	Cooktop	Sealed burners, EI	9.2(x2), 12(x2)
	Oven	Tube under bottom/spreader	18
	Broiler	Waist high w/spreader	13

Both ranges obtained from private sellers via Craig's List

Fuel:	PG&E line*	Mix 3A	3A + N_2
HHV	1013 – 1068	1117 – 1127	1100 – 1106
Wobbe	1332 – 1362	1414 – 1419	1384 – 1387

*PG&E mostly in range of 1330-1340 Wobbe. Result for 9/21 (W = 1362) will be checked against PG&E database of distributed gas quality.