U.S. EPA's Laboratory Test Results for Household Cookstoves

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October 10, 2012
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Introduction

- First round of cookstove testing completed in 2007. Results in *Biomass and Bioenergy* http://www.pciaonline.org/node/904
- Second round of stove testing completed in 2010. Results in *Environmental Science & Technology* http://dx.doi.org/10.1021/es301693f
- Third round of testing in progress

Study Goals – Round Two

Objective of second round of stove testing was to provide a more extensive evaluation, useful to partners in PCIA and the Global Alliance for Clean Cookstoves, including:

- Testing of many new stoves of interest
- Measuring emissions of air pollutants that affect human health and global climate
- Testing with various fuels with low- and high-moisture content
- Testing of variations in operating conditions for the 3-stone fire and for rocket stoves
- Reporting results as a large set of data that are convenient for further analyses

Stoves Tested

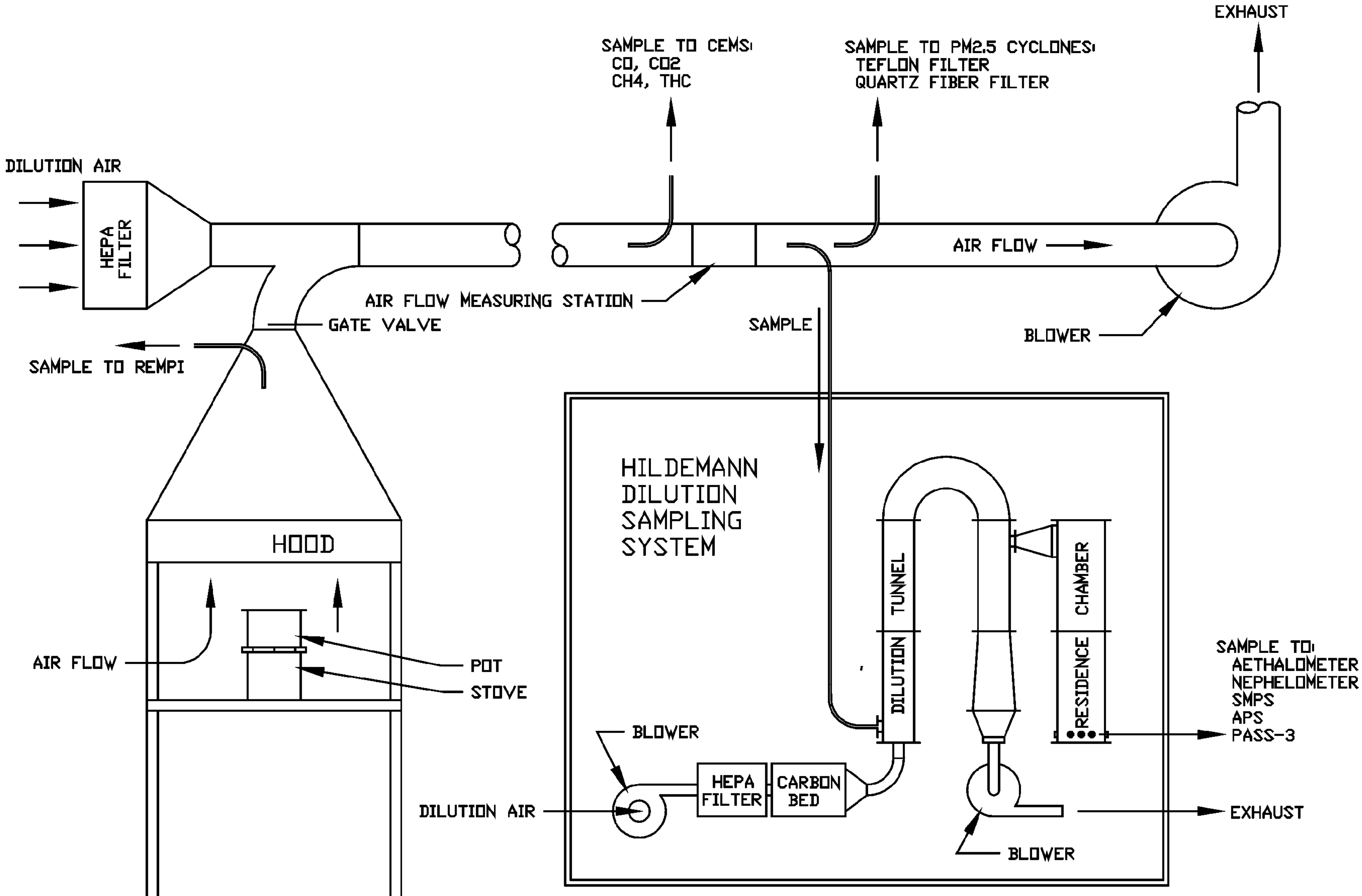
Independent evaluation of performance and emissions

A. Ceramic Jiko, charcoal
B. Metal Jiko, charcoal
C. Belonio, rice hull
D. Onil, wood
E. Protos, plant oil
F. Mayon Turbo, rice hull
G. Oorja, pellet
H. KCJ, charcoal
I. GERES, charcoal
J. StoveTec, charcoal
K. Jinqilin CKQ-80I, cobs
L. 3-Stone Fire, wood
M. Upesi, wood
N. Uhai, charcoal
O. Gyapa, charcoal
P. Envirofit G-3300, wood
Q. Sampada, wood
R. Berkeley Darfur, wood
S. StoveTec TLUD, pellet
T. Philips HD4012, wood
U. Philips HD4008, wood
V. StoveTec, wood

Laboratory Test Parameters

- Fuel consumption, energy efficiency, power
- PM, integrated samples: gravimetric
- PM, real-time: SMPS, APS, nephelometer
- CO, CO_2: NDIR analyzers
- CH_4, THCs: FID analyzers
- BC: aethalometer, transmissometer
- EC/OC/TC: thermal-optical analysis
- Aerosol light absorption and scattering, *in situ*: PASS-3
- Mutagenicity potential: Ames Assay

Stove Testing System



Test Method

- Used WBT (Water Boiling Test), available at: www.pciaonline.org/testing
- Measured emissions during each phase of WBT protocol (cold start, hot start, simmer)
- Used modified WBT for charcoal stoves
  - Cold start included measurement of emissions during ignition of charcoal (relatively high PM)
  - Hot start began with hot charcoal (relatively high CO)

Stove Emissions Reporting

For all pollutants measured, we report:

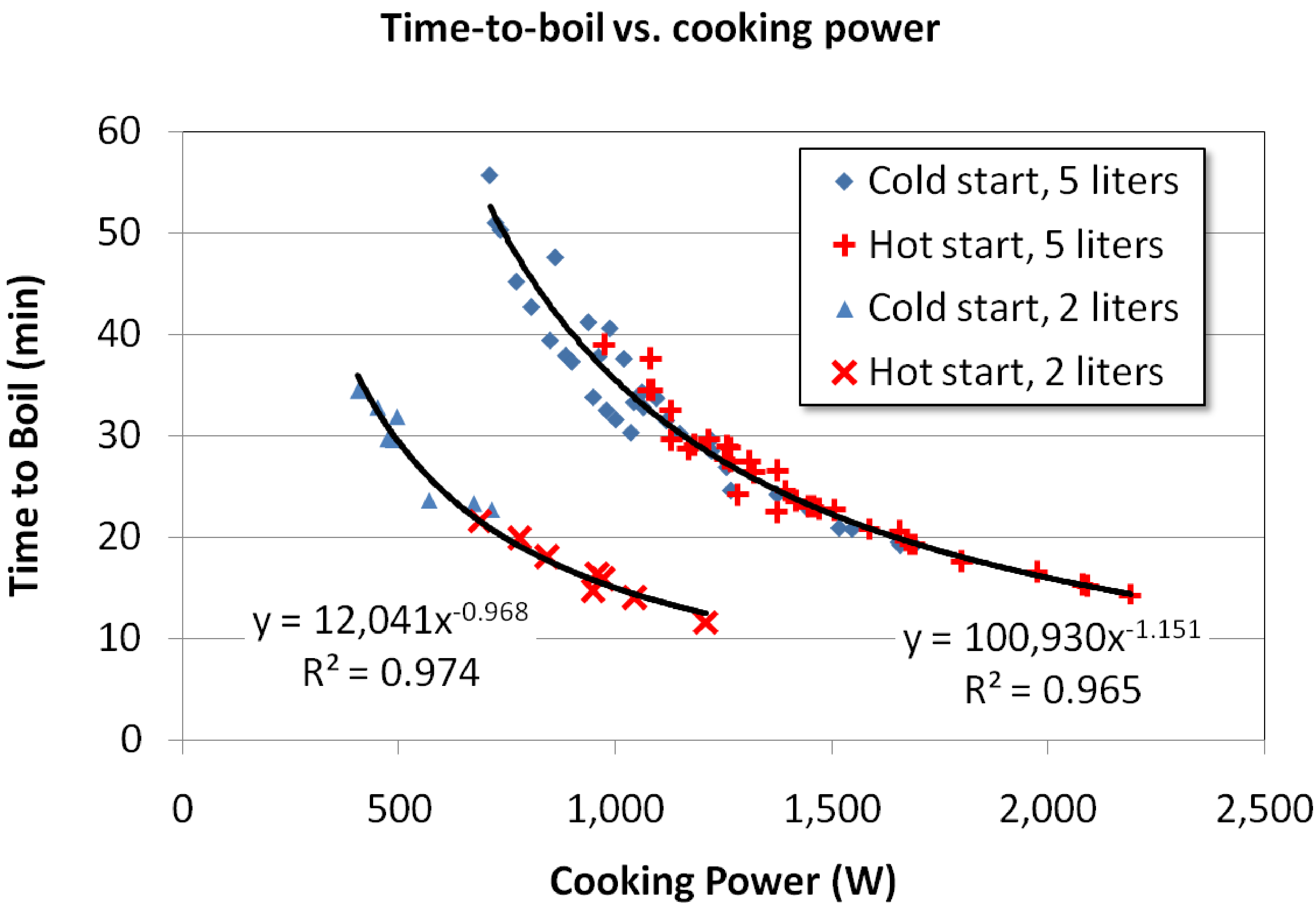
- Emission rates (mass/time)
- Emission factors
  - (mass/mass of fuel)
  - (mass/energy of fuel)
  - (mass/energy delivered to cooking pot)
- Emissions per task (mass)
- Emission of ultra-fine particles - number (instead of mass)

Study Results – How Used

- WBT results can be used for:
  - Informing design of cookstoves
  - Comparing performance of stoves under the same operating conditions
  - Benchmarking stoves before field trials
- Emission rates (per time) can be used for modeling indoor air pollutant concentrations
- Emission factors can be used to estimate emissions when fuel use is known

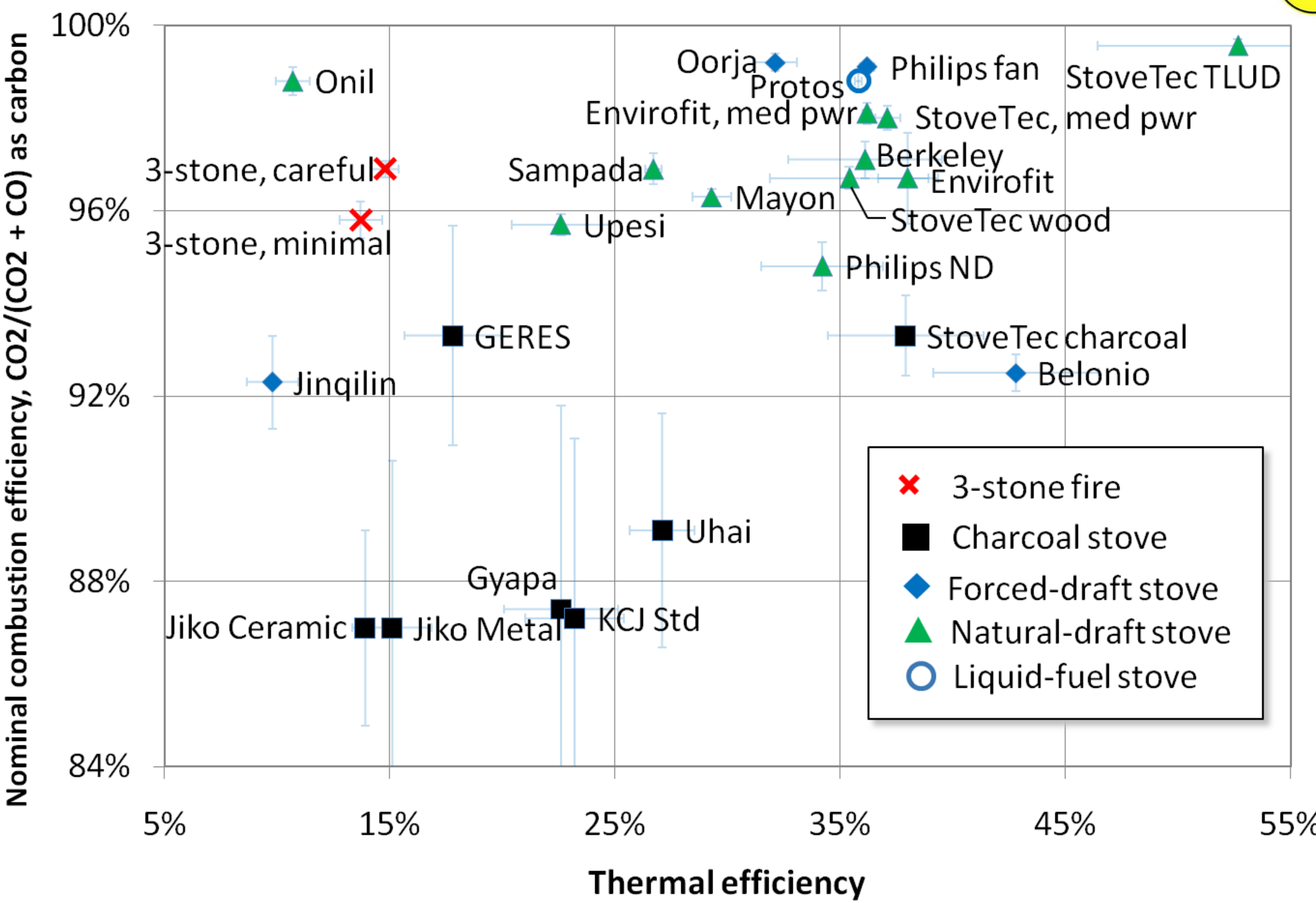
Limitations of Laboratory Results

- Laboratory testing is not a substitute for field testing
- Laboratory test results have often not been predictive of field results – especially when lab and field conditions differ
- WBT simulates cooking with pots – WBT does not simulate cooking on a grill or griddle (plancha stoves) and/or providing space heat (heating stoves)
- Lab results more likely to agree with field results for stoves that require less operator attention (such as batch-loaded or fan stoves)



Time-to-boil vs. cooking power
Time to Boil (min)
60
50
40
30
20
10
0
0
500
1,000
1,500
2,000
2,500
Cooking Power (W)
Cold start, 5 liters
Hot start, 5 liters
Cold start, 2 liters
Hot start, 2 liters
y = 12,041x-0.968
R² = 0.974
y = 100,930x-1.151
R² = 0.965

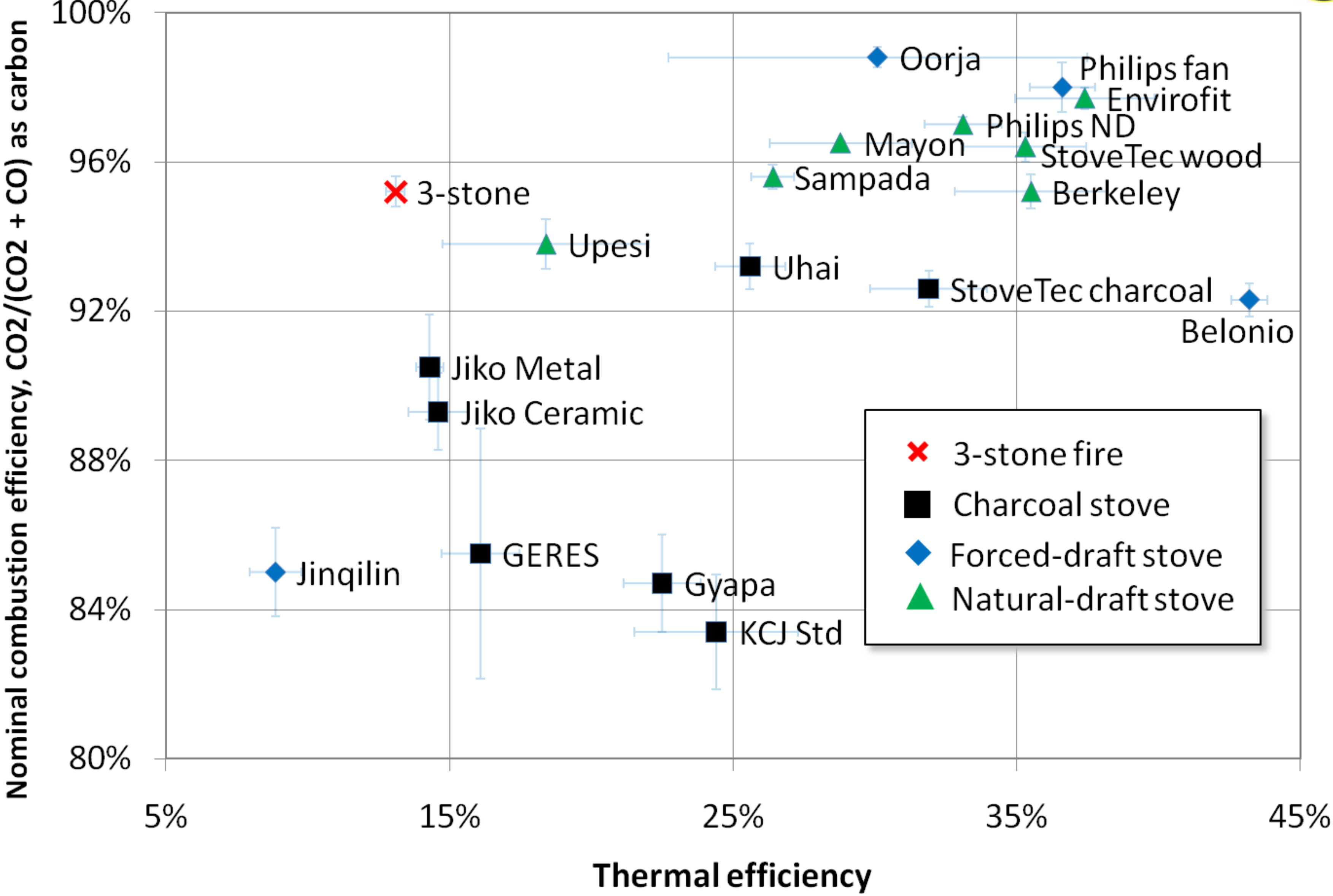
Efficiency, low-moisture fuel, high power (cold start)



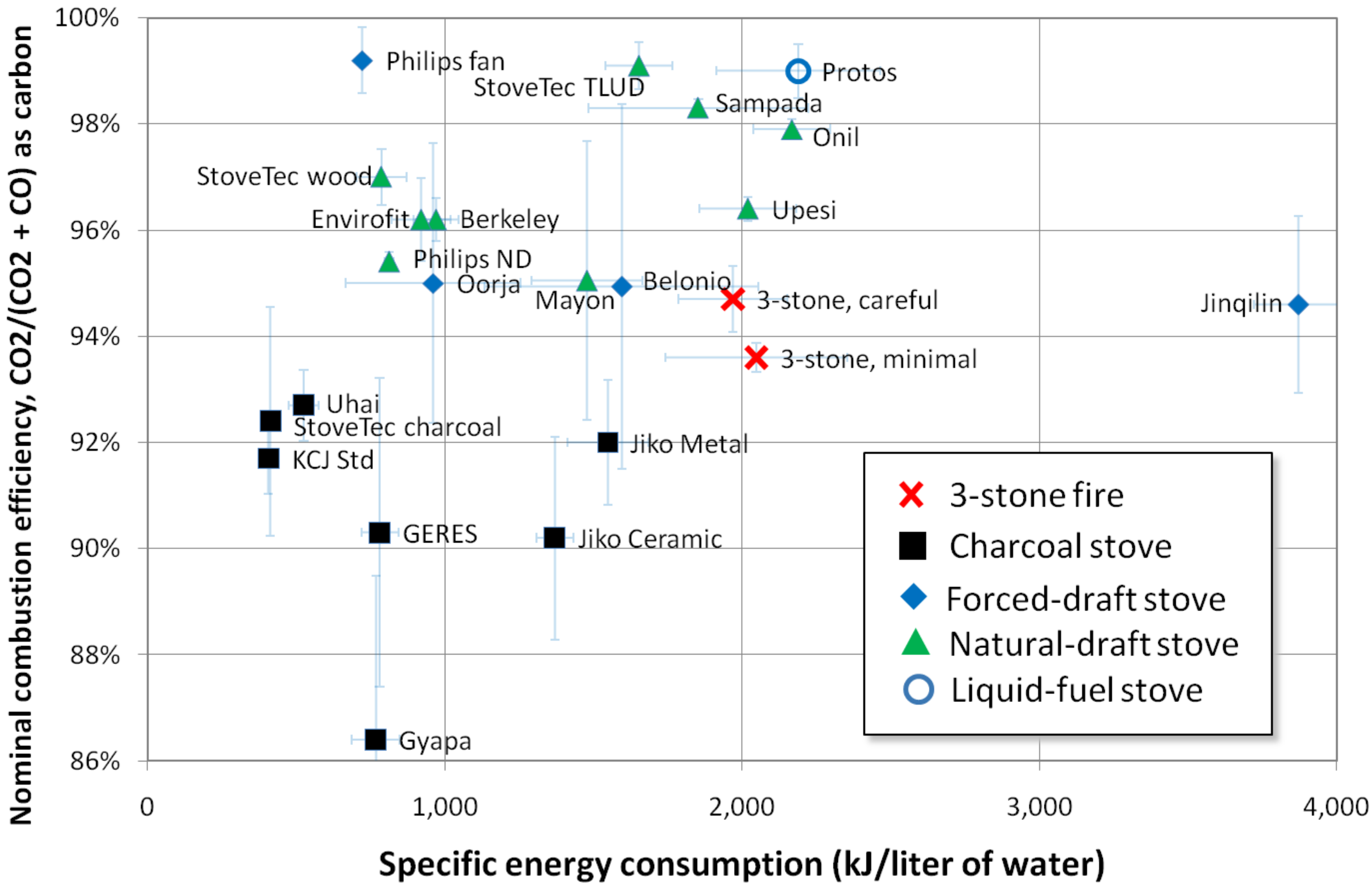
Efficiency, low-moisture fuel, high power

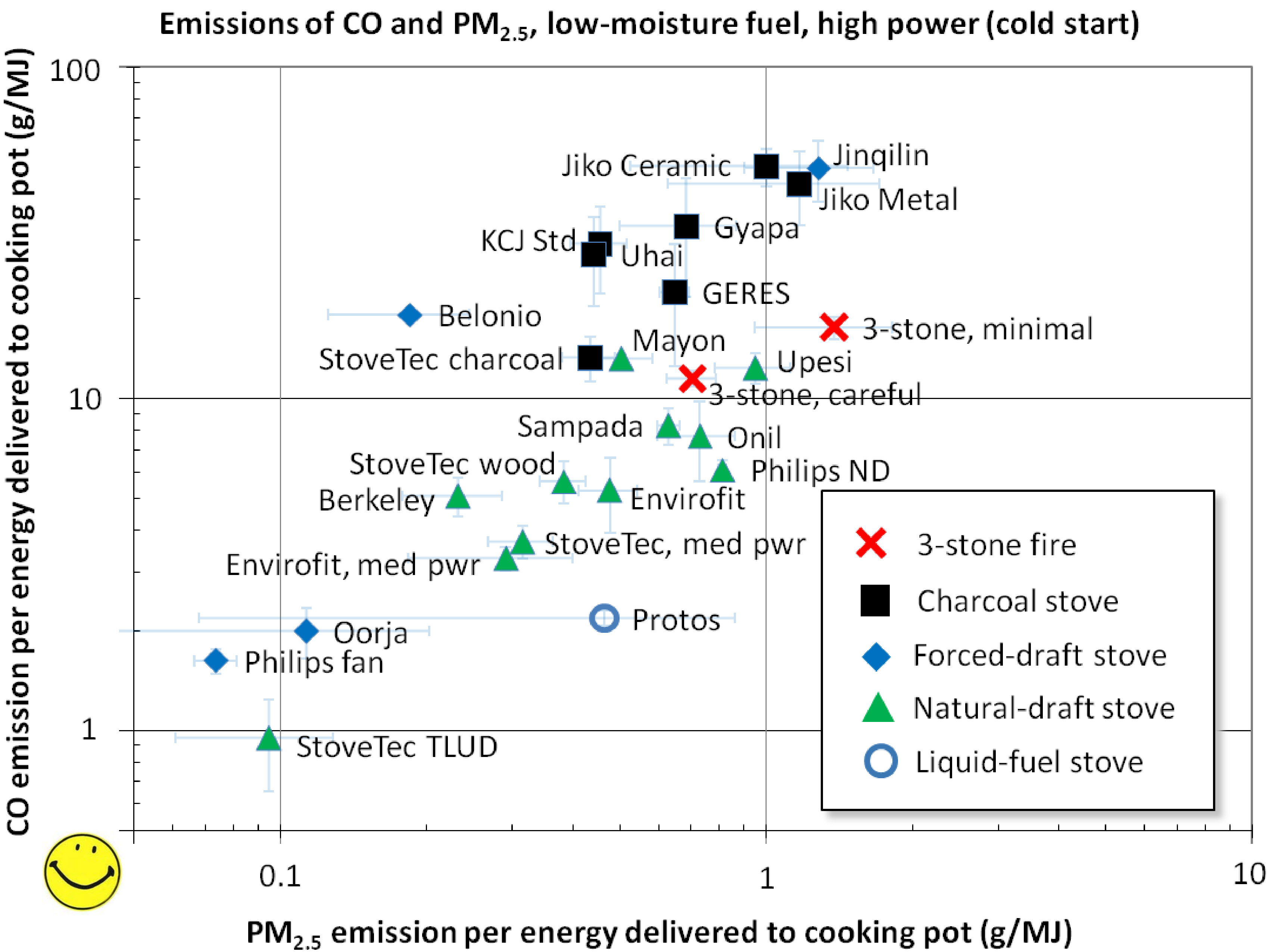
- Compared with the 3-stone fire, most stoves that were tested had better thermal efficiency, but some did not
- Compared with the 3-stone fire, many stoves that were tested had better combustion efficiency, but many did not
- Some fan stoves had very high combustion and thermal efficiencies, but not all did
- A natural-draft TLUD stove had remarkable performance with processed, wood-pellet fuel with low-moisture content

Efficiency, high-moisture fuel, high power (cold start)



Combustion efficiency vs. specific energy consumption, low-moisture fuel, low power

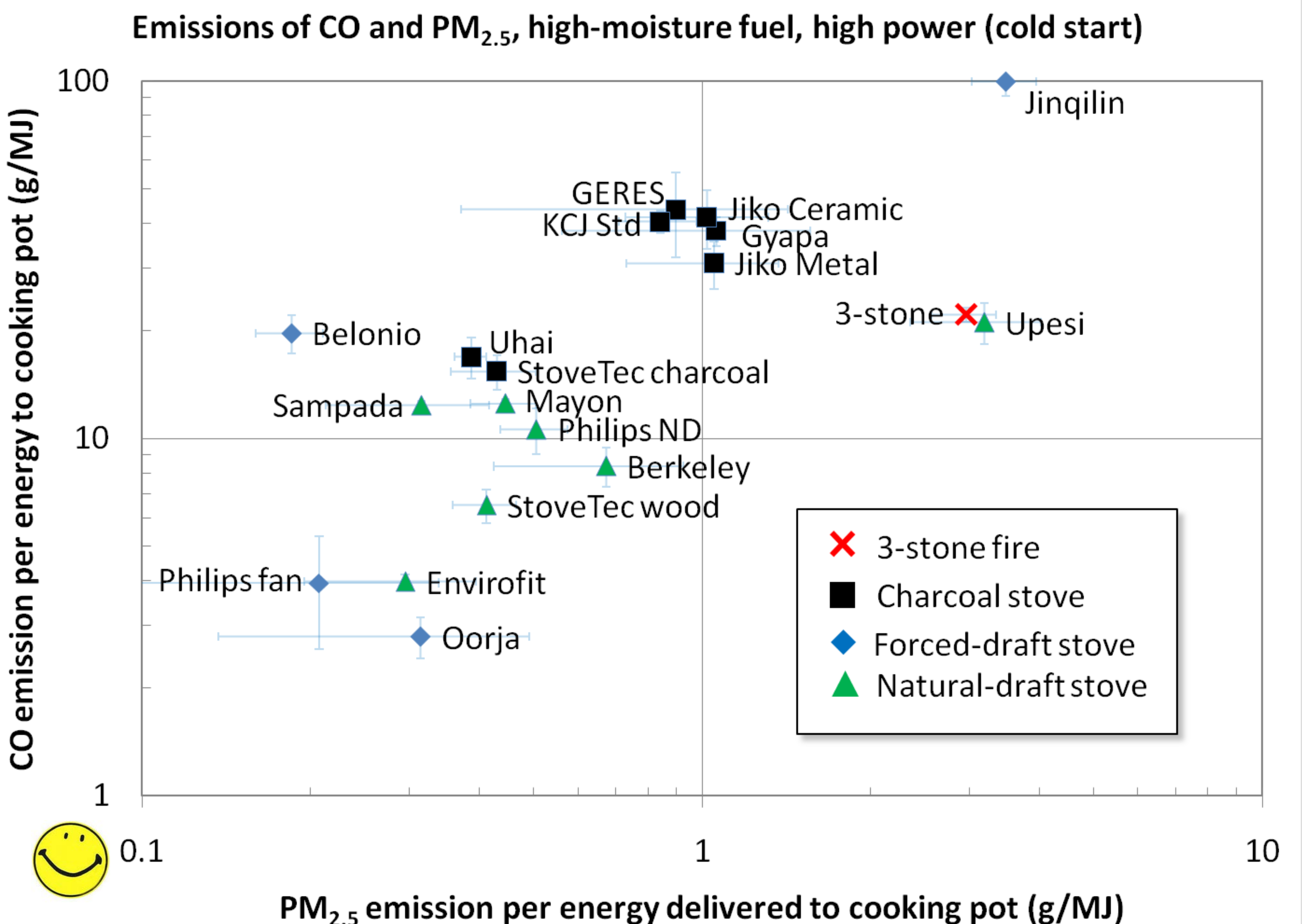




Emissions of CO and $PM_{2.5}$, low-moisture fuel, high power (cold start)
CO emission per energy delivered to cooking pot (g/MJ)
$PM_{2.5}$ emission per energy delivered to cooking pot (g/MJ)
100
10
1
0.1
1
10
Jiko Ceramic
Jinqilin
Jiko Metal
Gyapa
KCJ Std
Uhai
GERES
Belonio
3-stone, minimal
Mayon
StoveTec charcoal
Upesi
3-stone, careful
Sampada
Onil
StoveTec wood
Philips ND
Berkeley
Envirofit
StoveTec, med pwr
Envirofit, med pwr
Protos
Oorja
Philips fan
StoveTec TLUD
3-stone fire
Charcoal stove
Forced-draft stove
Natural-draft stove
Liquid-fuel stove

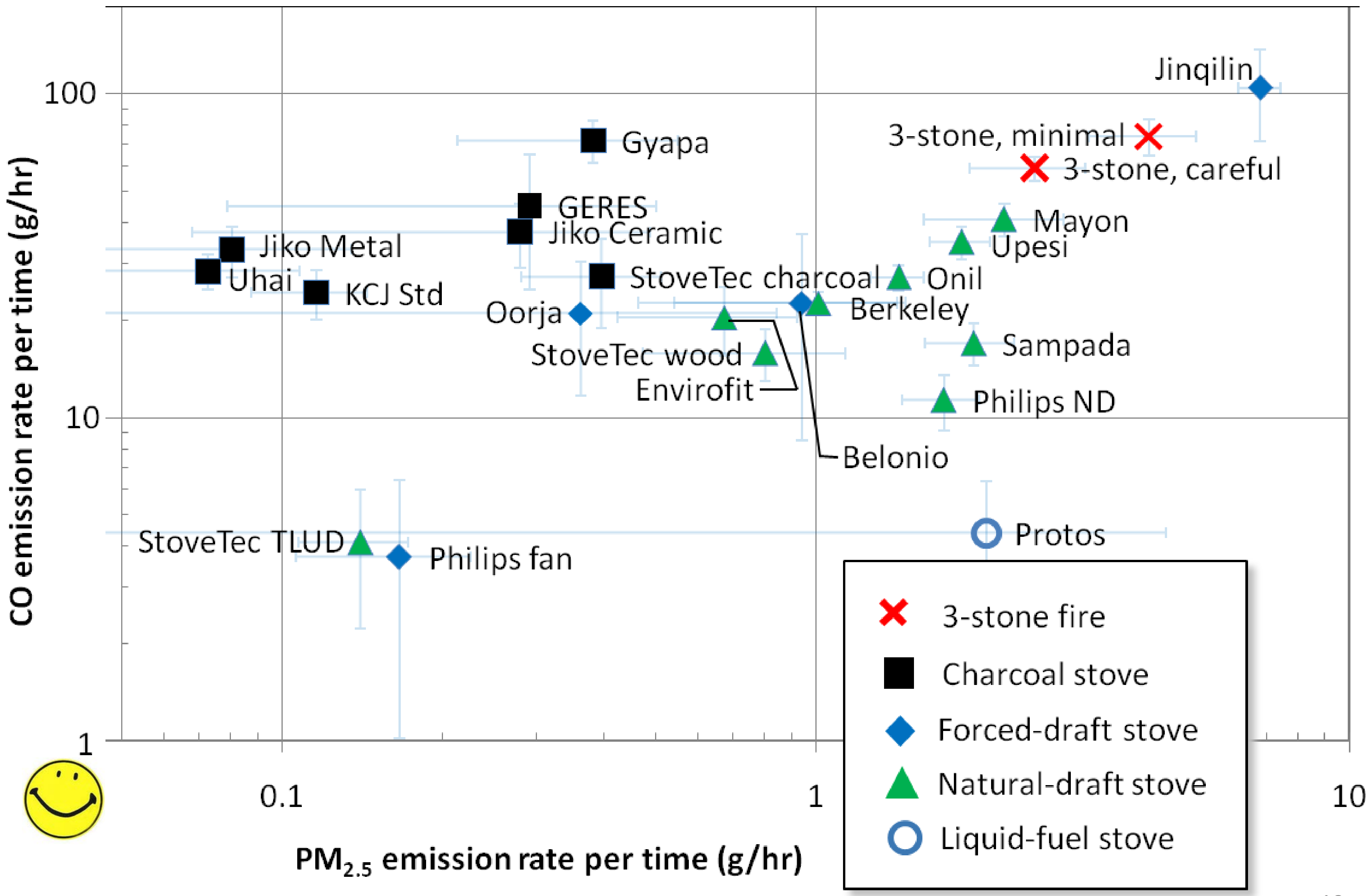
Emissions, low-moisture fuel, high power

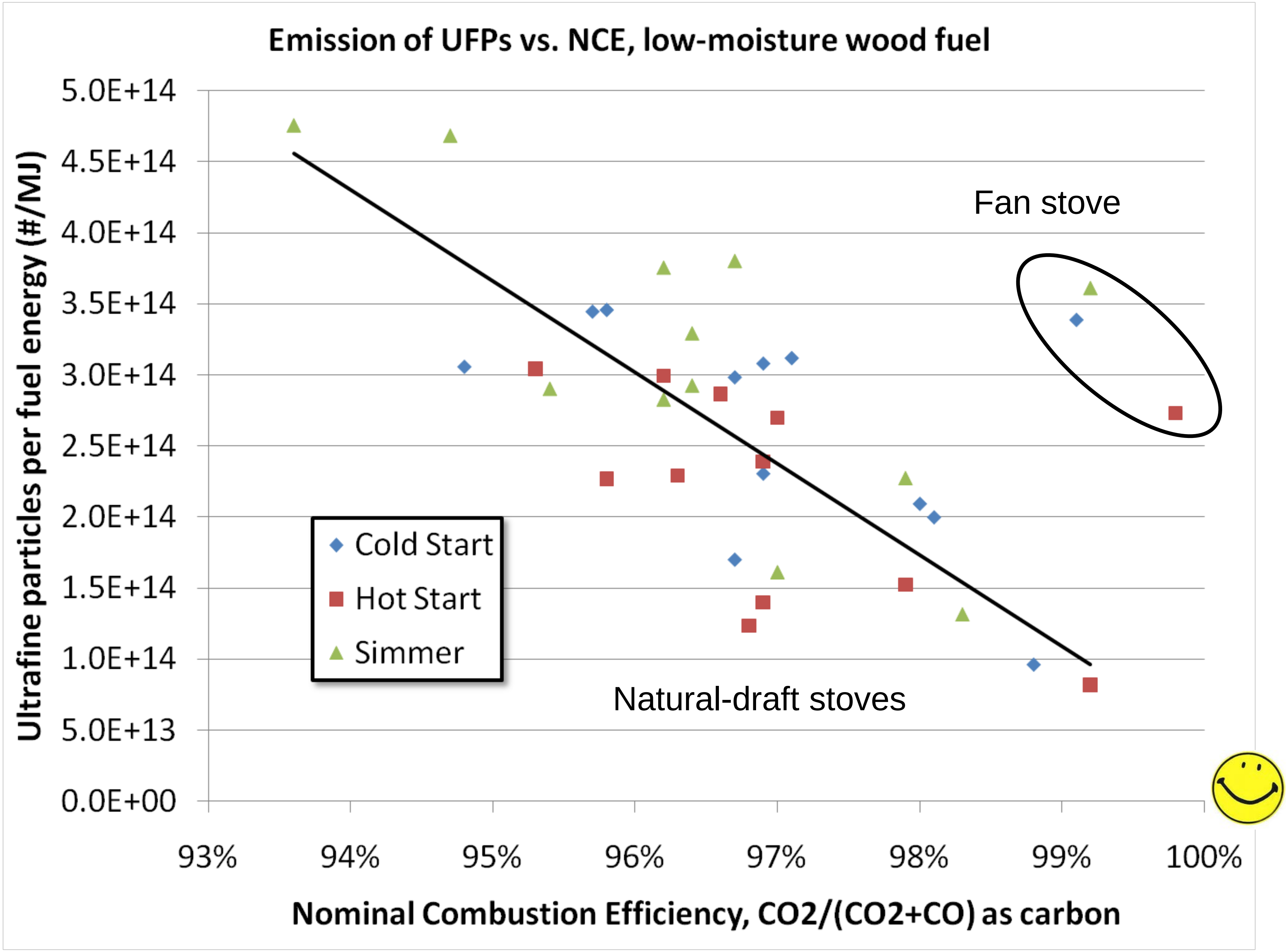
- A natural-draft TLUD stove had very low emissions with low-moisture fuel
- Two fan stoves had very low emissions
- Compared with 3-stone fire, most natural-draft stoves had lower emissions
- Two rocket stoves had lower emissions at “medium” power than at maximum power
- Charcoal stoves had high emissions of CO and PM during the cold start phase of the test



Emissions of CO and PM2.5, high-moisture fuel, high power (cold start)
CO emission per energy to cooking pot (g/MJ)
100
10
1
0.1
1
10
PM2.5 emission per energy delivered to cooking pot (g/MJ)
Jinqilin
GERES
KCJ Std
Jiko Ceramic
Gyapa
Jiko Metal
3-stone
Upesi
Belonio
Uhai
StoveTec charcoal
Sampada
Mayon
Philips ND
Berkeley
StoveTec wood
Philips fan
Envirofit
Oorja
3-stone fire
Charcoal stove
Forced-draft stove
Natural-draft stove

Emissions of CO and $PM_{2.5}$, low-moisture fuel, low power




Emission of UFPs vs. NCE, low-moisture wood fuel
Ultrafine particles per fuel energy (#/MJ)
5.0E+14
4.5E+14
4.0E+14
3.5E+14
3.0E+14
2.5E+14
2.0E+14
1.5E+14
1.0E+14
5.0E+13
0.0E+00
93%
94%
95%
96%
97%
98%
99%
100%
Nominal Combustion Efficiency, CO2/(CO2+CO) as carbon
Cold Start
Hot Start
Simmer
Fan stove
Natural-draft stoves

Study Results – Key Findings

- Compared with the 3-stone fire, most stoves that were tested had better thermal efficiency, but some did not
- Compared with the 3-stone fire, many stoves that were tested had better combustion efficiency, but many did not
- A natural-draft TLUD stove had very high efficiency with processed, wood-pellet fuel with low-moisture content

Study Results – Key Findings

- Some forced-draft (fan) stoves had very low emissions – but not all fan stoves did
- Most natural-draft stoves that were tested showed a bigger improvement (lower emissions) over the 3-stone fire with high-moisture fuel than with low-moisture fuel
- A natural-draft TLUD stove had very low emissions – but required processed, wood pellet fuel with low-moisture content

Study Results – Key Findings

- Two rocket stoves were tested at a “medium power” level – and had lower emissions (per energy delivered to cooking pot) than at maximum power.
- Charcoal stoves had high emissions of CO and high emissions of PM during start-up
- For some stoves, problems were noted during testing: materials (cracked ceramic, warped metal) and malfunctions (fan speed controller, liquid fuel burner) – continued product development is needed

Considerations: Stove Design and Performance

- Fuels are most important. For stove design, Paal Wendelbo says, “Always start with the fuel.”
- For designing stoves for household cooking (not for space heating), thermal mass is not our friend.
- Kirk Smith urges us to compare performance of cookstoves with best case (gas stoves) as well as worst case (open fires).

Improving Study Methods: Recommendations

- Specify laboratory test conditions similar to field conditions
- Specify appropriate, consistent fuels
- Specify pots with appropriate size and shape
- Specify appropriate operator techniques
- Record temperature of water in pot during WBT
- For testing with high-moisture wood, freeze wood in air-tight container to preserve moisture content and prevent molding/rotting

Improving Study Methods: Recommendations

- Frequently check operation of scale with a “test mass”
- For measuring fuel moisture content, oven drying method is more accurate than moisture meter
- If possible, measure heat of combustion of fuel and remaining char
- For measuring emissions, use good design practice for emissions collection hood and sampling duct (dilution tunnel)

Improving Study Methods: Recommendations

- At the end of each test phase of the WBT, it is easier and faster to weigh entire stove with remaining charcoal (instead of removing and separately weighing) – but be careful – some stoves lose mass when moisture is driven off from ceramic materials by heat
- Reporting combined results (fuel use and emissions) for three phases of WBT is convenient for benchmarking, but reporting separate results provides more information and may be more useful for comparing with field data
- Increasing number of test replications improves ability to determine statistically significant differences between stoves

Acknowledgements

- Brenda Doroski, EPA/PCIA – coordination and support
- John Mitchell, EPA/PCIA – coordination and support
- Yongxin Zhao, Ph.D., Arcadis – on-site contractor lead
- Jerry Faircloth, Arcadis – stove and instrumentation operations
- Bernine Khan, Ph.D., EPA post-doc – thermal-optical analyses
- Tiffany Yelverton, Ph.D., EPA – black carbon analyses
- Peter DeCarlo, Ph.D., AAAS Fellow – PASS-3 analyses
- Tami Bond, Ph.D., University of Illinois – advisor
- Michael Hays, Ph.D. EPA – advisor
- Chris Pressley, EPA – instrumentation support
- Mike Tufts, Arcadis – metrology lab support
- Sam Brubaker, Arcadis – metrology lab support
- N. Dean Smith, Ph.D., Arcadis – metrology lab support
- Jonathan Thornburg, Ph.D., RTI International – advisor
- Shayna Martin, EPA student contractor – lab support