Low-Temperature Diesel Combustion Cross-Cut Research

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Sandia National Laboratories

Project ID: ACE005

FY 2010 DOE Vehicle Technologies Program Annual Merit Review
Project ACE005, V Virginia C, 11:00 – 11:30 AM, Tuesday, June 8, 2010

Sponsor: **DOE Office of Vehicle Technologies**
Program Managers: **Gurpreet Singh and Kevin Stork**

Overview

Timeline

- Project provides fundamental research that supports DOE/ industry advanced engine development projects.
- Project directions and continuation are evaluated annually.

Budget

- Project funded by DOE/VT:
  FY09- $570K
  FY10 - $660K

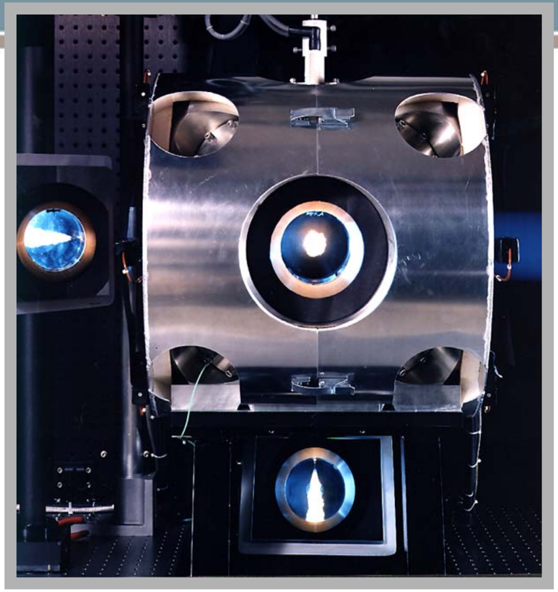
Barriers

- Engine efficiency and emissions
  - Sources of unburned hydrocarbons and CO for LTC combustion
- Load limitations for LTC
- CFD model improvement for engine design/optimization

Partners

- 15 Industry partners in the Advanced Engine Combustion MOU
- Participants in the Engine Combustion Network
  - Experimental and modeling
- Project lead: Sandia
  - Lyle Pickett (PI)

Overall Approach



- Facility dedicated to fundamental combustion research for both heavy-duty and light-duty engines (cross-cut research).
  - Well-defined charge-gas conditions
    - Pressure, temperature, EGR level
  - Well-defined injector parameters
    - Injection pressure, fuel, multi-injections

Experiments in CV
- Well-defined boundary conditions
- Quantitative diagnostics at engine conditions
- Improved physical understanding

Computer models
- "Retain" insights from experiment
- Adds knowledge about things that are not "measurable"
- Parametric design optimization
- Saves time and cost over "hardware" iteration

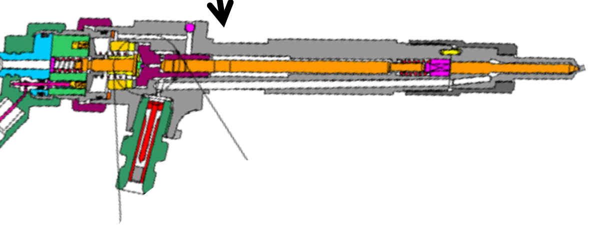
High-Efficiency, Low-Emissions Engine

Objectives/Milestones

- Aid the development of computational models for engine design and optimization (ongoing).
  - Experimental and modeling collaboration through the Engine Combustion Network: http://www.ca.sandia.gov/ECN
  - FY10 (1): Attain injector set for experimentation by multiple laboratories. Characterize “Spray A” high-temperature, high-pressure condition.
- Determine the factors that cause liquid wall impingement at post-injection (DPF-regeneration) conditions (FY09-FY10).
  - Urgent need to understand oil dilution, inefficiency using diesel/biodiesel fuel.
  - FY10 (2): First vaporization measurements at low-density, high-T conditions.
- Quantitative characterization of soot processes in transient sprays at LTC conditions (FY08-FY10).
  - Emitted soot is an emissions burden, source of inefficiency, expense.
  - FY10 (3): Comparison of biodiesel and diesel soot distributions. Methods to reduce soot even with mixing-controlled (negative-dwell) heat release.
  - FY10 (4): Measurement of soot size distribution using thermophoretic sampling. Critical information needed for soot modeling at LTC conditions.

(1) Industrial and academic collaboration in the Engine Combustion Network

Bosch
Donates 10 "identical" common-rail injectors



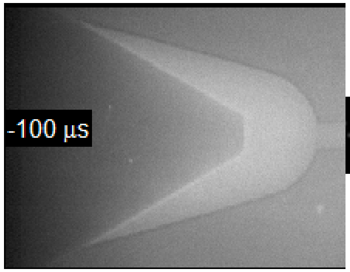
Argonne (x-ray source)
Internal needle movement
Near-nozzle liquid volume

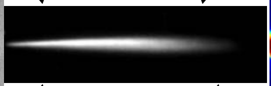
General Motors
Mixing
Droplet sizing

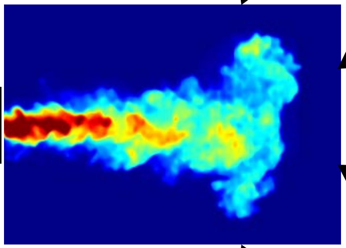
Michigan Tech. Univ.
Vessel temperature composition

IFP (France)
Spray velocity
Combustion

Internal nozzle geometry







- Operation at the same ambient and injector conditions: "Spray A"

CMT (Spain)
Rate of injection
Spray momentum

Caterpillar
Lift-off length
Liquid length

Meiji (Japan)
Soot formation

Sandia
Liquid and vapor mixing
Combustion diagnostics

Experimental participation in the ECN

Institution	Facilities	Personnel
Sandia	Preburn CV	Lyle Pickett, Caroline Genzale
IFP	Preburn CV	Gilles Bruneaux, Louis-Marie Malbec
CMT	Cold CV, Flow PV	Julien Manin, Raul Payri
Chalmers	Flow PV	Mark Linne
GM	Flow PV	Scott Parrish
Mich. Tech. U.	Preburn CV	Jeff Naber, Jaclyn Nesbitt, Chris Morgan
Argonne	Cold V, X-ray Synchrotron	Chris Powell, Alan Kastengren
Caterpillar	Flow PV	Tim Bazyn, Glen Martin
Aachen	Flow PV	Heinz Pitsch
Meiji U.	Preburn CV	Tetsuya Aizawa
Seoul Nat. U.	Preburn CV	Kyoungdoug Min

Past/future modeling participation in the ECN

Institution	Lead
Sandia	Joe Oefelein
IFP	Christian Angelberger
Chalmers	Fabian Kärrholm
Polit. di Milano	Tommaso Lucchini
City Univ.	Manolis Gavaises
Imperial College	David Gosman
Univ. Wisconsin-Madison	Rolf Reitz, Chris Rutland
Doshisha Univ.	Jiro Senda
Aachen/Stanford	Heinz Pitsch
Purdue Univ.	John Abraham
Penn State	Dan Haworth
Convergent Science	Kelly Senecal
Many other companies (like Bosch) and institutions…..	

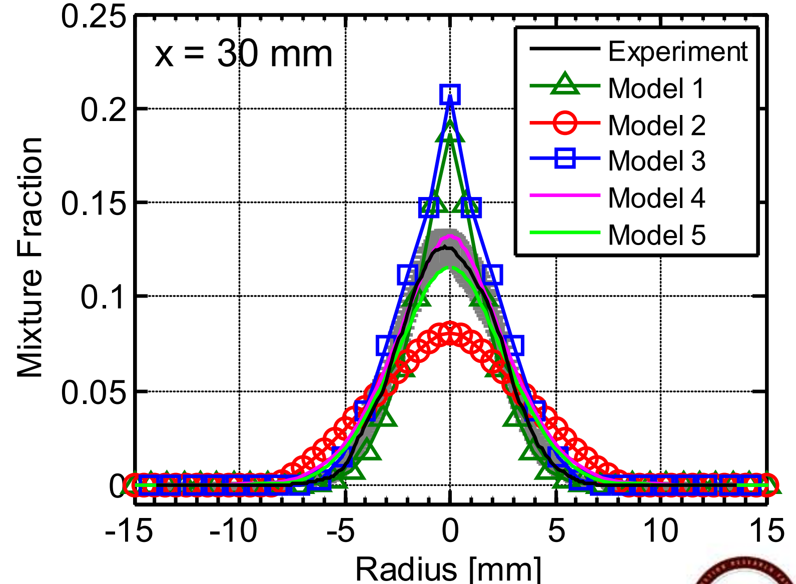
How will focus at “Spray A” conditions advance understanding of spray combustion?

- Quantitative, complete datasets (velocity, species, temperature) still do not exist at engine conditions.
  - Need to move beyond “conceptual model” to more detailed comparison.
  - Follows direction of successful activities using more basic flames (TNF workshop).
- Leveraging of work by many experimental and modeling activities will accelerate research.

Spray A Specifications

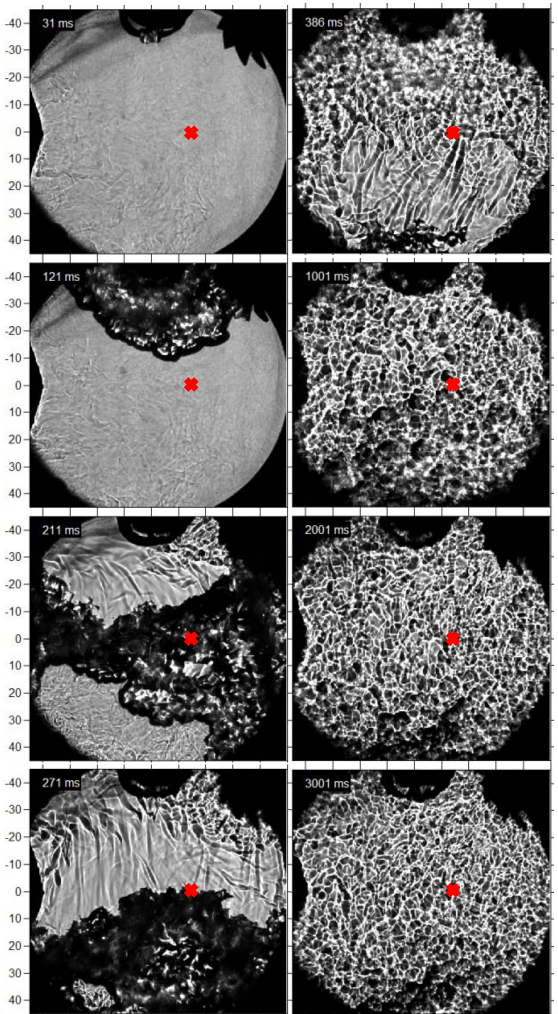
Ambient gas temperature	**900 K**
Ambient gas pressure	**6 MPa**
Ambient gas density	**22.8 kg/m^3**
Ambient gas composition	**15% O_2, 75.1% N_2, 6.2% CO_2, 3.6% H_2O**
Common rail fuel injector	**Bosch solenoid-activated, generation 2.2**
Fuel injector nozzle outlet diameter	**0.090 mm**
Nozzle K factor	**1.5 { $K = (d_{inlet} - d_{outlet})/10$ [use μm] }**
Nozzle hydro-erosion	**Discharge coefficient = 0.86 with 100 bar ΔP.**
Spray full included angle	**0° (1 axial hole) or 145° (3-hole)**
Fuel injection pressure	**150 MPa**
Fuel	**n-dodecane**
Fuel temperature at nozzle	**363 K (90° C)**
Common rail volume/length	**22 cm^3/ 28 cm (Use GM rail model 97303659)**
Distance, injector inlet to common rail	**24 cm**
Fuel pressure measurement	**7 cm from injector inlet / 24 cm from nozzle**
Injection duration	**1.5 ms**
Approximate injector driver current	**18 A for 0.45 ms ramp, 12 A for 0.345 ms hold**

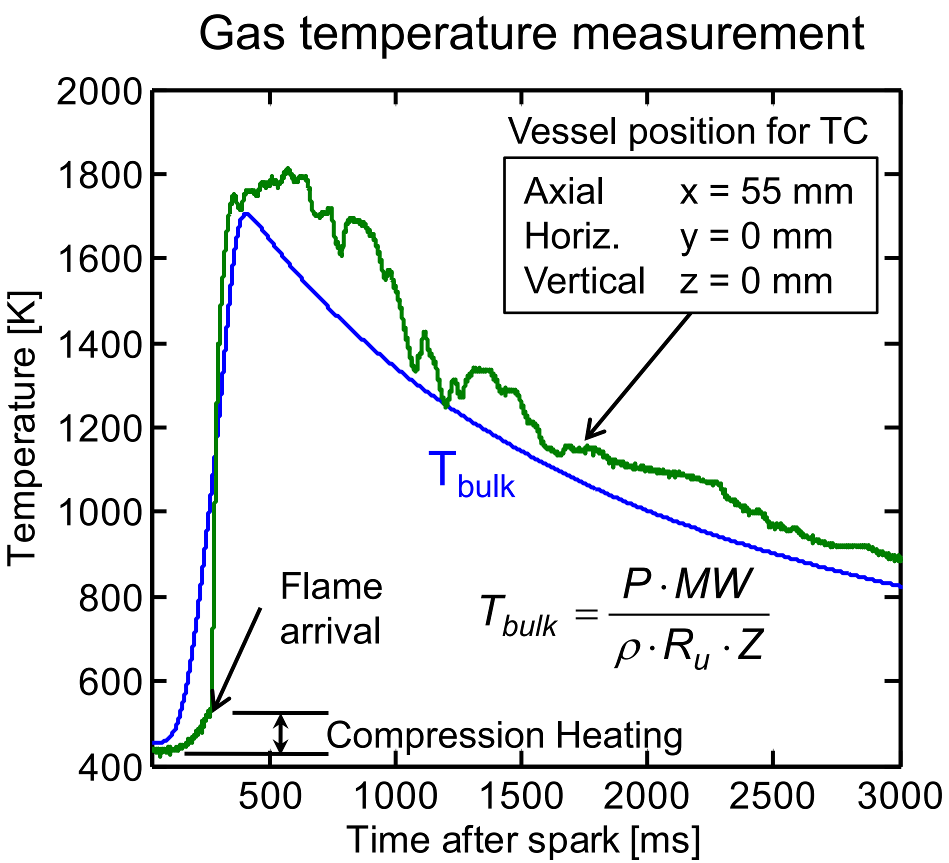
Model comparisons to baseline dataset available on the ECN



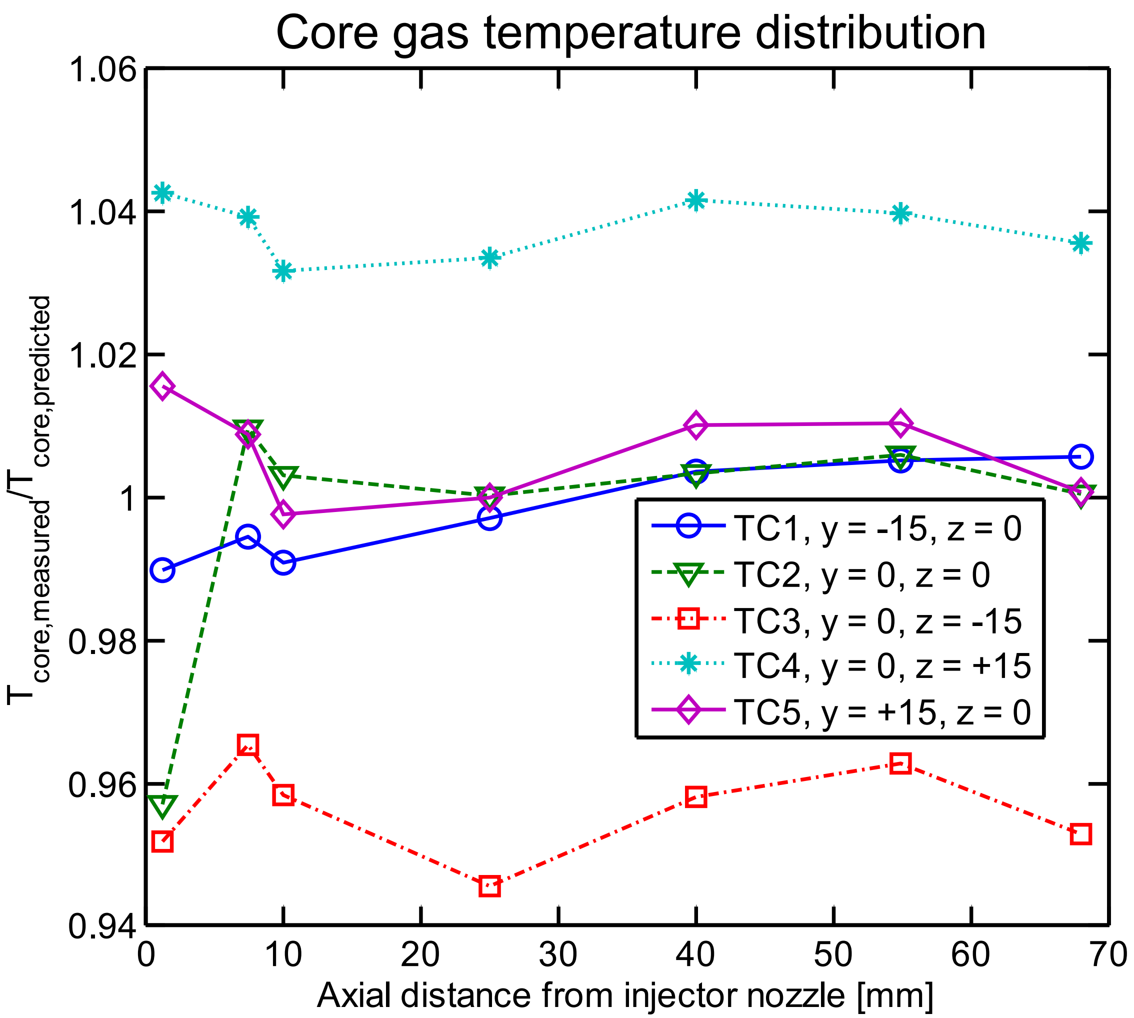
Careful characterization of vessel boundary conditions (temperature) is required.

Schlieren of preburn and cooldown

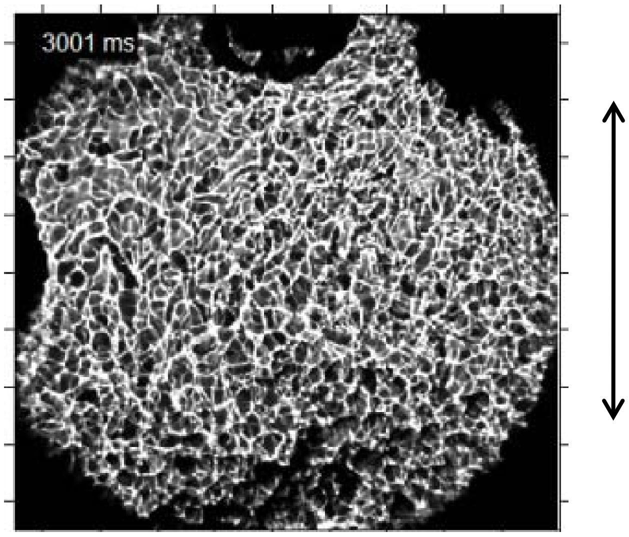




Ambient gas has uniform, horizontal “core”.



Buoyancy induced vertical variation in temperature



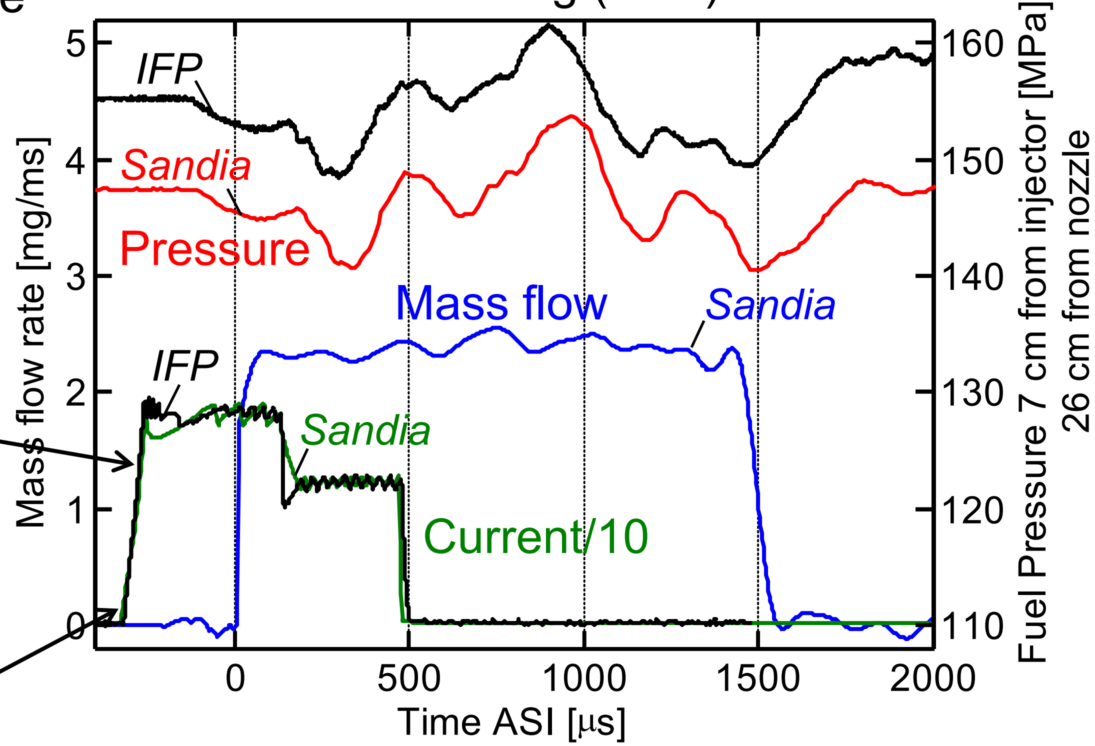
Injector boundary conditions characterized at multiple facilities.

n-dodecane
90 C
1 atm back pressure

Spray A specification:
1500 μs injection duration
mass = 3.5 mg (here)

18 Amps 450 μs +
12 Amps 345 μs

330 μs
hydraulic
delay



Comparison of vapor/liquid penetration at two facilities shows reasonable agreement.

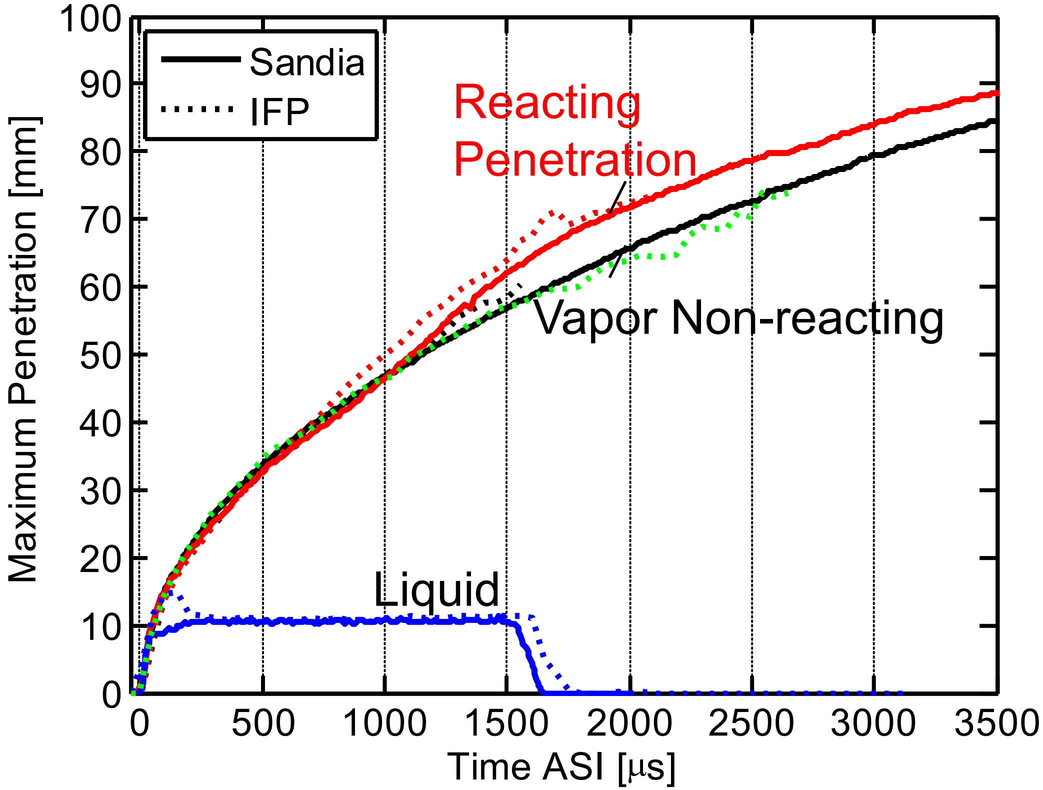
Schlieren visualization.
Liquid Mie-scatter border in blue.
0% O_2: non-reacting

movie

IFP

movie

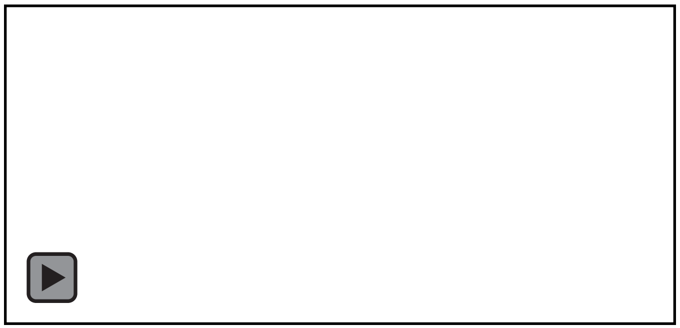
Sandia



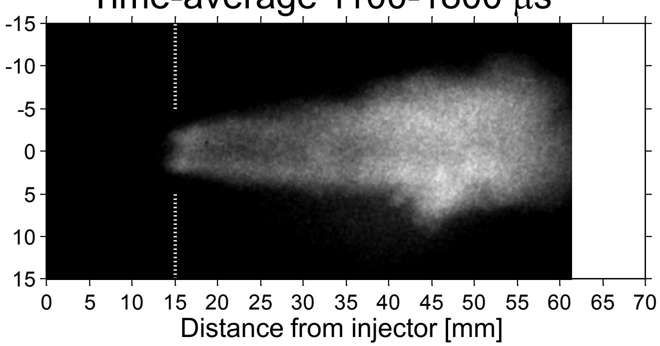
Ignition at 450 μs is followed by a quasi-steady lift-off length at 15-17 mm.

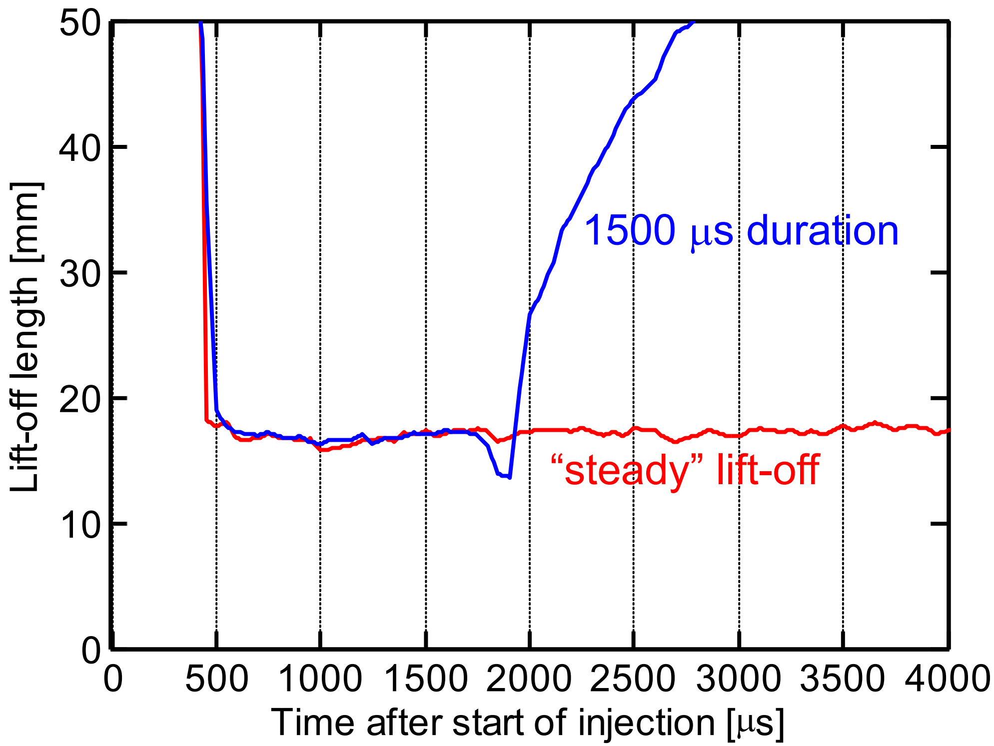
< 450 nm chemiluminescence (Sandia)

movie



OH chemiluminescence (IFP)
Time-average 1100-1800 μs





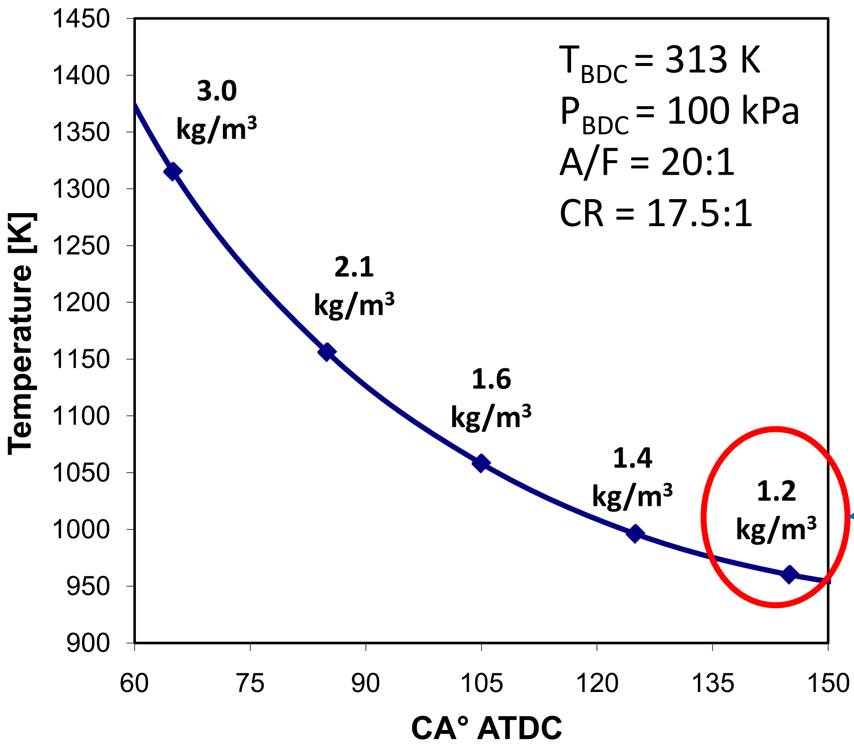
- Ignition/lift-off are examples of other measurements for Spray A.
- Refined, quantitative measurements are being pursued to follow these initial measurements (e.g., mixture fraction, liquid volume fraction).

(2) Liquid penetration for late-cycle post-injections is problematic, uncharacterized.

- One strategy used for DPF regeneration is to implement a late-cycle post-injection to enrich the exhaust stream.

HOWEVER,

- These injections typically occur well after TDC (near EVO), when in-cylinder densities are quite low. Wall-wetting, oil dilution are concerns!



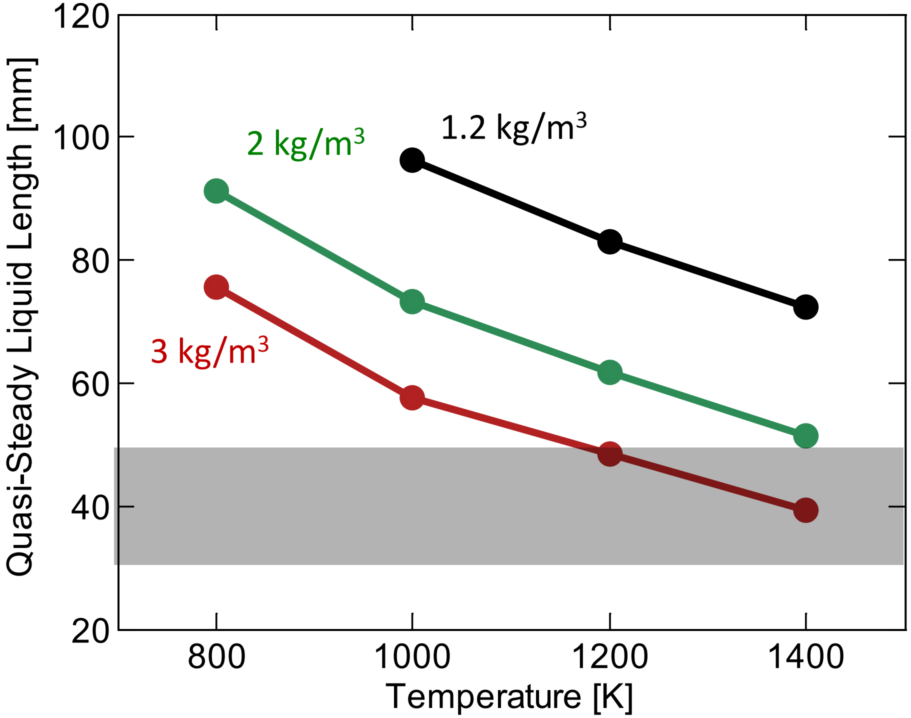
1. **Very low densities**
2. **Relatively high temperatures (post-combustion)**

Typical post-injection timing for DPF regeneration

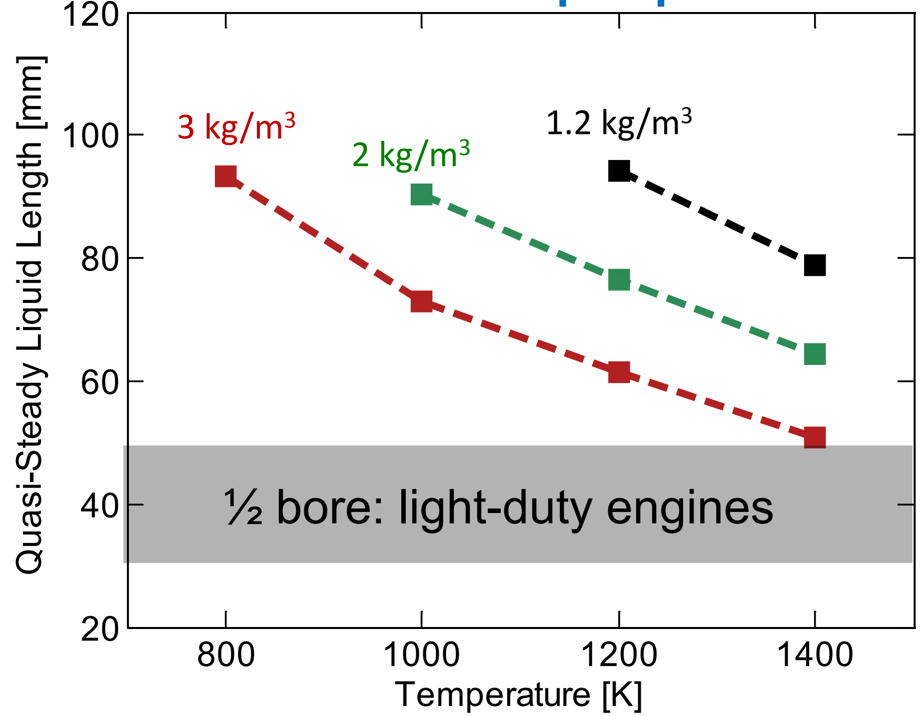
Even though temperature are high, liquid penetration exceeds engine dimensions.

0.108 mm nozzle, 1500 bar injection pressure

#2 Diesel



Neat Soy-based Biodiesel: 15-25% increase in liquid penetration



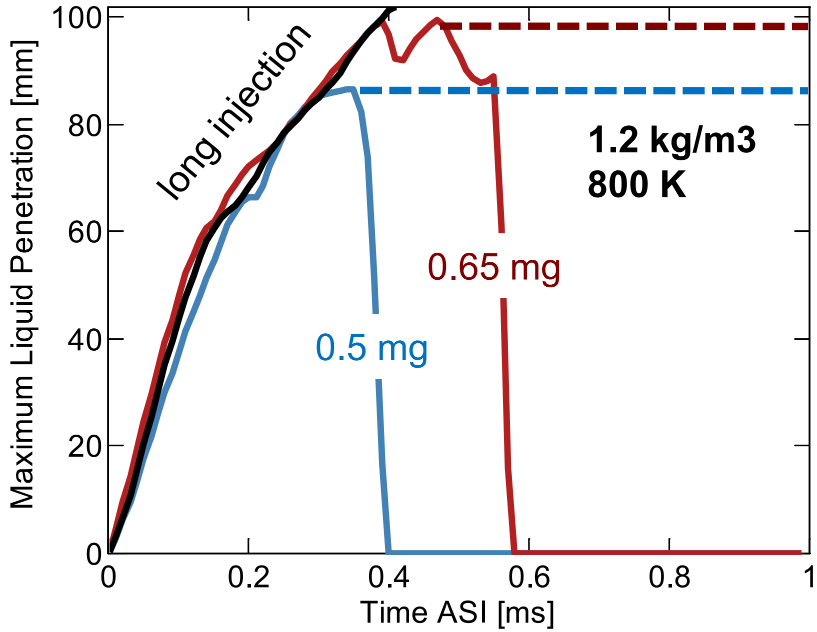
Fuel	#2 Diesel	Biodiesel
T90 [°C]	315	351
ρ at 100°C [kg/m³]	767	793

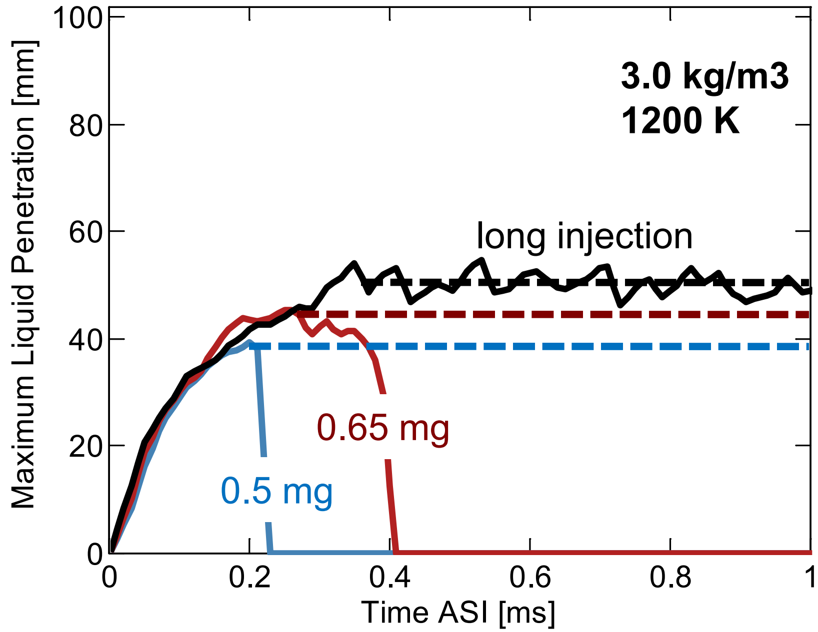
Short injections can limit the maximum liquid penetration, but fuel quantities are small

movie

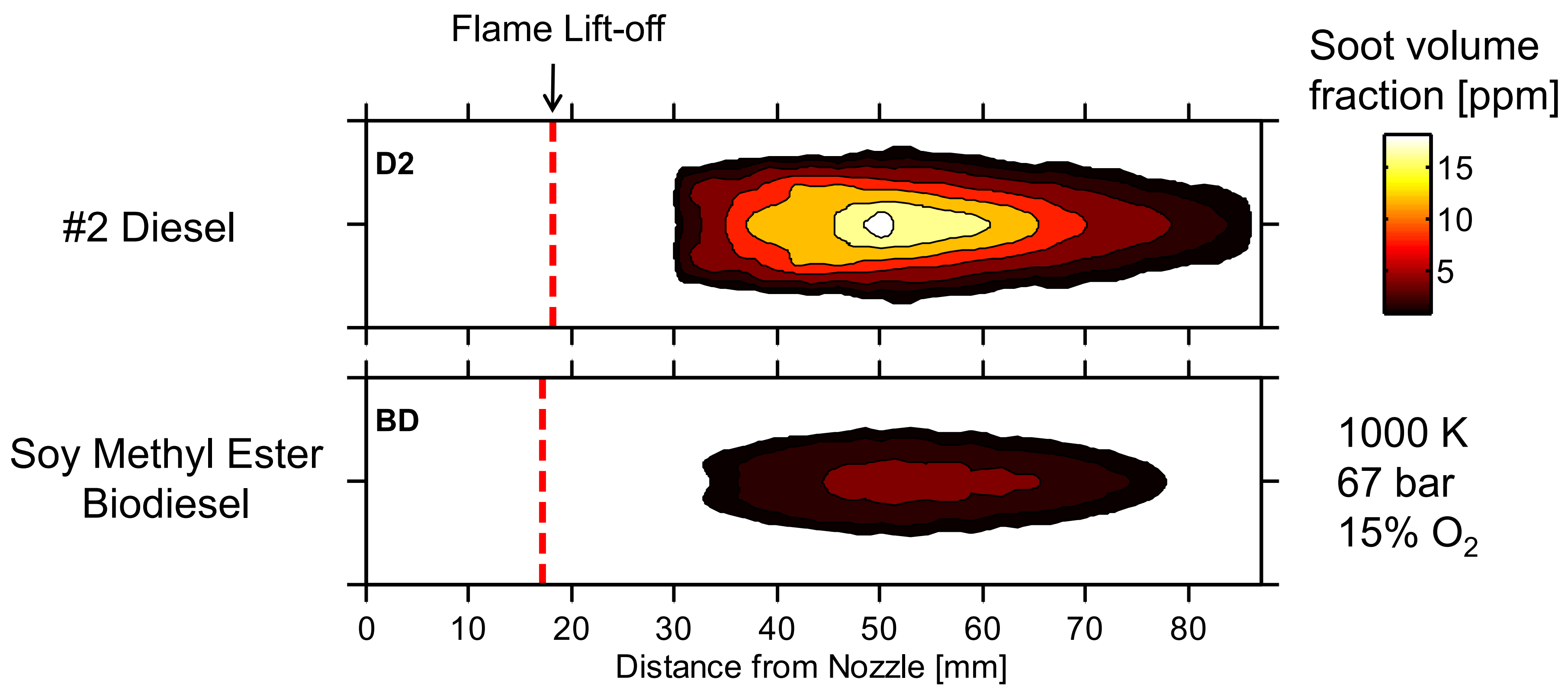
movie

1.2 kg/m3
800 K





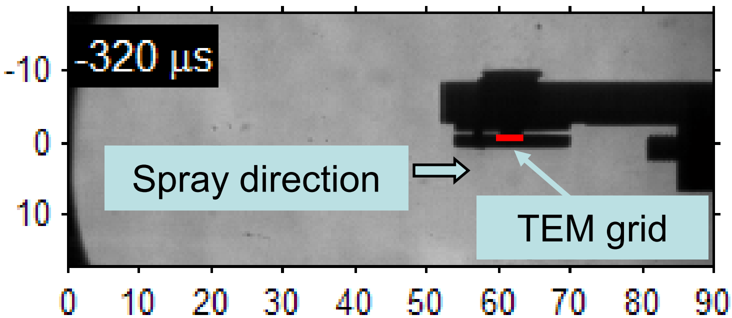
(3) First measurements of soot distribution within combusting biodiesel sprays.



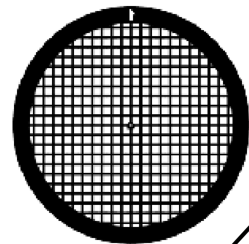
- Factor of five reduction in total soot formed within reacting spray.
- Long inception time permits soot-free combustion with negative ignition dwell, lower heat release.

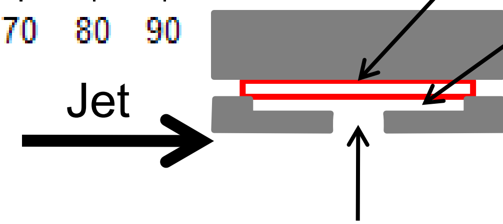
(4) Soot sampling from sprays within high-temperature, high-pressure combustion vessel.

TEM probe within the combustion vessel



3 mm diameter TEM grid: copper mesh covered by an amorphous carbon film



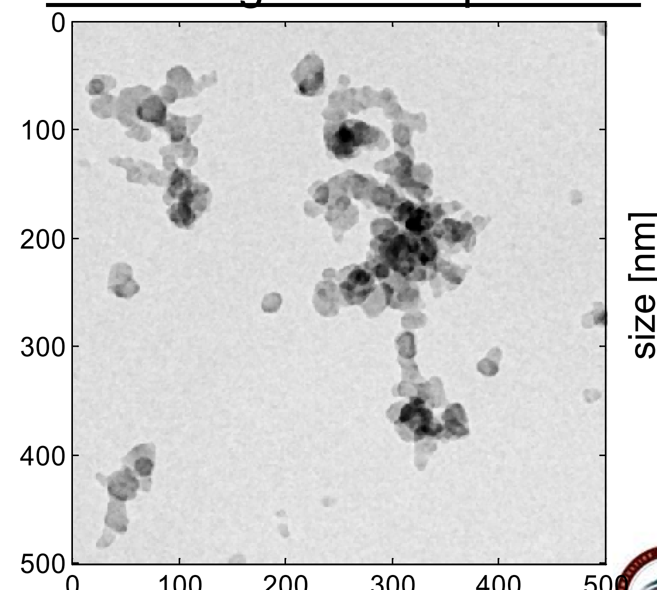


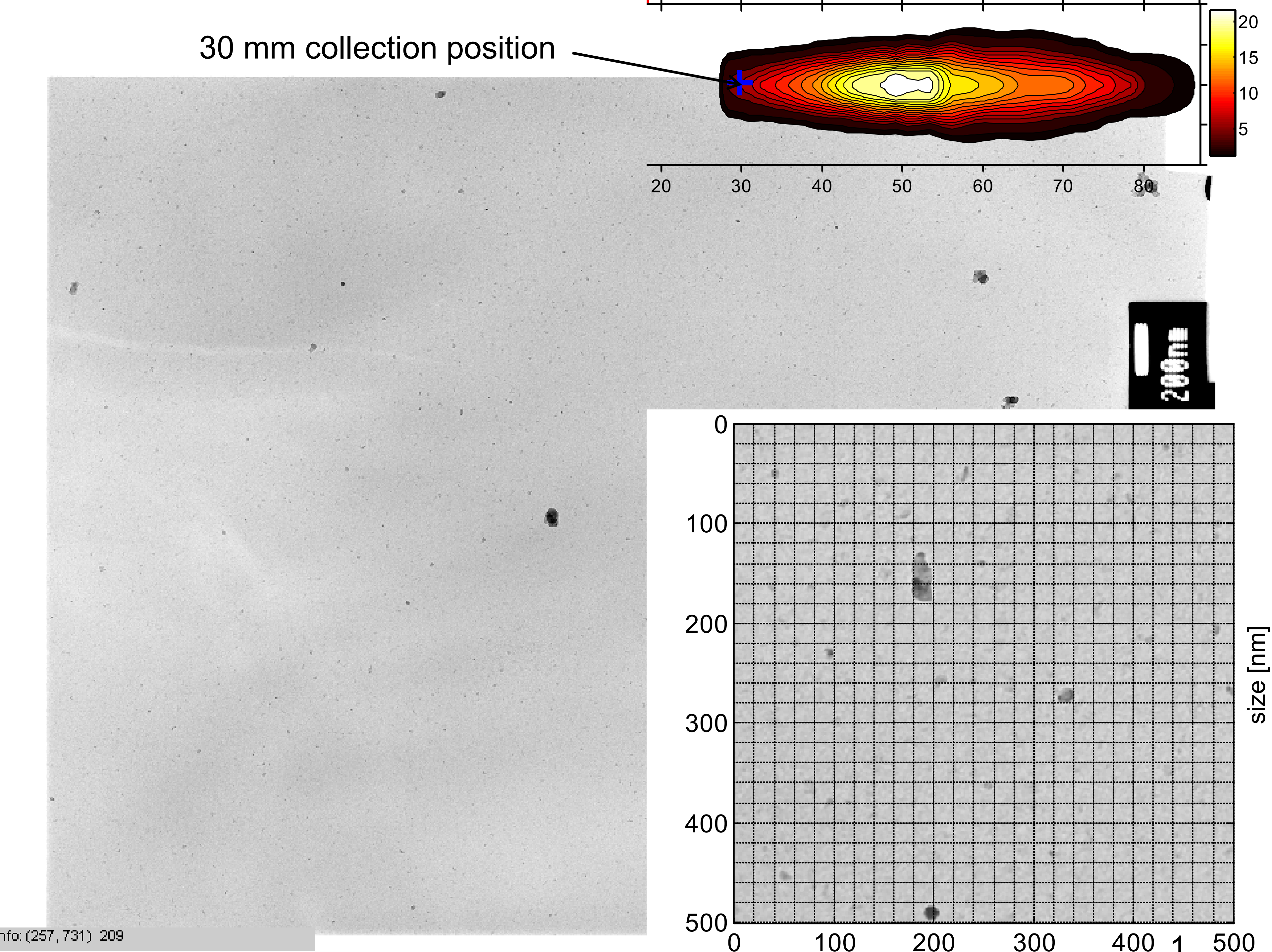
TEM grid held within the probe to protect it from excessive heating

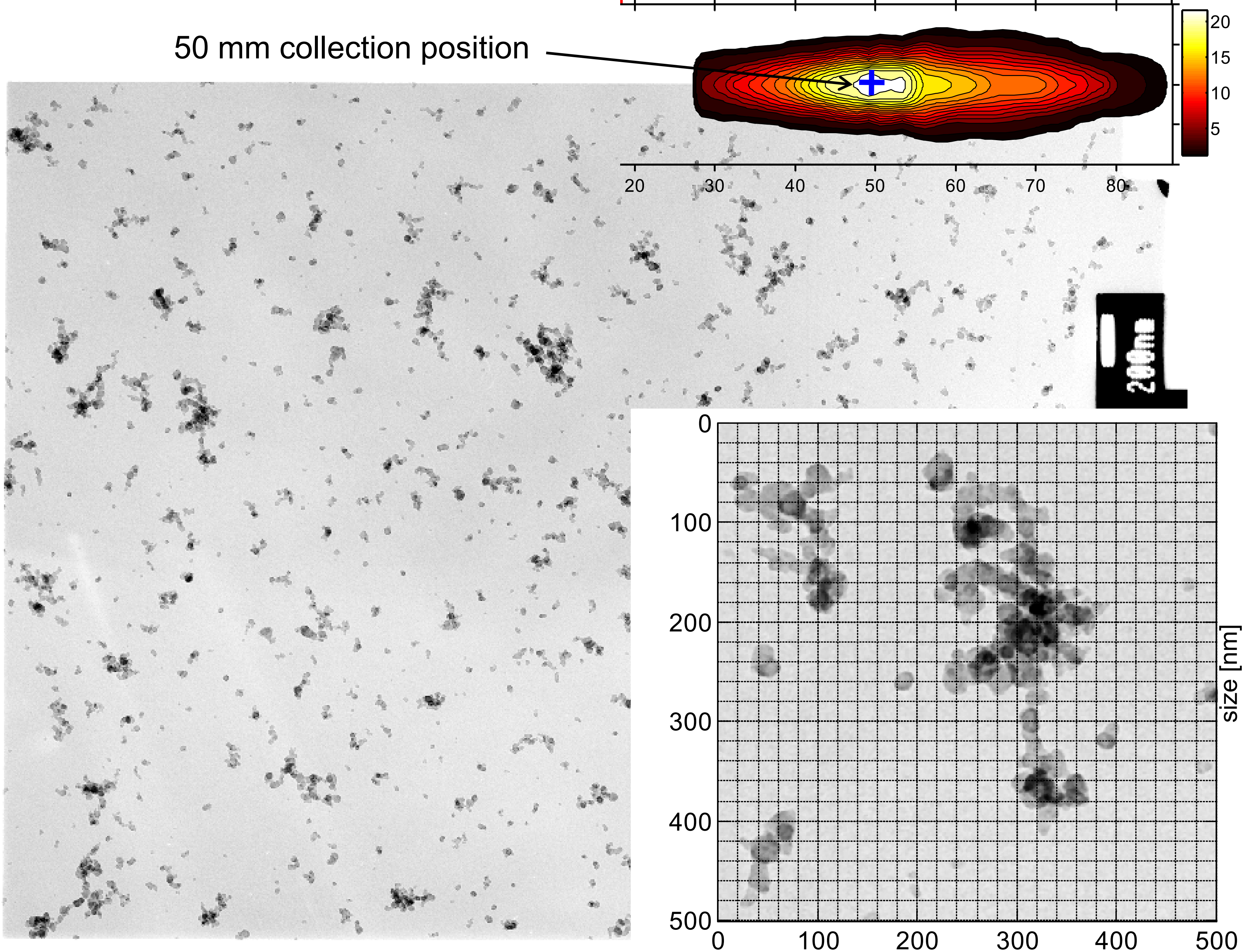
Restrictive passage quenches reaction and protects the TEM grid.

Soot-laden gas skims past the probe, enters through a 1-mm diameter hole, and deposits on the TEM grid.

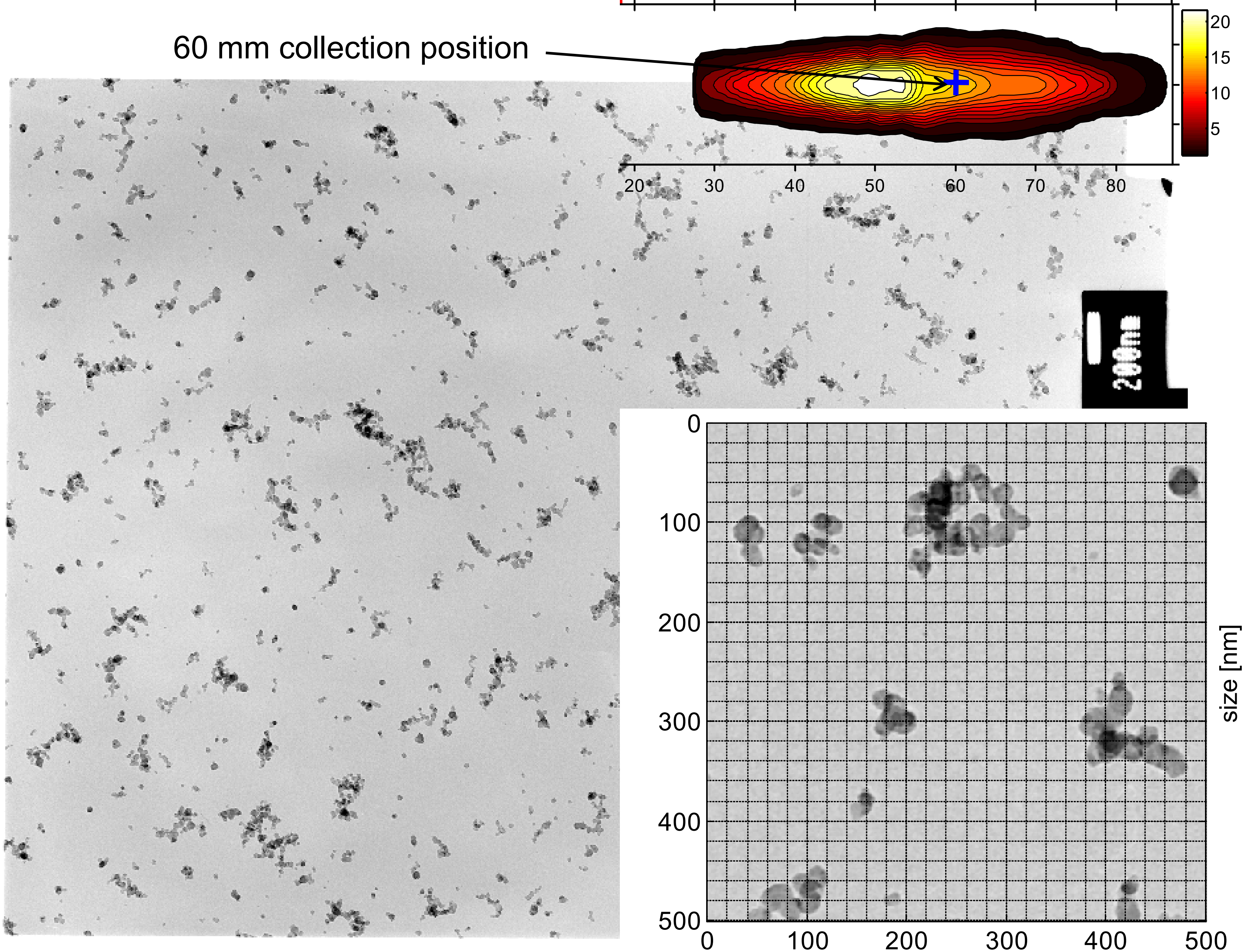
TEM image of soot particles



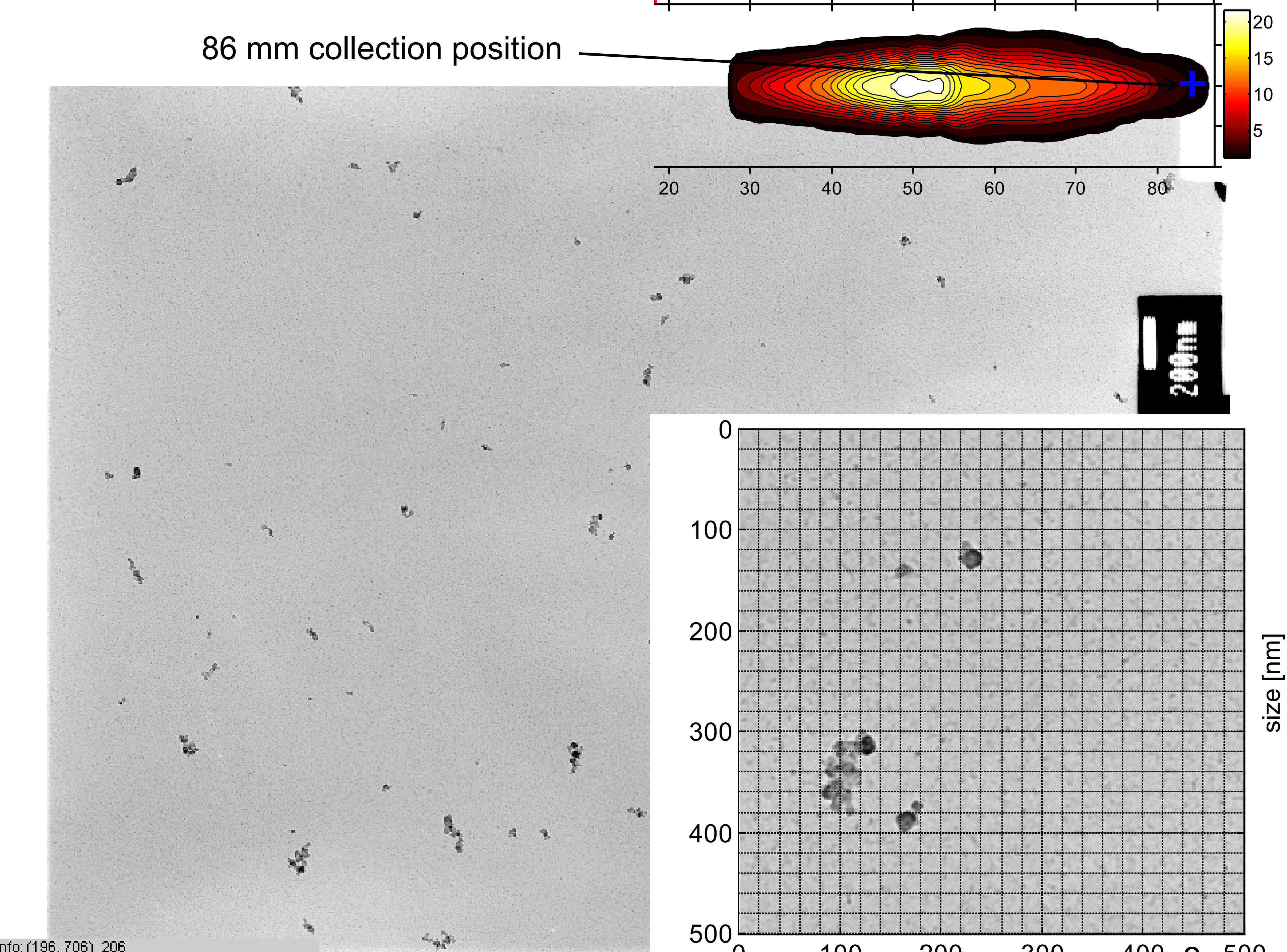

30 mm collection position
20
15
10
5
20 30 40 50 60 70 80
200nm
0
100
200
300
400
500
0 100 200 300 400 500
size [nm]
nfo: (257, 731) 209
1



50 mm collection position
20
30
40
50
60
70
80
20
15
10
5
200nm
0
100
200
300
400
500
size [nm]

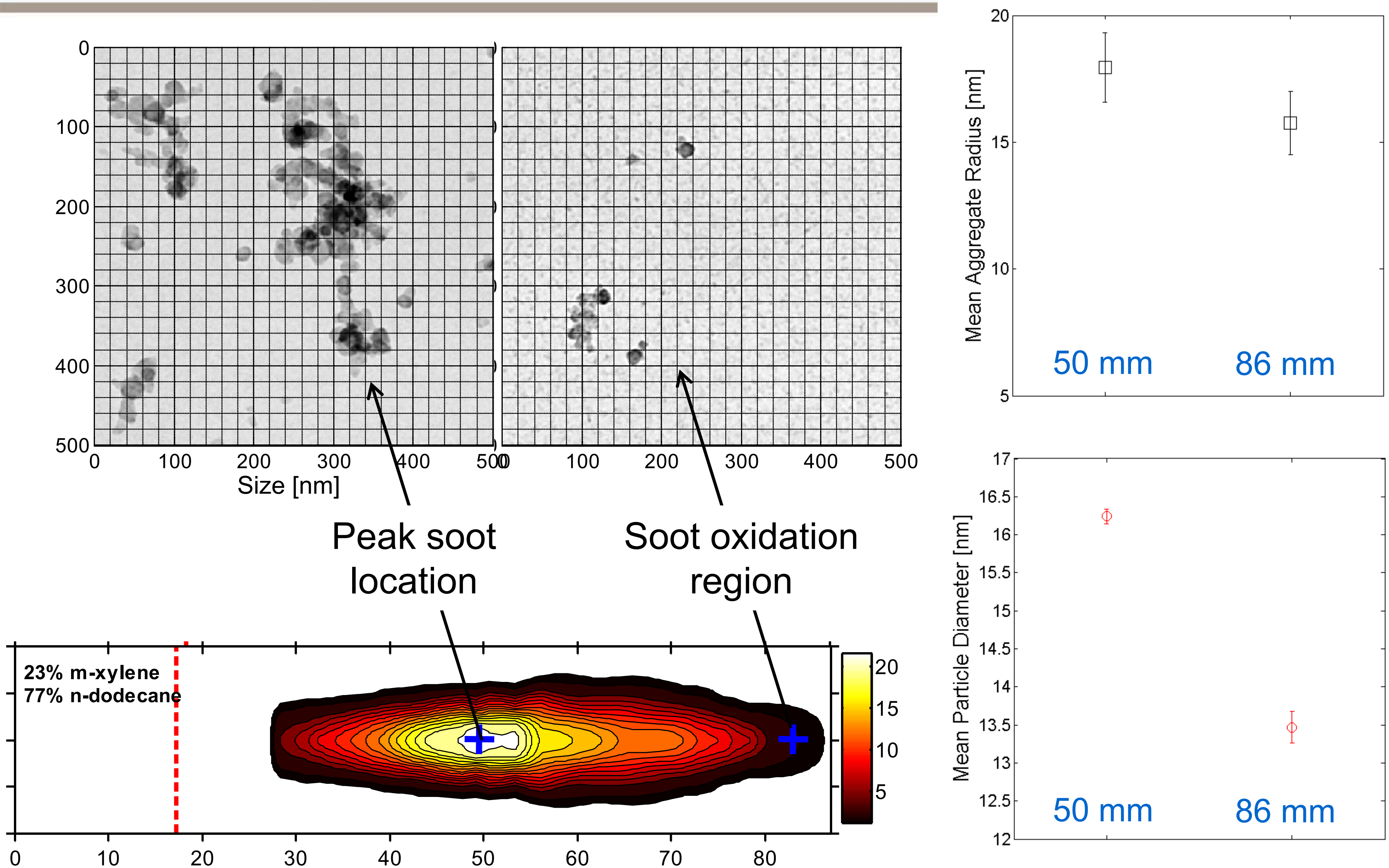


60 mm collection position
20
15
10
5
20
30
40
50
60
70
80
200nm
0
100
200
300
400
500
0
100
200
300
400
500
size [nm]



86 mm collection position
20
15
10
5
20 30 40 50 60 70 80
200nm
0
100
200
300
400
500
size [nm]
0 100 200 300 400 500
nfo: (196, 706) 206

A key input for soot models, the particle size and shape are now characterized.



Future work

- Outlook for the Engine Combustion Network
  - Measurements (not a complete list, Sandia in blue):
    - Nozzle shape
    - Internal needle movement
    - Discharge and area contraction coefficients
    - Rate of injection
    - Near-nozzle liquid volume fraction
    - Droplet size, velocity, shape
    - Maximum liquid penetration
    - Vapor penetration rate
    - Velocity and turbulence within spray
    - Mixture fraction (non-reacting and reacting)
    - Ignition delay
    - Cool flame position and timing
    - Heat-release rate
    - Quantitative soot, soot precursor distribution
    - Lift-off length
  - Side-hole spray compared to axial hole
  - Liquid volume fraction near the liquid length
- Spray-spray interaction effects on mixing and lift-off length.
- Biodiesel soot processes, including soot particle morphology.
- Gasoline direct injection sprays
  - Isolate ignition processes using laser ignition.
  - Identify regimes with both autoignition and flame propagation.
  - Use diesel and GDI-type injectors.

Presentation Summary

- Project is relevant to the development of high-efficiency, low-emission engines.
  - Observations of combustion in controlled environment lead to improved understanding/models for engine development.
- FY10 approach addresses long term and short term needs.
  - Lead team to develop the ECN Spray A condition.
  - Massive dataset is being generated, which will be a key component for future model improvement.
  - Responding to new problems for DPF regeneration, characterized late-cycle post-injection liquid penetration.
  - Made first measurements of soot distribution in biodiesel sprays.
  - Quantified the soot size and morphology within sprays at engine conditions.
- Collaboration expanded to accelerate research and provide greatest impact (MOU, Engine Combustion Network)
- Future plans will continue effort
  - "Spray A" characterization for the ECN.