Fuel Spray Research Using X-Ray Radiography

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Outline

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- Barriers
- Approach
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Purpose of Work

- **DOE Goal: Reduce Petroleum Consumption**
  - ⇨Wider adoption of diesels in US can reduce oil consumption
  - ⇨Advanced combustion strategies can do so while reducing emissions

- **DOE Strategy: Develop Clean Diesel Technologies**
  - ⇨Requires detailed understanding of sprays, atomization, fuel/air mixing
  - ⇨Use computational spray modeling to assist engine development

- **Role of this project:**
  - ⇨Serve industry by providing near-nozzle spray diagnostic
  - ⇨Assist in development of improved spray models using unique quantitative measurements of sprays

Responses to FY2007 Reviewers' Comments

- "The researchers should seek input on… high efficiency, low emissions engines, and should measure under those conditions primarily."
  - CAT measurements mimic engine conditions, move toward GM-Fiat platform

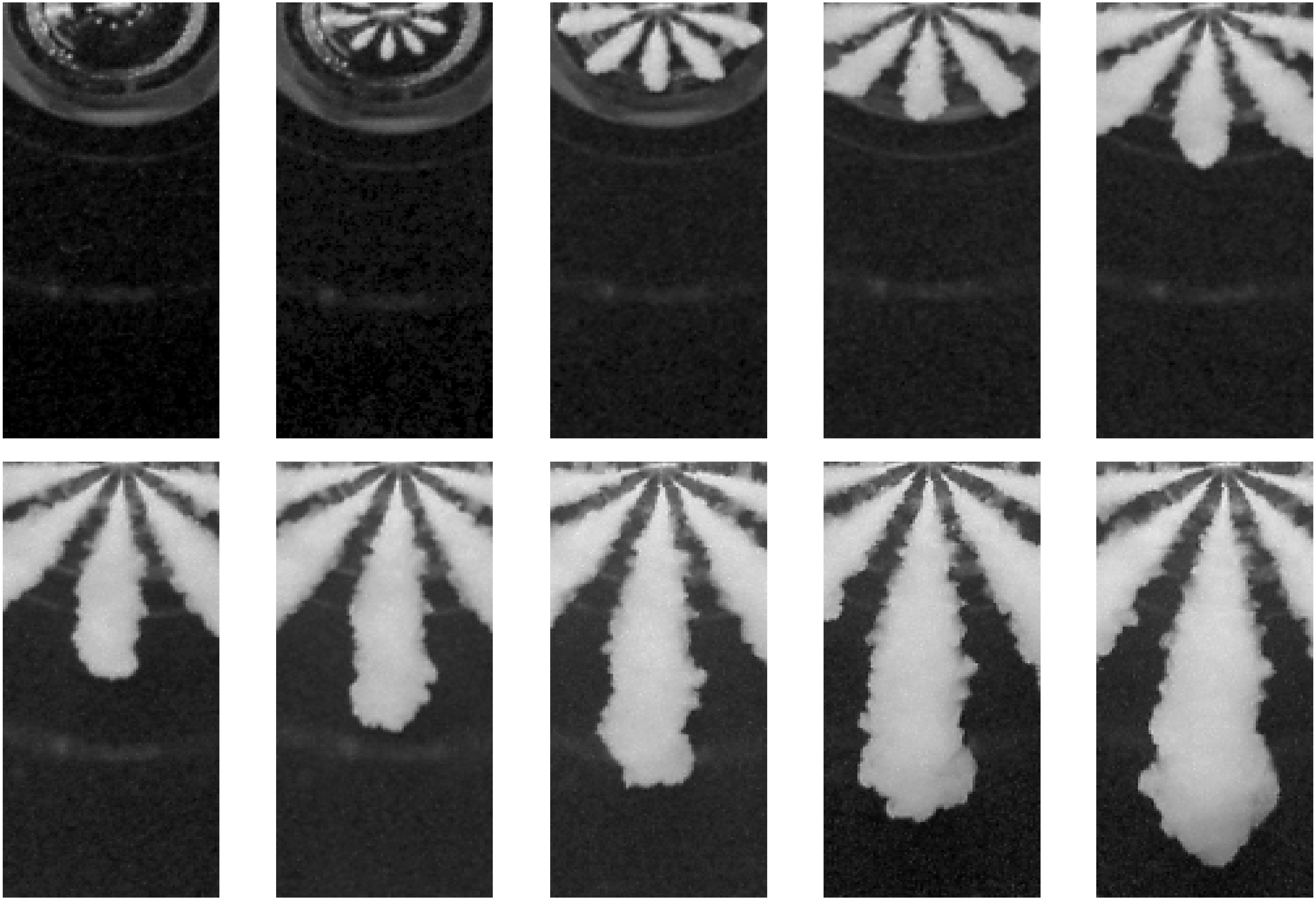
- "Project needs to have more interaction with industry and the modeling

  - FY2008 experiments with Bosch, GM, ERC. All of these are non-proprietary.

- "More effort is needed to improve the explanation and understanding of the impact of internal nozzle geometries."
  - Several measurements in FY2008 will focus on this goal.

- "Lack of vaporizing sprays is a significant shortcoming"
  - We have begun testing the feasibility of high-temperature measurements

Barriers – Shortcomings of Visible Light Spray Imaging



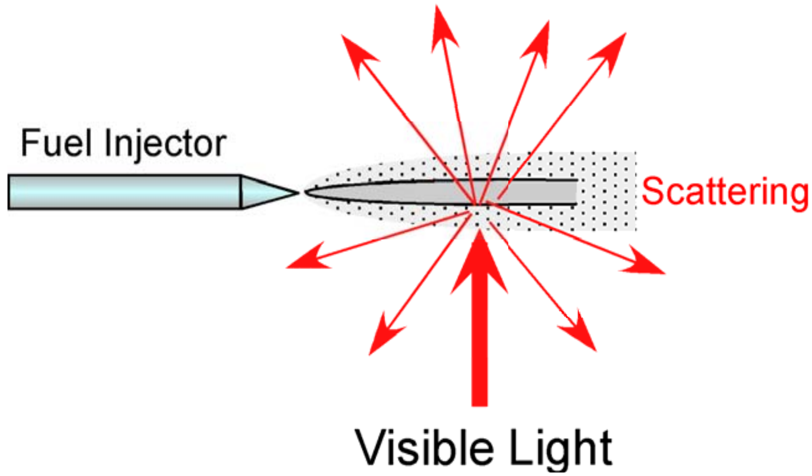
Images courtesy of EMD, Essam El-Hannouny

Barriers

- Optical spray measurements are limited in the near-nozzle region
  - There is little quantitative spray data available near-nozzle
  - Computational spray/engine models have been validated against limited data
  - Models have limited predictive power
- Injector and nozzle design is still “black magic”
- New engines must still be designed by trial and error
- Modeling offers limited guidance for the development of advanced combustion strategies

Barriers: X-Rays Overcome the Limitations of Visible Light

Visible Light Imaging



Scattering is difficult to interpret

X-Ray Imaging

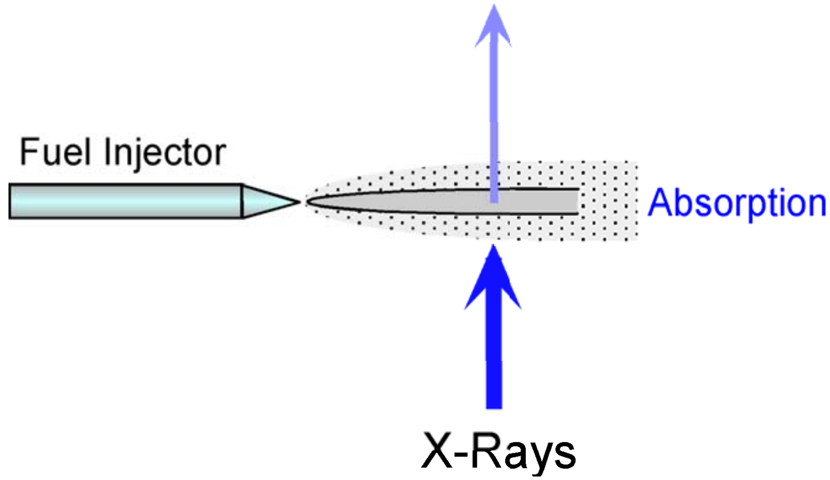


Image indicates the quantity of fuel.

Approach

Role of this project:

1. Serve industry by providing near-nozzle spray diagnostic
2. Assist in development of improved spray models using unique quantitative measurements of sprays

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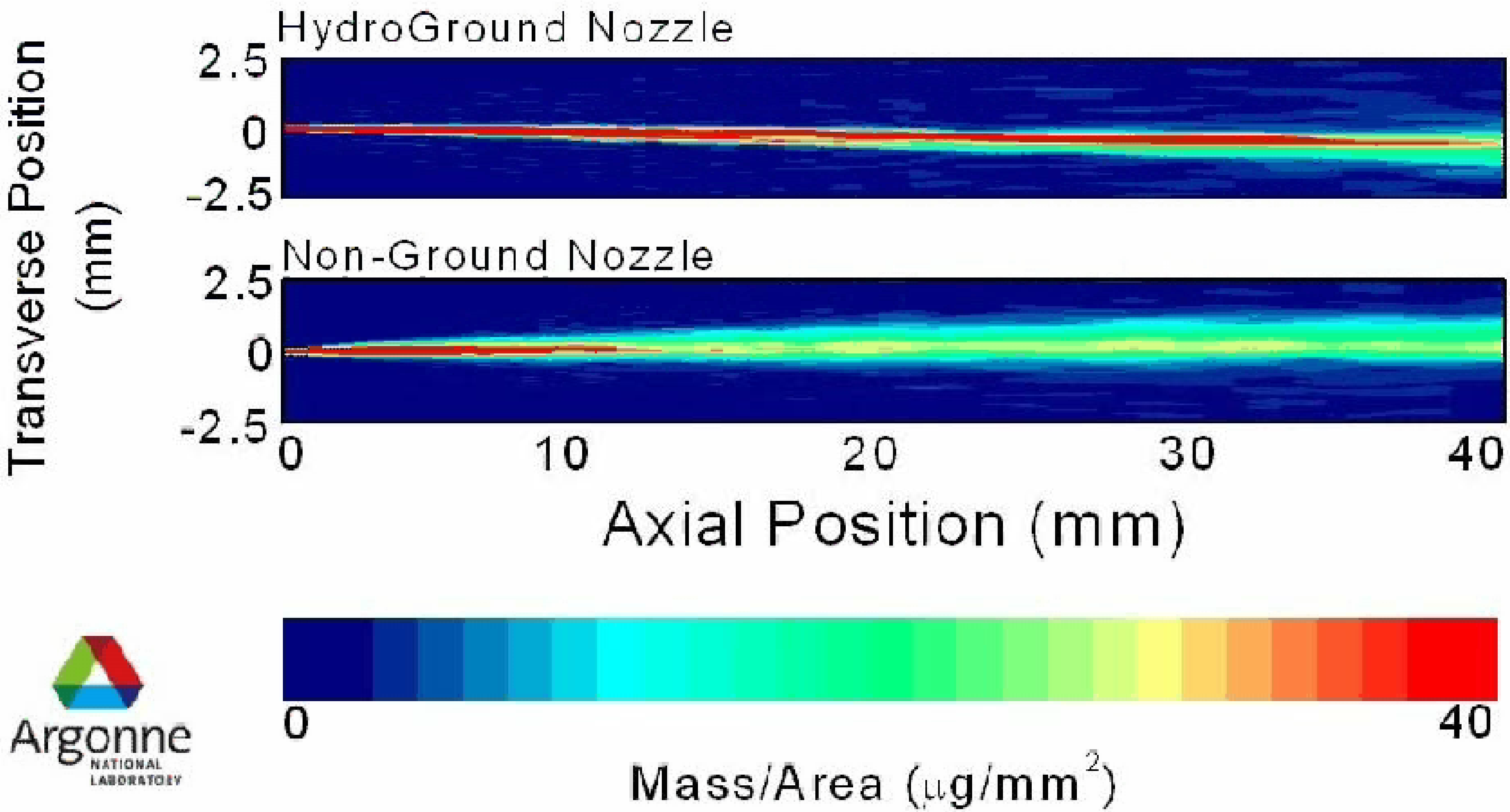
- X-rays allow precise, time-dependent measurement of the fuel distribution
- Fuel density can be calculated at any position and time throughout the spray, even as it emerges from the nozzle
- As injection parameters are changed, the effect on the spray can be observed and quantified.
- Provides stringent test of existing computational models
- Quantitative data enables model development

Approach: Time-Resolved Measurements of Spray Structure



Technical Accomplishments in FY 2008

- Analysis of the influence of ambient density on diesel spray structure

- Completed first x-ray measurements using Caterpillar HEUI system

- Tests of x-ray transparent windows at elevated temperatures.

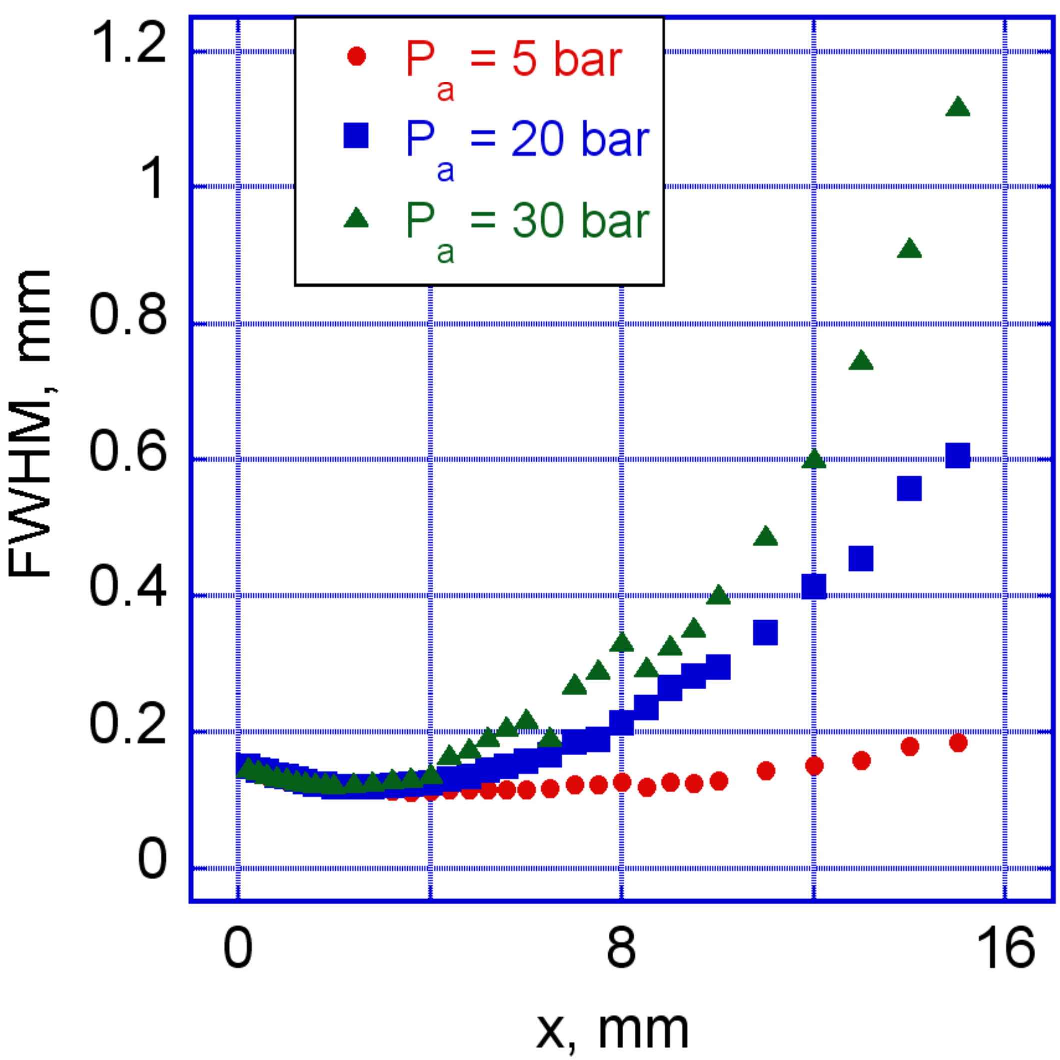
The Influence of Ambient Density on Diesel Spray Structure

- FY2007: 30 bar ambient pressure
- FY2008: Parametric studies of ambient pressure for two nozzles, three injection pressures, two durations
- Effect of ambient pressure has been studied by several groups:

Hiroyasu & Arai SAE 900475: $P^{0.26}$
Naber & Siebers SAE 960034: $P^{0.19}$
Araneo *et al.* SAE 1999-01-0525: $P^{0.5}$

- Important for spray modeling
- X-ray radiography measures the fuel distribution, spray width can be determined quantitatively

Dependence of Spray Width on Ambient Pressure



Hydroground Nozzle

- Steady-state spray width
  - 600-640 µs after SOI
- Features of curves:
  - Initial decrease as distribution transitions from flat-topped to roughly Gaussian
  - Broadens closer to nozzle as ambient density increases
- Difficult to define a cone angle due to curvature

Normalizing x Explains Trends with Ambient Density

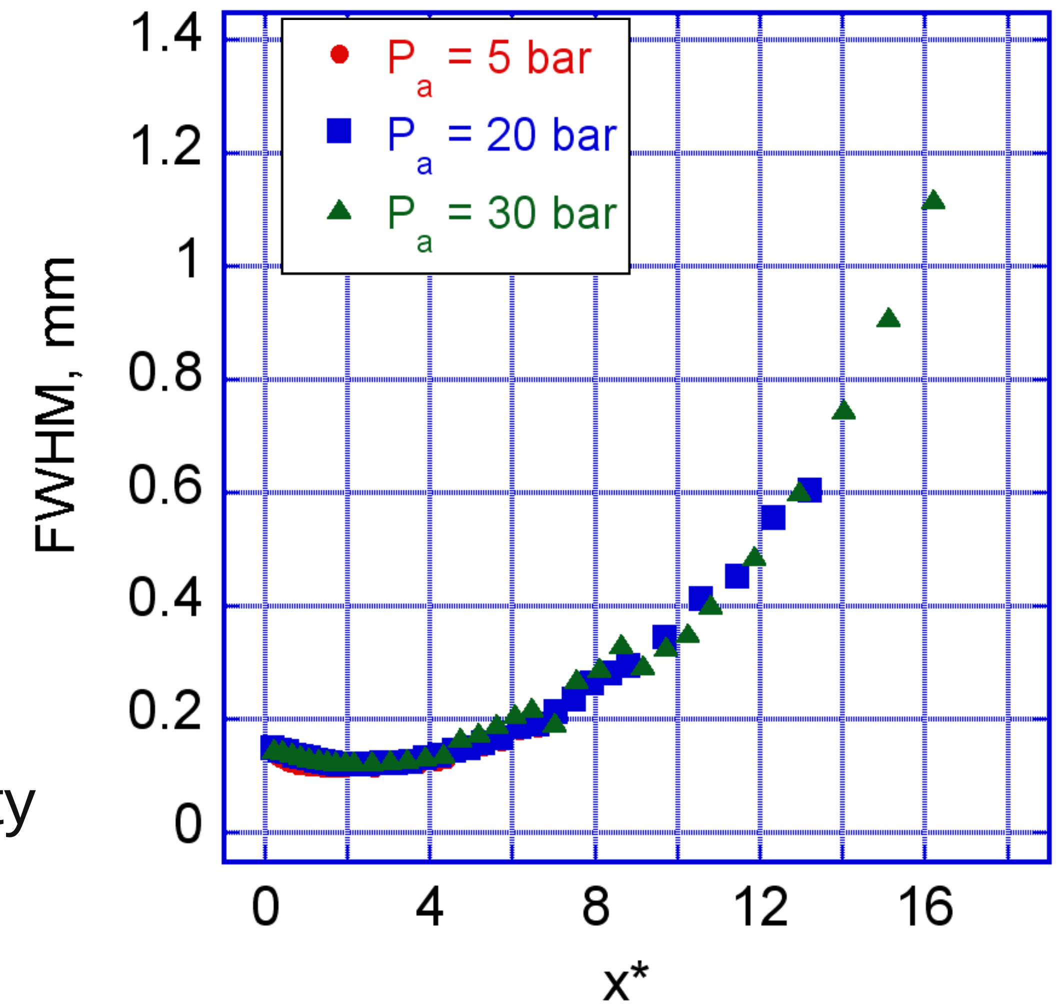
- Literature on variable-density gas jets suggests replacing diameter with:

$$d_{eff} - d_0\sqrt{\frac{\rho_\ell}{\rho_a}}$$

- Normalize *x* by:

$$x^* = \frac{x}{d_{eff}} = \frac{x}{d_0}\sqrt{\frac{\rho_a}{\rho_\ell}}$$

- Accounts for the vast majority of the variation with ambient density



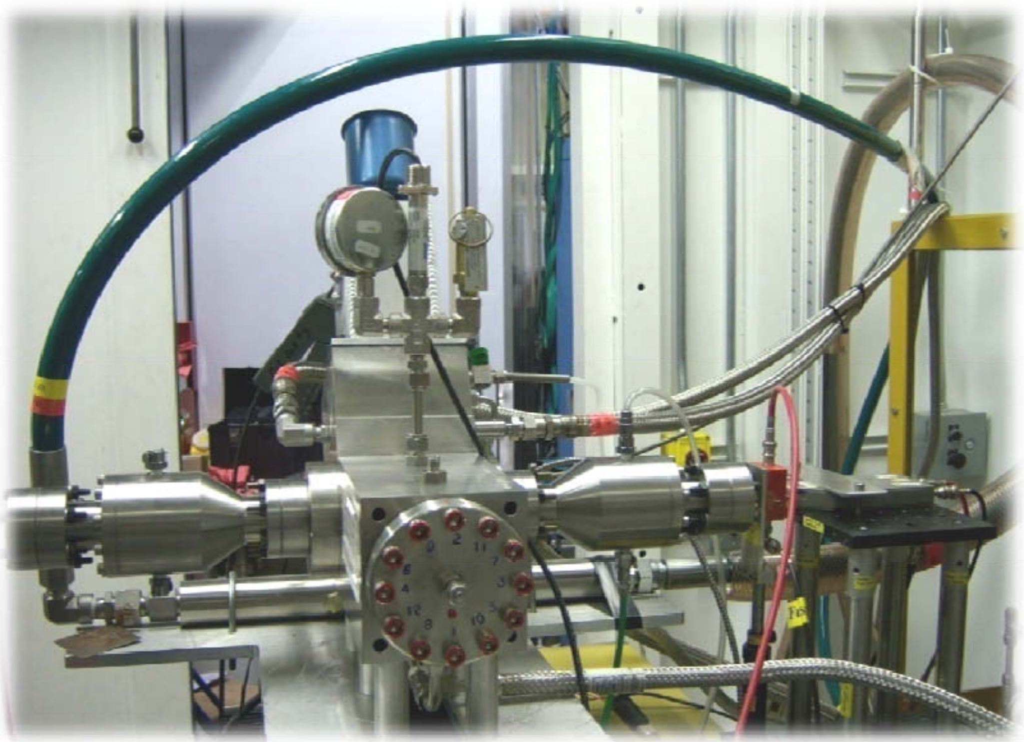
Studies of Heavy-Duty Sprays

- Goal is to link x-ray measurements with engine performance
  - Study sprays using x-ray radiography
  - Perform engine testing with same hardware
  - Use spray/engine modeling to understand link between fuel distribution and engine performance

- Completed x-ray measurements of Caterpillar HEUI 315B
  - Isolated single spray plume from production 6-hole nozzle
  - Measured sprays at two different rail pressures
  - Hardware, spray chamber gas density, fueling match part-load engine conditions

Spray Measurements Under “Engine-Like” Conditions

- Chose conditions that can be attained in engine testing
- Fixed quantity of fuel injected, varied oil rail pressure (injection pressure)



Injection System	Caterpillar HEUI 315B
Number of Orifices	6
Orifice Diameter [μm]	169
Oil Rail Pressure [MPa]	Case 1: 17 Case 2: 21
Oil Temperature [°C]	60
Fill Gas	Nitrogen
Chamber Density [kg/m^3]	34.13
Fuel	Viscor and Cerium additive blend
Fuel Temperature [°C]	40
Amount of Fuel Injected [mm^3/stroke]	100

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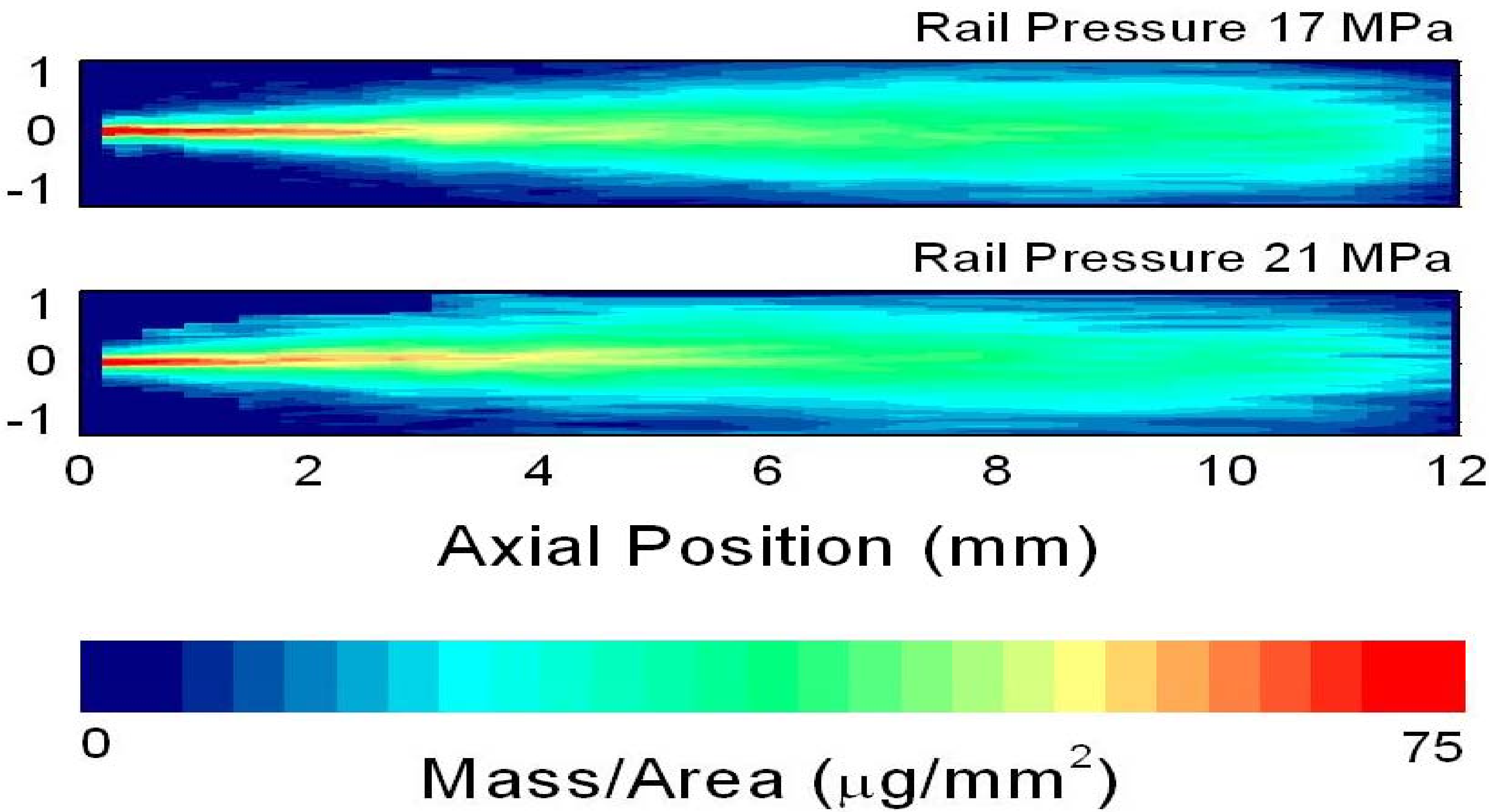
X-Ray Results Point to Areas for Further Investigation



- Near-nozzle fuel distribution is wider at higher injection pressure
- Less fuel clustering at spray's leading edge than other injectors

Engine Conversion to HEUI Fuel Injection Status

- Analysis of x-ray data is ongoing
  - Collaboration with UIC, Ph.D. Thesis of Anita Ramirez
  - Measure fuel distribution, speed, rate of injection, spray width
  - Calculate fuel density

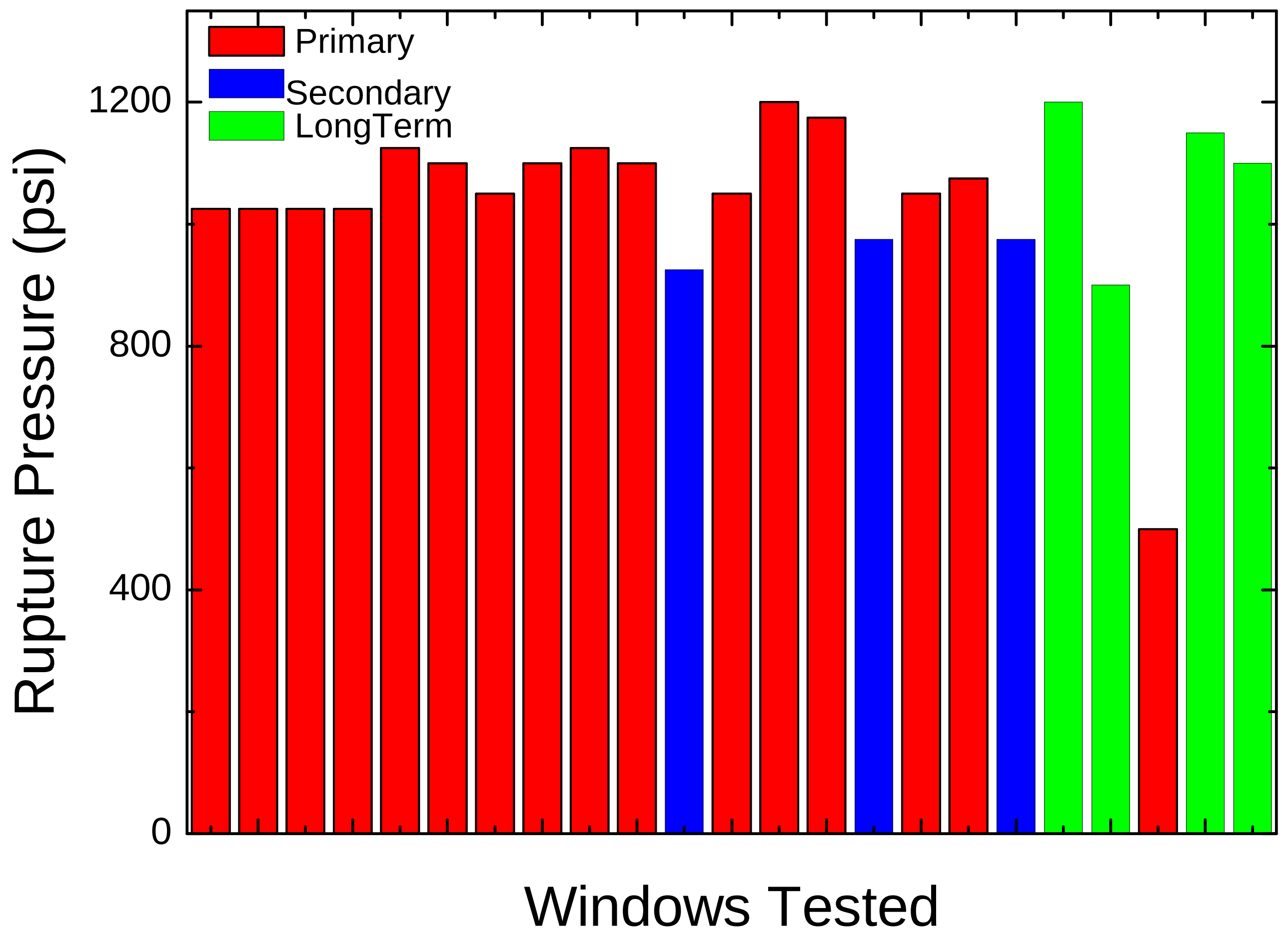
- Computational spray modeling
  - Collaboration with UIC, Ph.D. Thesis of Sibendu Som
  - Can models reproduce the measured fuel distribution?
  - Development of new spray submodels?

- Engine tests in Cat 3401E using Cat HEUI 315B injector at similar conditions
  - 1500 rpm, ½ load (30 kW), ESC Mode 3
  - Endoscopic spray and combustion imaging
  - Emission analysis - Gaseous & PM

- Computational engine modeling
  - Can models reproduce the spray data, combustion data, and engine performance simultaneously?
  - How do changes in the spray impact engine performance?

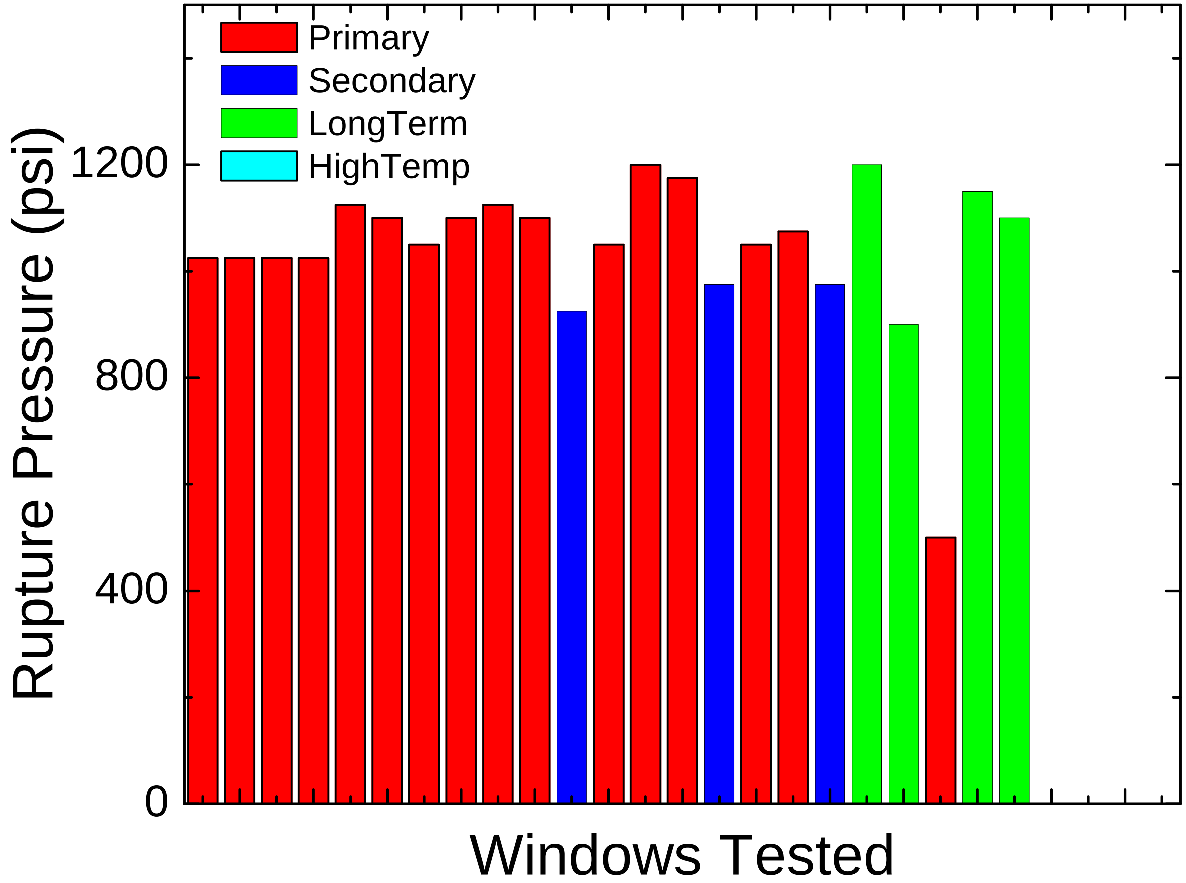
Feasibility Testing of Spray Measurements at High Pressure and Temperature

- X-ray windows are the biggest technical challenge
  - Must be transparent to low energy x-rays
  - Polymer is best choice for high pressure



Feasibility Testing of Spray Measurements at High Pressure and Temperature (continued)

- Elevated temperatures add additional challenges
- Existing windows are polyimide, a high-temperature polymer
- Explore the capabilities of the current windows
- Failure mode may suggest design improvements



Technology Transfer

- **Robert Bosch GmbH**
  - Bosch-ANL publication was presented at ILASS Europe 2007
  - Bosch will send Dr. Philippe Leick to Argonne for six weeks in June 2008.
  - Tests of “state-of-the-art” nozzle geometry for model development
  - Non-proprietary

- **Caterpillar** – Heavy-duty project. Providing tech support for injection system.

- **University of Illinois at Chicago** - Heavy-duty project. Experiments, spray

- **General Motors** - Ongoing collaboration studying effects of nozzle finish and conical nozzles. Most recent measurements Feb 2007

- **Engine Research Center, UW-Madison -** Data analysis for GM collaboration, PhD thesis of Amaury Malave.

- **Wayne State University** – Experiments, modeling, joint publication in preparation.

Plans for Next Fiscal Year

- Measurements of Caterpillar injector have demonstrated feasibility of using production 6-hole injectors
  - Build adapter to mount 3- and 6-hole light-duty injectors in spray chamber
  - Multi-hole nozzles, high pressure, elevated temperature
- Move to Bosch generation 2/3 hardware:
  - Higher injection pressure
  - Study hardware and conditions that match GM-Fiat 1.9 liter
  - Engine is running at Argonne, other labs also have this engine
  - Enables direct comparison between x-ray measurements and Argonne’s full suite of engine diagnostics: endoscopic imaging, emissions, performance.
  - Bosch will donate custom injectors, study variations in injector orifice design (size, conicity, finishing)

Plans for Next Fiscal Year (continued)

- Upcoming experiments with Bosch
  - Explore effects of injection pressure, ambient pressure

- Caterpillar engine tests
  - Cylinder head complete (Injector + Visioscope access)
  - Engine rebuild 50% complete
  - Will measure performance, emissions
  - Modeling will link spray measurements with engine performance

Summary

- Accomplishments:
  - Discovered that spray core width scales with $P^{0.5}$
    Completed first measurements of Caterpillar HEUI system
  - Completed first steps toward measurements at elevated temperature

- Future plans:
  - Adapt CAT chamber for light-duty nozzles
  - Match hardware, conditions of GM-Fiat 1.9 liter
  - Upcoming experiments with Bosch
  - Caterpillar engine tests
    Explore possibility of high temperature measurements

Publications, FY2008

- Kastengren, A., Powell, C. F., Wang, Y.-J., and Wang, J., "Study of Diesel Jet Variability Using Single-Shot X-Ray Radiography," in press, ASME Journal of Engineering for Gas Turbines and Power.
- Kastengren, A., Powell, C. F., Riedel, T., Cheong, S.-K., Im, K.-S., Liu, X., and Wang, J., "Nozzle Geometry and Injection Duration Effects on Diesel Sprays Measured by X-Ray Radiography", in press, ASME Journal of Fluids Engineering.
- Miers, S., Kastengren, A., El-Hannouny, E., and Longman, D., "An Experimental Investigation of Biodiesel Injection Characteristics Using a Light-Duty Diesel Injector," ASME Paper ICEF 2007-1735, ASME Internal Combustion Engines Division Fall Technical Conference, Charleston, SC, October 2007.
- Kastengren, A., Powell, C. F., Wang, Y.-J., and Wang, J., "Study of Diesel Jet Variability Using Single-Shot X-Ray Radiography," ASME Paper ICEF2007-1663, ASME Internal Combustion Engines Division Fall Technical Conference, Charleston, SC, October 2007.
- Kastengren, A., Powell, C. F., Wang, Im, K.-S., Y.-J., and Wang, J., "Measurement of Biodiesel Blend and Conventional Diesel Spray Structure Using X-Ray Radiography," ASME Paper ICES 2008-1646, ASME Internal Combustion Engines Division Spring Technical Conference, Chicago, IL, April 2008.
- Kastengren, A., Powell, C. F., Wang, Im, K.-S., Y.-J., and Wang, J., "X-Ray Radio graphy