Development of Advanced Diesel Particulate Filtration (DPF) Systems

(ANL/Corning/Caterpillar CRADA)

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DOE Merit Review

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Motivation of Current DPF CRADA Project

- PM Emission Standards (2007 - 2010): U.S. Federal
  - Heavy-duty: 0.01 g/bhp-hr (90% reduction)
  - DPFs are known to be most promising for the efficient control of PM emissions.
- *"Corning wants to further improve material properties, related to the pore structures, durability, filtration/regeneration efficiencies, and back pressure."*
- *Caterpillar*
  - *Technical and intellectual capabilities of Argonne will provide the fundamental understanding necessary to derive efficiency of aftertreatment systems.*
  - *Working closely with the industry leader in PM filtration will accelerate the learning process and eventually a choice of diesel aftertreatment technology.*

Purpose of Work

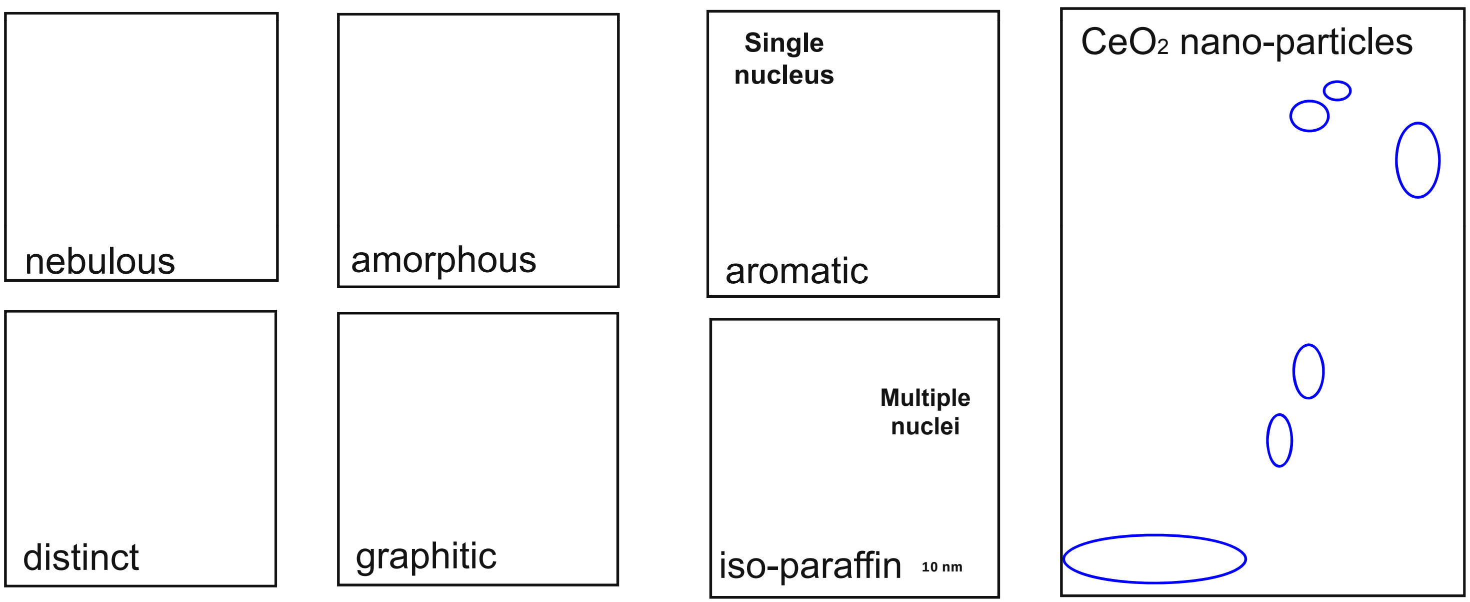
- Characterize filtration and regeneration processes in the course of visualization (both still and video images) by micro-imaging system.
  - Establish a bench-scaled flow reactor (which simulates filtration and regeneration processes of DPFs), and a μ-imaging system (which consists of a stereo-microscope, CCD camera, and image acquisition software).

- Provide efficient filtration/regeneration strategies for industry sponsors.
  - Reduce the DPF pressure drop
  - Evaluate material durability caused by regenerations and ash build-up
  - Reliable start of regeneration at low exhaust temperatures (elec. heater, fuel injection)
  - Thermal run-away control
  - Characterize properties of deposits (soot cake & ashes) in terms of morphology, nano-structures, and chemistry
  - Characterize properties of nano-particles (< 100 nm) and find control technologies

- Parametric studies
  - Engine operating conditions → Effects of particle size, fractal geometry, chemistry
  - Exhaust gas compositions (NO_x, O_2)
  - Filter material and geometry (Cordierite vs. SiC, catalyst, pore size, porosity)

Previous Review Comments

- Other institutes, such as Univ. of Minnesota, Michigan Tech., and PNNL, have done similar work.
  - Detailed microscopic analysis on DPF filtration and regeneration processes have not been done yet. Instead, they mostly conducted DPF system performance tests on engines or vehicles.
  - Detailed morphological characteristics of PM emissions have not been considered in their research. For examples,



Engine operating conditions effects

Nano-structures effects

Fuel properties effects

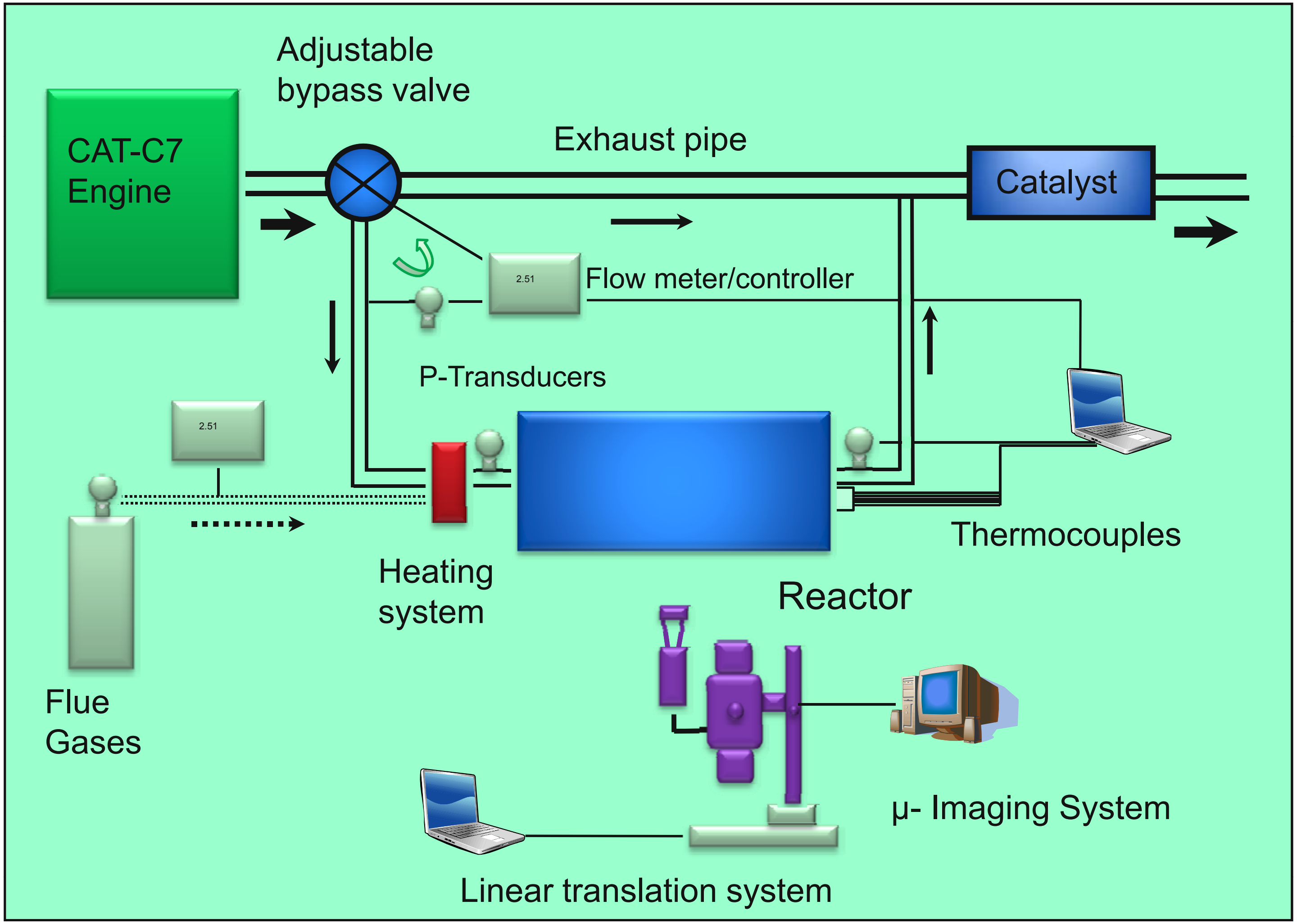
Fuel additives effects

Barriers

- PM filtration mechanisms have not been revealed to the same scale as nano-sized diesel particulates.
  - Nano-particle control technologies.
- PM regeneration causes material failure during the period of high thermal-energy release, due to thermal run-away.
  - Optimal regeneration schemes.
- Use of DPF systems may result in an excess energy consumption.
  - Operational schemes of DPF system with minimized energy input.
- A high-resolution μ-imaging system is required to provide images for diesel particulates and filter-membrane structures.
- Experimental equipments and conditions must be scaled down for bench-tests.

Approach

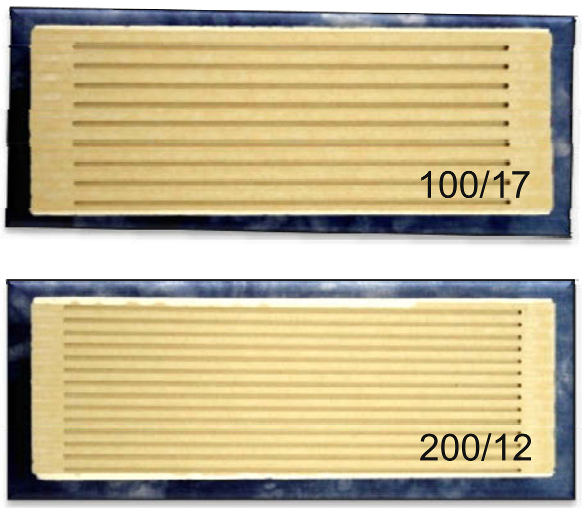
- Schematic of Experimental Setup



Accomplishments

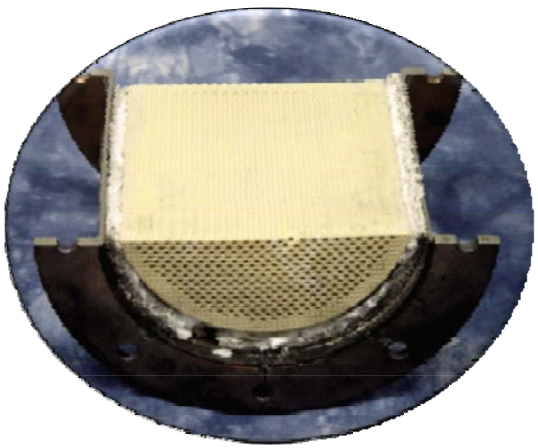
Contributions from industry sponsors have been significant

- Corning
  - Wall-flow type cordierite membranes (full/bench scales, various models) with detailed material properties
  - Accurate diamond-cutting, canning, and assembly-part supply



Φ2” X 6” bisected
(bench scale)

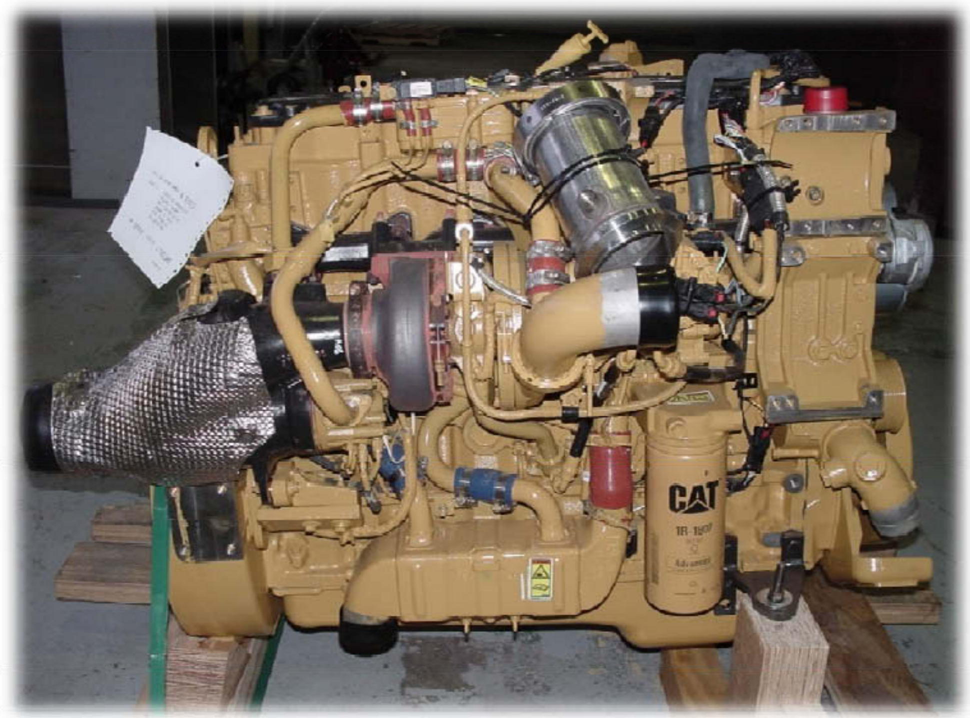
Φ2” X 6”
Canned DPF



Φ5.66” X 6” bisected
(Full scale)

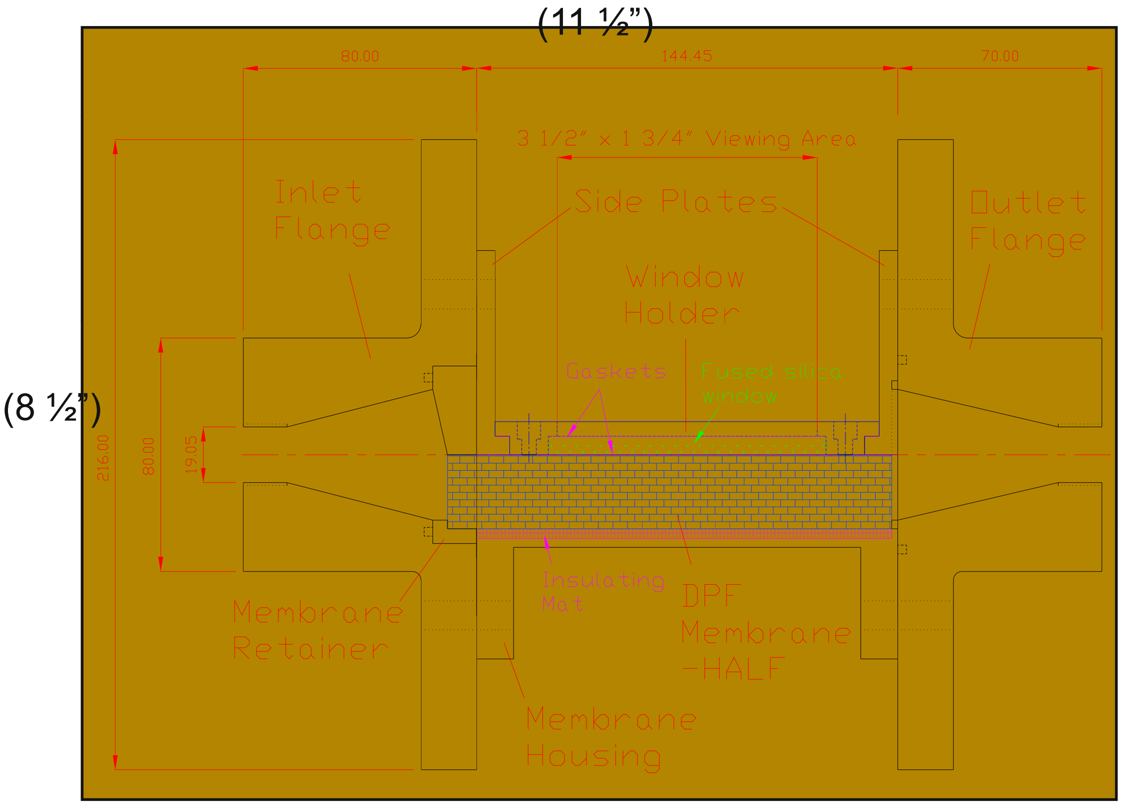
Contributions from Industry Sponsors (cont'd)

- Caterpillar
  – Catalytic coating of membranes
  – Development of a diesel-simulating combustor for PM generation.
  – A most advanced 2007 model C7 diesel engine has been delivered to Argonne (07 EPA Certified).

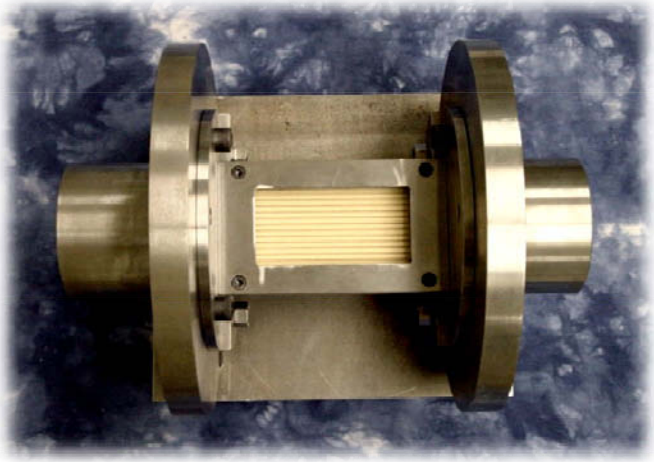


- 7.2L Inline 6-cylinder, DI, T/C, EGR
- CAT Common-rail Injection
- 350 hp max @ 2400 rpm; 860 lb-ft @ 1440 rpm
- The engine requires aftertreatment system to comply with 07 EPA emissions regulations.

A unique Flow/Thermal Reactor has been designed and fabricated successfully

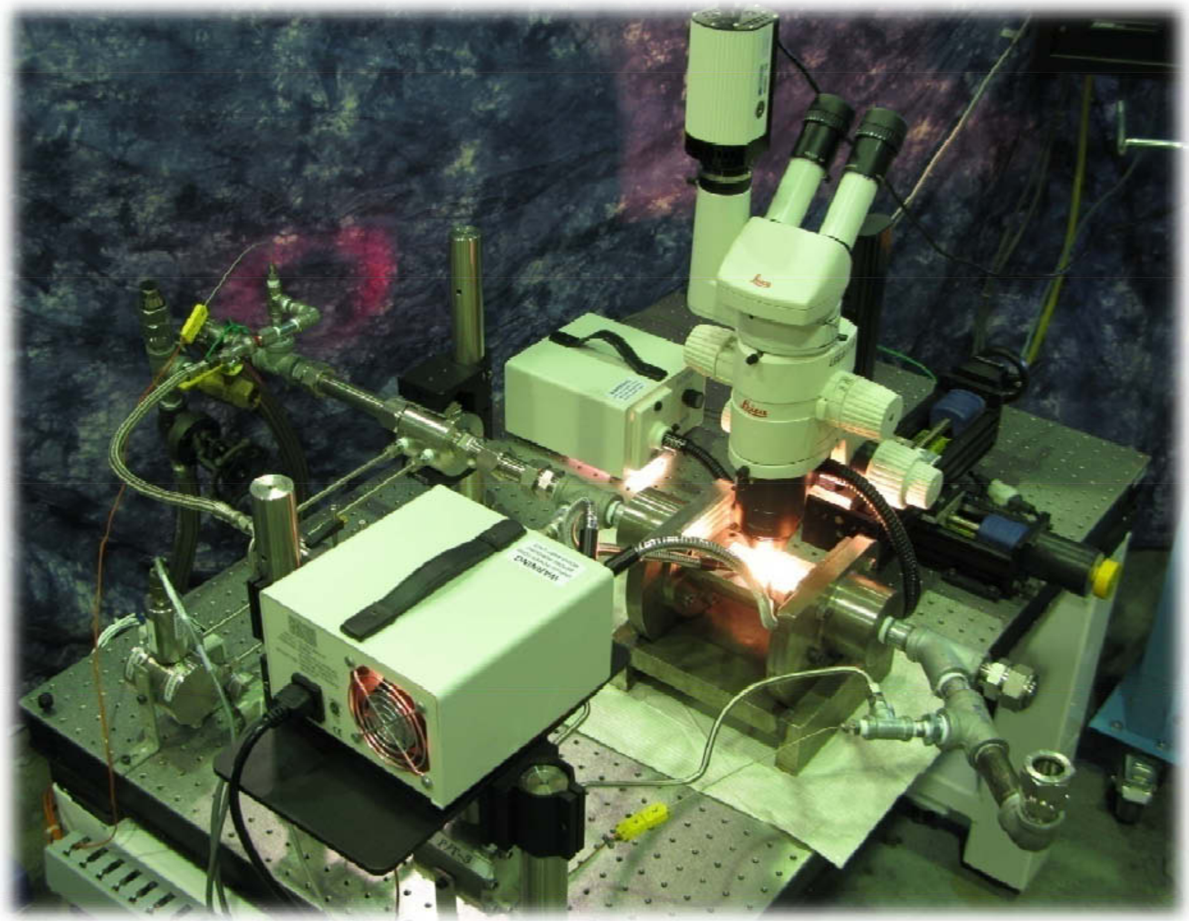


Auto-CAD design completed with safety review



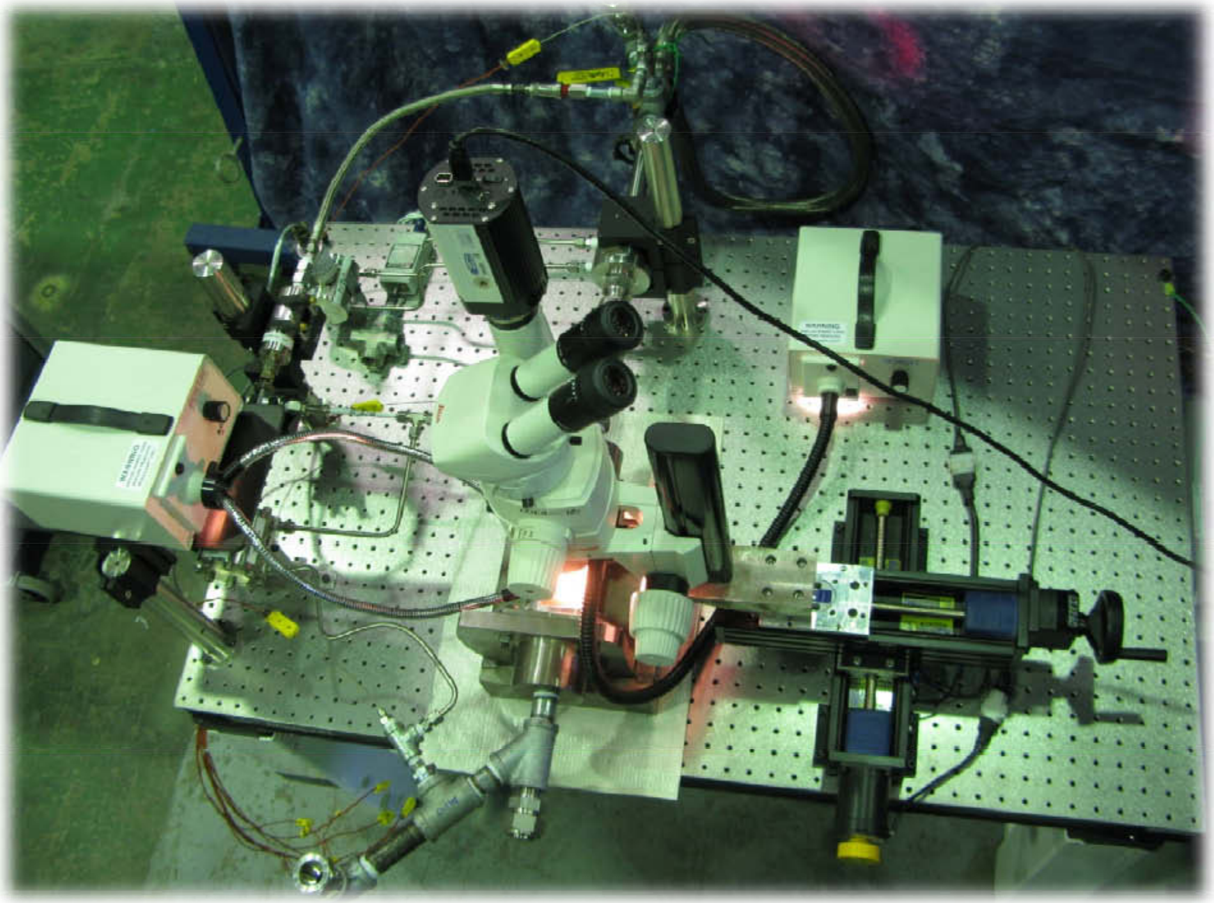
- Module design
- Durable design; a total weight of 50 lb
- Air-tight visualization quartz window:
  3-1/2” x 1-3/4

The State-of-the-art stereo-microscopic imaging system provides unprecedented high-resolution still and video images



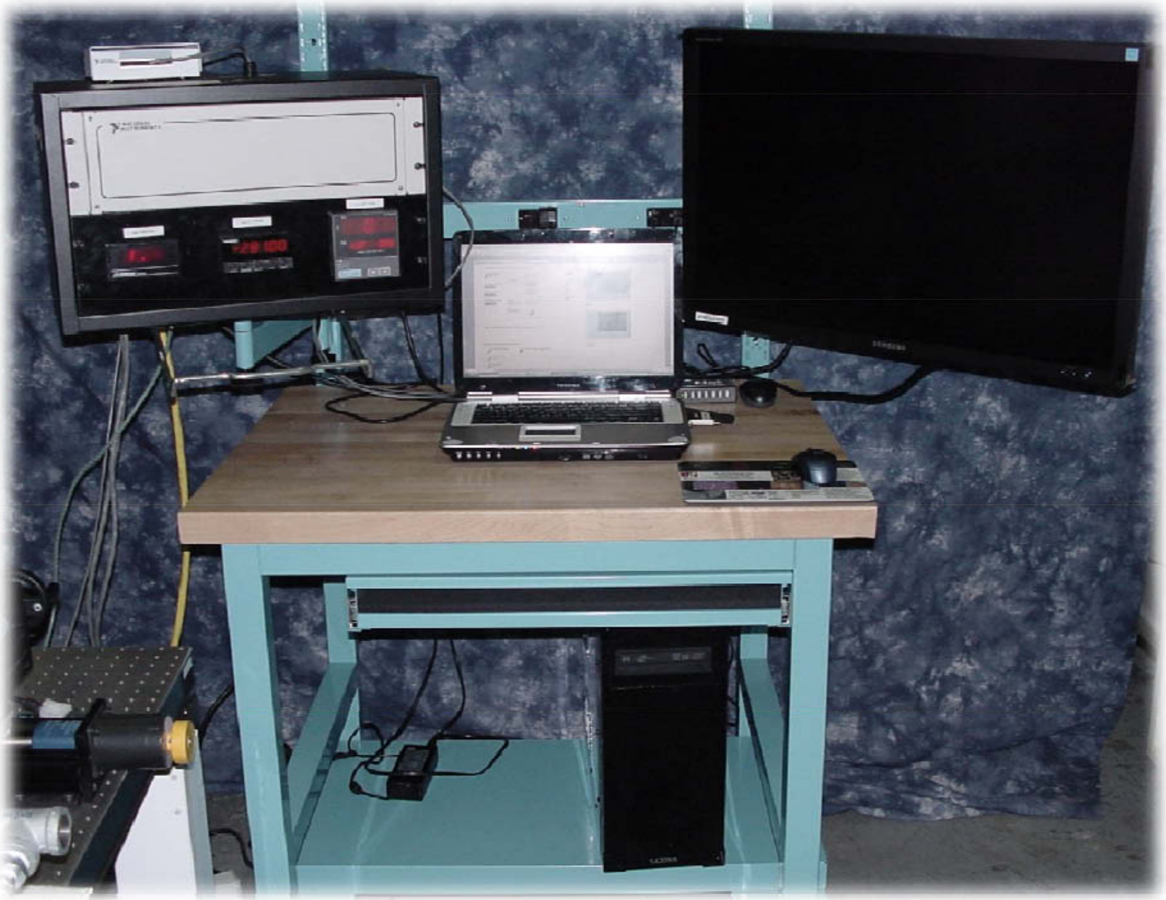
- Leica stereo-microscope (x640)
- Q-Imaging Retiga-EXI digital color CCD camera:
  - Ultra-high sensitivity and speed
    1920x1040 (1.5M pixels)
  - Video image: 110 fps max; 10 fps @ full resolution
- Two light sources

Microscopic Imaging System (cont'd)



- Pneumatic optical table – vibration free
- X-Y remote/motorized linear translation system
- 3 pressure transducers (abs. & differential)
- 2 flow meters
- 16 thermocouples adaptable

Computer-controlled Data Monitoring/Controlling/Recording Systems



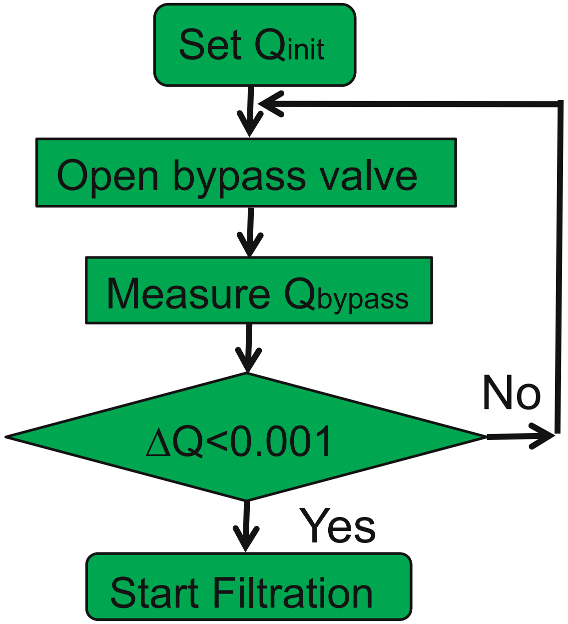
- State-of-the-Art image recording system
  - Total 1.5 terabyte data storage capacity in two hard drives
  - High-speed video streaming software (Streampix)
- Ultra high-resolution 30” monitor (2560X1600)
- Remote control by Labview programming
  - Pressure
  - Temperature
  - Bypass flow

A customized Labview program remote-controls bypassing emissions flows for the lab-scaled membrane

Speed (rpm)	M_{total} (g/min)	T_{exh} (°C)	Q_{exh} (scfm)	Q_{bypass} (scfm)
2400	20088	500	591	9.2
1440	12053	500	355	5.5
700	3054	100	90	1.4

- Membrane volume ratio = 64:1
  (commercial : lab-scale)
- 7.2L CAT C7 engine

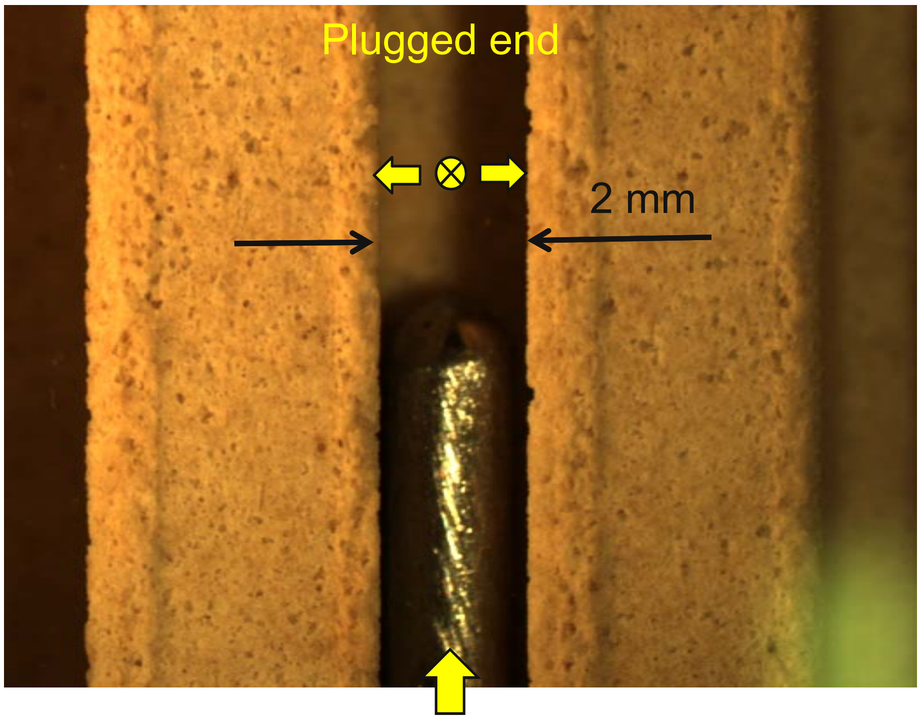
- Bypass Control Scheme



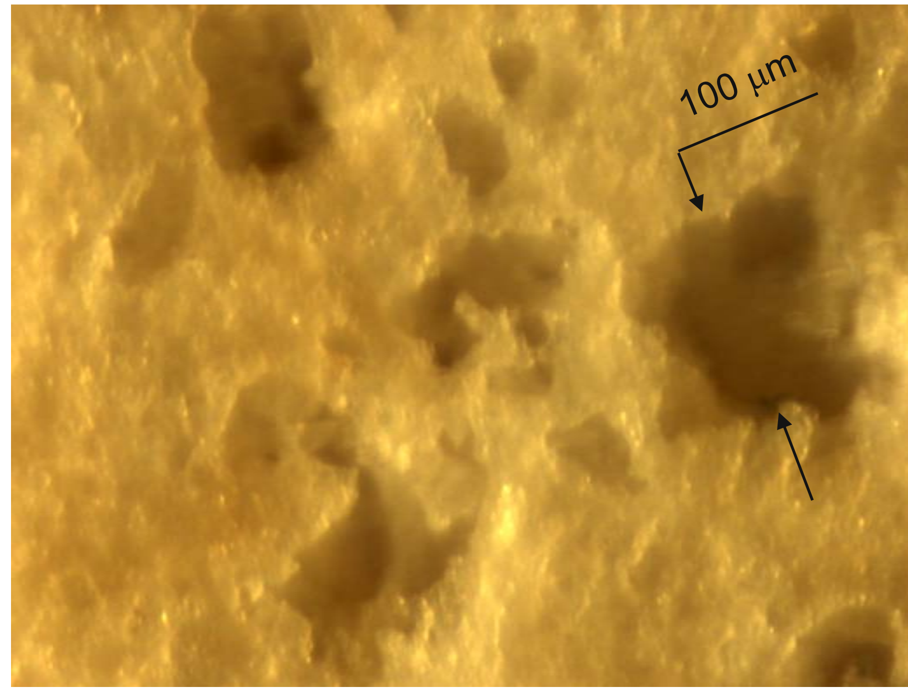
The DPF testing system needs to be integrated with the CAT's most advanced C7 diesel engine installed on a dynamometer.

Experimental Results

- Microscopic observation of DPF membrane structures has been successful.



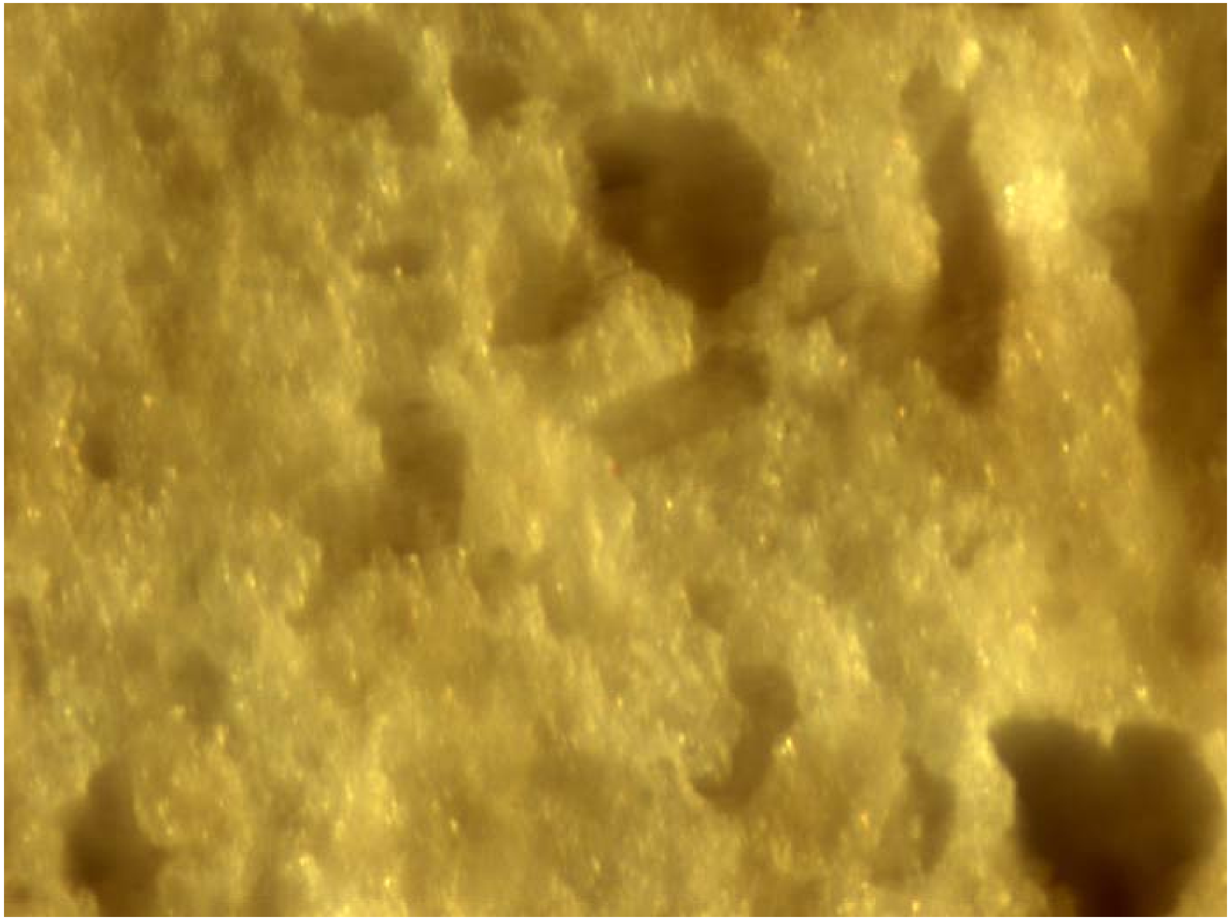
Still image – low magnification (x51)



Video image (10 Sec, 490 Mb)

- Mean pore size: 20 – 30 μm
- Total volume of pores can be measured in collaboration with our Chemistry Div.

The μ-imaging system associated with automated translation system provides an extra capability for material defect inspection



Technology Transfer

- Corning
  - Provide design criteria for developing advanced DPF membrane materials, which are durable for thermal reactions and highly efficient in filtration and regeneration.

- Caterpillar
  - Provide design criteria for developing a low-energy consumption, high-efficiency DPF system, which is optimized for CAT's C7 engine.

FY08 Research Plans and Collaborations

- FY08 research plan
  - μ-images of membrane pores during filtration and regeneration
  - Filtration/regeneration efficiencies; ignition energy consumption
  - Morphology of soot deposits
  - Parameters to be varied
    - Engine speed and load
    - Gaseous emissions composition
    - Inlet gas temperature
  - CAT's C7 engine installation on a upgraded dynamometer
- Collaborating research partners
  - Univ. of Wisconsin – Madison (Prof. Foster)
  - Honda Motor in Japan
- Complimentary Part Supply
  - Iljin Electric Co. (DPF heating systems for regeneration)

Summary

- Experimental setup for DPF filtration and regeneration tests has been completed.
  - Flow reactor with PM sampling system, μ-imaging system, data acquisition system with custom-made Labview programs, remote/auto control systems.
- Visualization of membrane substrates has successfully been achieved at a high resolution.
  - Both still- and video-images.
- In addition, an automated material inspection system has been developed.