Neutron Imaging of Advanced Transportation Technologies

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Advanced Combustion Engines
U.S. Department of Energy

ACE052
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Project Overview

Timeline

- Started in FY2010
- Ongoing study

Budget

- FY2015: $200k
- FY2014: $200k

Partners

- BES-funded neutron scientists and facility operation
- ORNL-internal funding
- Academia
  - University of Tennessee and MIT
- Industry
  - GM, Continental Automotive, MIT consortium members (12+)

Barriers

- **2.3.1B: Lack of cost-effective emission control**
  - Improved regeneration efficiency in particulate filters (PFs)
- **2.3.1C: Lack of modeling capability for combustion and emission control**
  - Improved models of fluid flow inside fuel injectors
  - Need to improve models for effective PF regeneration with minimal fuel penalty
- **2.3.1.D: Durability**
  - Fuel injector durability
  - Potential for PF thermal runaway
  - Ash deposition and location in PFs which limit durability

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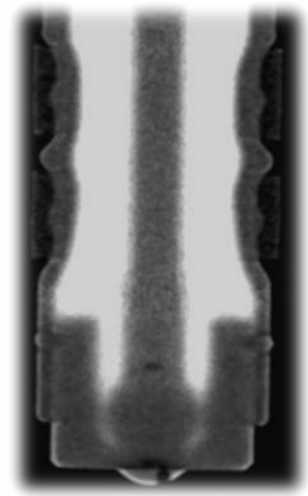
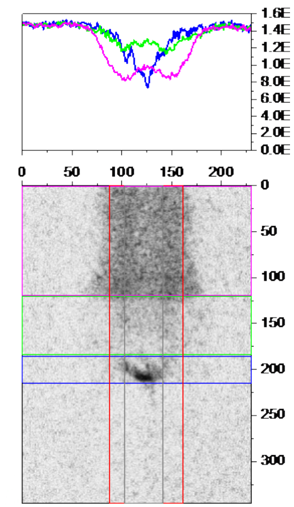
Objectives and Relevance

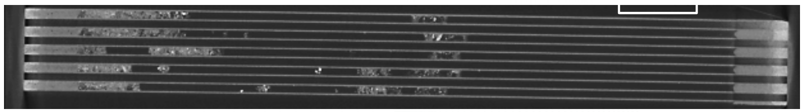
<u>Implement</u> non-destructive, non-invasive neutron imaging technique to improve understanding of advanced vehicle technologies

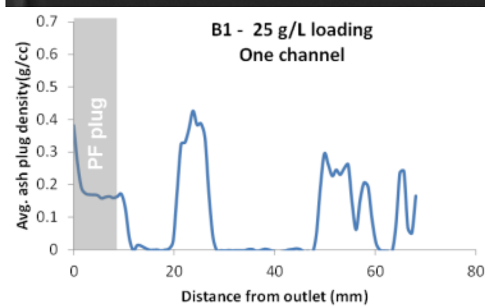
- Injectors: GDI, Diesel, urea
  - Goal: Visualize internal flow dynamics
    - Fluid density variation including location and timing of cavitation
  - Aid model development; injector design
    - Injector design significantly influences efficiency and emissions

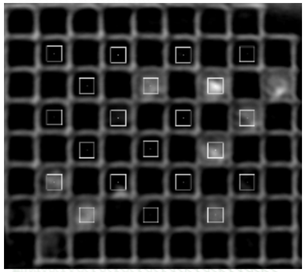




- Particulate filters (PF)
  - Both gasoline and diesel PFs
  - Improve understanding of internal distribution of soot and ash
    - Including density of ash
  - Comprehensive, quantitative device analysis targeting model parameters

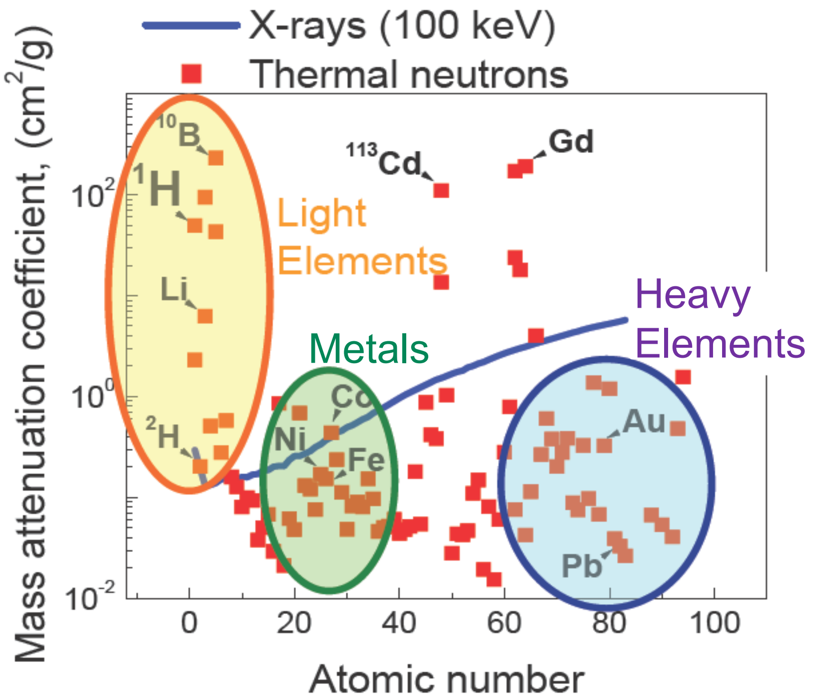


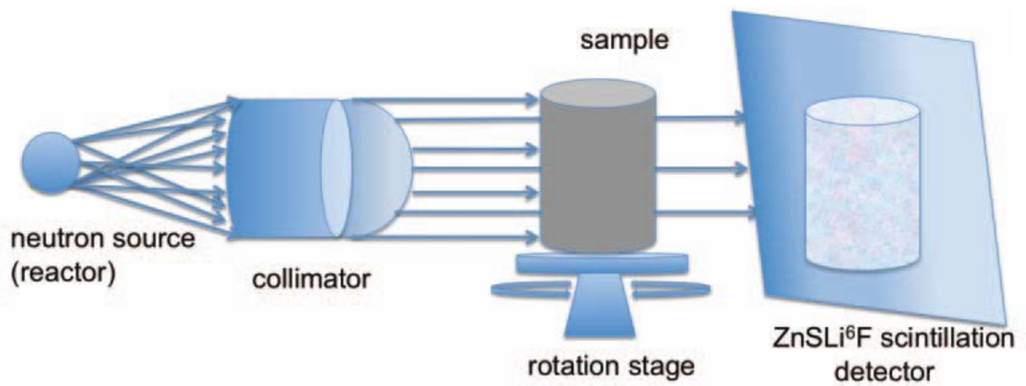




Neutrons are absorbed by a range of elements including light elements

- Neutrons are heavily absorbed by light elements such as Hydrogen and Boron
  - Can penetrate metals without absorbing
  - Highly sensitive to water and hydrocarbons/fuel
    - Can image carbon soot layer due to absorption of water and HC
  - Image is based on absence of neutrons
- X-ray absorption increases for heavy/dense elements



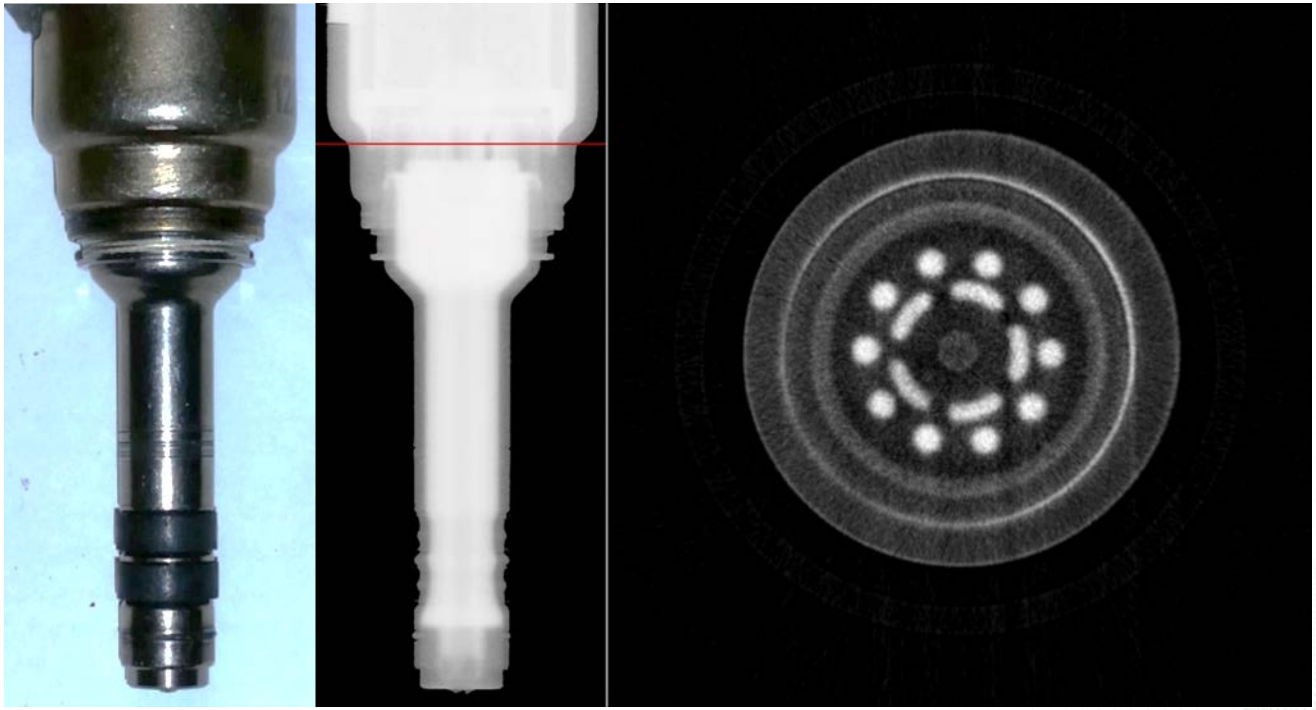


Neutron imaging is a complementary analytical tool

Attenuation Coefficient Reference: N. Kardjilov's presentation at IAN2006
http://neutrons.ornl.gov/workshops/ian2006/MO1/IAN2006oct_Kardjilov_02.pdf

Complete sample analysis can be achieved with non-destructive techniques

- Samples can be analyzed at one cross-section or a complete reconstruction can provide a cross-section of the entire sample
  - Originally ~50 microns achievable at ORNL's High Flux Isotope reactor (HFIR)
  - As low as 10-20 microns possible with MCP(micro-channel plate) detector
- Illustration of technique on GDI-based injector with fuel inside:



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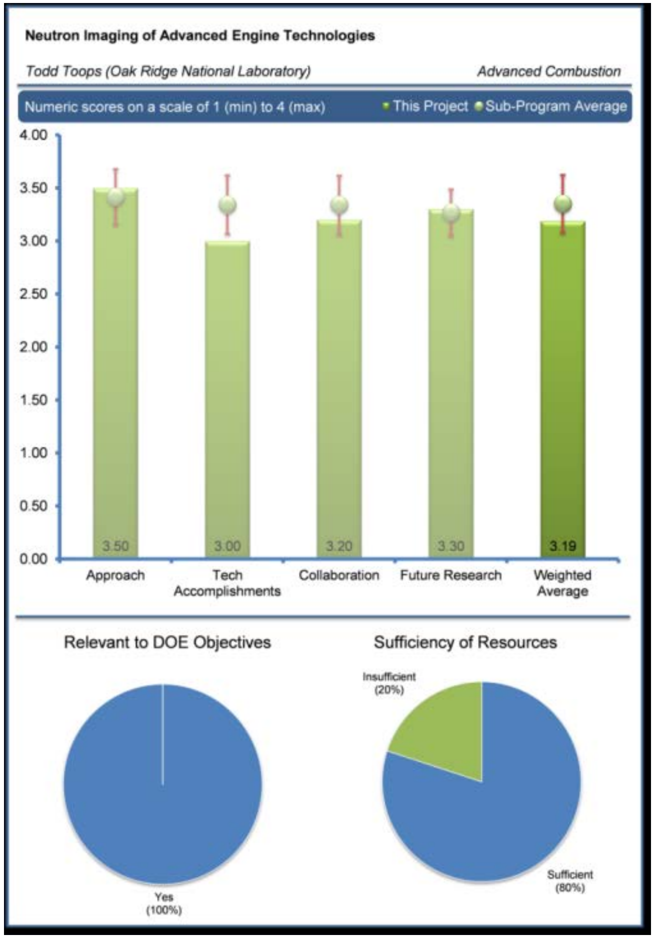
Milestones

- Complete reconfiguration of spray chamber to enable evacuation and heating for outer injector condensation control (6/30/2014).
  - **Completed**
- Image internal fluid during injection using a gasoline direct injection component (9/30/2014).
  - **Completed**
- Synch injector timing with neutron detector timing (3/31/2015).
  - **Completed**
- {SMART} Obtain time-stamped neutron images of injection to study internal fluid dynamics (9/30/2015)
  - **On target/completed**

Collaborations

- **Basic Energy Sciences** (Hassina and Jean-Christophe Bilheux)
  - High Flux Isotope Reactor (HFIR); Spallation Neutron Source (SNS)
  - Development and operation of beamline facilities
  - Scientists time, data reconstruction, analysis and writing publications
- **University of Tennessee** (Jens Gregor, Alex Pawlowski)
  - JG: Developing algorithms for improving contrast, 3-D tomography and removing artifacts
  - AP: Bredesen Center Fellow, CAD development, image analysis
- **GM** (Ron Grover, Scott Parrish)
  - Coordination of injectors, fluid dynamic modeling
- **Continental Automotive** (Bill Imoehl, Nic Van Vuuren)
  - Ash filled DPFs, X-ray CT-scans and detailed analytical discussions
- **MIT Consortium** (J. Kamp, A. Sappok, V. Wong, 12+ members)
  - Ash filled DPFs, X-ray CT-scans and detailed analytical discussions
- **University of California** (Anton Tremsin)
  - Development and installation of MCP detector at ORNL
- **University of Alabama** (Marcus Ashford)
  - Injector exchange; visiting students working on image analysis

Responses to 2014 Reviewers (5) – Neutron

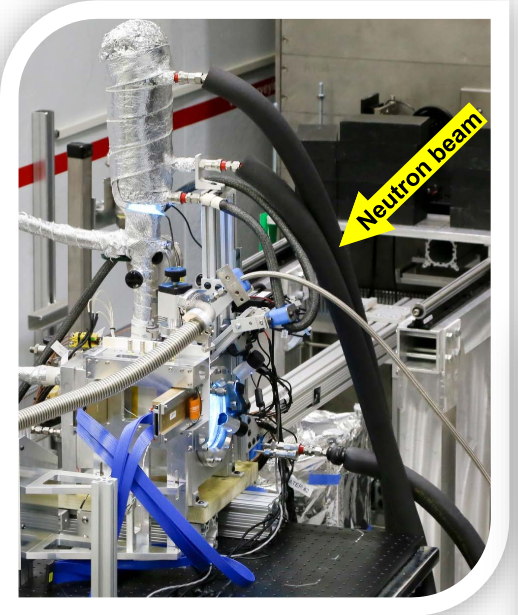


- **Resources**
  - Comments: **great program for the money**…funding seemed too low to cover significant development

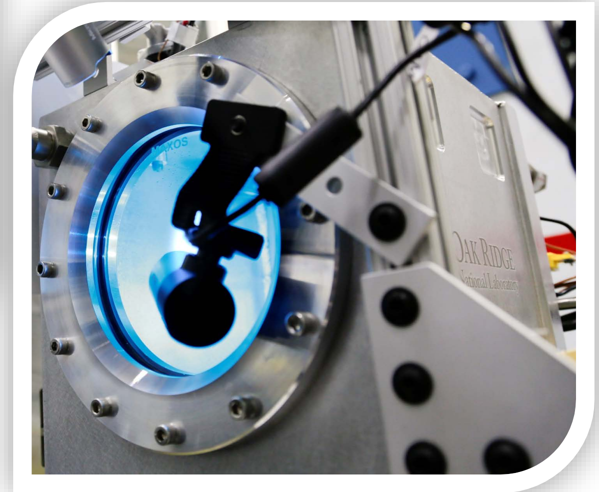
- **Approach (3.5/4.0)**
  - Comments: excellent approach with much potential…good to see more gasoline based measurements
- **Technical Accomplishments (3.0/4.0)**
  - Comments: resolution needs to be improved for injector…**would like to see how these could impact practical issues**…**unclear what to do with the ash loading distribution inside a DPF**
  - Response: Efforts are ongoing on improving temporal and spatial resolution primarily through BES-funded programs…**focusing on proof of principal demonstration will move to practical systems** …**modelers use ash results to understand how soot is distributed in ash filled PFs; want to avoid local high temperatures from soot redistribution**
- **Collaborations (3.2/4.0)**
  - Comments: **involve injector OEM and ANL/APS**…may need to wait until technique adequately developed
  - Response: **have been working more closely with injector suppliers and planning visit to ANL in FY15** …proceeding cautiously; ready to start collaborations once limitations of technique are known
- **Future plans (3.3/4.0)**
  - Comments: progress looks good…future plans logical
- **Relevance (100%)**
  - Comments: novel techniques to support DOE's goals…unique diagnostic provide insight into the behavior of engine components

Approach

Receive or obtain relevant devices

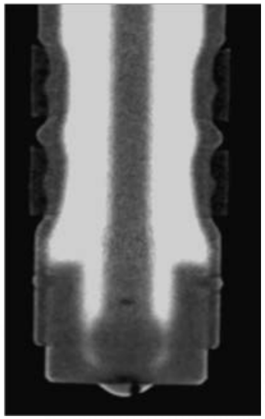


Record raw images of devices with neutron beam, scintillator and/or MCP detector

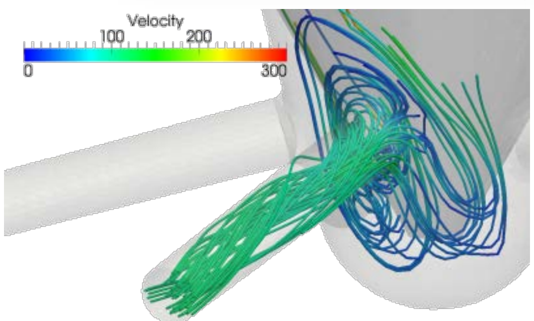


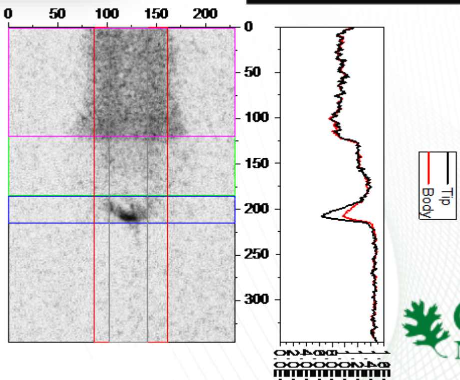
Non-destructive technique allows multiple studies to be performed on single commercial or prototype device

Reconstruct device using or enhance contrast using imaging software



Technique being employed to study both internal geometries and fluid flow during operation; linked to HPC efforts





K. Neroorkar, R.O. Grover, Jr. et al., “Simulations and Analysis of Fuel Flow in an Injector Including Transient Needle Effects”, ILASS-Americas 2012, San Antonio, TX.

Summary of Technical Accomplishments

- Verified applicability of neutron imaging to measure injector fouling in collaboration with Continental Automotive
- Completed quantified ash study in collaboration with MIT
  - identified ash profiles and densities for different regen strategies
- Completed series of GPF studies with varying levels of particulate matter and regeneration levels
  - particulate matter also generated with biofuel blends
- Two dynamic imaging campaigns completed; promising images obtained
  - Two spray chambers commissioned and evaluated
    - Second design necessary to allow more heating and higher flow rates
  - Obtained two series of fuel injection images in evacuated chambers
- Imaged Continental Automotive urea injectors with fluid

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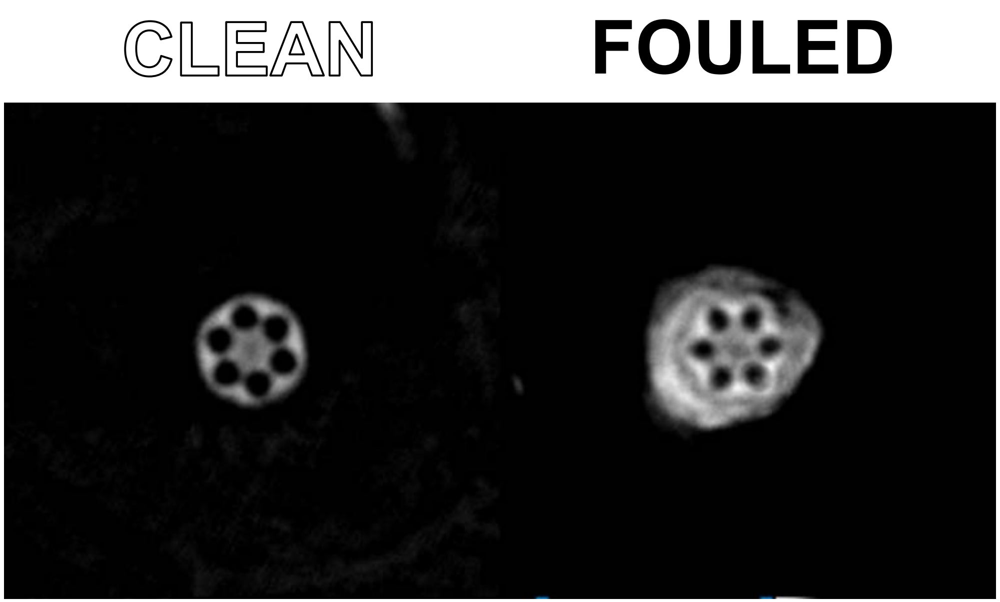
Technical Accomplishments

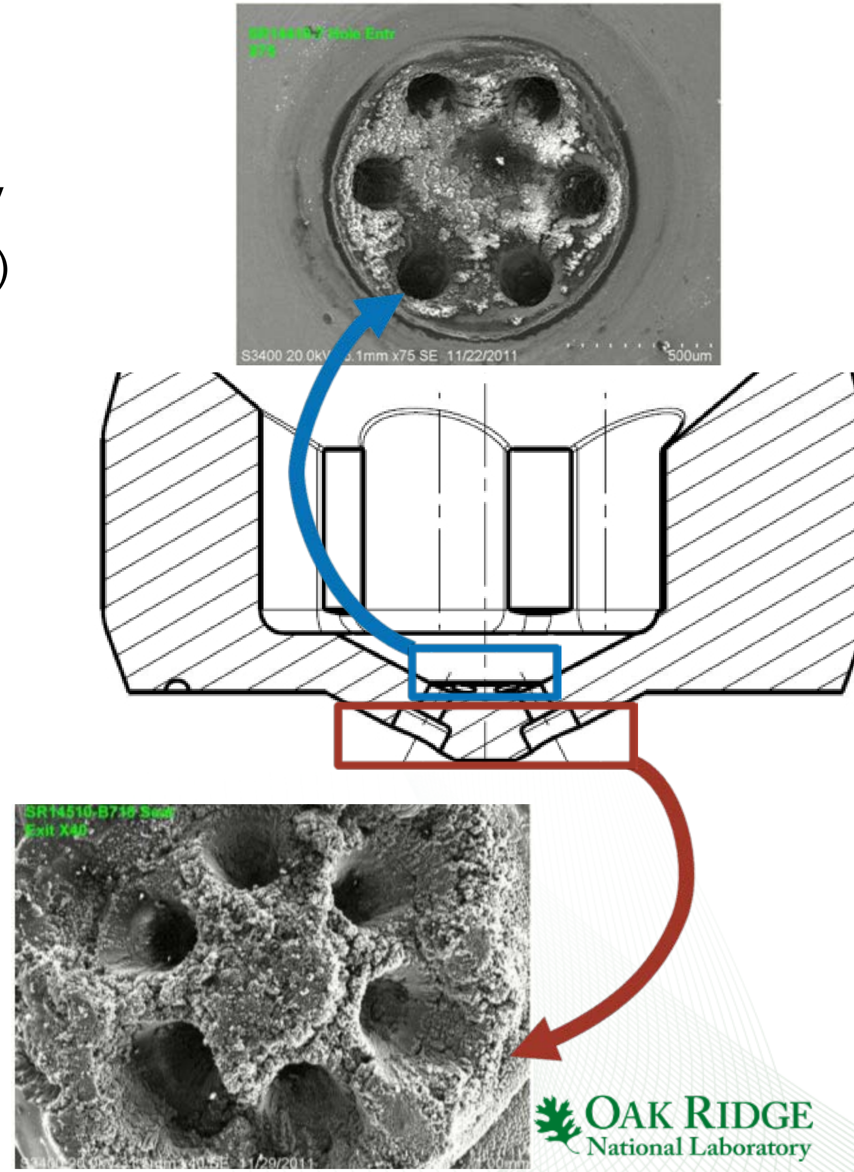
- Fouled injector investigation
- Quantitative ash distribution study in particulate filters
- GDI-generated particulate study in GPFs*
- Dynamic imaging of fluid dynamics inside GDI-based injectors
- Urea injectors*

* - briefly discussed in back-up technical backup slides

Collaboration with Continental Automotive to investigate fouled GDI-based injectors

- Can fouling be detected inside of injectors without cutting them open?
- Follow-on investigation of Continental study
  - W. Imoehl et al. SAE 2012-01-1642 (images)
  - Severe deposit fuel from Afton Chemical
- Un-dissected injectors sent to ORNL





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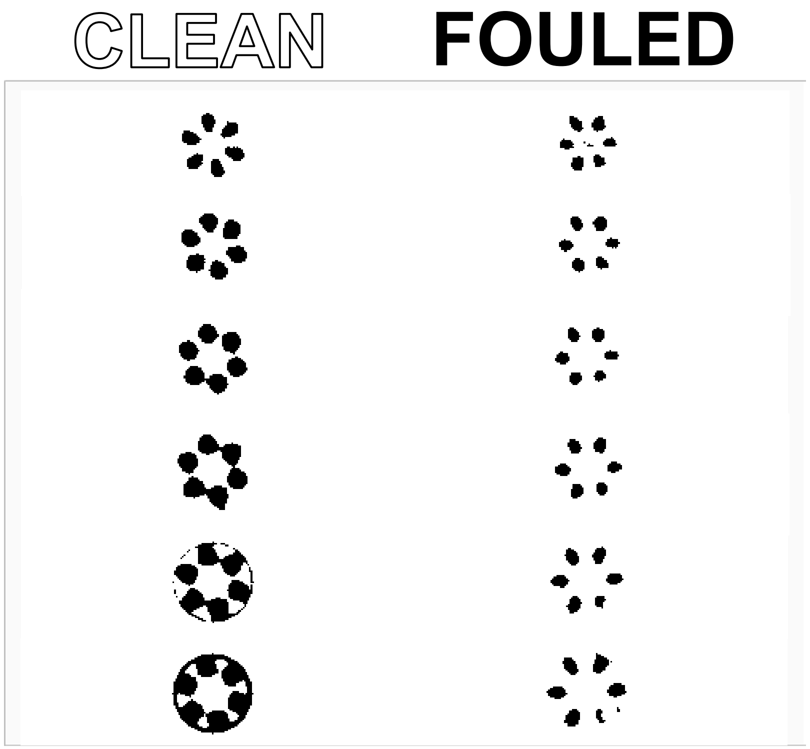
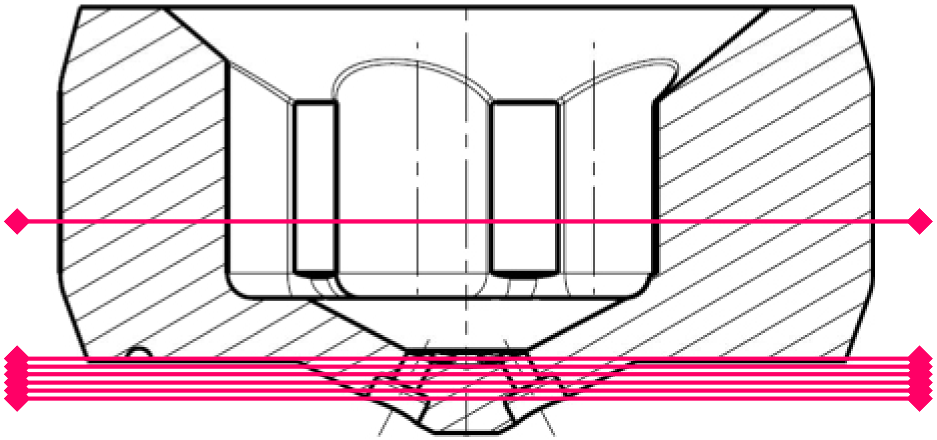
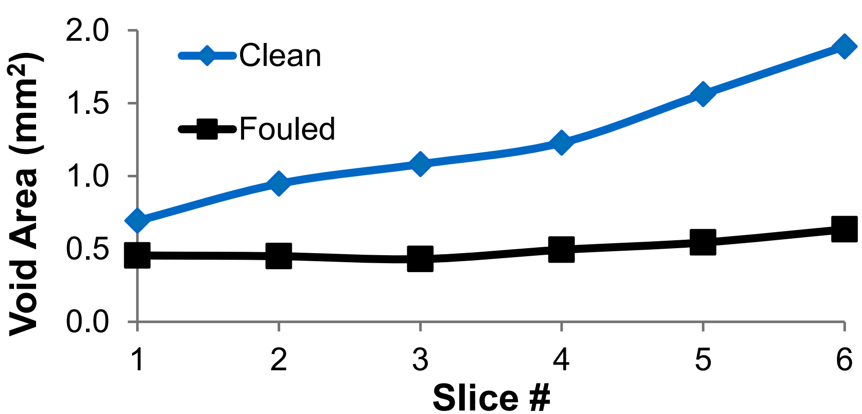
Neutron CT scan indicates deposit formation in non-destructive analysis

- Less void volume in column clean of injector
  - CT scan analysis shows 7% less
- Void difference also observed at pintle tip
  - 20-40% in small orifice







- Fouling evident below internal seal
- Fouling significantly occludes injector holes and is readily detected
  - 30-65% occlusion calculated at 6 slices
  - Consistent with destructive SEM images

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Technical Accomplishments

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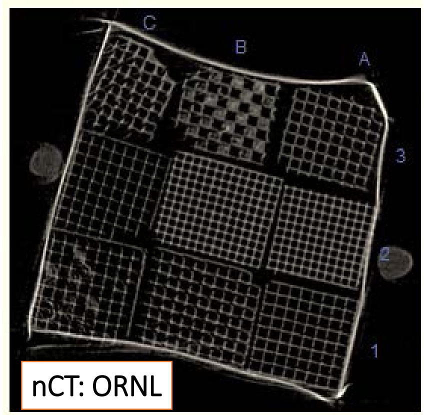
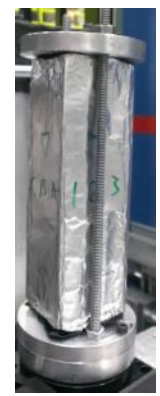
* - briefly discussed in back-up technical backup slides

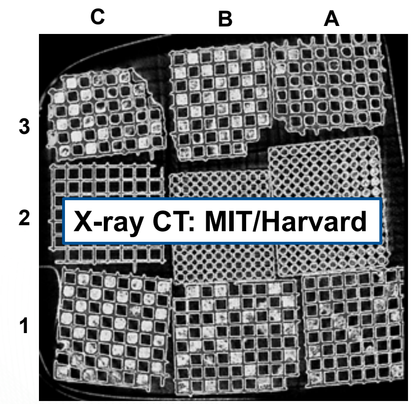
Collaboration with MIT consortium to analyze ash distribution and impact of regeneration strategies

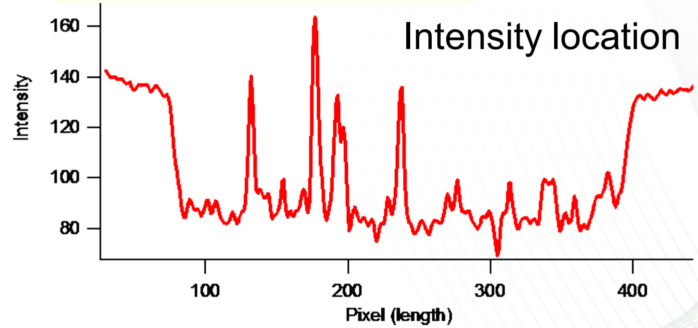
- Well-characterized samples
- Regeneration procedures
  - Continuous, passive
    - Held at 350˚C; NO_2-regen
  - Periodic, passive
    - 250˚C to 400˚C,
    - PM allowed to accumulate
    - NO_2-regen
  - Periodic, active
    - Soot load at 250˚C
    - Regeneration at 620˚C
- Quantify ash densities in a series of DPF sections from MIT studies
  - Neutrons at ORNL
  - X-rays at MIT/Harvard
  - CJ4 ash standard: 0.52 g/cc
    - Neutron: 12.9 g/cc/"count"

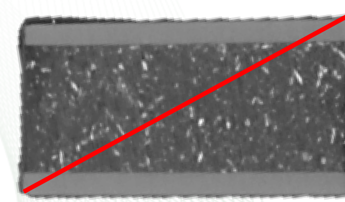
Regeneration process	DOC (Y/N)	Ash load
A1. Continuous, passive	Y	25.2 g/L
B1. Periodic, passive	Y	25.0 g/L
C1. Periodic, passive	N	24.6 g/L
A3. Periodic active	N	12.5 g/L
B3. Periodic active	N	42 g/L





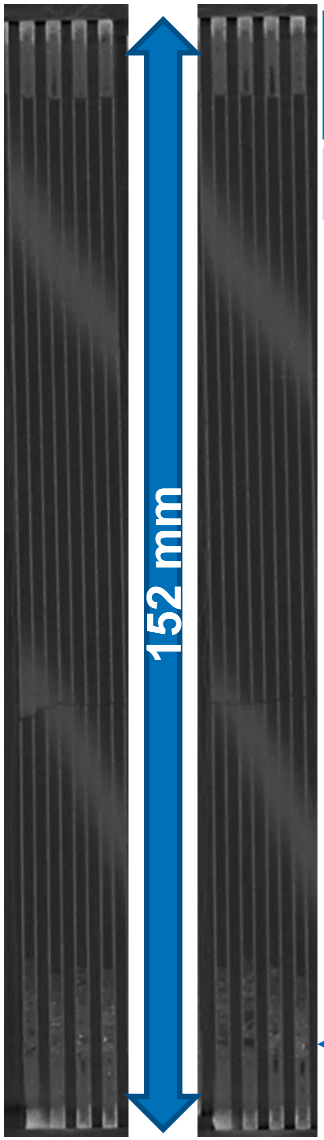




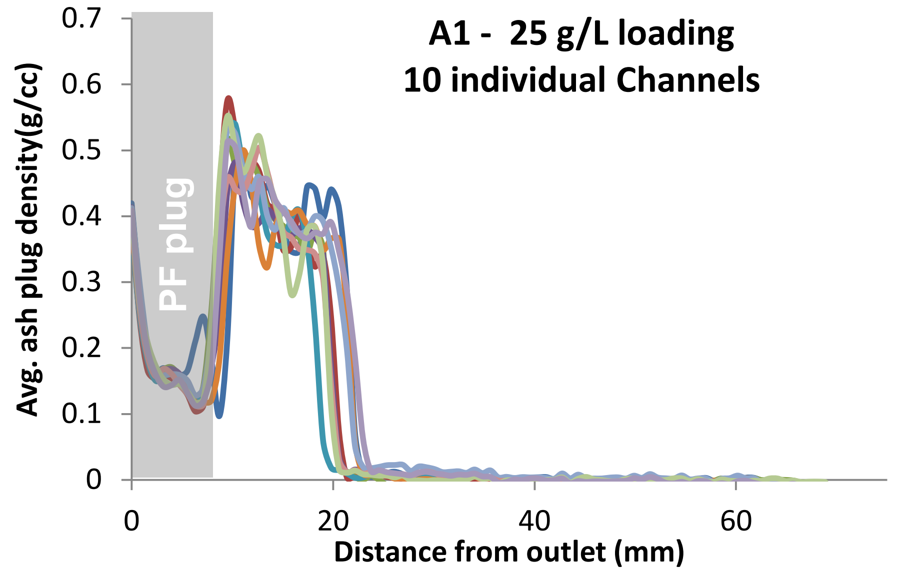


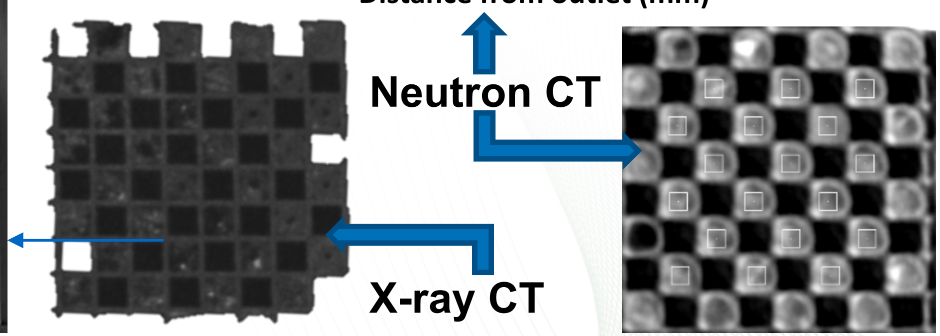
Continuous, passive regeneration resulted in uniform plugs with a packing density of 0.4 g/cc

- Ash plug observed at back of channel
  - Can be differentiated from PF cordierite plug
- Average ash density across single channel determined
  - Isolate area of interest to ensure no overlap with cordierite wall
  - Calculate average “counts” over area
    - Use factor from standard
- Ash distribution is very uniform



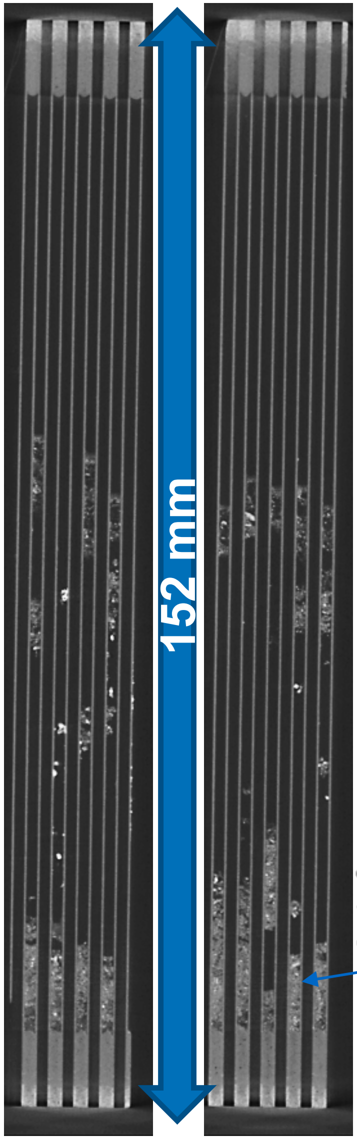
Description of regeneration process	DOC (Y/N)	Ash load
A1. Continuous, passive	Y	25.2 g/L



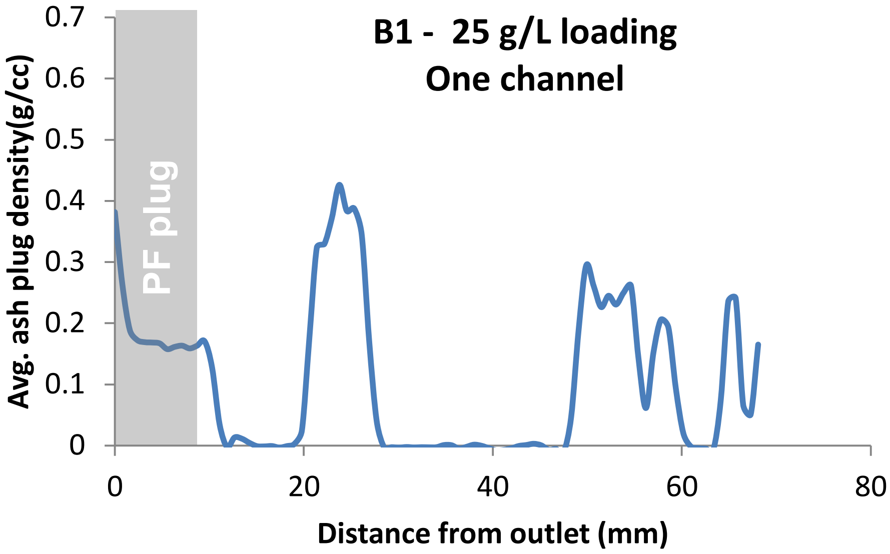


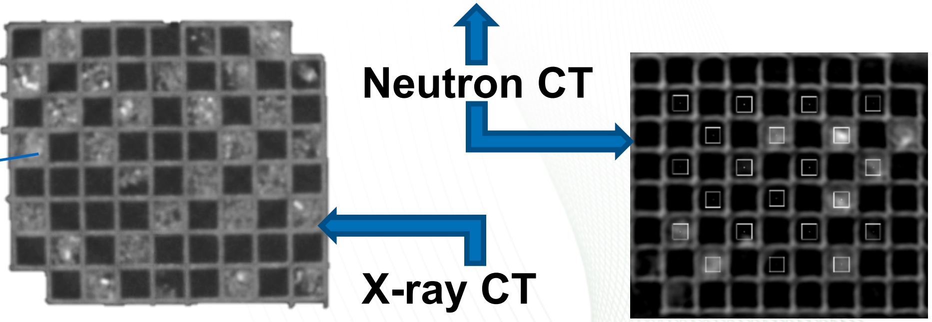
Periodic, passive regeneration resulted significant blockages with high fraction of dense ash particles

- Significant gaps observed
  - Ash "blockades" observed in middle of PF
  - Channel to channel variation is high
    - Average density across channels is misleading
- Large voids and mid-channel deposits consistent with some field observations
  - Possible correlation to poor passive regen



Description of regeneration process	DOC (Y/N)	Ash load
B1. Periodic, passive	Y	25.0 g/L





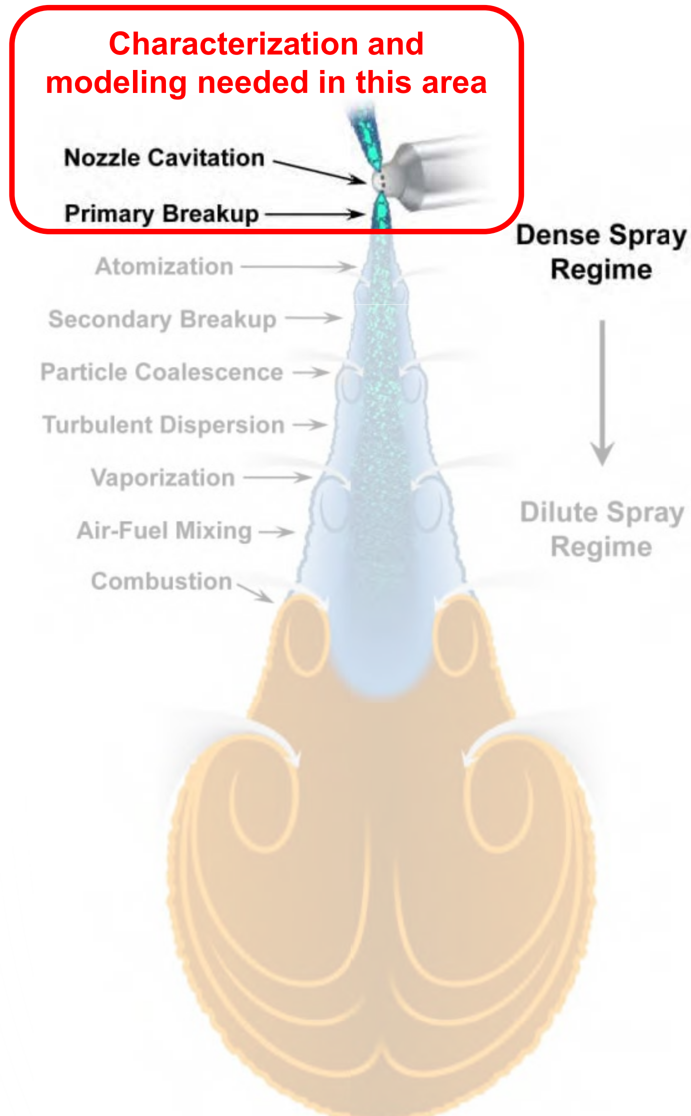
Technical Accomplishments

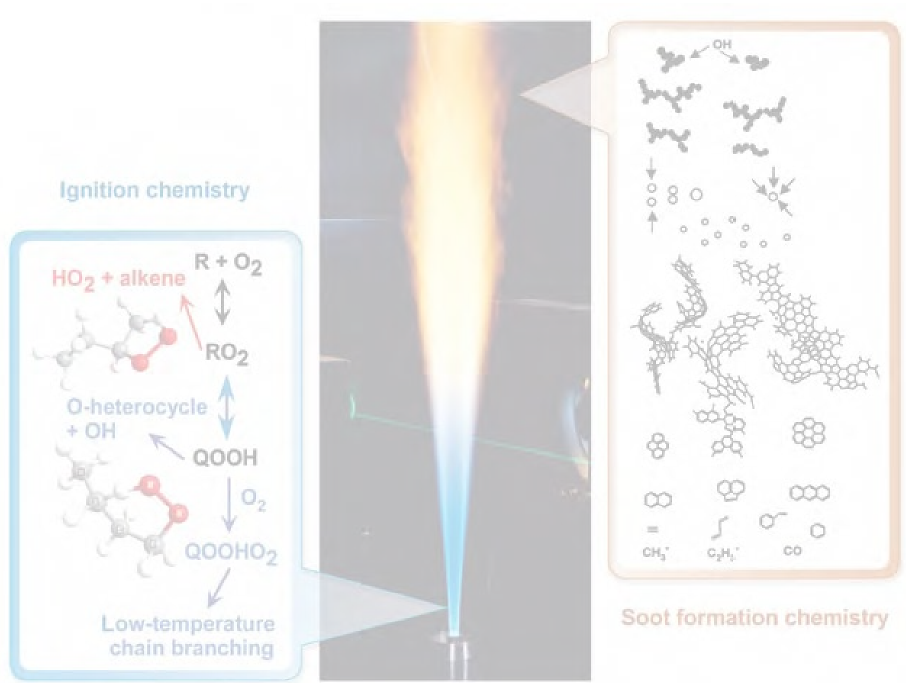
- Fouled injector investigation
- Quantitative ash distribution study in particulate filters
- GDI-generated particulate study in GPFs*
- Dynamic imaging of fluid dynamics inside GDI-based injectors
- Urea injectors*

* - briefly discussed in back-up technical backup slides

Spray pattern and impact on product formation has been heavily studied, but critical information is still needed

- Events occurring in the injector impact the spray dynamics and product distribution
  - Products form at different points in fuel spray
- Knowledge of how internal dynamics/events affect the spray pattern are not well understood
- Improved diagnostics critical to make this connection



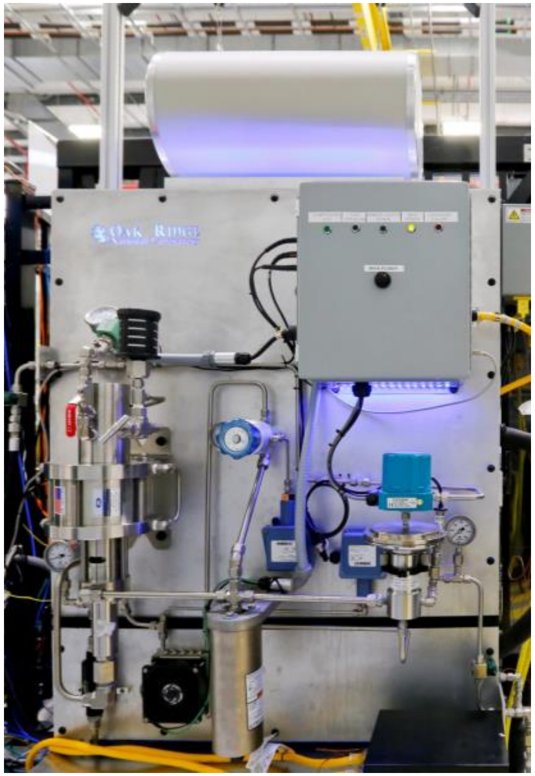


DOE report, "A Workshop to Identify Research Needs and Impacts in Predictive Simulation for Internal Combustion Engines (PreSICE)", March 3, 2011.

Designed and implemented two generations of spray chambers for dynamic neutron imaging*

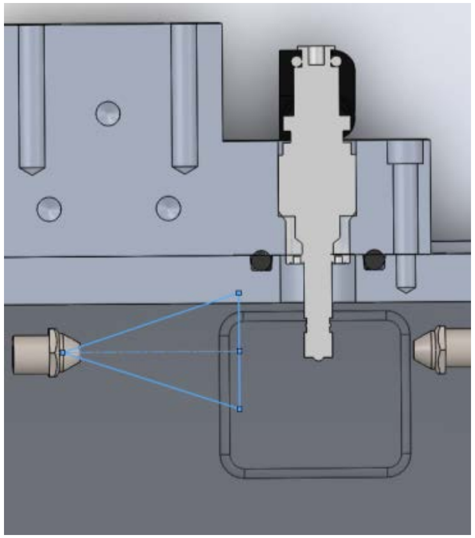
1st generation chamber

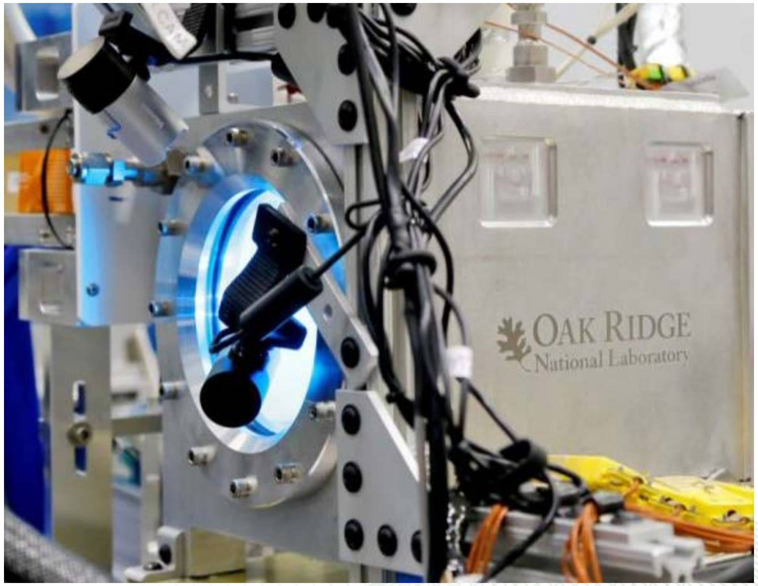
- heated inlet gas
- Pressure ≤ 1 bar absolute
- Fixed injector design
- Cooling/condensation issues



2nd generation chamber

- Multiple cartridge heater ports for full injector and chamber temperature control
- Modular CAD design to allow multiple injector designs
- Wide pressure range: 0.01 to 3-4 bar absolute
- Directed heated sweep gas with high flowrate pumping system (> 20 scfm)





* - Effort supported by ORNL internal funding

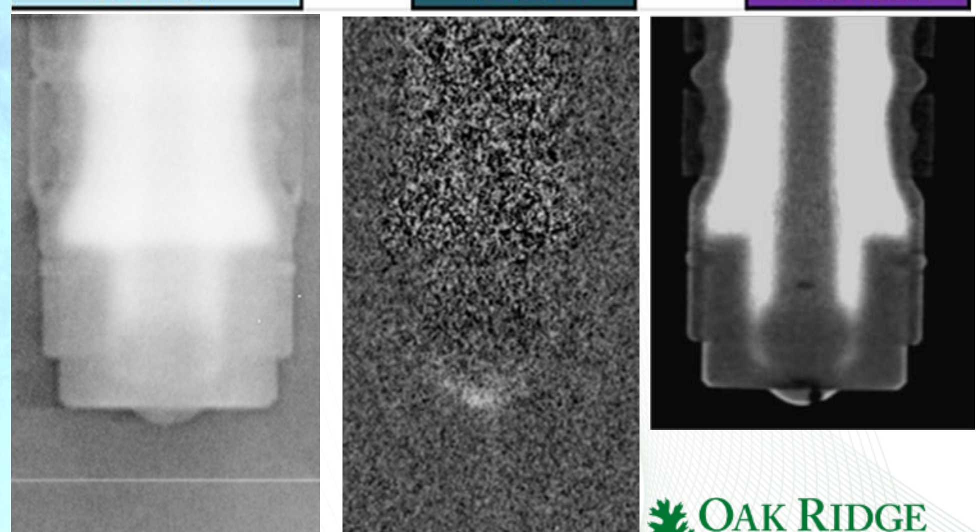
Second campaign performed at conditions to minimize fogging and encourage flash evaporation*

- Single hole injector from GM
- To accentuate cavitation
  - Rail pressures: 140 bar
  - Rail Temperature: 70°C
  - Chamber pressure: 0.3 bar
- Injection timing for com image:
  - 1.2 ms injection
  - 10 Hz with
  - 20 µs resolution
    - 60 frames
  - 20s of neutron exposure for each 20 µs frame
    - >900k injections

Cyclopentane

$P_{amb.}$ (kPa) \ T_{fuel} (°C)	25	35	45	55	65	75	85
20	0.48	0.33	0.23	0.16	0.12	0.09	0.07
30	0.71	0.49	0.34	0.25	0.18	0.14	0.10
40	0.95	0.65	0.46	0.33	0.24	0.18	0.14
100	2.38	1.63	1.14	0.82	0.61	0.46	0.35
200	4.75	3.25	2.29	1.65	1.21	0.91	0.70

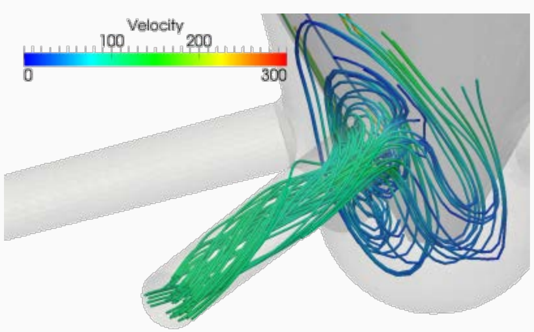
Non Flash | Transition | Flare flash



* - Effort supported by ORNL internal funding

Initial analysis of single hole injector dynamic imaging yielded surprising results*

- Single hole injector obtained from GM (Ron Grover and Scott Parrish)
- Fuel: cyclopentane; Rail: 140 bar; 70°C injector; chamber: 0.3 bar
- Image analysis in early stages, but shows an area of high contrast in area in front of nozzle hole
  - Additional analysis ongoing looking for cavitation in the nozzle…early stages



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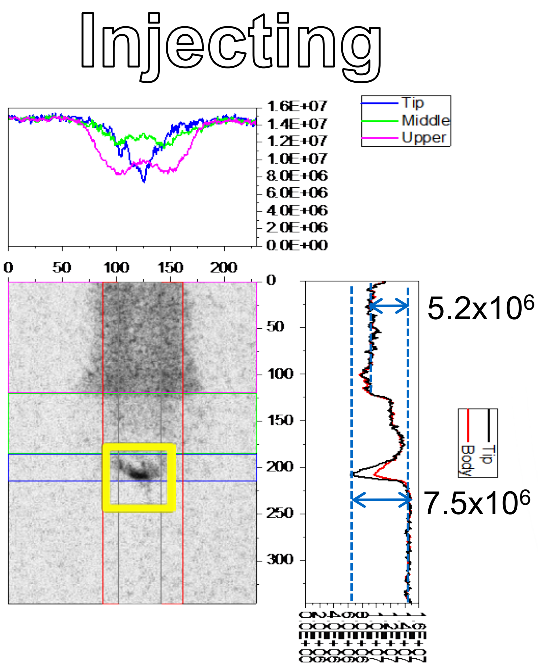

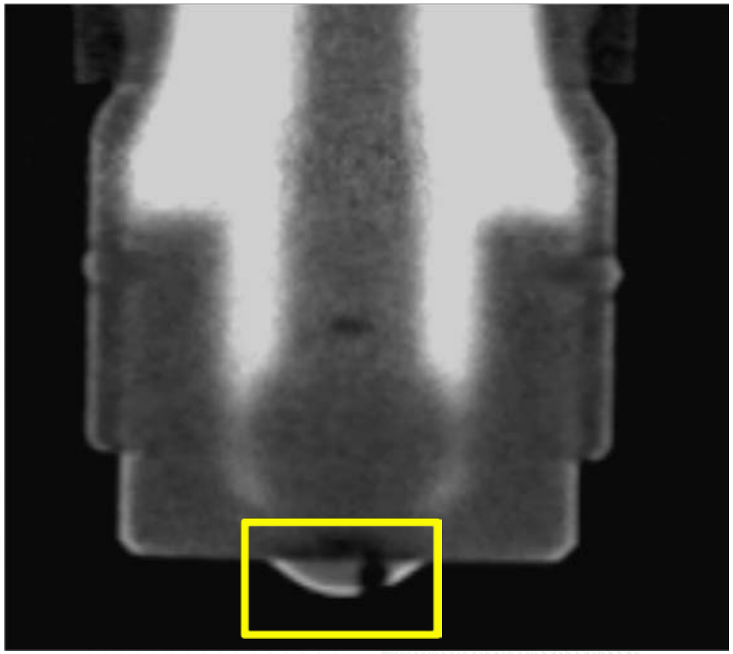

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Remaining Challenges & Barriers, and Proposed Future Work

Remaining Challenges:	Future Work:
• Fouled injector investigation	• Technique demonstrated as useful; looking to team with injector suppliers to participate in full studies
• Coordination of soot regeneration in ash-filled samples	• Partnering with MIT-consortium will continue • As possible in specific PM-focused projects, technique will be employed to provide detailed understanding of soot and ash distribution
• Study progression of GPF regeneration compared to DPF	• Sequential regeneration study initiated; will be completed as beam time allows on this project • Efforts moving to PM-focused projects in future efforts
• Dynamic fuel injection studies (Most challenging application) ***ORNL internal funding ending in September 2015***	• Continue effort under extreme injection conditions; cavitation-likely conditions, contrast with unlikely conditions • Invest significant time and effort into image analysis including 6-hole injector images obtained • Move to standard fuel employed in ECN (iso-octane); request access to ECN GDI-based injector (Spray G)
• Urea injector/injection study	• Working with Continental Automotive to identify research plan that would have wide ranging value to VTO-EERE

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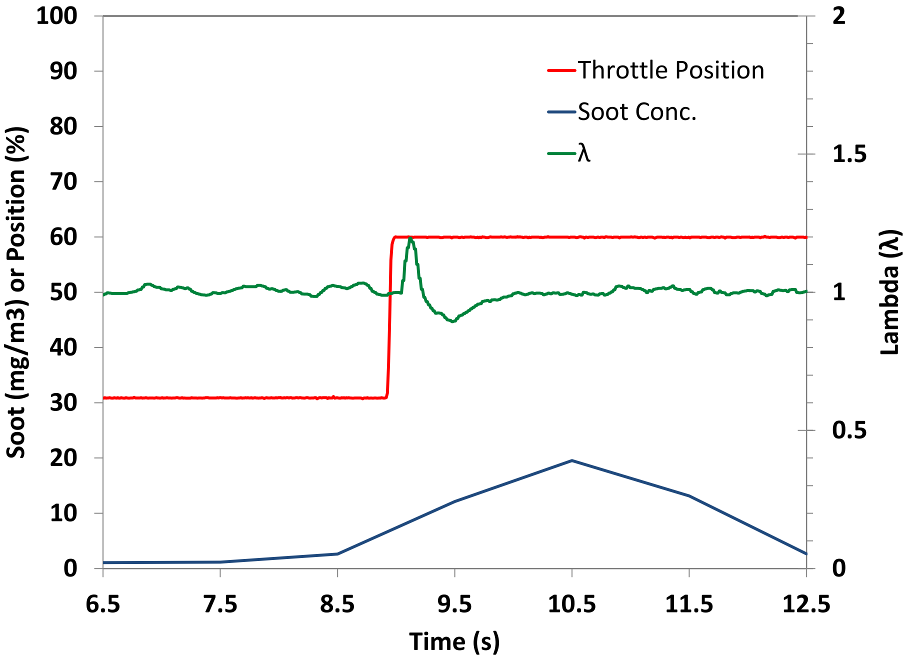
Summary

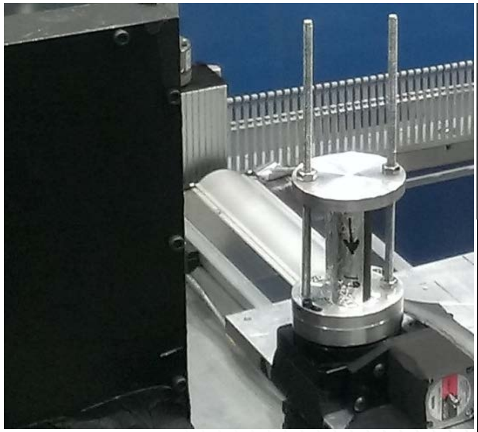
- **Relevance**:
  - Non-destructive, non-invasive analysis to improve understanding of lean-burn vehicle systems, targeting fuel economy improvements and durability; focused on fuel injectors and particulate filters
- **Approach**:
  - Neutron Imaging as a unique tool applied to automotive research areas to visualize, map and quantify deposits in engine parts as well as investigating fluid dynamics inside injector
  - Fuel injectors being studied under both static and dynamic conditions; PFs under static conditions
- **Collaborations**:
  - BES-funded scientists and programs, ORNL internal funding, Industrial (GM and Continental Automotive), and Academic (MIT, U. Tennessee, U. California and U. Alabama)
- **Technical Accomplishments**:
  - Verified applicability of neutron imaging to measure injector fouling with Continental Automotive
  - Identified ash profiles and densities for different regen strategies in collaboration with MIT consortium
  - Completed series of GPF studies with varying levels of particulate matter and regeneration levels
  - Two dynamic imaging campaigns completed; promising images obtained
  - Obtained two series of fuel injection images in evacuated chambers
  - Imaged Continental Automotive urea injectors with fluid
- **Future Work**:
  - Primary effort going forward in the project will be on fuel injectors
  - Investigate extreme injection conditions; cavitation-likely conditions, contrast with unlikely conditions
  - Analyze recorded images to the full extent to identify potential cavitation and other fluid dynamics
  - Move to standard fuel employed in ECN; request access to ECN GDI-based injector (Spray G)

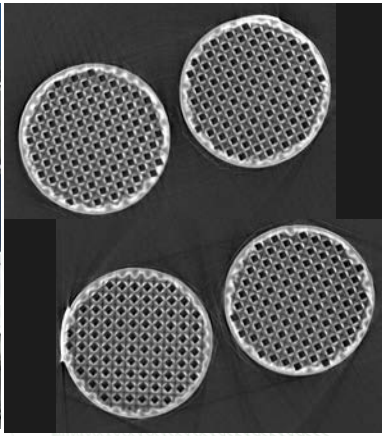
Technical back-up slides

GPF particulate study using tip-in



- GDI stoichiometric engine operated to mimic “tip-in” point of acceleration
  - novel approach designed to capture mode of maximum PM generation*
  - Brief period of rich operation (λ = 0.91) , medium-high load
  - Sample holder with four 1” GPFs
    - allows repeated measurements
    - Filled to nominal 4 g/L
- Characterize with Original CCD detector at HFIR



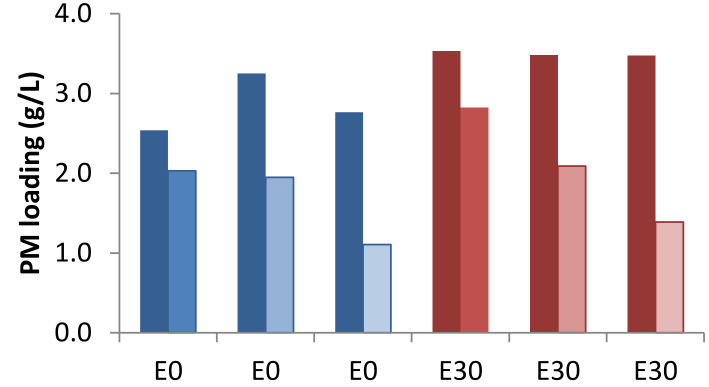


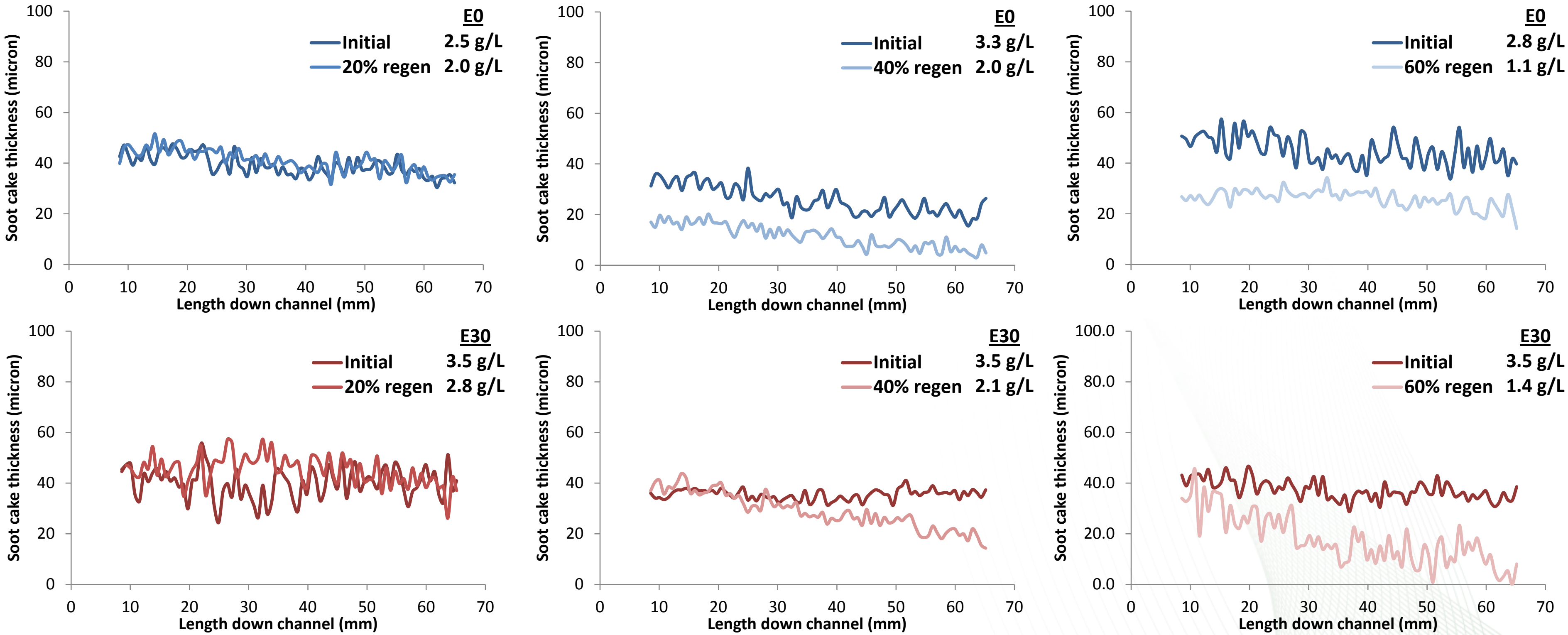
* - generated PM in ORNL collaboration: FT007, to be presented Thursday June 19

OAK RIDGE National Laboratory

Analysis of GPF soot cake properties are challenging due to the layer thickness being near the detection limit

- Coordinated with project in Fuels Technology program on fuel effects on particulate formation and regeneration; E0 vs. E30*
- Soot cake is less than 50 microns and near detection limit
  - Computed tomography analysis does not always yield consistent results from sample to sample
- Results continue to suggest GDI-based particulate packs denser than diesel-generated particulate layers





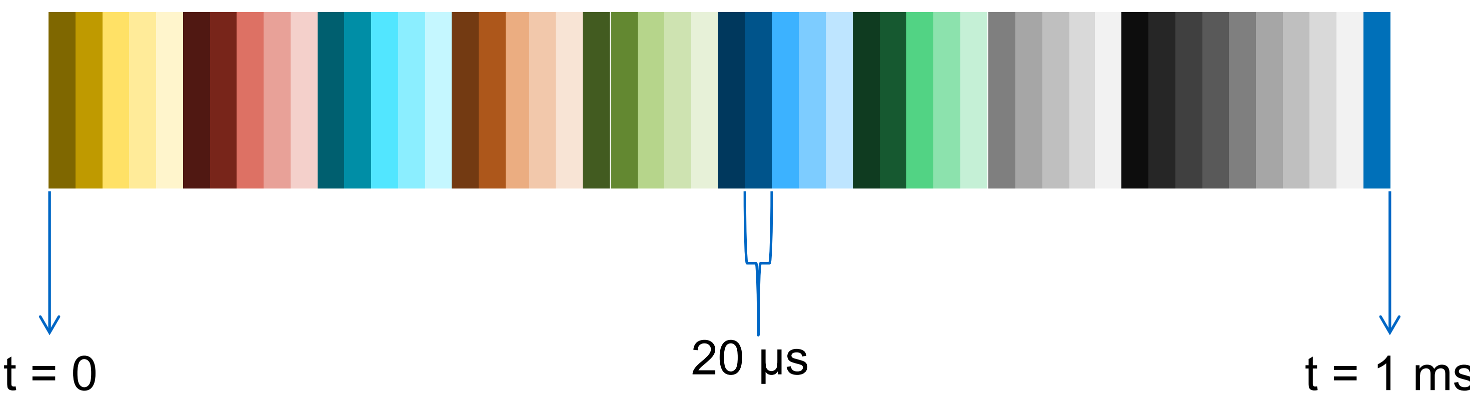
* - FT007, presented at 2:45 PM Thursday 6/11/2015 (Crystal City Salon D)

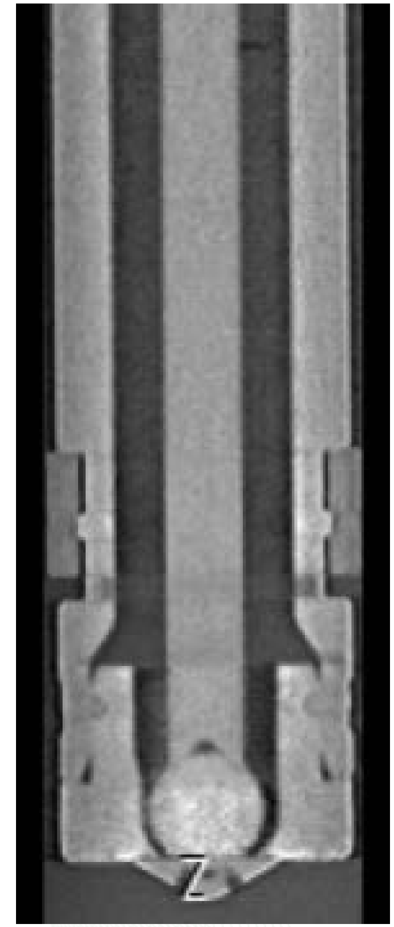
Urea injector study in planning stages

- Similar to GDI-based injectors, internal geometries and fluid readily visible
- Nozzle holes are larger and dynamics easier to capture
  - Would likely only use water to study injection, so easier handling
- Working with Continental Automotive to identify research plan that would have wide ranging value to VTO-EERE

Goal is to develop technique to image internal fluid property changes with 1 ms injection, 20 µs resolution

- To maximize cavitation during injection, high rail pressures, heated nozzles and evacuated chamber used
  - Highest rail pressures (GDI: ~200 bar)
  - Heat nozzle to 100°C and evacuate the spray chamber
  - Increases likelihood of cavitation and limits condensation
- Injection timing for composite image:
  - 1 ms injection with 20 µs resolution (50 frames)
  - Targeting 30 s of neutron exposure for each 20 µs frame
- After proof of principle, move to more realistic systems



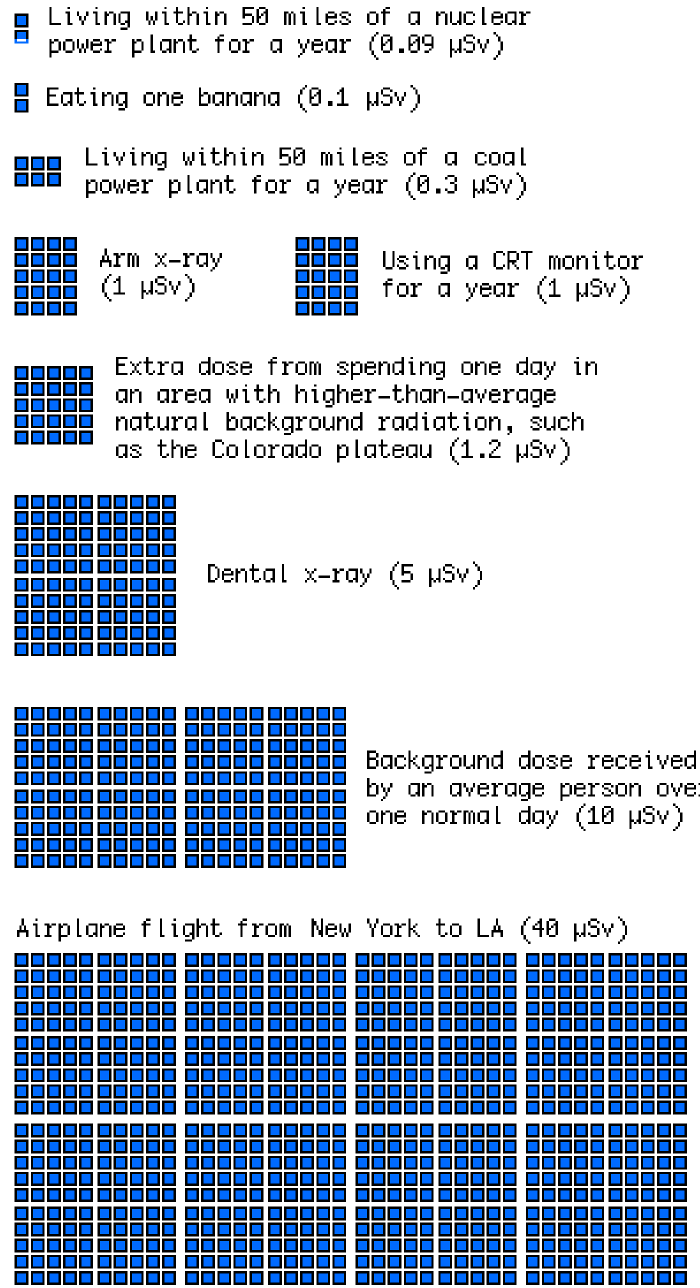


* - Another ORNL-funded project awarded to develop and validate this dynamic imaging capability with the relevant dynamic resolution.

Radiation/Activation

- Average radiation exposure
  - Working at 12 h HFIR, handling specimens: 10-20 µSv
  - Airplane trip Knoxville to DC: ~10 µSv
  - 1 day on earth: ~10 µSv
  - Chest CT-Scan: 7000 µSv

- After exposing materials to neutron beam, they can become "activated"
  - materials give off radiation as they return to their stable state
  - Time of decay varies for materials and time-in-beam
- SiC particulate filters (PFs)
  - After 20 hour CT scan
    - Can be handled within 10 minutes
    - Can be removed from facility within 1 day
- Injectors
  - After 20 hour CT scan
    - Can be handled within 30 minutes
    - Can be removed from facility after ~1 year



"source": Randall Munroe's Radiation Dose Chart (http://xkcd.com/radiation/)