Neutron Imaging of Advanced Transportation Technologies

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Project Overview

Timeline

- Started in FY2010
- Ongoing study

Budget

- FY2016: $200k
- FY2015: $200k

Partners

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

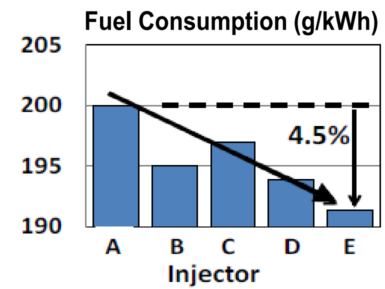
Barriers

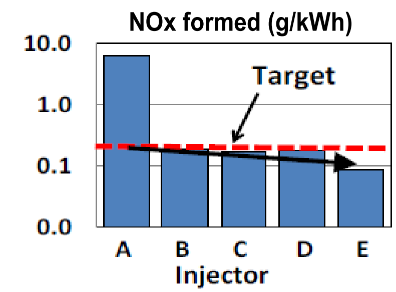
- **2.3.1B: Lack of cost-effective emission control**
  - Improved regeneration efficiency in particulate filters (PFs)
- **2.3.1C: Lack of modeling capability for combustion and emission control**
  - Improved models of fluid flow inside fuel injectors
  - Need to improve models for effective PF regeneration 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

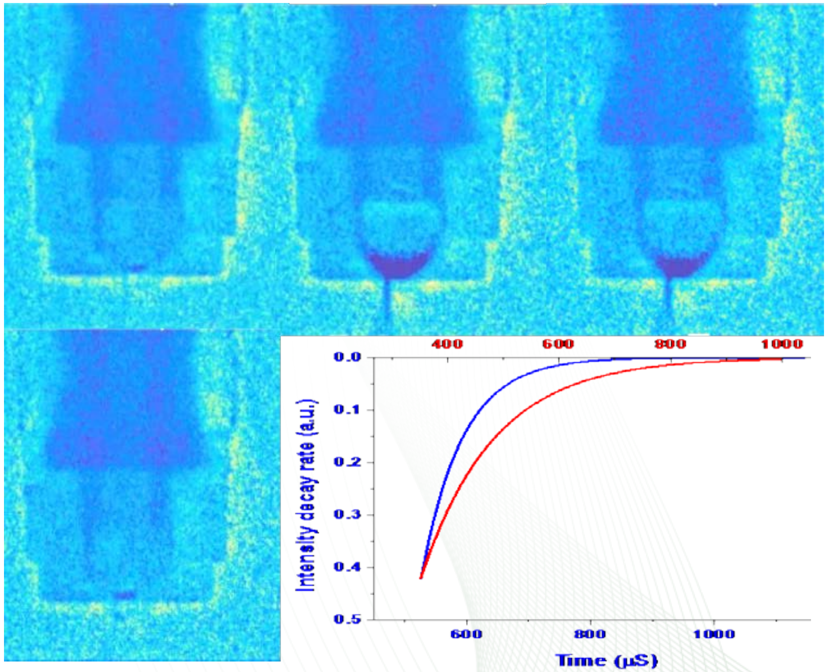
Objectives and Relevance

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

- Injectors: gasoline direct injection (GDI)
  - Visualize fuel inside metal injector
    - Fluid flows internal and near nozzle
    - Goal: location and timing of cavitation
  - Aid model development; injector design
    - **Injector design significantly influences efficiency and emissions***
  - diesel and urea injectors also possible
- Particulate filters (PF)
  - PF effort primarily moved to other projects, but technique developed here
  - Comprehensive, quantitative device analysis targeting model parameters
  - Data from FY15 presented here



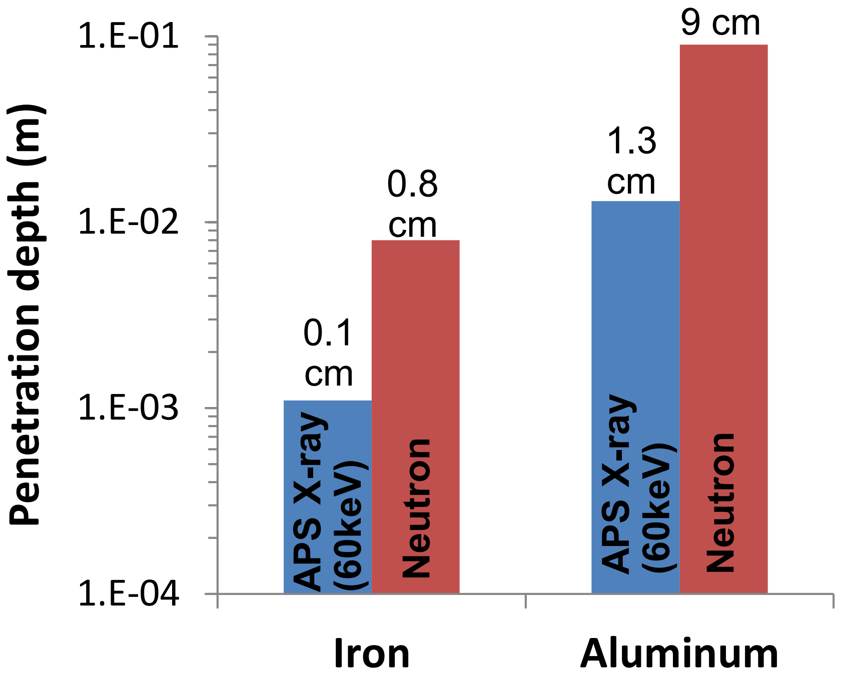


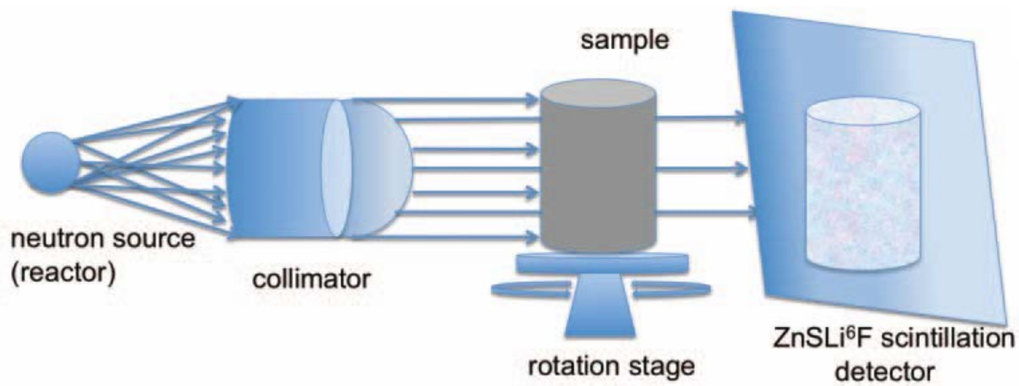


* - e.g., Keith Confer (Delphi), "Gasoline Ultra Fuel Efficient Vehicle", 2012 DOE AMR, Crystal City, VA, ACE064, May 18, 2012.

Neutrons can penetrate metals while still strongly interacting with light elements

- Neutrons are heavily attenuated by some light elements (^{1}H, ^{10}B, etc…)
  - Can penetrate metals with minimal interactions
  - Highly sensitive to water and hydrocarbons/fuel
  - Image is based on absence of neutrons
- X-ray absorption increases for heavy/dense elements



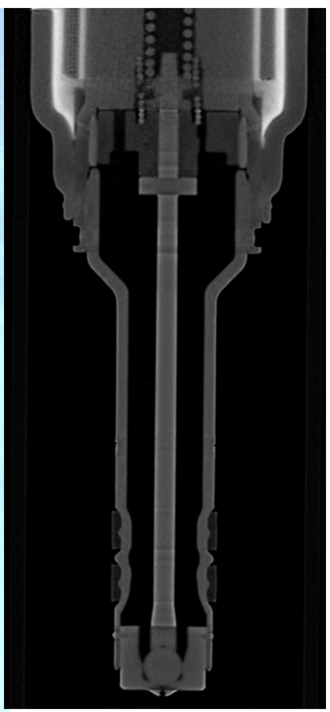


Neutron imaging is a complementary analytical tool

Attenuation Coefficient Reference: N. Kardjilov's presentation at IAN2006
http://neutrons.ornl.gov/workshops/ian2006/MO1/IAN2006oct_Kardjilov_02.pdf
Neutron Penetration depth : R. Pynn, "Neutron scattering: a primer." *Los Alamos Science* 19 (1990): 1-31.
APS X-ray penetration depth: C. Powell, personal communication.

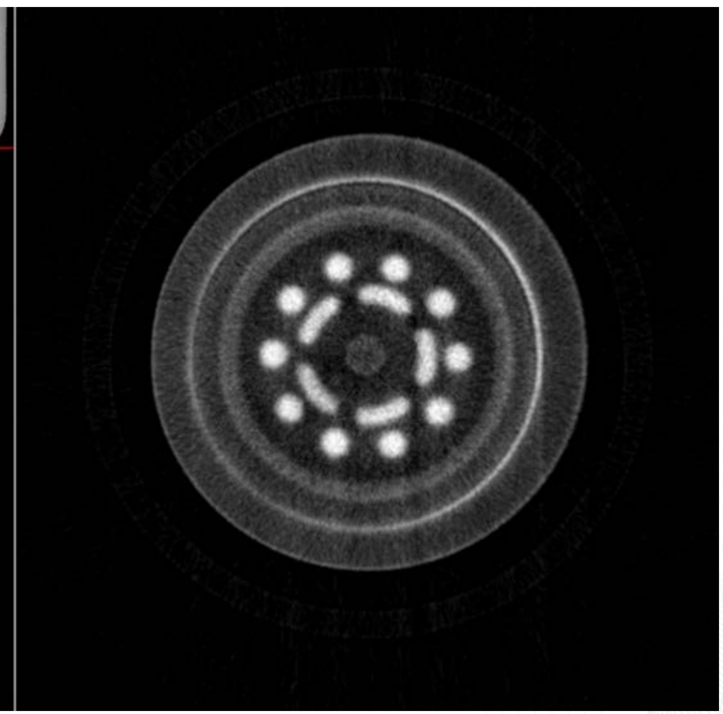
Complete sample analysis can be achieved with non-destructive techniques

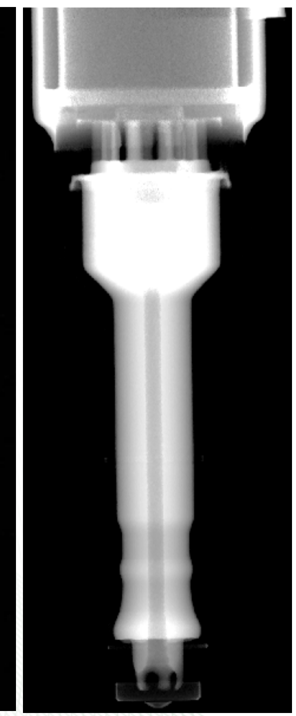
- Samples can be analyzed at one cross-section or a complete reconstruction can provide a cross-section of the entire sample
  - Originally ~50 microns achievable at ORNL’s High Flux Isotope reactor (HFIR)
  - As low as 10-20 microns possible with MCP (micro-channel plate) detector
- Illustration of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



Empty

Fuel-filled





H-containing

Milestones

- {SMART} Obtain time-stamped neutron images of injection to study internal fluid dynamics (9/30/2015)
  - **completed**
- Compare dynamic injection images of two conditions using GDI-based injectors. One when cavitation events are likely and one when they are not (6/30/2016).
  - **completed**
- {SMART} Demonstrate chamber and dynamic neutron detection can occur using ECN-relevant fuel (iso-octane) and temperatures (9/30/2016).
  - **on-target/complete**

ECN = Engine combustion network

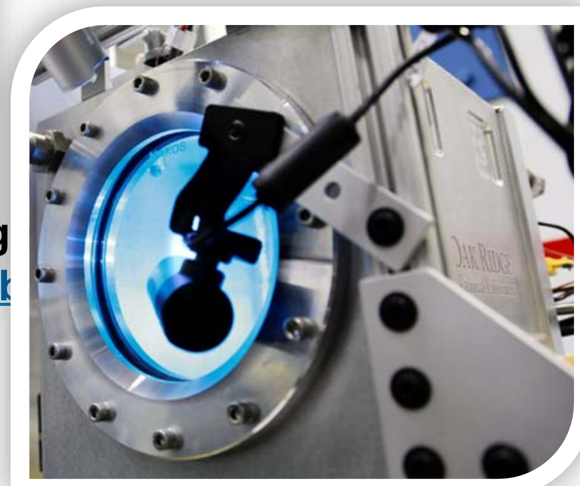
Collaborations

- **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)
  - Fouled and clean injectors, urea injectors
- **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
- **Boston University** (Emily Ryan, Sheryl Grace, Glynn Holt)
  - Development and multiscale validation of Euler-Lagrange based computational Methods for modeling fluid dynamics in fuel injectors

Approach

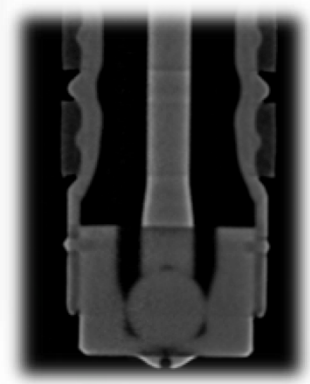
Receive or obtain relevant devices

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

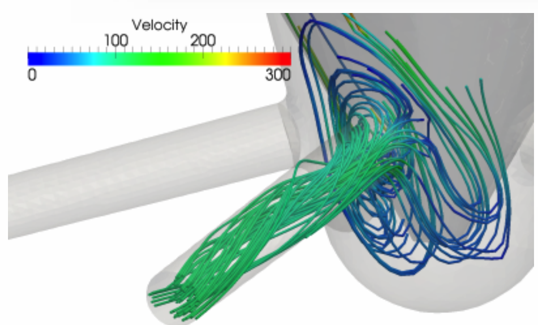


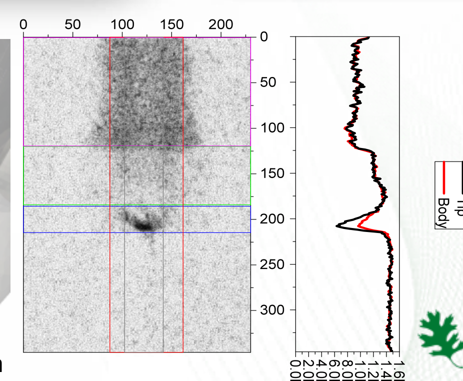
Non-destructive technique allows multiple studies to be performed on single commercial or prototype device

Reconstruct device 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

- Dynamic imaging of fluid dynamics inside GDI-based injectors
  - Analyzed flow inside injector using cyclopentane under 2 conditions
  - Identified fuel in sac long after pintle closed in both cases
- Applying ECN conditions and fuel in dynamic imaging study
  - Iso-octane at Spray G2 and G3 conditions
  - Obtained series of images showing deep penetration of liquid into chamber, fluid in sac after closing, prolonged fluid on tip
- CT scan of Spray G-type injector
  - Obtained from Argonne National Laboratory
  - To be combined with their high definition tip CT scan (X-ray)
- GDI-generated particulate study in GPFs
  - Particulate characteristics continue to demonstrate very different behavior compared to diesel-based particulate

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Technical Accomplishments

- Dynamic imaging of fluid dynamics inside GDI-based injectors

- Applying ECN conditions and fuel
  - Iso-octane

- CT scan of Spray G injector

- GDI-generated particulate study in GPFs

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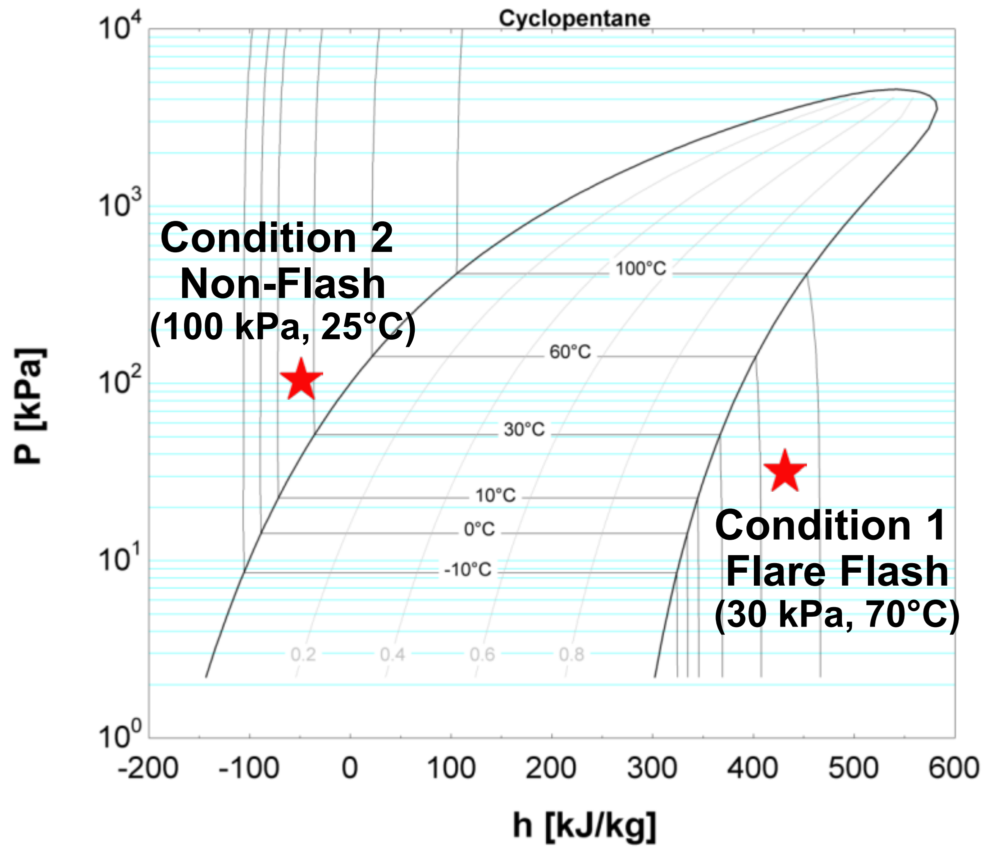
Campaign performed at conditions to minimize fogging and encourage flash evaporation

- Single hole injector from GM
  - Ron Grover and Scott Parrish
- Fuel is cyclopentane
  - Flash boils near ambient
- Injection timing for composite image:
  - 1.2 ms injection
  - 10 Hz
  - 20 µs resolution
    - 60 frames during injection
    - 5 ms after injection too
  - ~20 s of neutron exposure for each 20 µs frame
    - >1M injections



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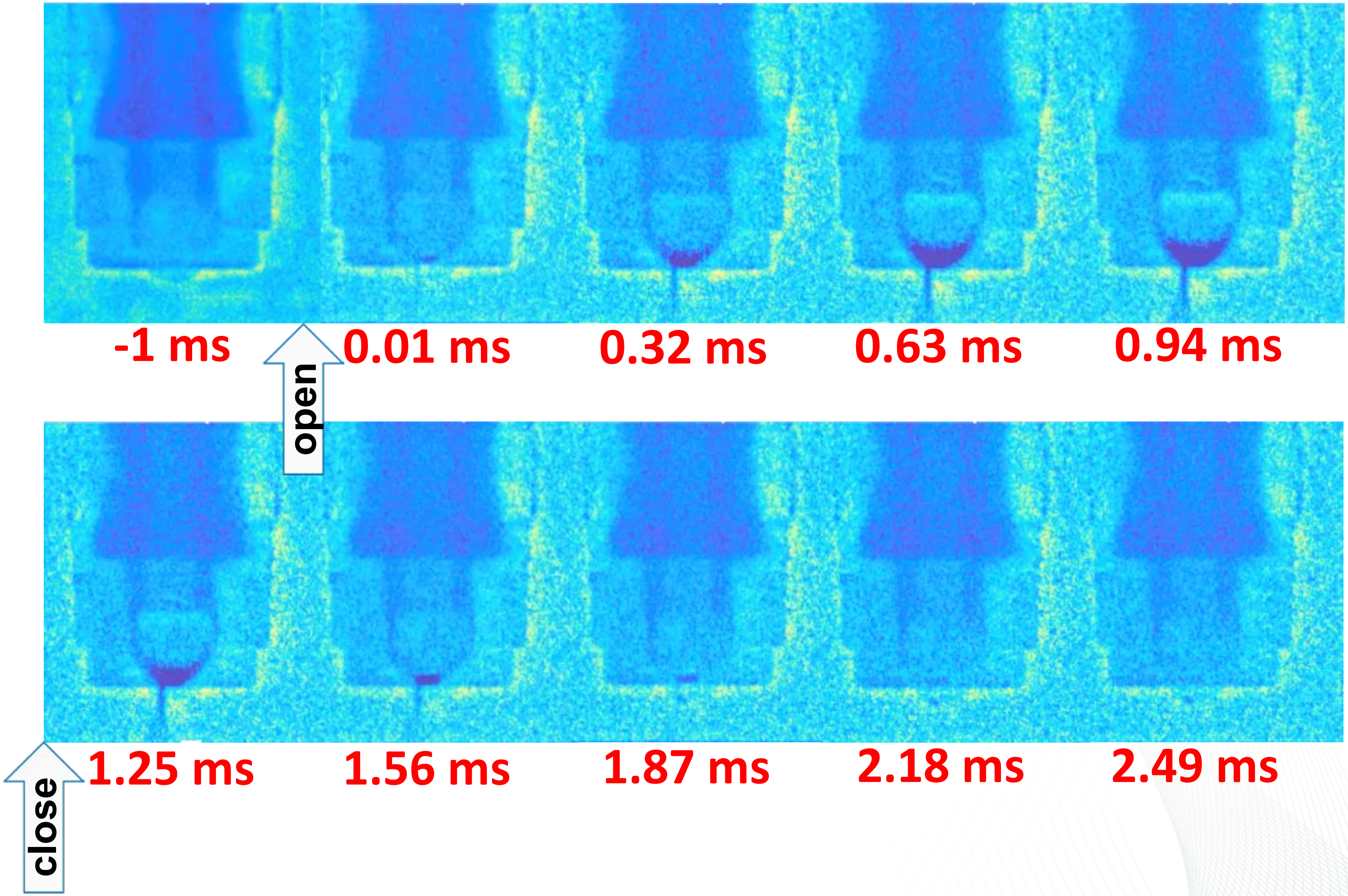
Time-stamped images show composite injection event and illustrate fuel in sac long after pintle closes (flash conditions)



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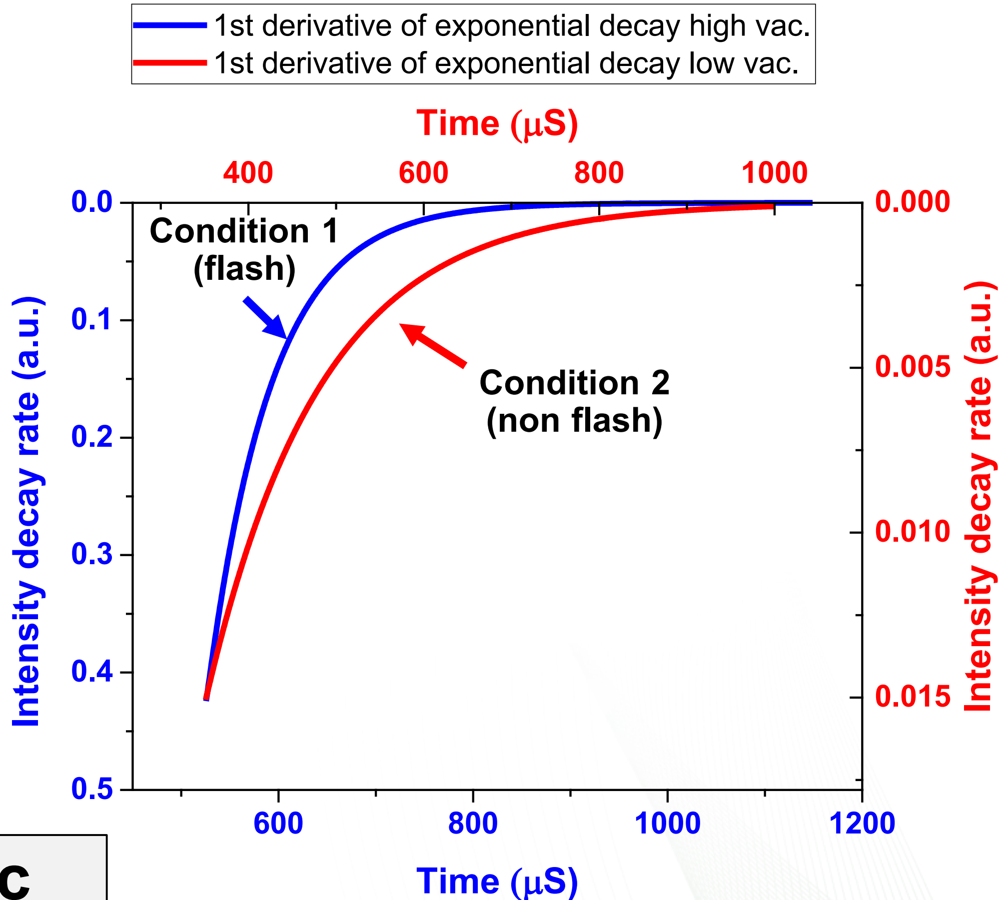
Flash boiling conditions reduced sac fuel resonance time by a factor of 2

- Align starting time of sac decay
- Determine duration when condition1 attains same slope as end point of condition 2
  - Condition 1 = 354 μs
  - Condition 2 = 644 μs



Flash boiling emptied sac almost twice as fast

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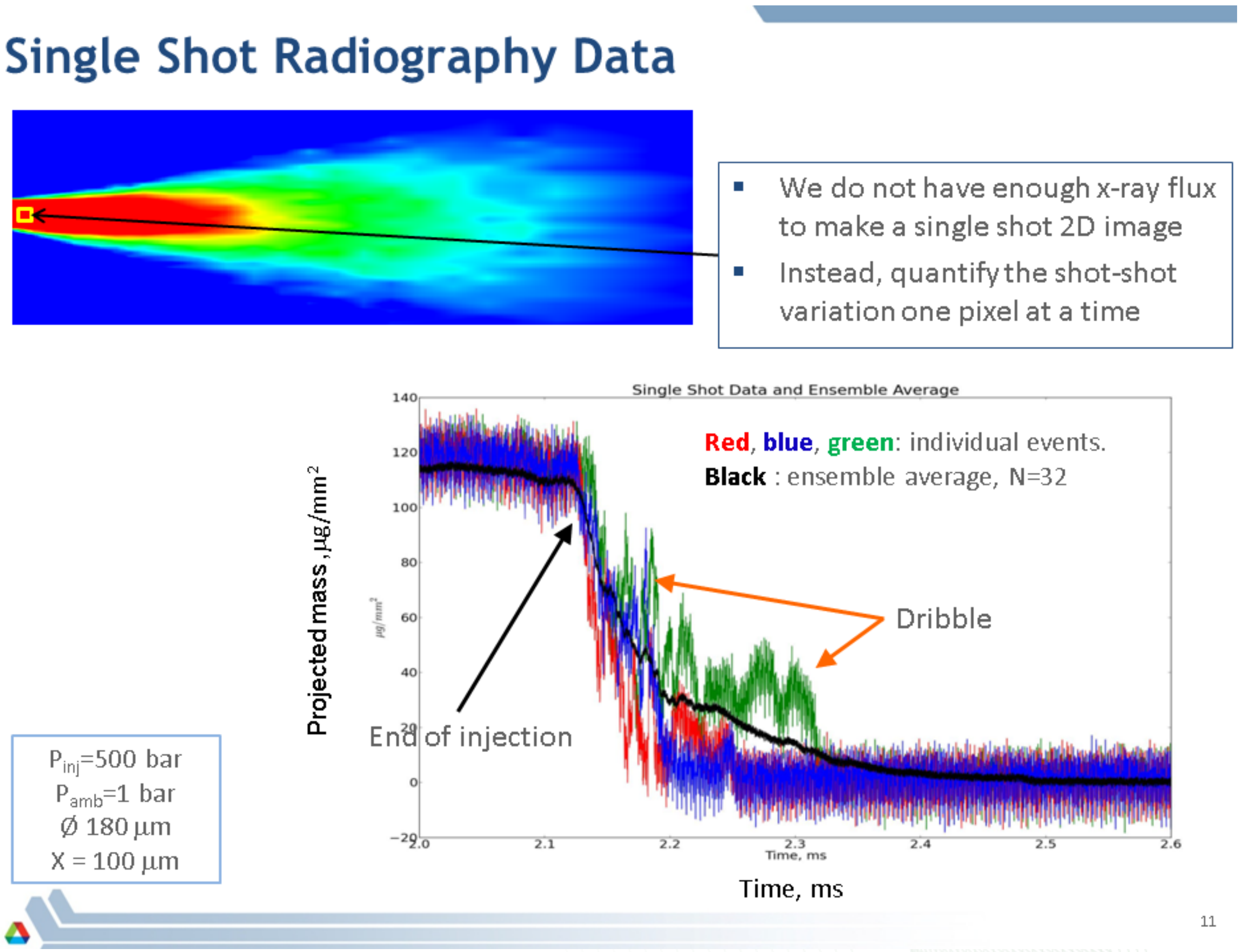
Argonne National Laboratory (ANL) has shown spray decay/dribble outside of nozzle

- ANL has shown spray dribble occurs after end of injection external of injector
  - Diesel injector shown with different conditions
- Our data corroborates this observation internally and offers complementary analysis



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Technical Accomplishments

- Dynamic imaging of fluid dynamics inside GDI-based injectors
- Applying ECN conditions and fuel
  - Iso-octane
- CT scan of Spray G injector
- GDI-generated particulate study in GPFs

Current efforts targeting ECN conditions, employing iso-octane, and collaboration

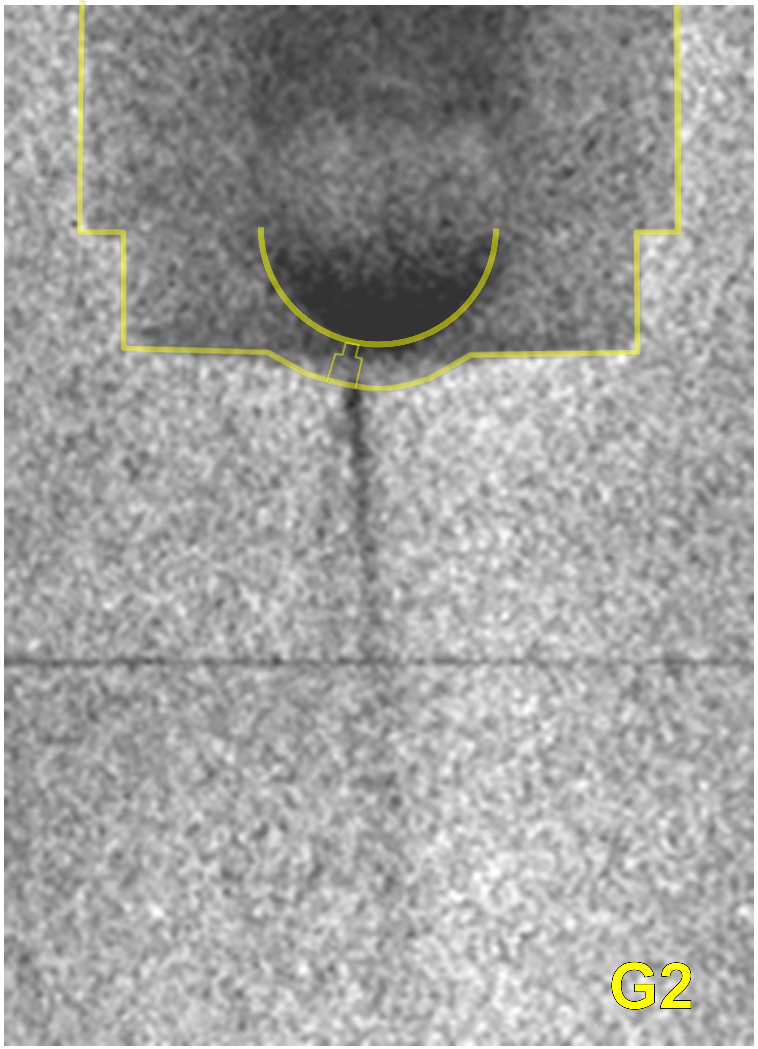
ECN = Engine combustion network

Parameter	Spray G Late injection	Spray G2 Early injection	Spray G3 Early injection
•		Flash boiling	Non-flash-boiling
• Fuel	Iso-octane	Iso-octane	Iso-octane
• Fuel pressure	20 Mpa	20 Mpa	20 MPa
• Fuel temperature	90° C	90° C	90° C
• Injector temperature	90° C	90° C	90° C
• Ambient temperature	300° C	60° C	60° C
• Ambient density	3.5 kg/m³	0.5 kg/m³	1.0 kg/m³
(Pressure - Nitrogen)	(600 kPa)	(50 kPa)	(100 kPa)
• Injected quantity	10 mg	10 mg	10 mg
• Number of injections	1	1	1

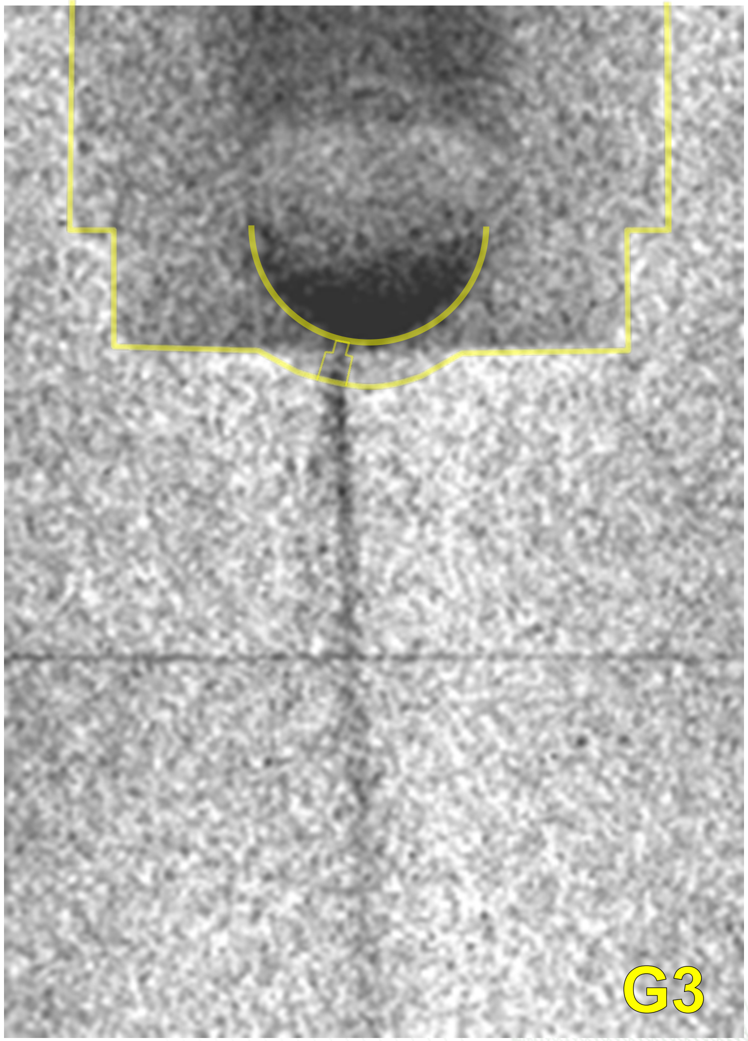
- New fuel flow meter installed at injector to enable confirmation of injected quantity
  - flow meter from Max Machinery to precisely control injection quantity
- Have completed experiments with iso-octane in condition G2 and G3
  - chamber modifications necessary for G1 condition; 600 kPa (6 bar)

Iso-octane injection with single hole injector

Fuel: 14 MPa, 10/8 mg, 90°C
Chamber: **50 kPa**, 90°C



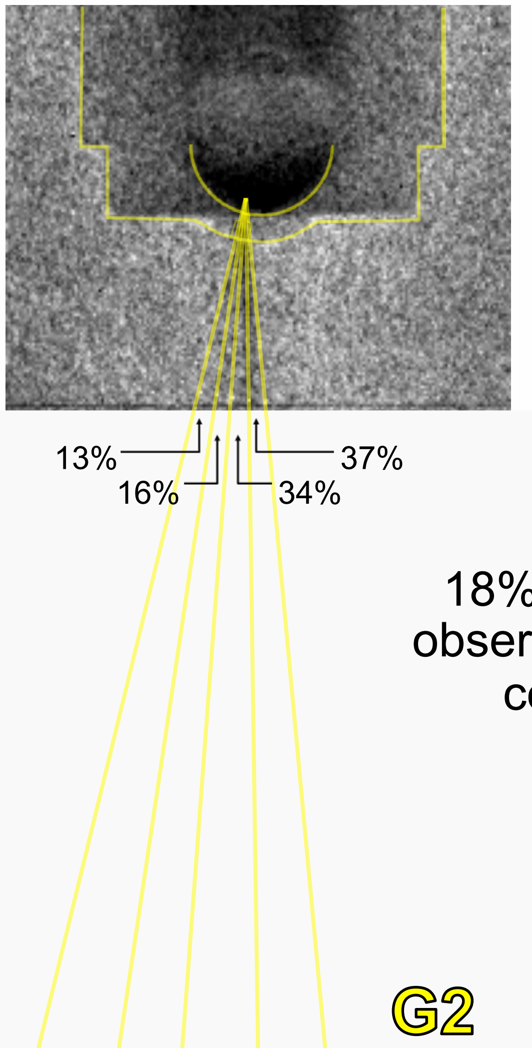
Fuel: 14 MPa, 10/8 mg, 90°C
Chamber: **100 kPa**, 90°C



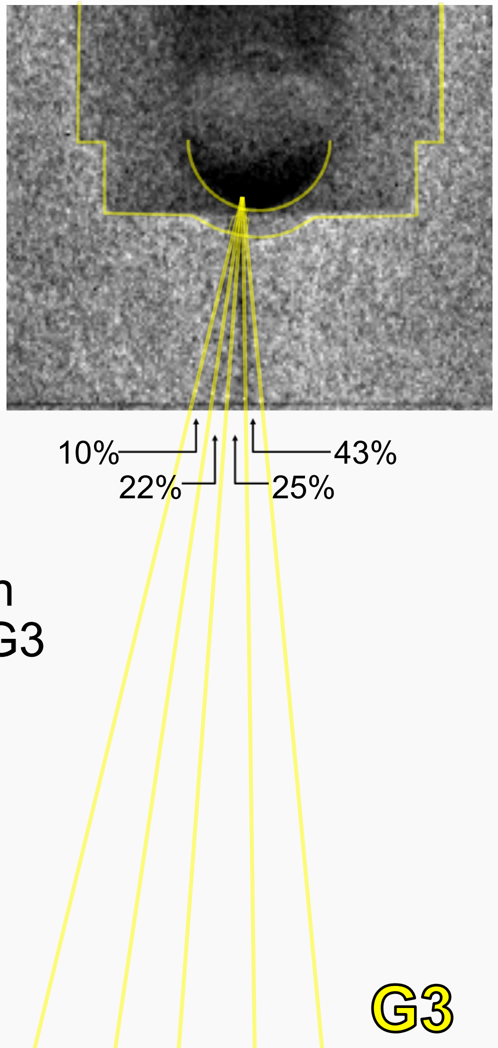
25 Hz, 0.46 ms pulse width

Analysis of spray indicates non-uniformity of liquid portion of fuel spray

Fuel: 14 MPa, 10/8 mg, 90°C
Chamber: **50 kPa**, 90°C



Fuel: 14 MPa, 10/8 mg, 90°C
Chamber: **100 kPa**, 90°C



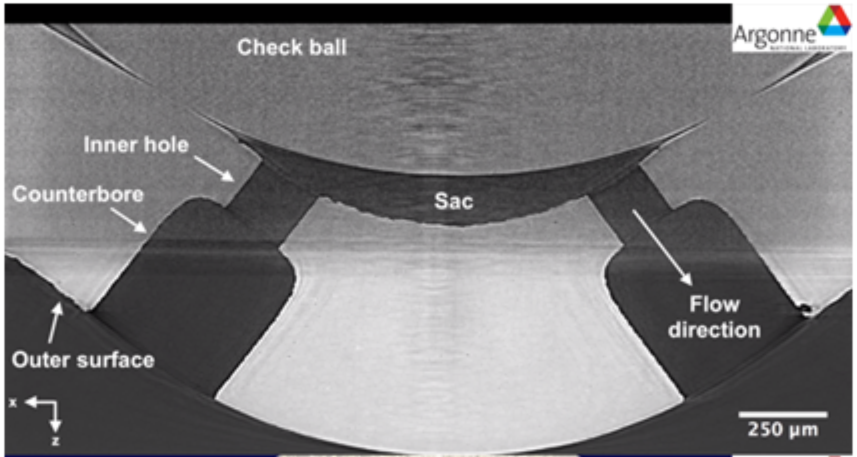
18% more attenuation observed in condition G3 composite spray

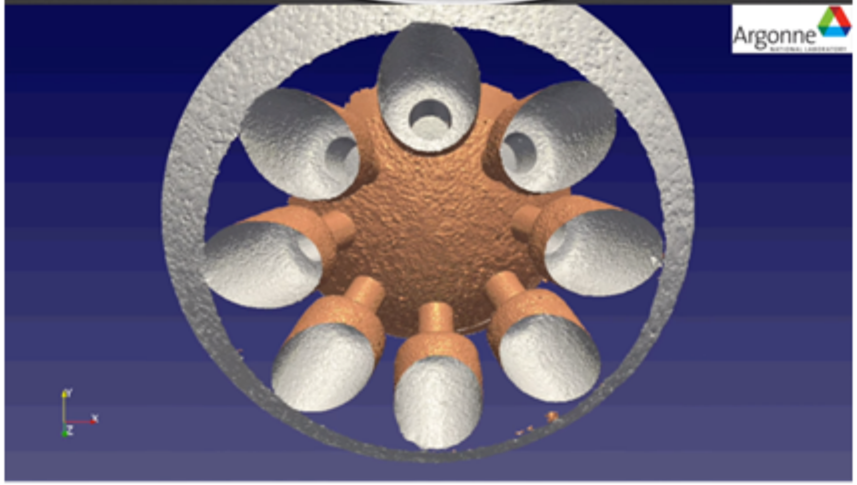
Technical Accomplishments

- Dynamic imaging of fluid dynamics inside GDI-based injectors
- Applying ECN conditions and fuel
  - Iso-octane
- CT scan of Spray G injector
- GDI-generated particulate study in GPFs

Collaborating with ANL to complete full injector scan with maximum resolution

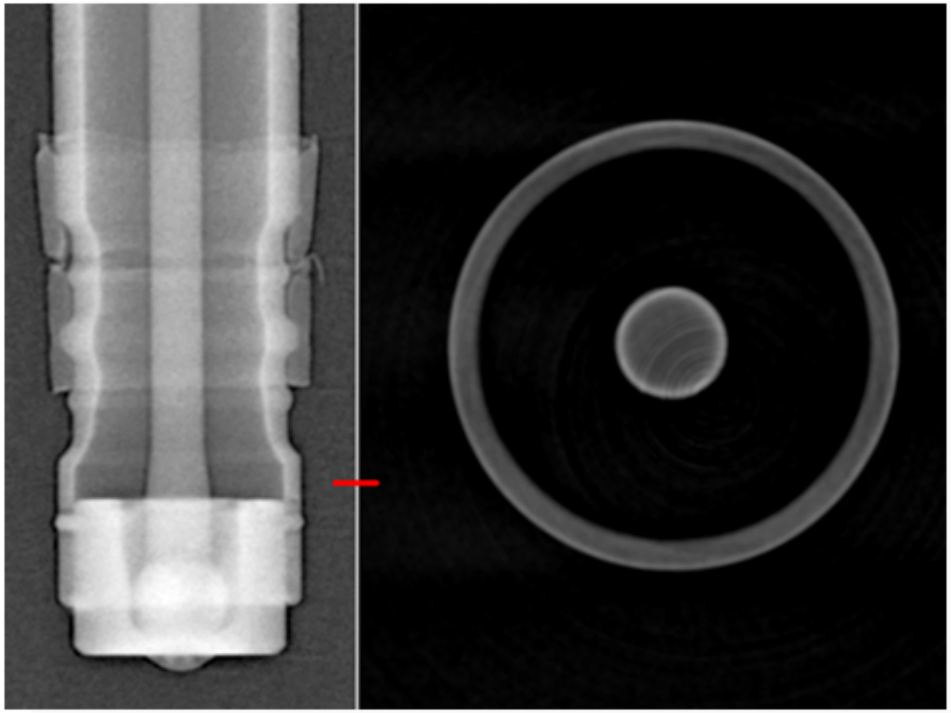
- ANL CT scan of tip shows excellent detail, but imaging sac difficult





https://www.youtube.com/watch?v=XQnNOn91ZP0

- Complementary effort at ANL to complete internal geometry of Spray G-based injector with neutrons
- Collected images
  - working to sync scans



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Technical Accomplishments

- Dynamic imaging of fluid dynamics inside GDI-based injectors
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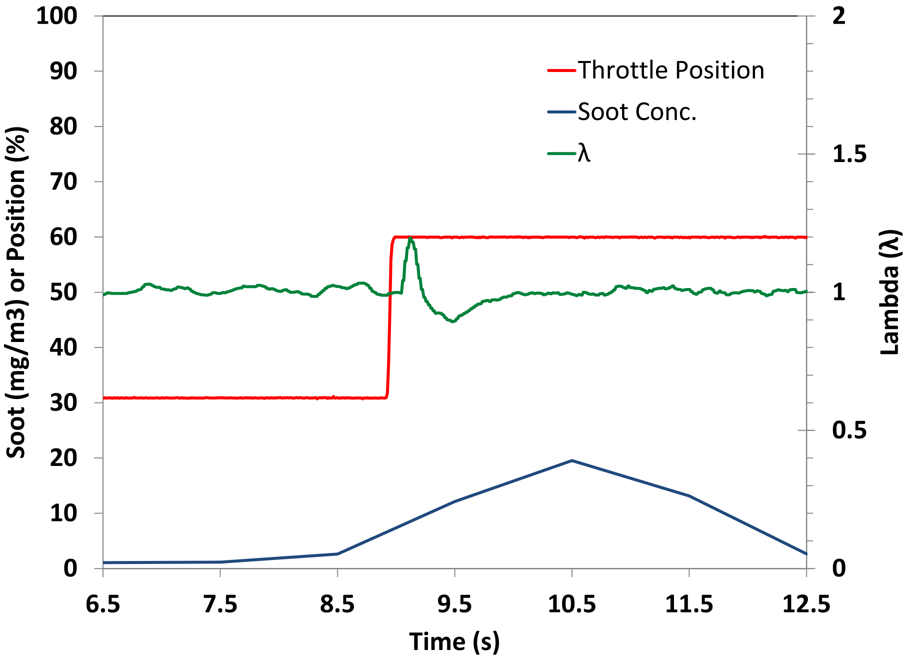
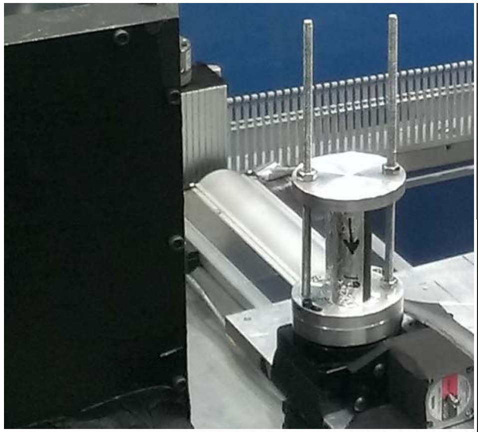
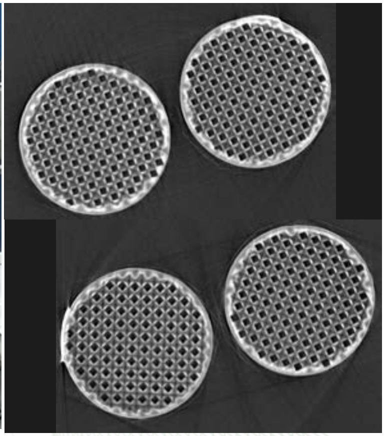
GPF particulate study using tip-in



- 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

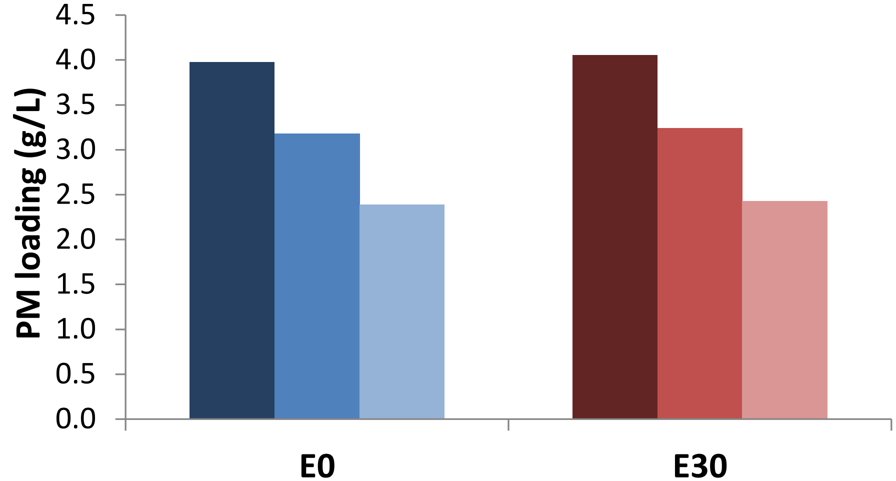




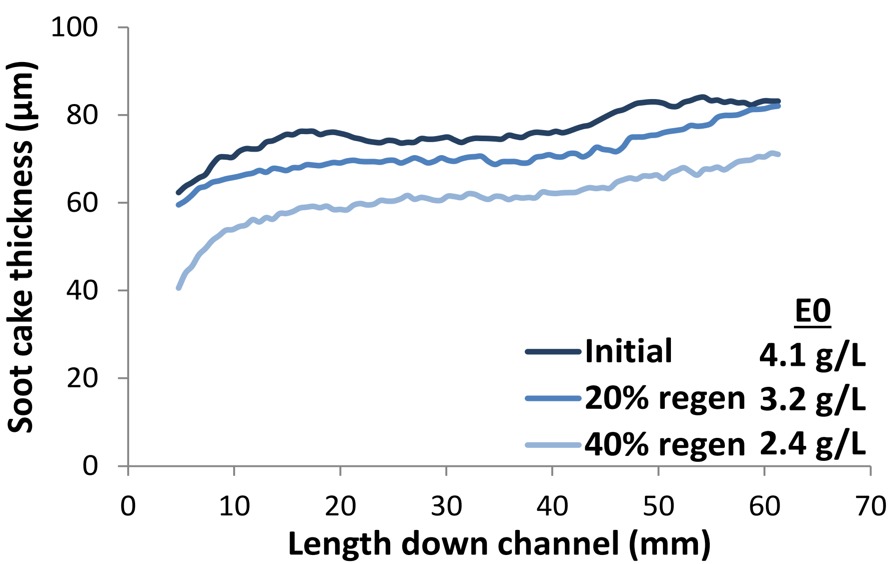
* - generated PM in ORNL GPF-focused project

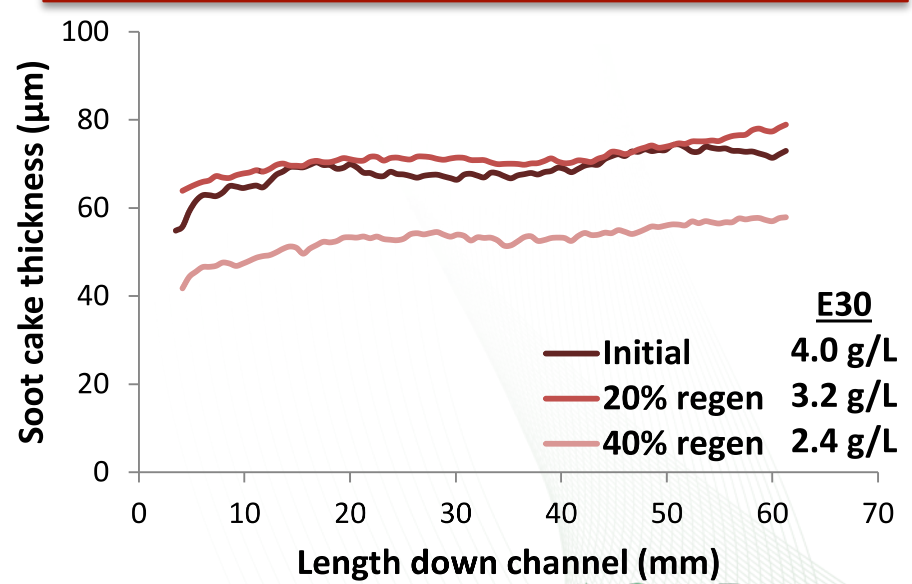
Analysis of GPF particulate deposition and oxidation behavior illustrates its reactivity is different from diesel

- Coordinated with project in Co-Optima program on fuel effects on particulate formation and regeneration; E0 vs. E30
- Soot cake is <80 microns and appears to slightly increase in thickness along flow channel
- Minimal decrease in soot cake layer during first 20% regen; after 40% regen, reduction observed
  - Likely adsorbed HC removal
  - Oxidation data shows different Ea in initial regeneration
- Not a large difference between E0 and E30



Results continue to show GDI-based particulate behaves differently than diesel-based particulate





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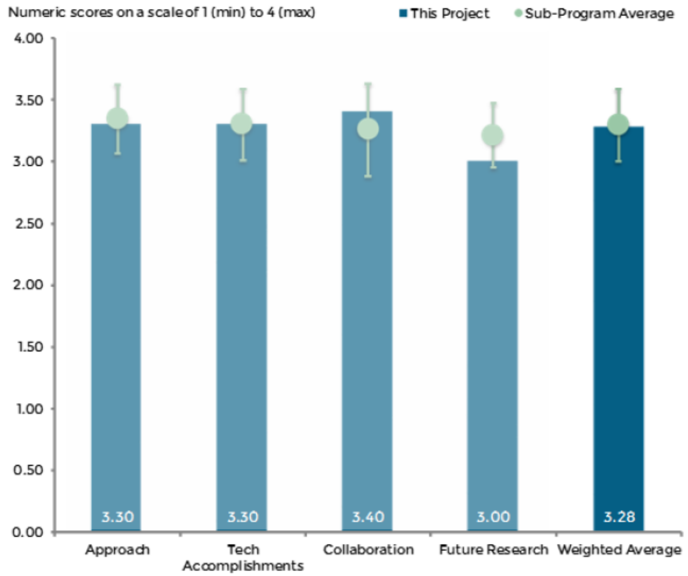
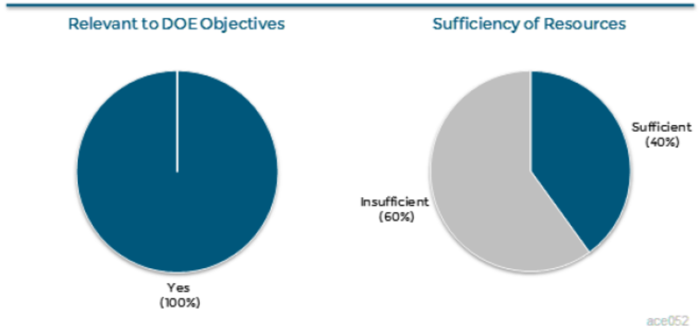
Remaining Challenges & Barriers, and Proposed Future Work

Remaining Challenges:	Future Work:
• Lack of understanding between fouling in injectors and fuel effects	• In collaboration with Continental, plans are being finalized for fouled injector study; impact of fuel and operating conditions for removing fouling conditions
• Translation of dynamic fuel injection data to modeling	• Improve image processing and analysis to derive more quantitative data sets for modeling • Collaborations initiated with ANL, Boston U., and U. Tennessee
• Influence from heavy hydrocarbon on chamber walls occluding image	• Identify source; either change injection delivery or filter fuel
• Need improved internal geometry data for the ECN spray G at locations above tip	• Combine high resolution CT scan data from APS with neutron-based data for spray G-based injector • Have collected data at both institutions; efforts are proceeding to digitally “stitch” the two data sets together
• Unknown behavior of gasoline particulate and how it differs from diesel particulate	• Complete study for full regeneration of the GPFs to provide visualization of oxidation characteristics (to be complete in particulate-based project)

Responses to 2015 Reviewers (5) – Neutron





- **Resources (60% Insufficient)**
  - Comments: might be a good investment for higher resolution
  - Response: outside proposal awarded to work with Boston University on modeling of fluid dynamics in injectors

- **Approach (3.3/4.0)**
  - Comments: good to see more gasoline based measurements… unique research tool… **clear connection to engine efficiency needed with OEM/supplier**… **have limits been scoped out**
  - Response: **relisted results from Delphi showing injector impact on fuel consumption; teaming with OEM's through ECN**… **limits continuously pushed at neutron facilities; systematic approach being employed to extract relevant data**
- **Technical Accomplishments (3.3/4.0)**
  - Comments: **resolution needs to be improved for injector**…fouled injector work very interesting…**concerned with low chamber pressure**
  - Response: **Efforts are ongoing on improving temporal and spatial resolution primarily through BES-funded programs**… **chamber pressure is relevant to 2 of 3 ECN conditions**
- **Collaborations (3.4/4.0)**
  - Comments: excellent collaboration noted
- **Future plans (3.0/4.0)**
  - Comments: **reviewer noted need to identify a concrete problem… focus on relevant conditions**… **if useful how can industry access equipment and tool**?
  - Response: **efforts were refocused to address conditions being studied in ECN; which are defined through industry support**… **anyone in industry can obtain access to Beamline; Cummins has; industry can work with us (and has)**
- **Relevance (100%)**
  - Comments: reviewers confirmed that the project can help diagnose component behavior related to engine efficiency

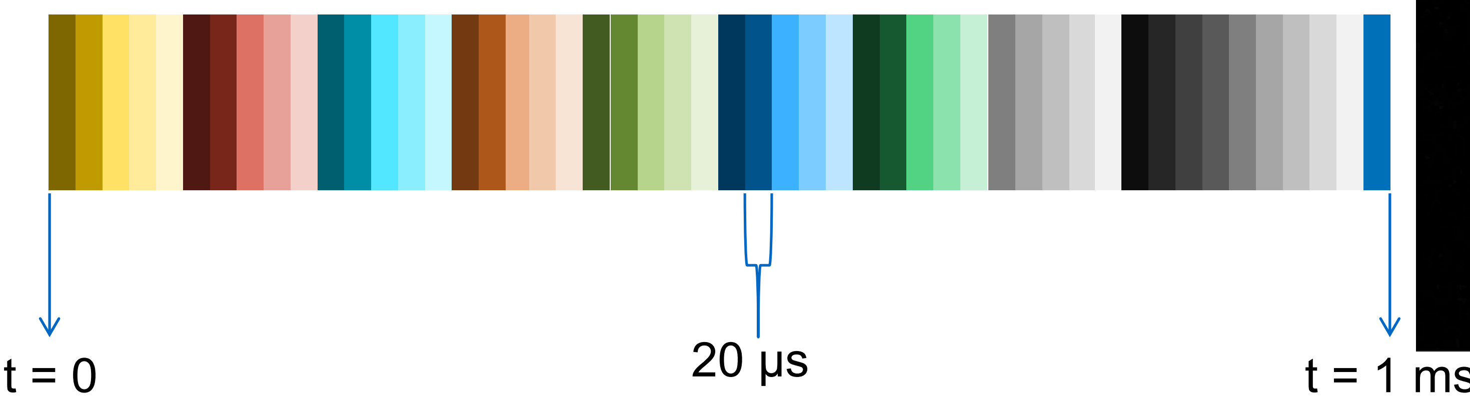
Summary

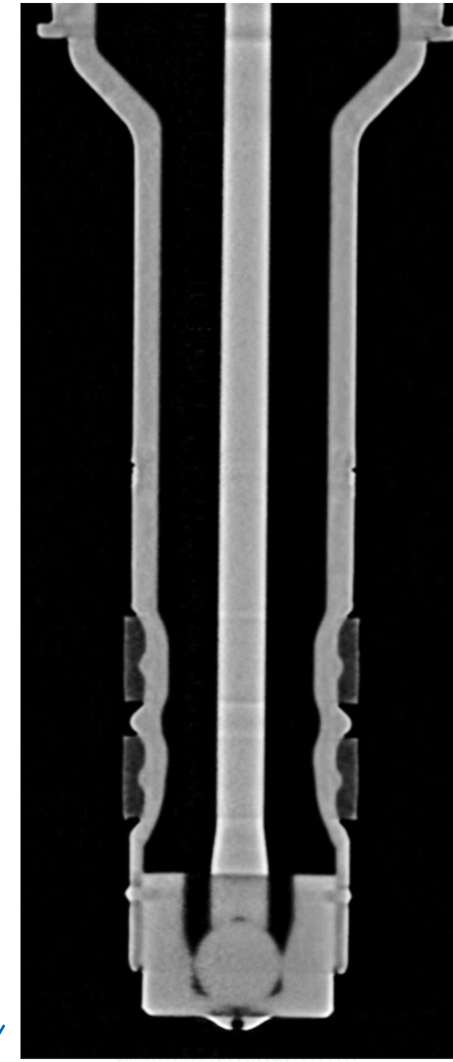
- **Relevance:**
  - Non-destructive, non-invasive analysis to improve understanding of lean-burn vehicle systems, targeting fuel economy improvements and durability; focused on fuel injectors and particulate filters
- **Approach:**
  - Neutron Imaging as a unique tool applied to automotive research 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:**
  - Partners include BES-funded scientists and programs, Industrial (GM and Continental Automotive), and Academic (MIT, U. Tennessee, U. California and Boston U.), ECN
- **Technical Accomplishments:**
  - Identified and quantified fuel inside injector sac after pintle closed with multiple fuels and conditions
  - Applied ECN conditions/fuel in dynamic imaging study (Iso-octane at Spray G2 and G3 conditions)
    - Images show deep penetration of liquid into chamber, fluid in sac after closing, prolonged fluid on tip
  - Recorded CT scan of Spray G-type injector in collaboration with Argonne National lab;
    - To be combined with their high definition tip CT scan
  - GPF characteristics continue to demonstrate different behavior compared to diesel-based particulate
- **Future Work:**
  - Impact of fuel and operating conditions for removing fouling conditions
  - Rectify occlusion from heavy hydrocarbon on walls during dynamic studies
  - Combine high resolution CT scan data from APS with neutron-based data for spray G-based injector
  - Improve image processing and analysis to derive more quantitative data sets for modeling

Technical back-up slides

Employ stroboscopic technique to image internal fluid with ~1 ms injection, 20 µs resolution

- Variables include: rail pressures, heated nozzles and evacuated chamber
  - Highest rail pressures (GDI: ~200 bar)
- 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
  - This is NOT a single shot study
- After proof of principle, move to more realistic systems

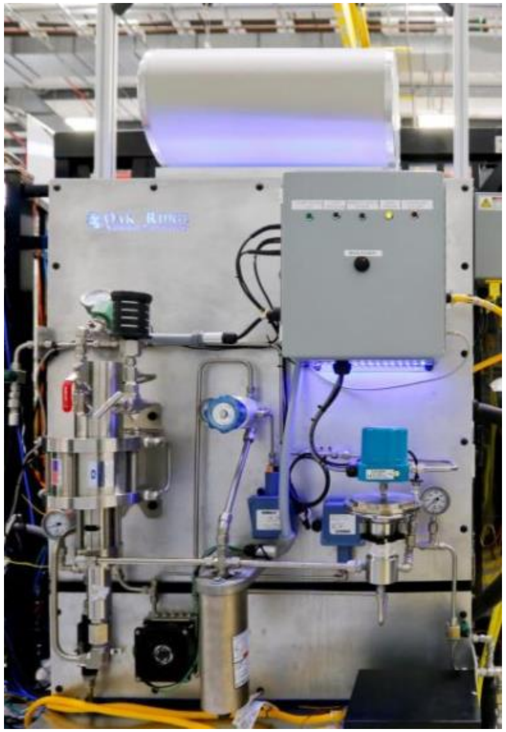


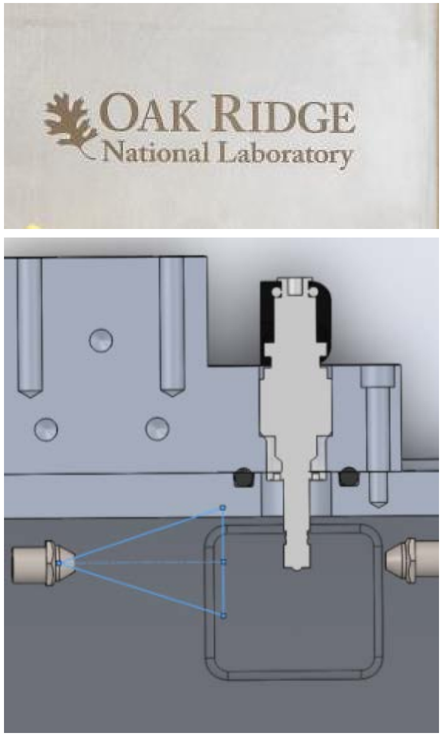


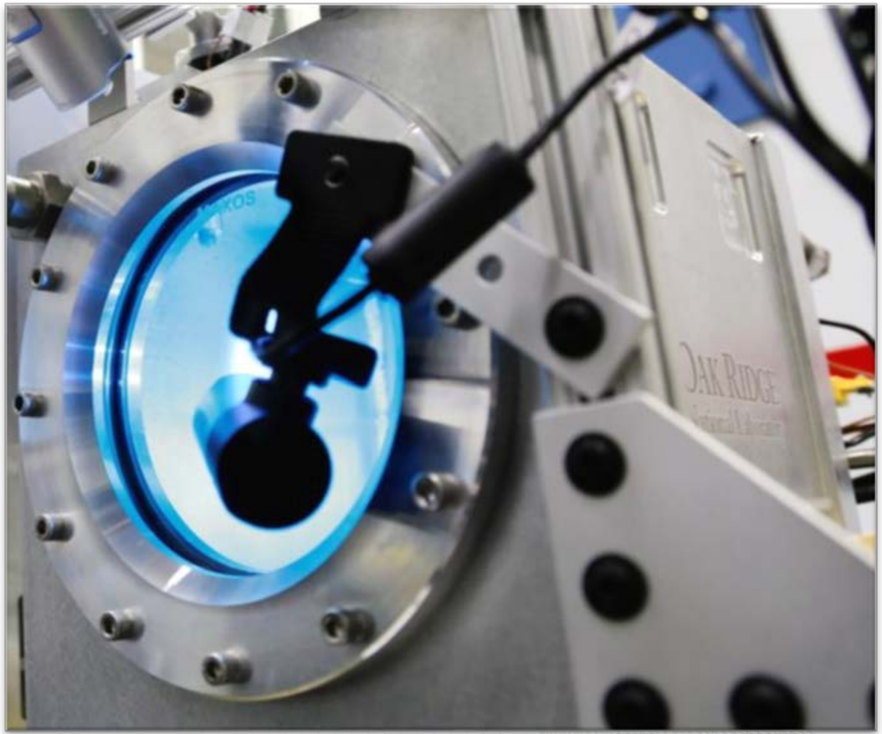
Spray chamber designed to allow for high sweep gas flow, sub-ambient P and elevated temperature

2nd generation chamber

- Multiple cartridge heaters for fuel injector and chamber temperature control (>100°C)
- Modular injector holder designed to allow multiple injector designs
- Wide pressure range: 0.01 to 3-4 bar absolute (next generation target 6 bar)
- Direct heated sweep gas with high flowrate pumping system (~8 scfm)

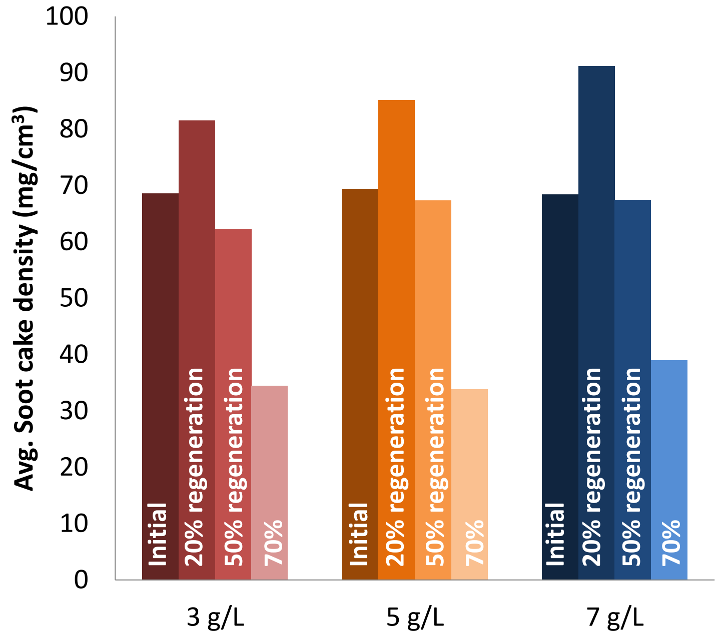


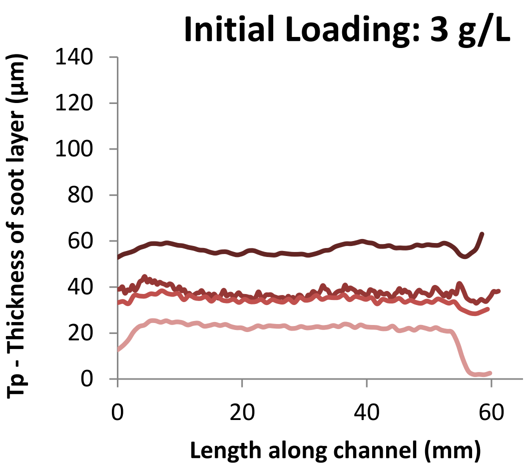


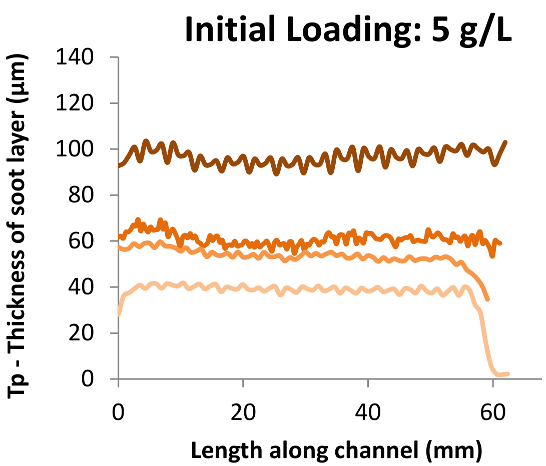


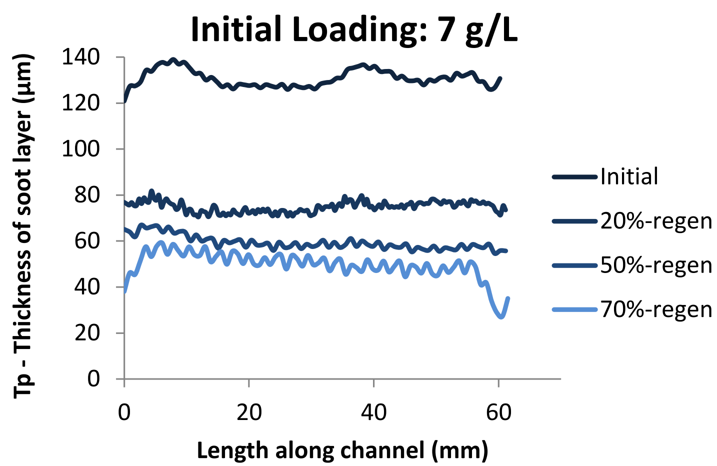
Packing density initially increases during regeneration followed by sharp decreases

- Initial loading of the PFs shows identical soot cake density
- During first 20% regeneration, soot cake compresses significantly
  - density increases by 15-25%
  - uniform distribution maintained
- After 20% regeneration, the soot cake density decreases significantly
  - Based on results of other studies this suggest that pores are opening in the layer; efforts ongoing to quantify this
- At 70% regeneration there are indications that the end of the channel has complete soot removal





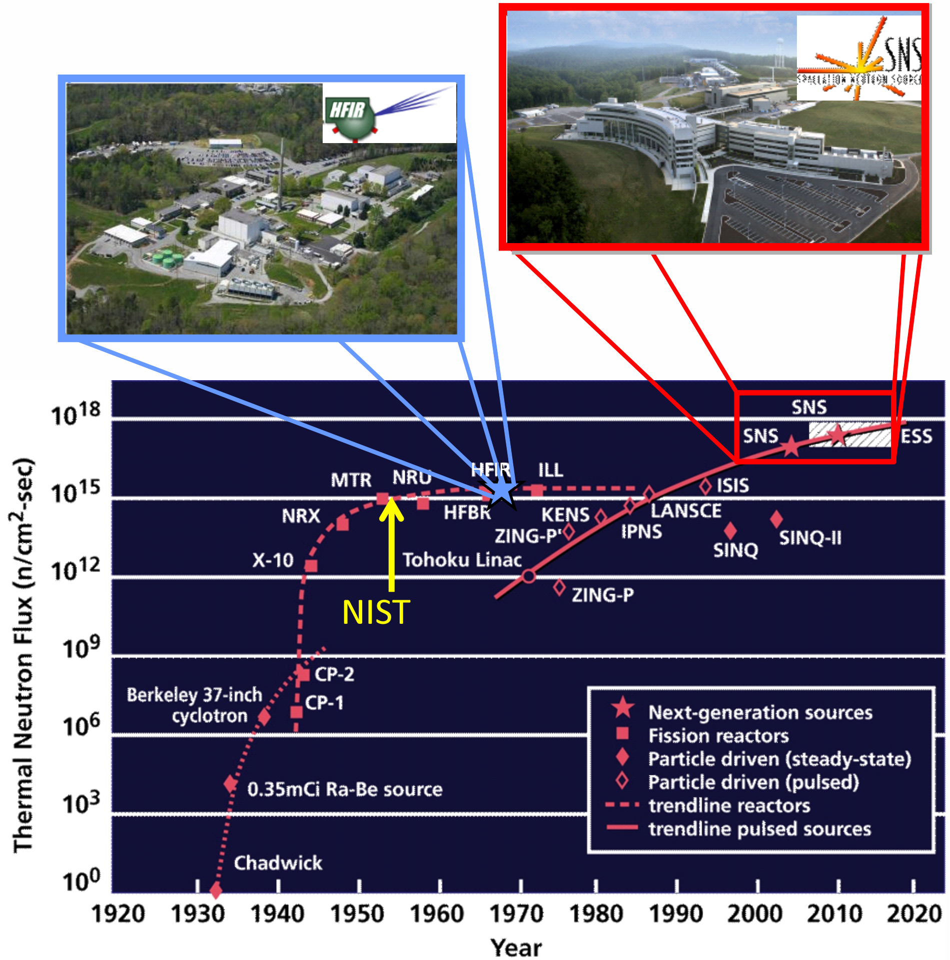




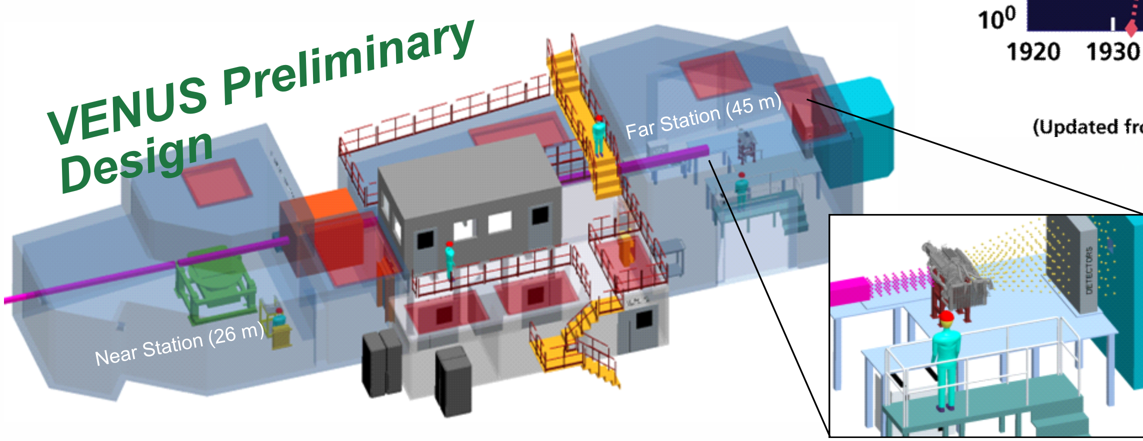
OAK RIDGE National Laboratory

Neutrons at ORNL

- High Flux Isotope Reactor (HFIR)
  - Steady (i.e., non-pulsed) neutron source; “white” beam
  - Imaging beam line accessible through user program
- Spallation Neutron Source (SNS)
  - Most intense pulsed neutron beam in the world; energy selective
  - EERE promised $12M to VENUS imaging beamline; manufacturing
    - 39 months to build



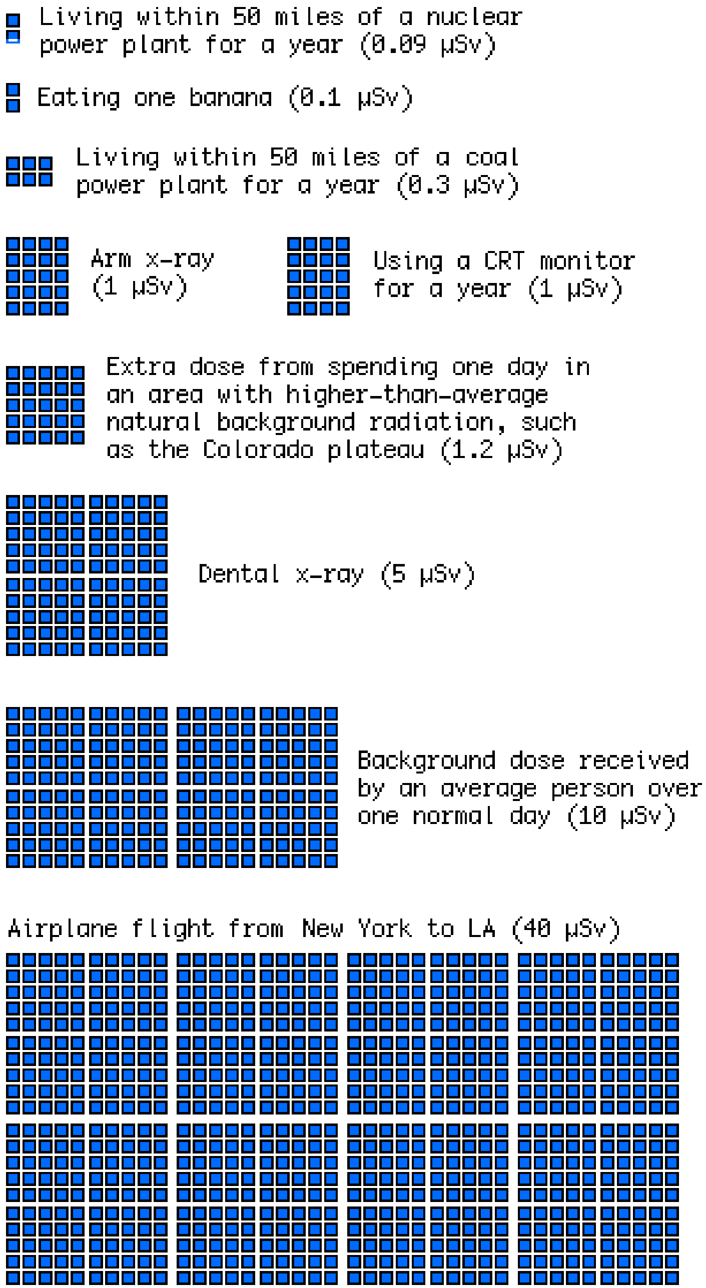
(Updated from *Neutron Scattering*, K. Skold and D. L. Price: eds., Academic Press, 1986)



Estimated Beam Characteristics			
Resolution	20 μm	50 μm	200 μm
Max Field of View (cm x cm)	2 x 2	20 x 20	30x30

Radiation/Activation

- Average radiation exposure
  - Working 12 h at 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/)