Heavy Duty HCCI Development Activities

DOE High Efficiency Clean Combustion (HECC)

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DOE Contract DE-FC26-05NT42412

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DOE DEER Conference
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- 2010 on-highway and 2014 Tier4b non-road engine regulations require ultra-low NOx and PM emissions levels
- Caterpillar is exploring a range of combustion and aftertreatment options to meet these emissions levels
- Homogeneous charge compression ignition offers some distinct advantages if the technical and commercial challenges can be overcome

Outline

- DOE Program background
- Sandia optical engine results
- CFD modeling results
- Nozzle geometry impacts
- Variable compression ratio engine
- Conclusions

DOE High Efficiency Clean Combustion Partners

Partner	Activities	Key Personnel
CATERPILLAR	Program coordination, Test/Analysis, system integration and packaging, Combustion development	Kevin Duffy, Carl Hergart
ExxonMobil Research and Engineering	Fuels effects, Combustion Chemistry/modeling	Charlie Schleyer, John Farrell, Paul Bessonette
Sandia National Laboratories	Optical diagnostics, Fuel spray and combustion, Fuel effects	Chuck Mueller, Glen Martin
AV	Closed loop control, Transient controls, Vehicle calibration, Sensors	Mike Traver, Chris Atkinson

Major Project Tasks

Task 1 Sandia Optical Experiments

Milestone: Complete initial optical engine tests to establish baseline fundamental understanding of HCCI spray/mixing/combustion process

Task 2 Combustion CFD Model Development Activities

Milestone: Validated CFD Combustion code to model the effects of injection timing, spray pattern and bowl geometry on HCCI combustion

Task 3 Fuel Property Effects

Milestone: Initial fuels evaluation on metal and optical engines

Task 4 Cooling System and Heat Rejection Analysis

Milestone: Recommendation, initial design/layout of cooling system

Task 5 Advanced Controls Algorithm Development

Milestone: Transient demonstration of multi-cylinder HCCI engine

Task 6 Advanced Fuel System Concept Identification and Selection

Milestone: Down-selection of the best concept for further development and testing

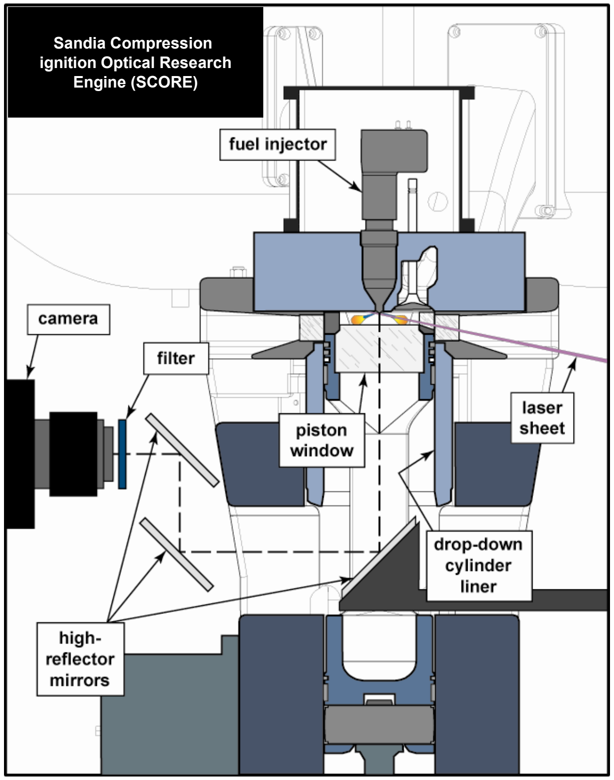
Task 7 Combustion Development for Multi-cylinder Engines

Milestone: Demonstration of <0.2 g/hphr NOx and <0.1 AVL smoke on C15 engine

Optical Engine Testing with Sandia National Lab

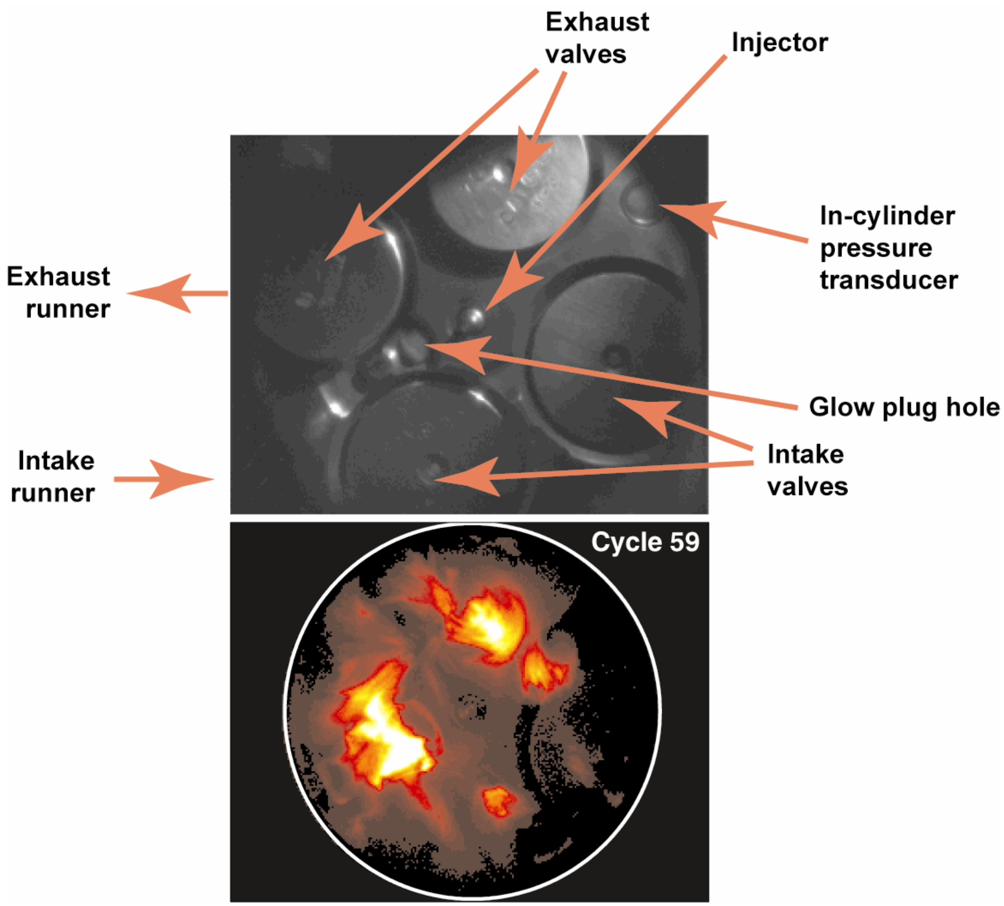
- Goal of Project: use optical diagnostic techniques to supply knowledge base of in-cylinder processes under LTC operating conditions
  - Understand reasons underlying observed emissions levels
  - Gain insight into approaches to implement fuel or hardware changes that ameliorate problems
  - Validate simulations of in-cylinder mixing and LTC
- Optical diagnostics techniques used include natural luminosity, liquid and vapor phase spray imaging, soot imaging, PLIF
- Work completed by Chuck Mueller and Glen Martin

Research engine	1-cyl. Cat 3176
Cycle	4-stroke CIDI
Valves per cylinder	4
Bore	125 mm
Stroke	140 mm
Intake valve open	32° BTDC exhaust
Intake valve close	153° BTDC compr.
Exhaust valve open	116° ATDC compr.
Exhaust valve close	11° ATDC exhaust
Conn. rod length	225 mm
Conn. rod offset	None
Piston bowl diameter	90 mm
Piston bowl depth	16.4 mm
Squish height	1.5 mm
Swirl ratio	0.59
Displacement per cyl.	1.72 liters
Fuel Injector	HEUI™ 450A
Injector tip	Multi-hole nozzle



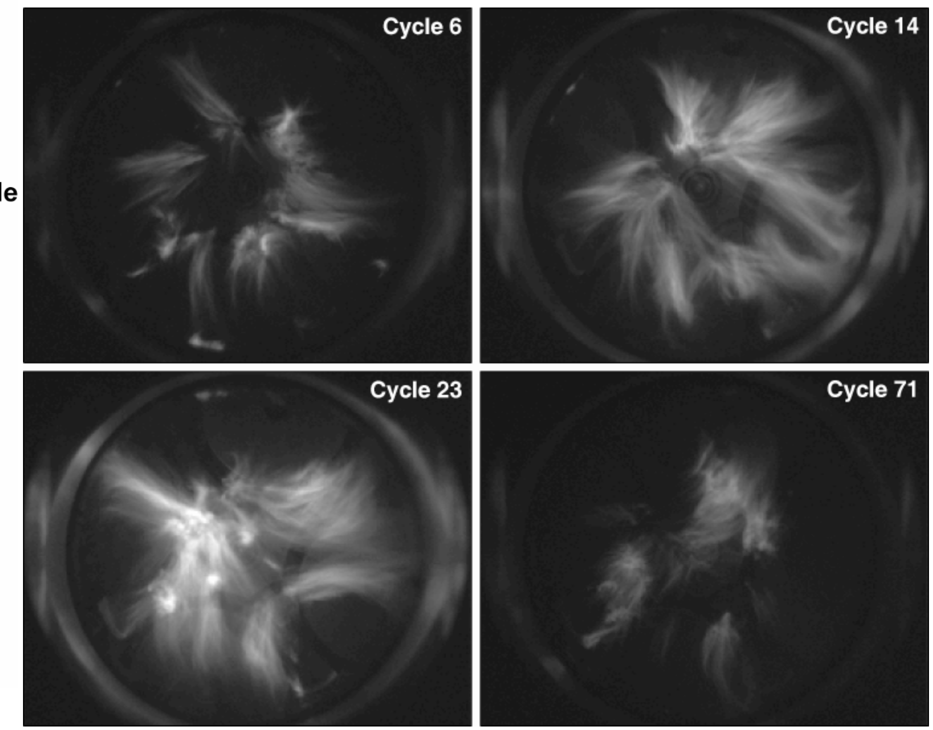
Cycle Integrated Natural Luminosity (CINL)

- Spatial resolution only → Cycle Integrated Natural Luminosity (CINL), shows where luminous combustion occurred during cycle



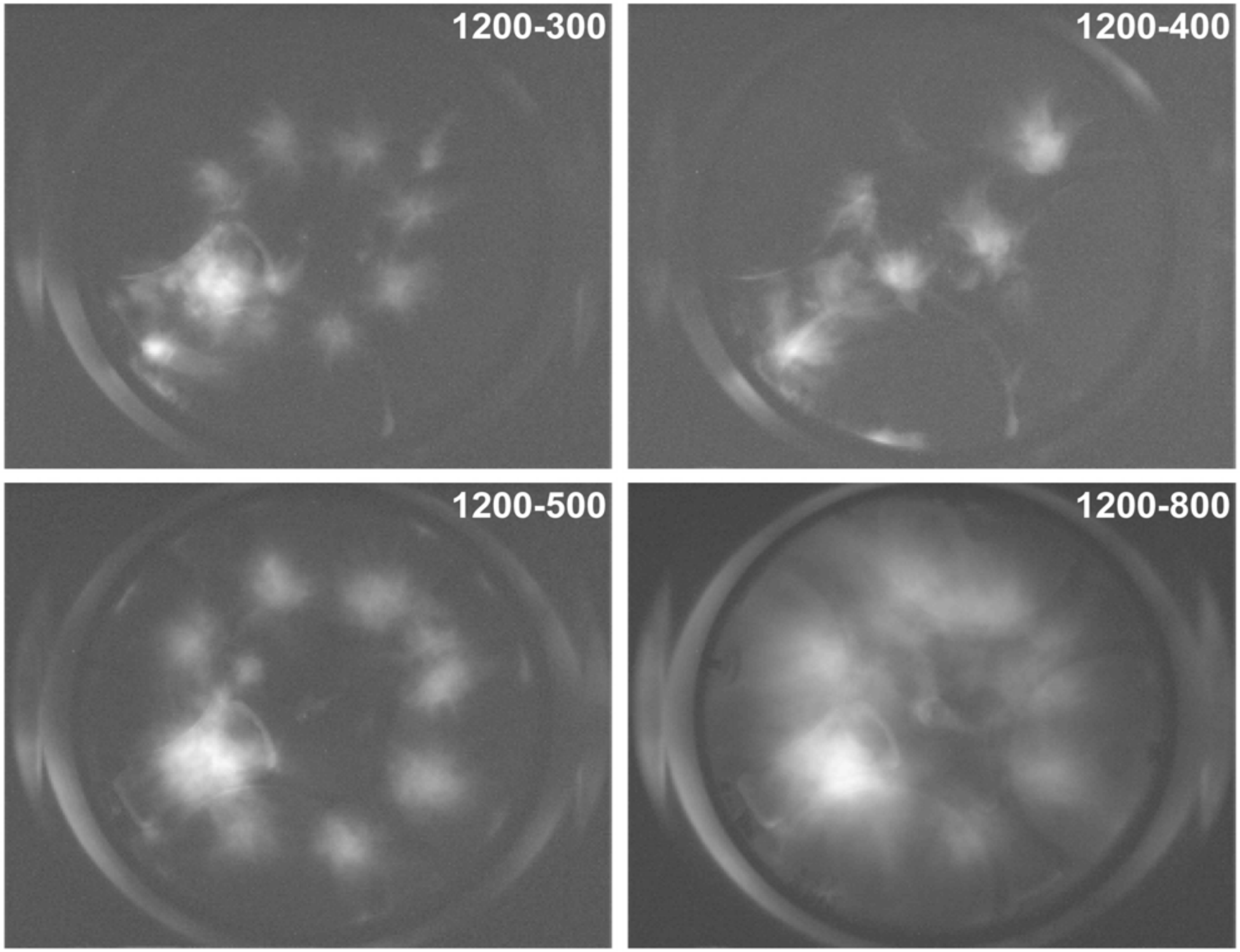
CINL images with multi-hole tip:

- **Cycles 6 and 14 approximately bracket the average**
- **What went wrong on Cycle 23?**
- **What went right on Cycle 71?**



Averaged 75 cycle CINL Images for Diesel

Speed - BMEP (kPa)



0.08 AVL Smoke (1200-300)

0.08 AVL Smoke (1200-400)

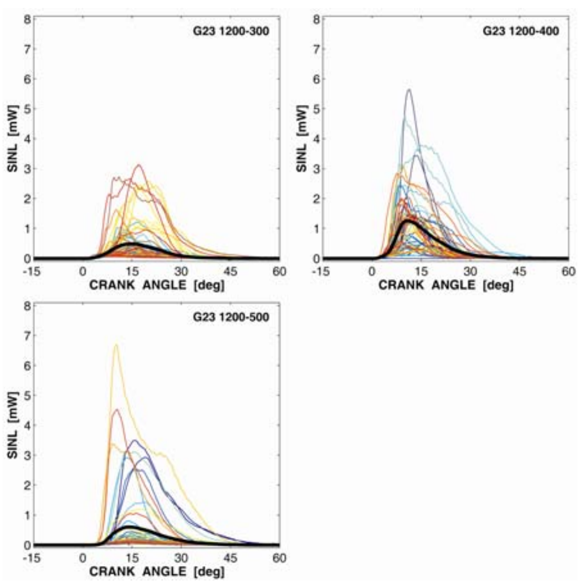
0.3 AVL Smoke (1200-500)

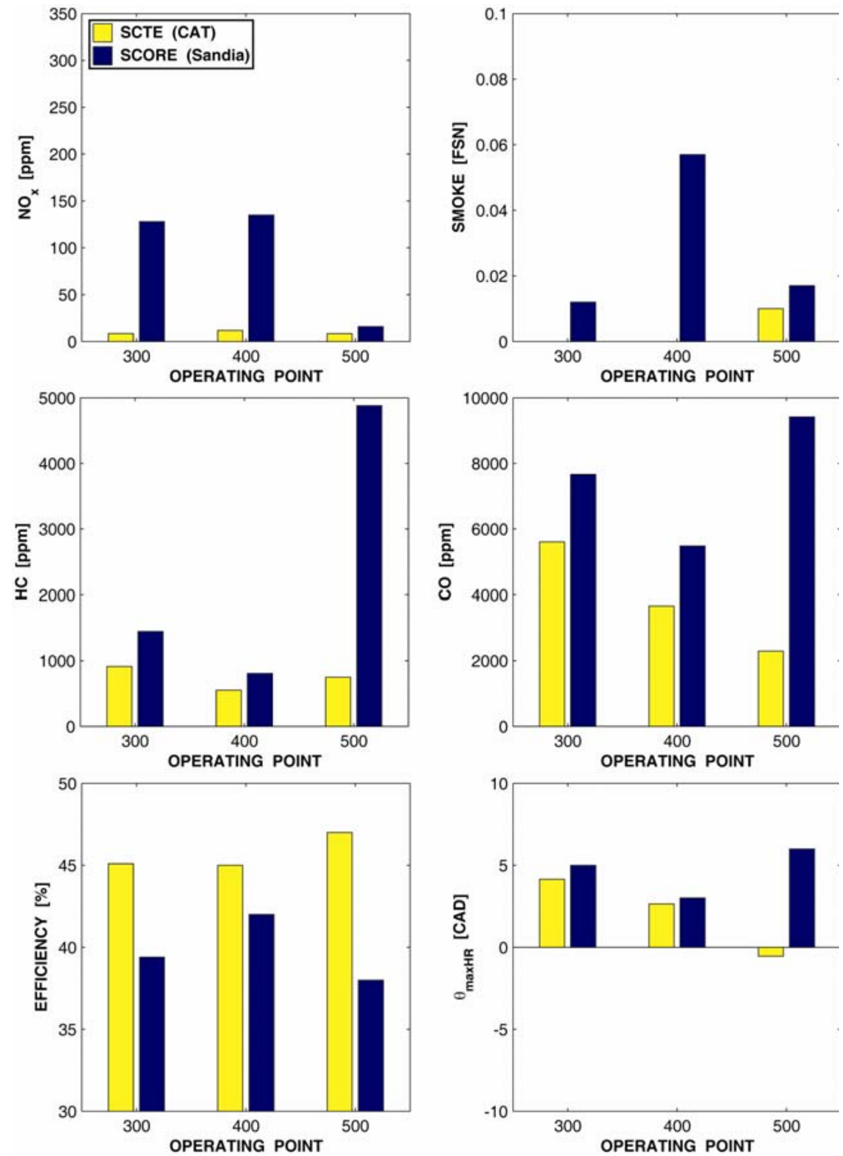
1.0 AVL Smoke (1200-800)

Validates theory of excessive spray impingement on bowl as cause of soot

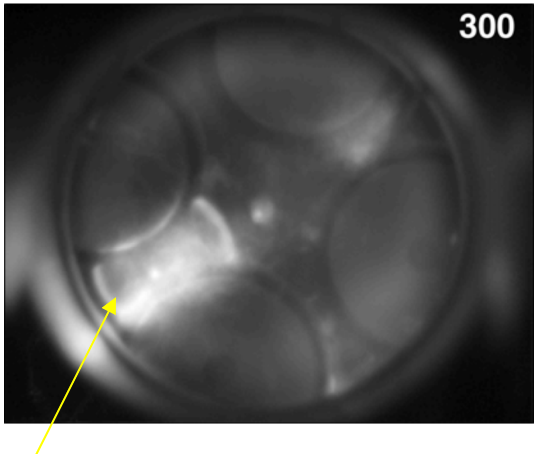
Gasoline Testing

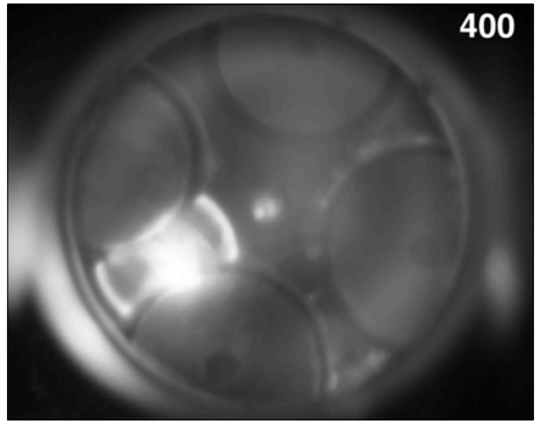
- 63 Octane gasoline from ExxonMobil
- Established 3 operating points that matched metal engine data
- Metal engine data showed ~zero smoke at all conditions
- Recorded emissions, heat release, natural luminosity, spray penetration
- Spray images indicate much faster evaporation and no liquid impingement on piston compared to diesel fuel

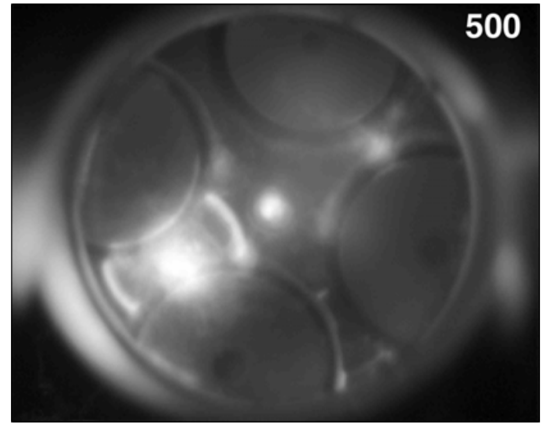




Averaged 75 cycle CINL Images for Gasoline







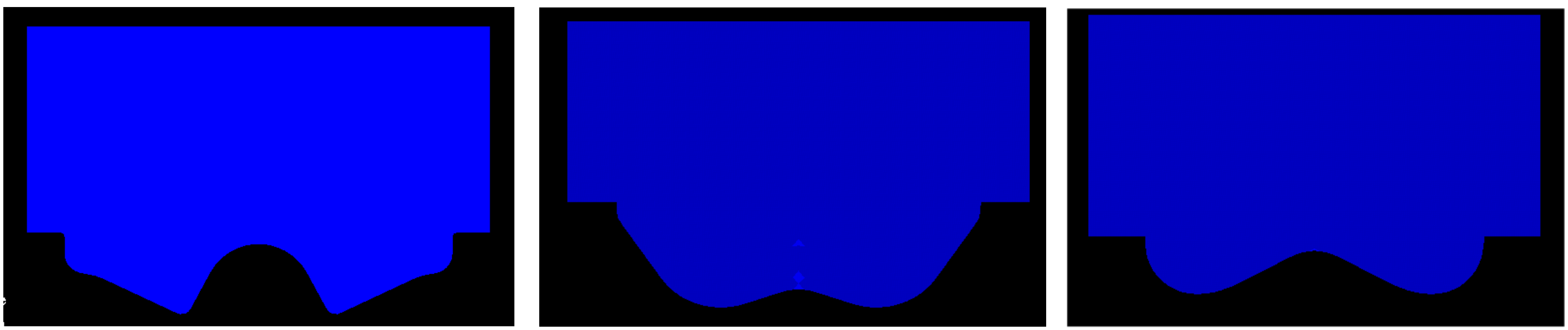
- Intense combustion luminosity observed in intake/exhaust valve bridge and near glow plug hole
- This is side of engine where oil is spilled from HEUI^{TM} fuel injector
- Speculate intense combustion luminosity near valve bridges results from lube oil
- Diesel CINL movies had glow plug hole filled with RTV, so less leakage potential
- Gasoline CINL movies had new steel plug inserted flush with head surface
- Currently Sandia is installing sealed valve guides into optical engine
- Intense combustion luminosity is observed at injector tip on several cycles
- Not observed as strongly in Diesel CINL movies, due to greater volatility of gasoline in the tip?

CINL Movie of Gasoline HCCI Combustion

1200_500_weak_filter.mov

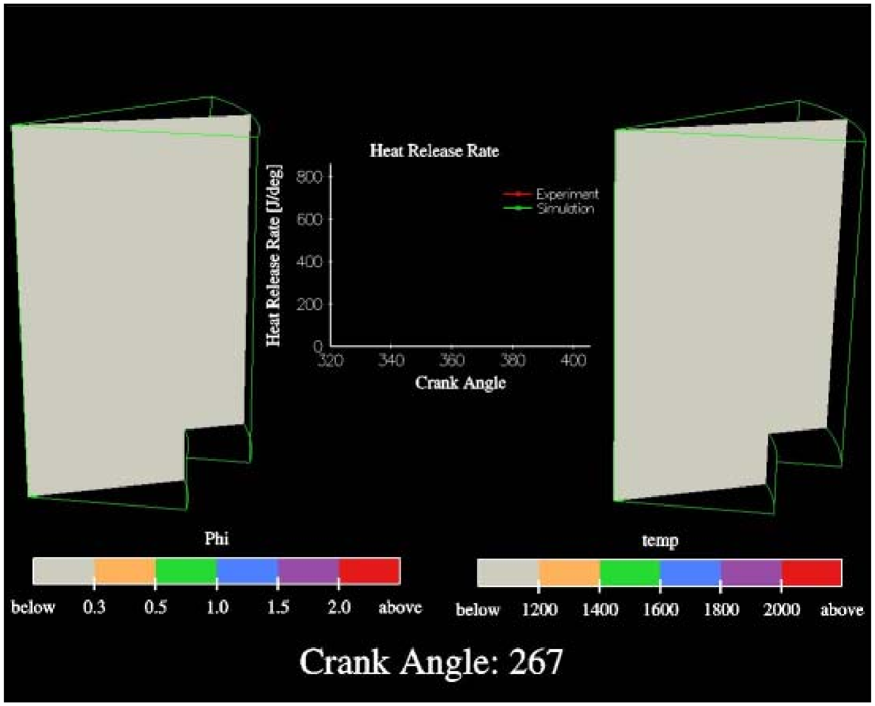
Combustion CFD Development

- Using in-house combustion CFD to design piston bowls, injection strategies for HCCI
- Spray models more robust, so more accurate fuel/air distribution can be predicted
- Ignition chemistry and emissions models improving; still need improvement to be predictive
- Liquid impingement/wall film modeling needs development



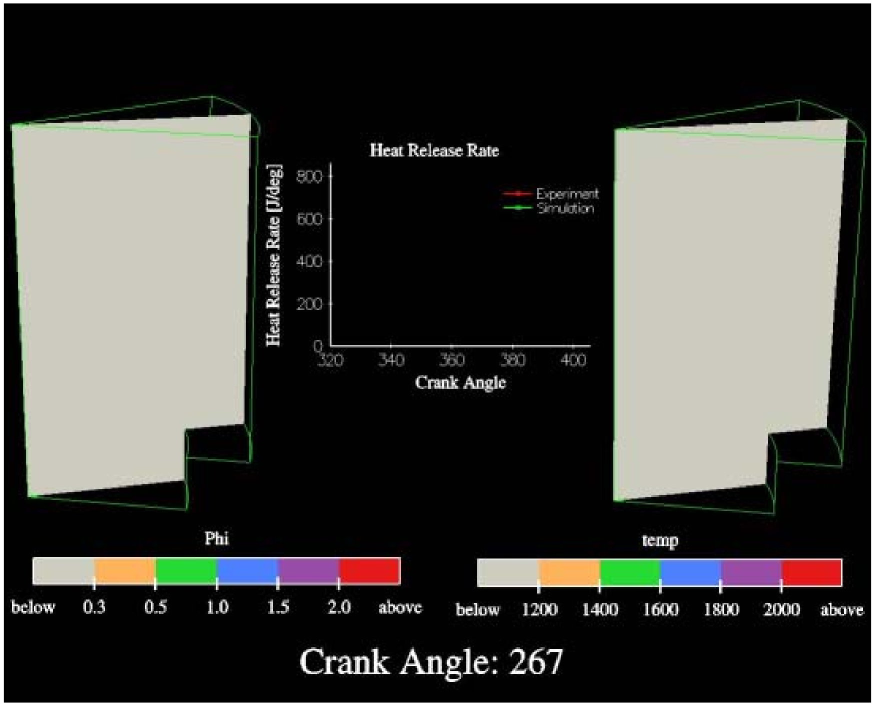
Sample HCCI piston bowls

90 ppm NOx, 0.08 Smoke



1200 RPM / 300 kPa

8 ppm NOx, 1.0 Smoke

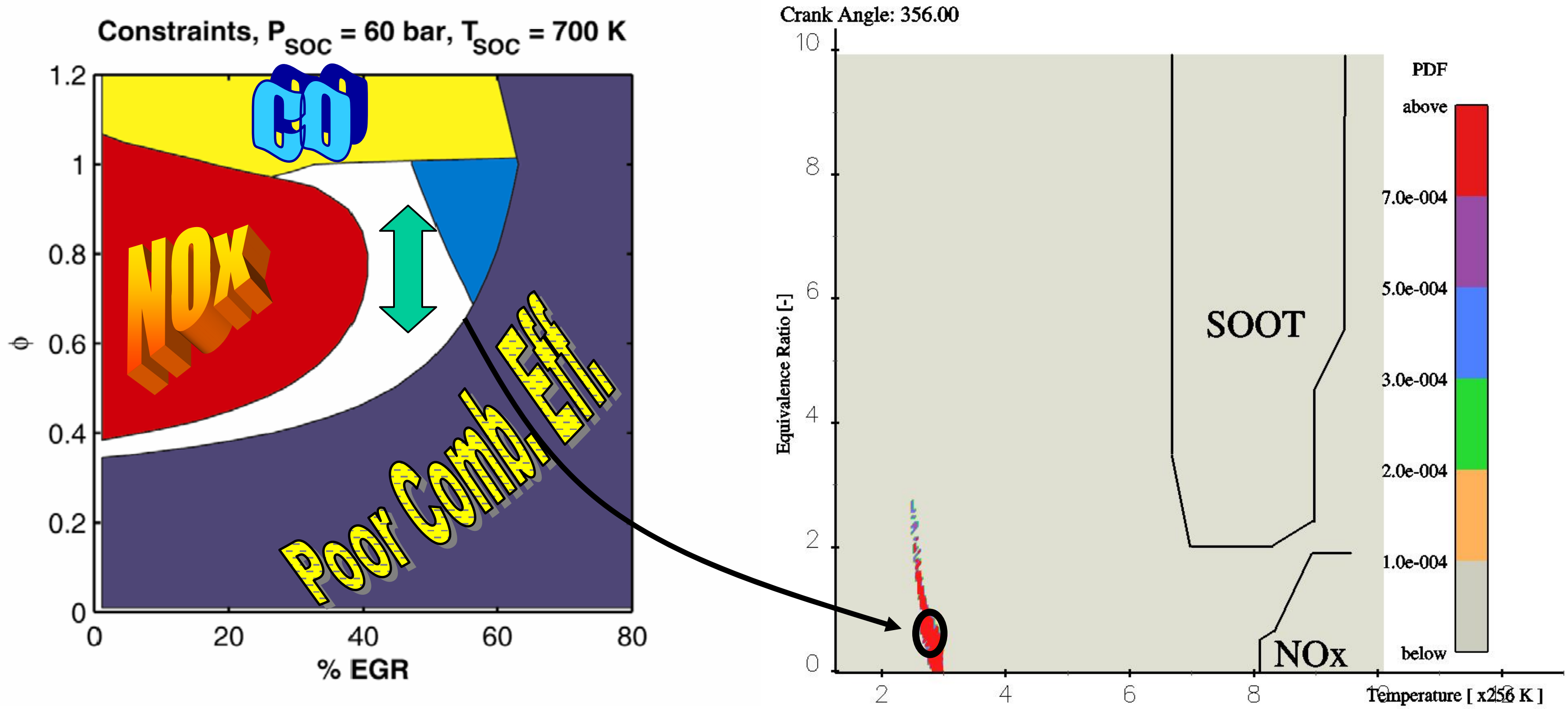


1200 RPM / 800 kPa

Developing a more fundamental understanding

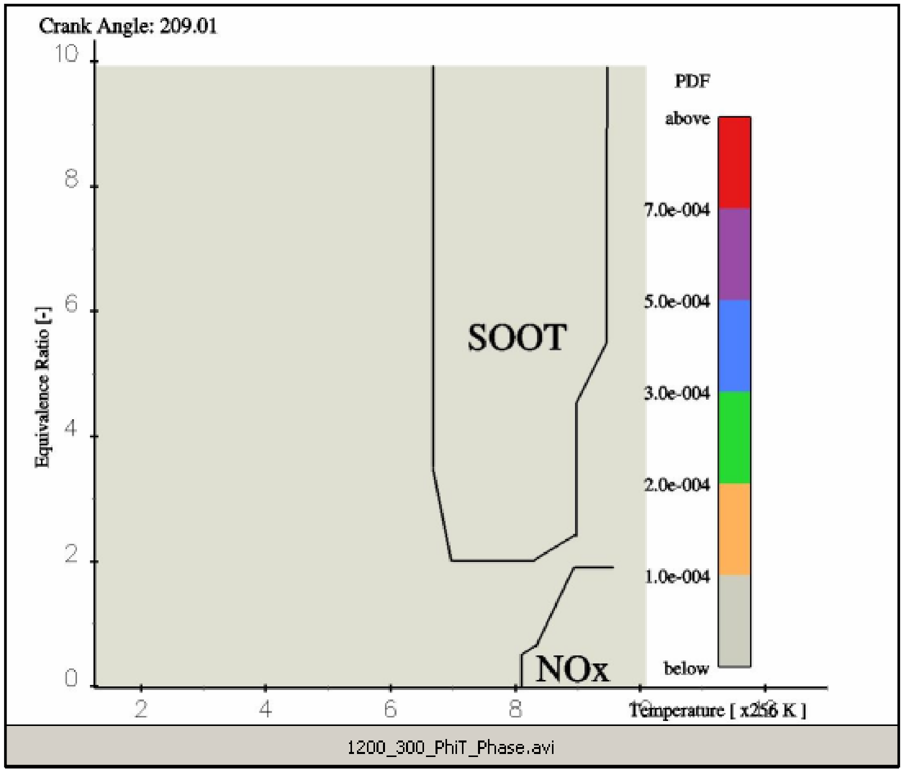
Given a set of input conditions (boost, IMT, EGR-Rate) we can generate phase-space conditions yielding clean combustion.

Maximize fraction of mixture that falls within the Region of Clean Combustion <u>at Start of Combustion</u>[1]



[1] **Hence no combustion calculation required in CAT3D**

90 ppm NOx, 0.08 Smoke



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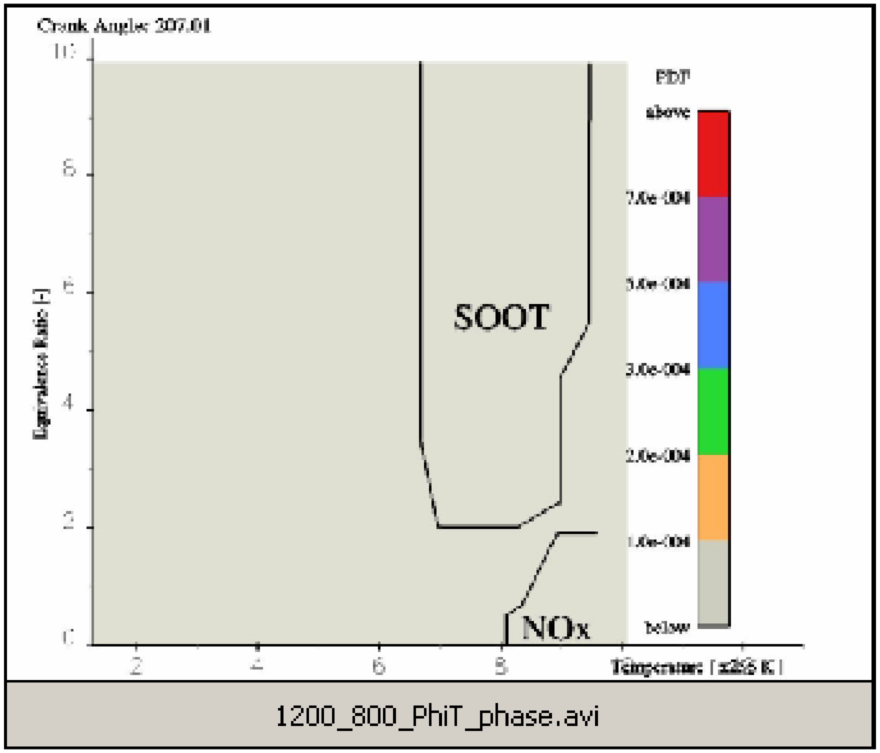
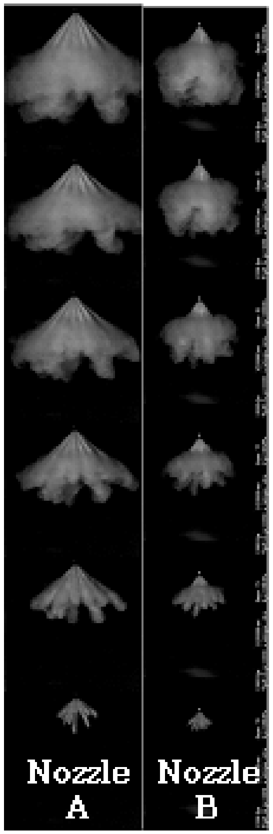
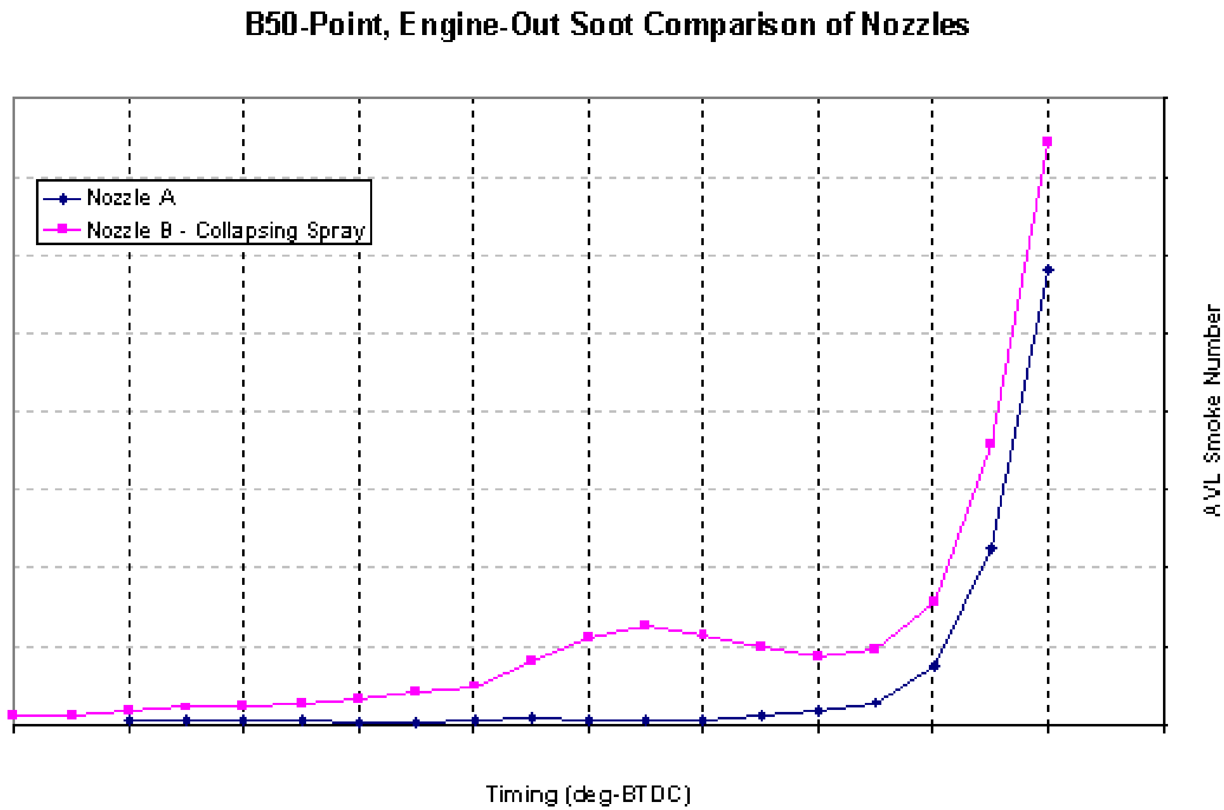


1200 RPM / 800 kPa

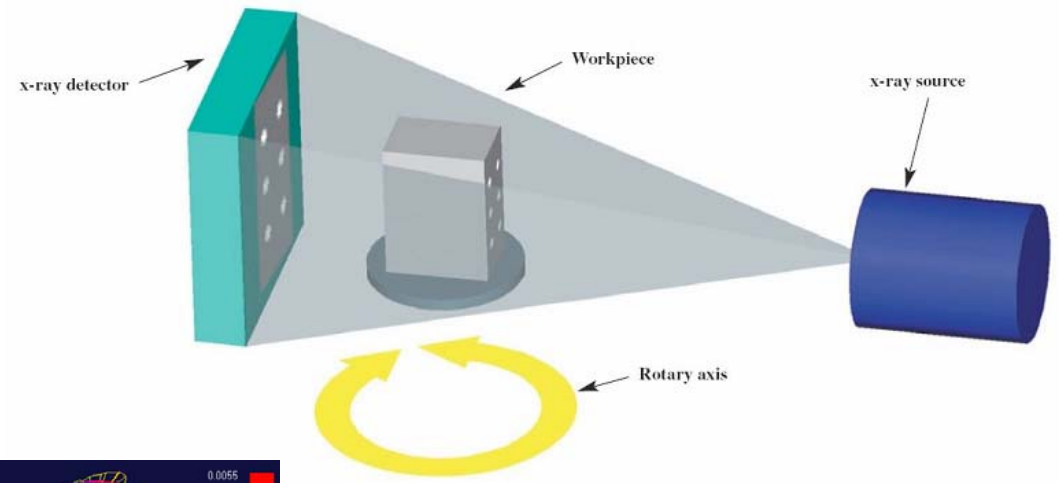
Accurate Nozzle Machining is Critical

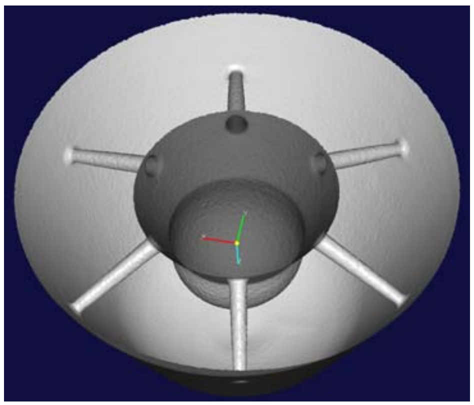


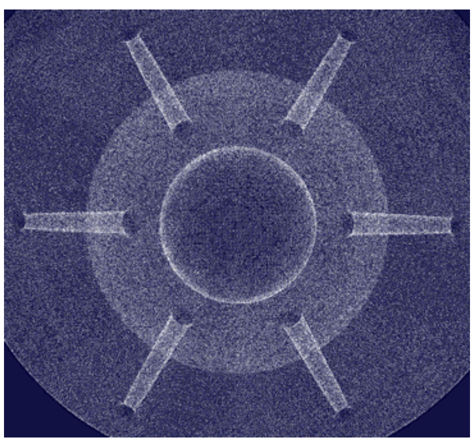


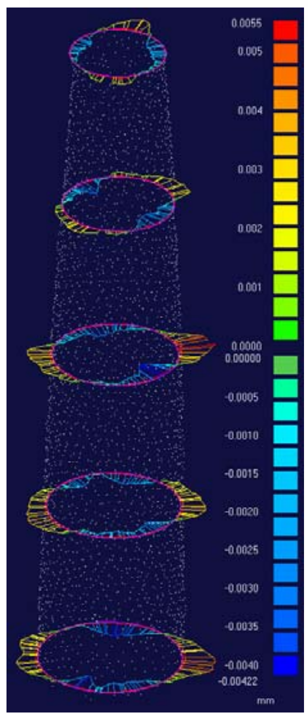
Two nozzles machined to be equal may behave differently

Micro-Focus Computed Tomography X-ray Scanning

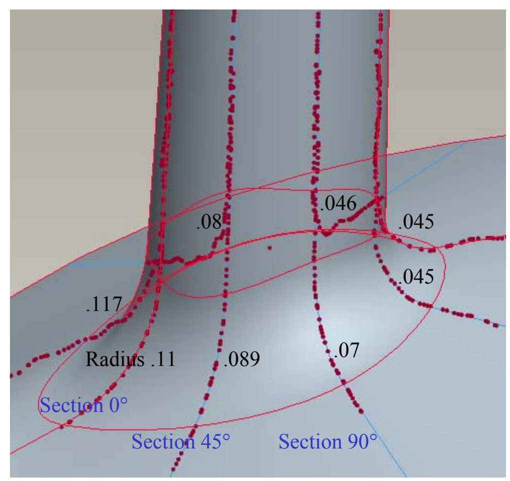


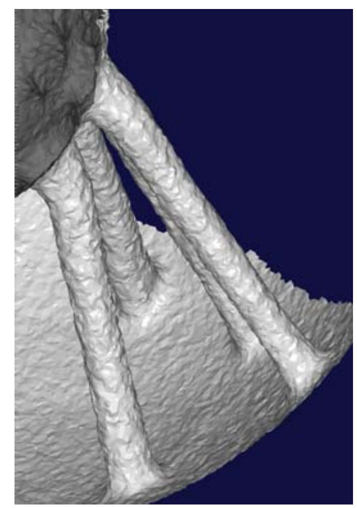




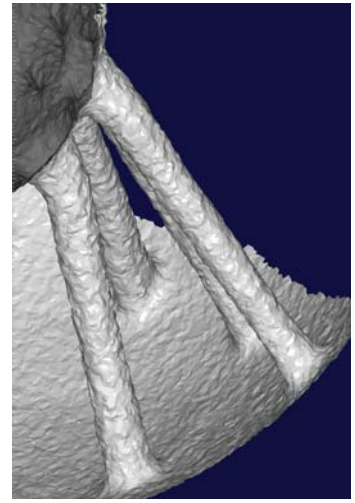


Provides outstanding clarity of detailed inner nozzle geometry

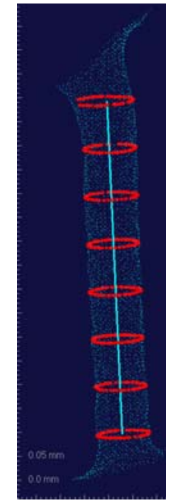


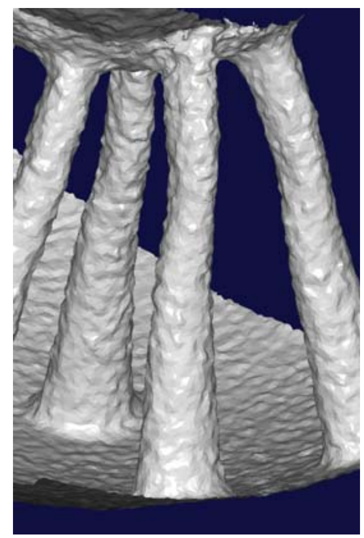


- X-ray clearly exposes root cause difference in nozzles
- Nozzle A has very straight, non-tapered holes resulting in high, constant velocity injection with sufficient spray inertia to penetrate far into cylinder and provide diverging spray pattern
- Nozzle B has trumpeted pattern which causes deceleration of spray, limiting penetration into cylinder; produces converging global spray pattern with resultant poor mixing and high smoke production
- Cause of nozzle variation traced to laser processing inconsistency that has since been corrected
- X-ray tool now a valuable method for understanding details of complex spray geometries

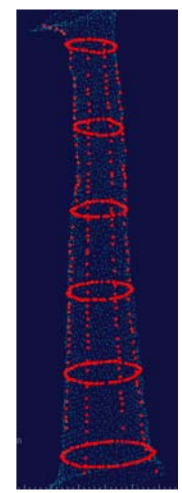


A



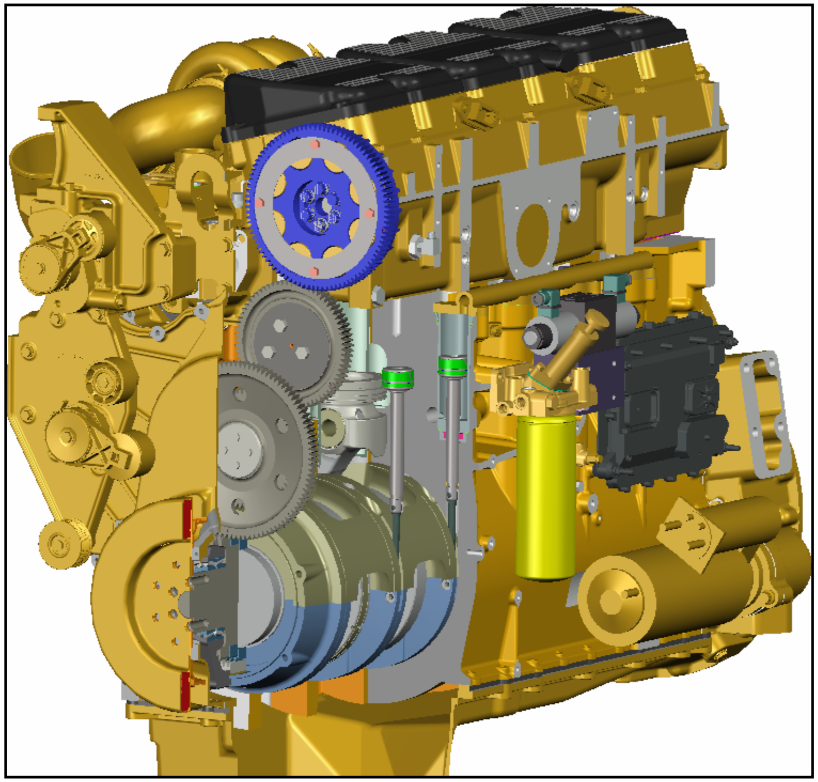


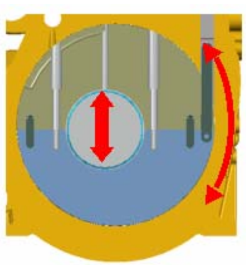
B



Variable Compression Ratio (VCR) Engine

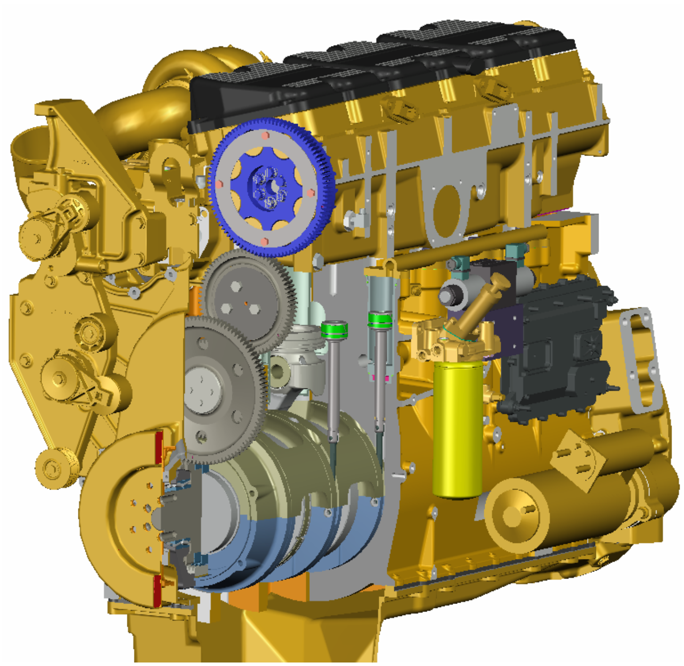
US Patent Application 2006/0112911

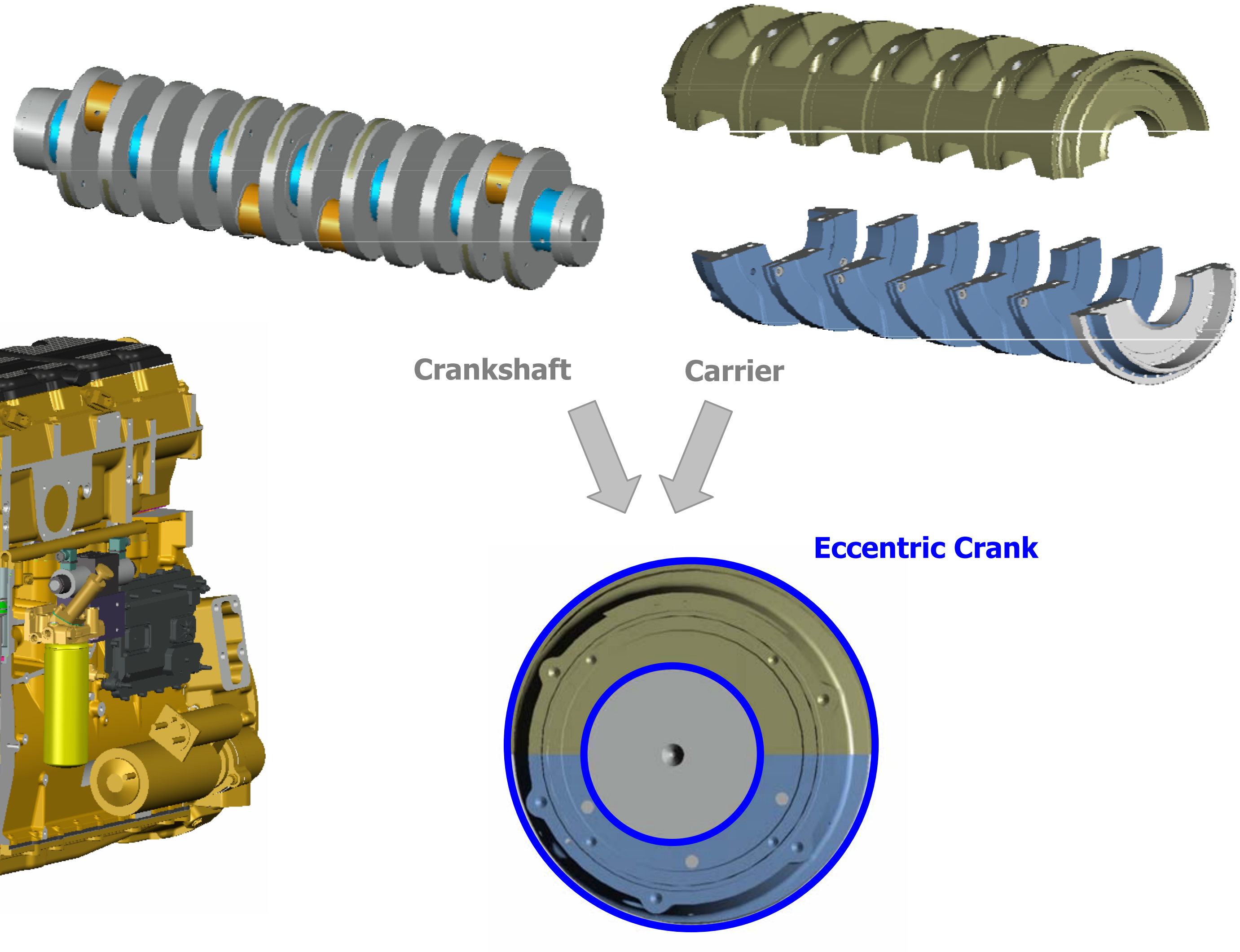




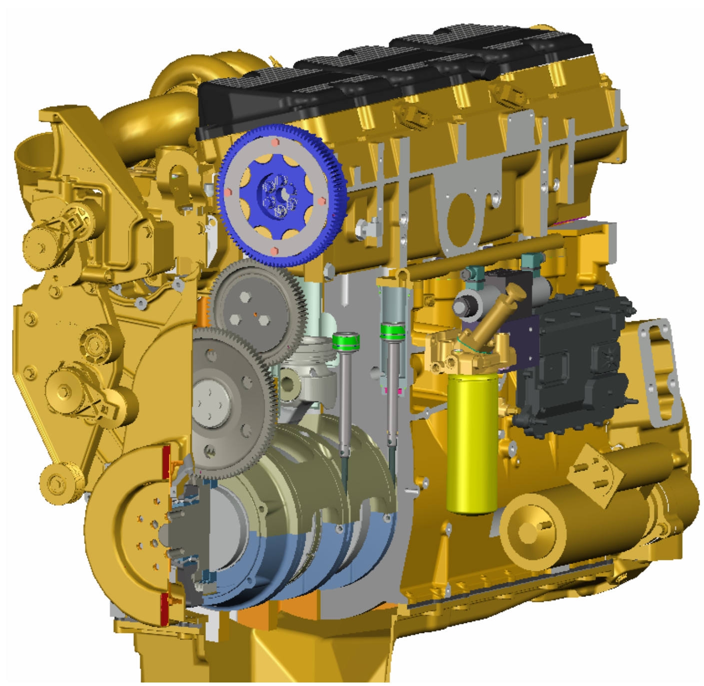
- Approach: Crankshaft mounted eccentrically in cradle which sits in cylinder block. Rotating cradle moves crankshaft which alters compression ratio. 15L displacement.
- Benefits: Allows high load operation at low CR; eliminates low CR cold start issue; improves light load combustion stability and HC/CO; allows for load/ emissions/ fuel economy optimization in between; allows for engine braking

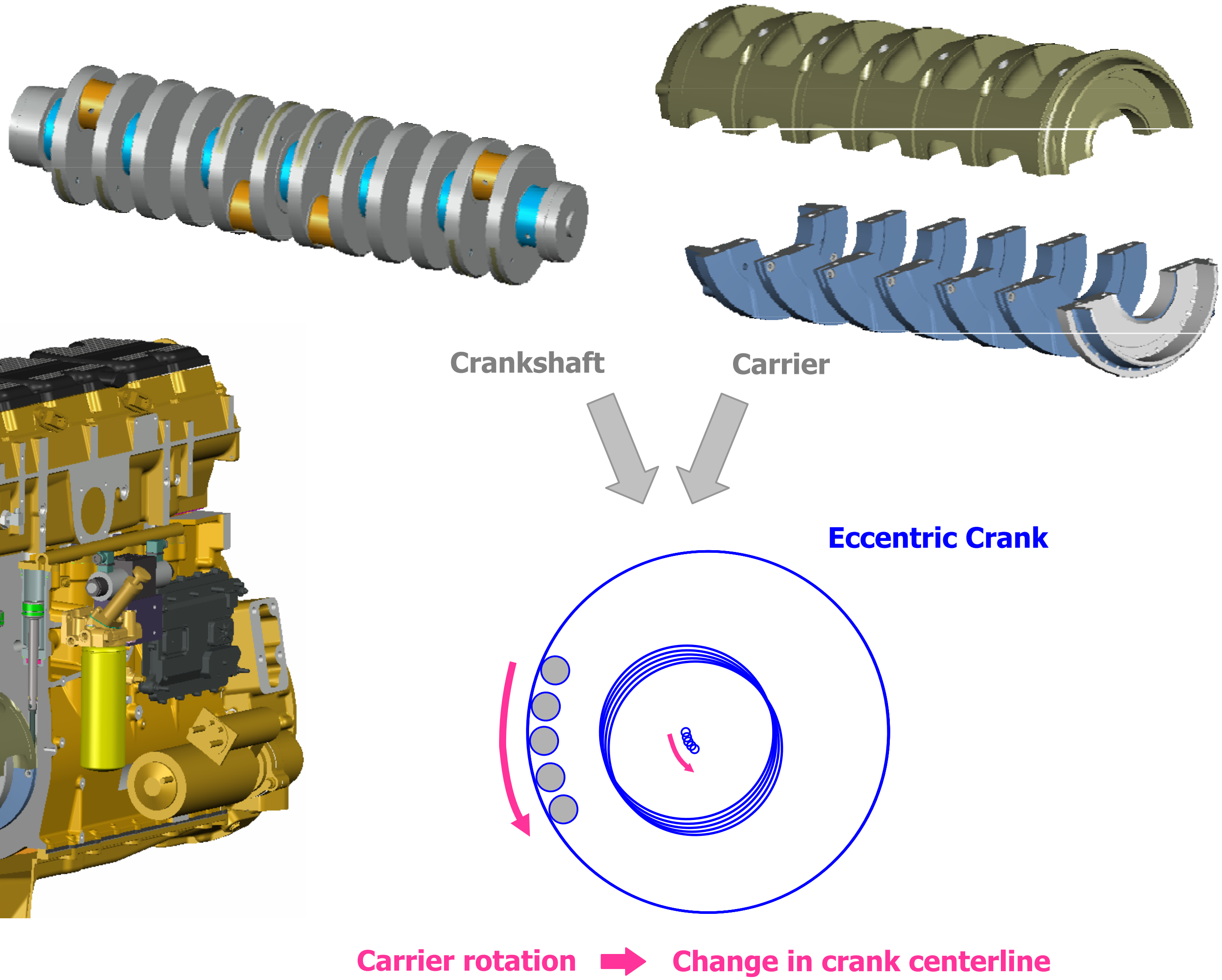
VCR Mechanism



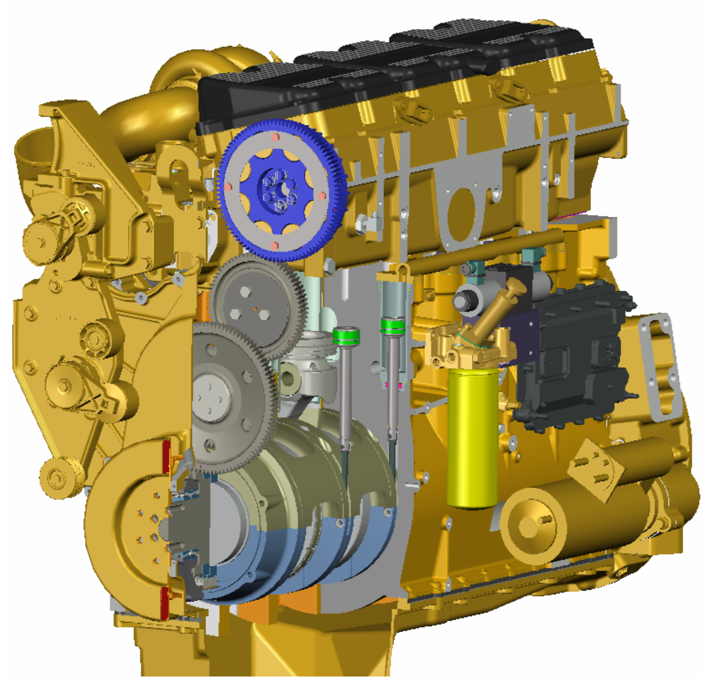


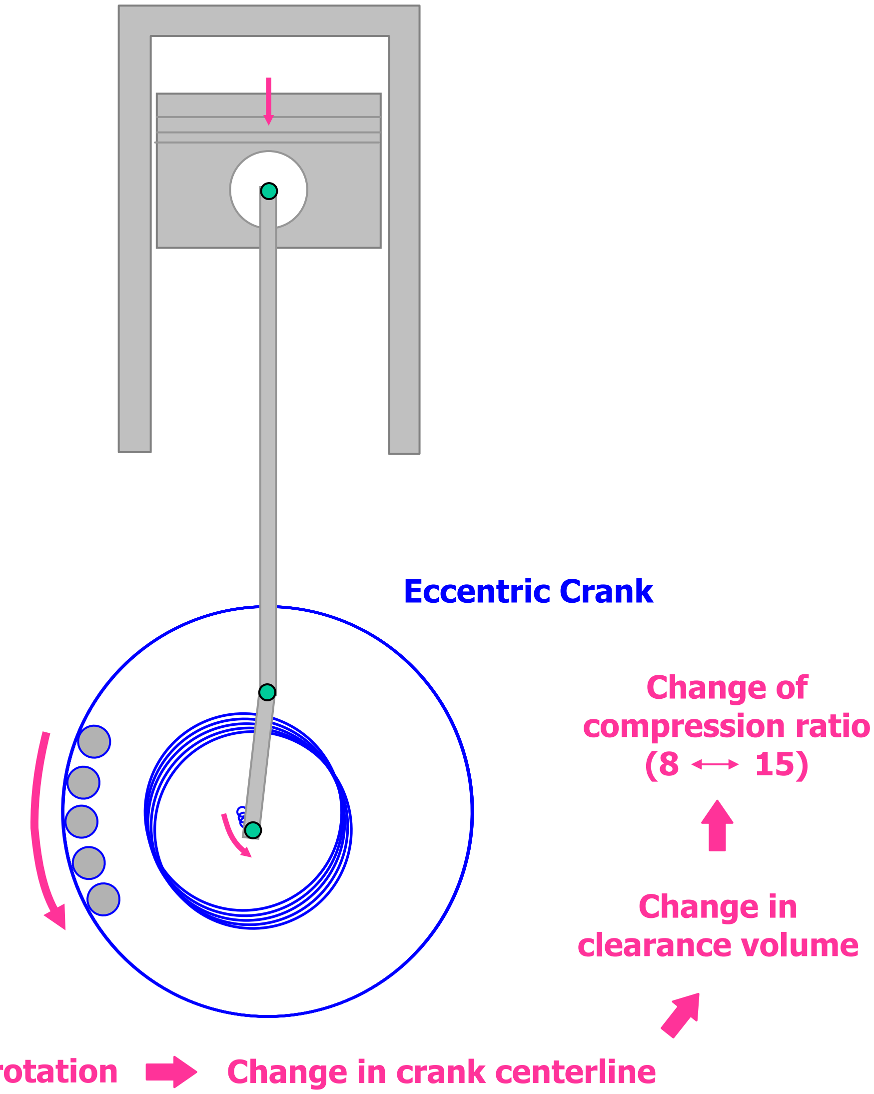
VCR Mechanism



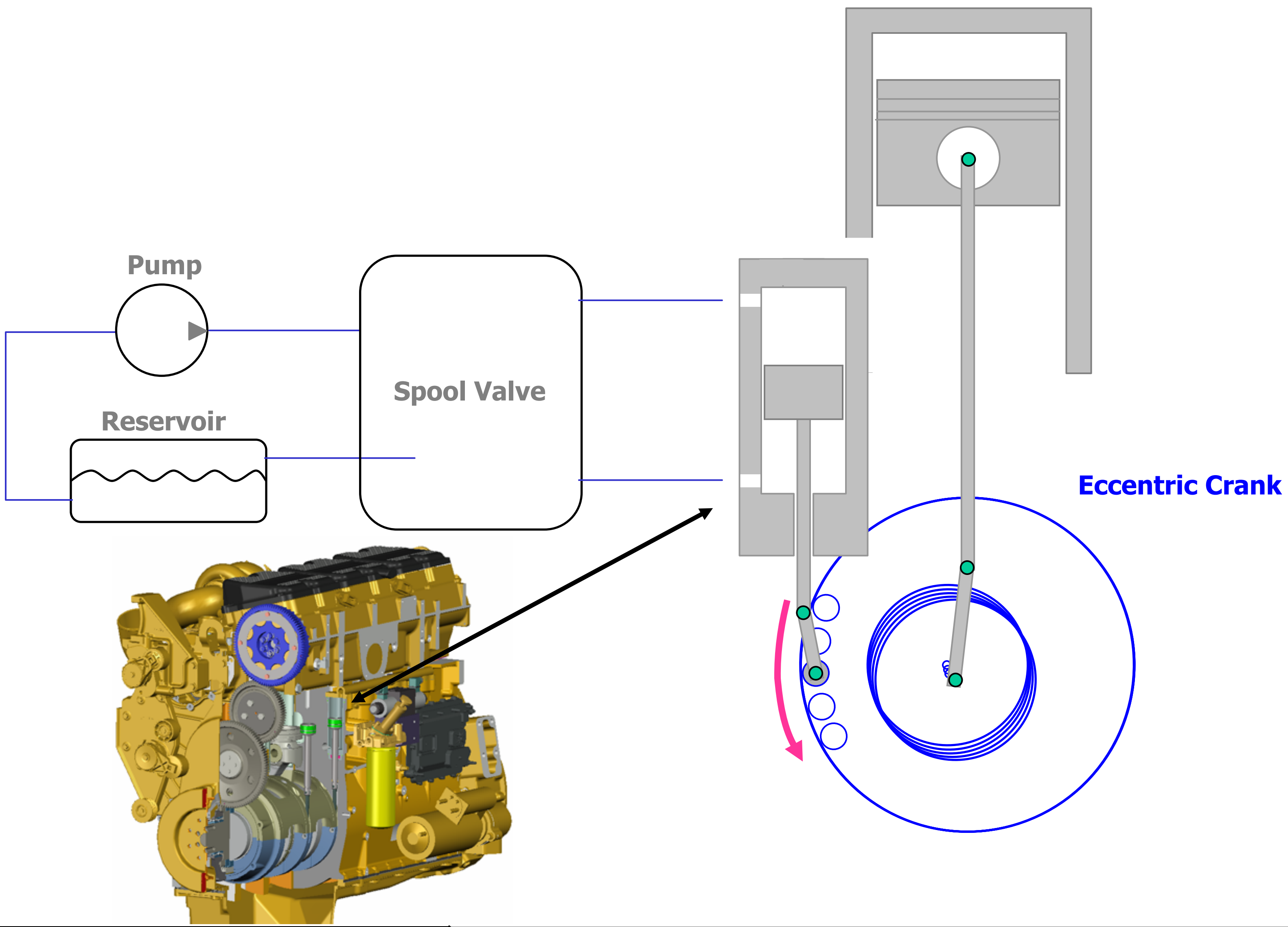


VCR Mechanism

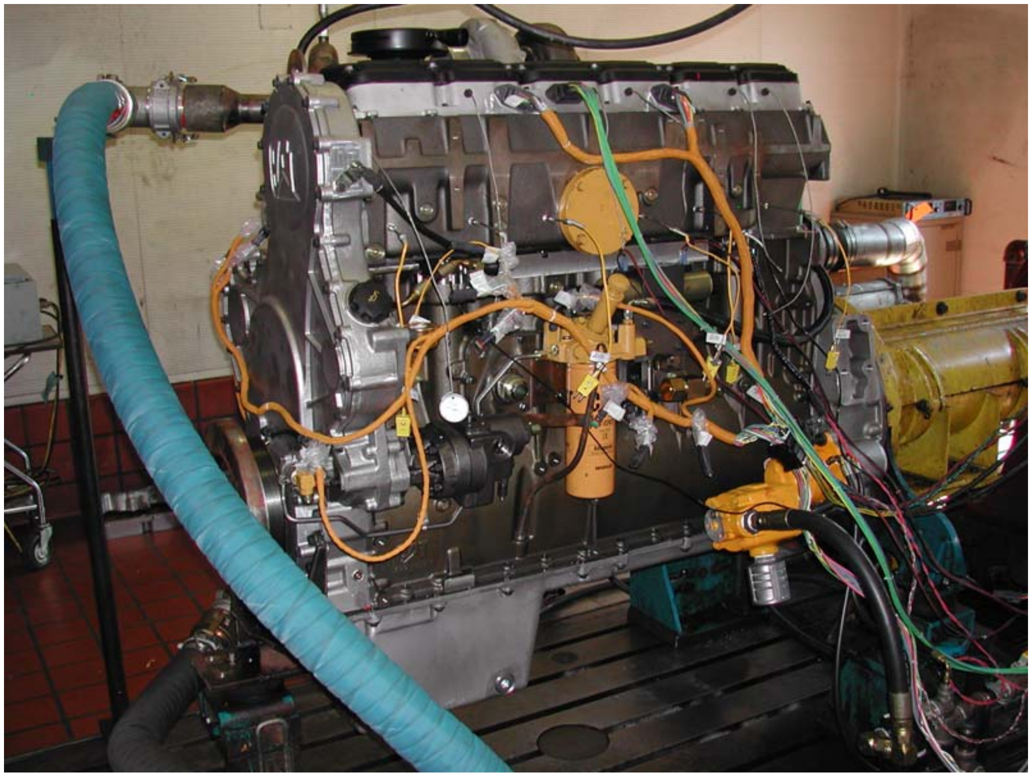


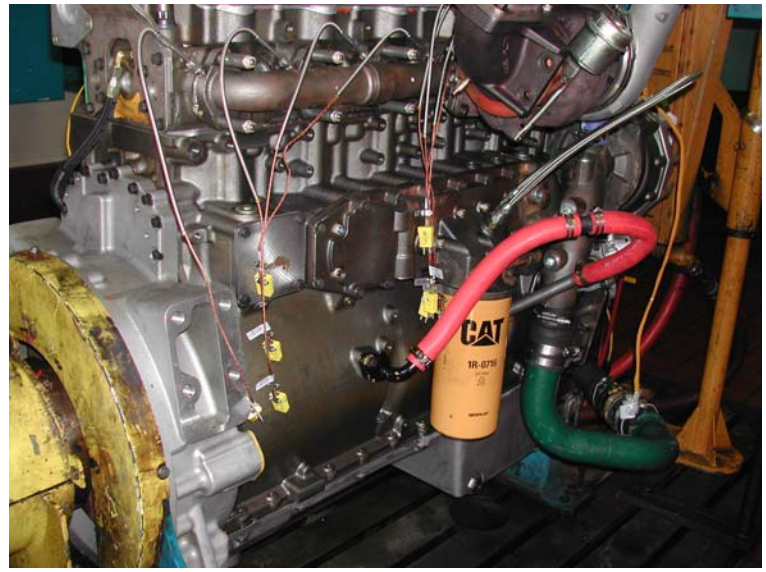


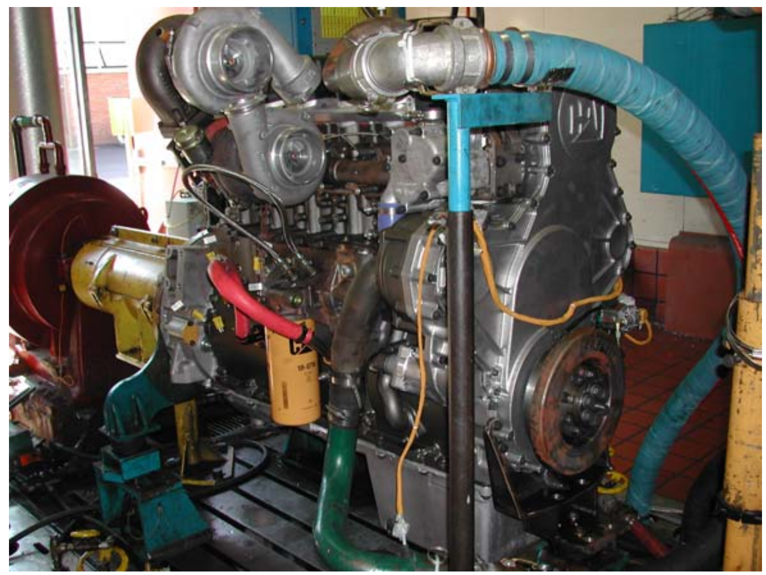
VCR Mechanism



VCR Engine

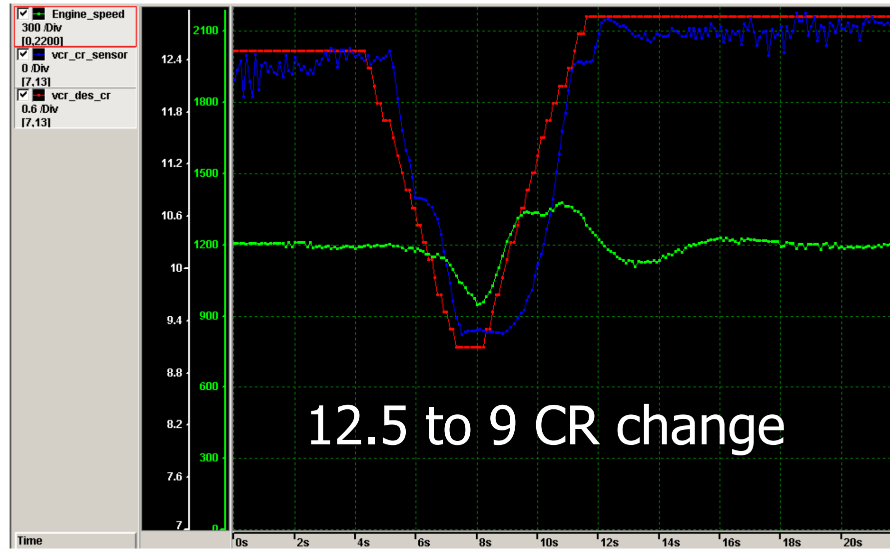


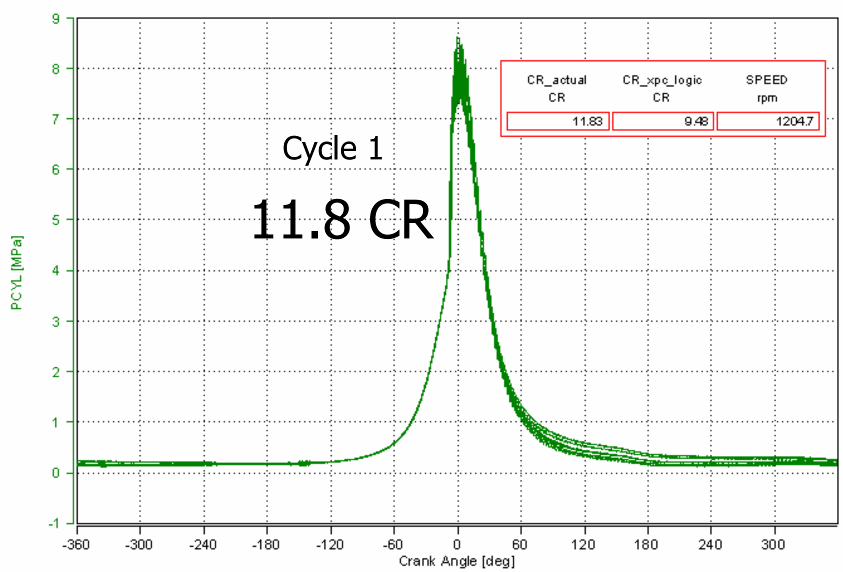


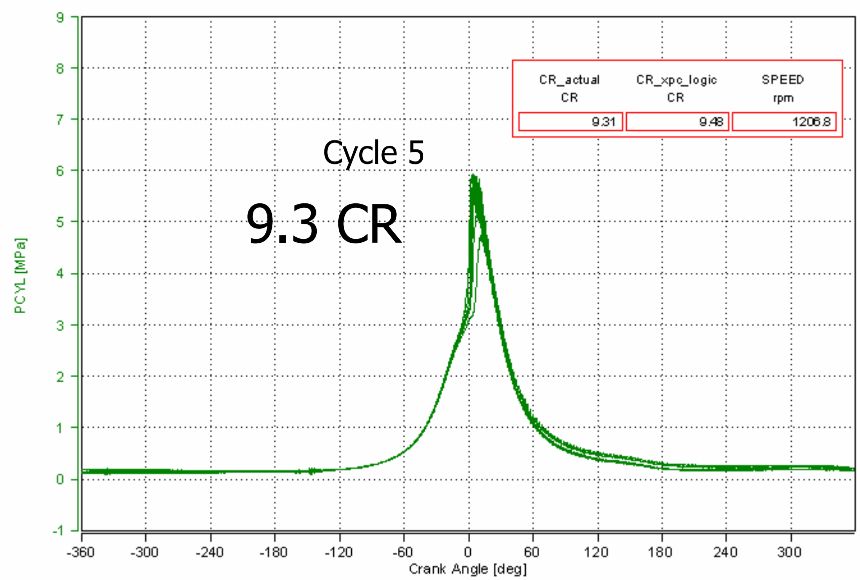


VCR: Compression Ratio Control Response @1200 rpm no load

Step Response







Conclusions

- Caterpillar is exploring a range of combustion and aftertreatment options to meet future emissions regulations
- Significant progress continues in our development and understanding of diesel HCCI
- Optical engine and CFD modeling provide new insights into detailed spray/combustion phenomena
- Nozzle geometry plays a key role and one must pay close attention to details
- Variable compression ratio engine is valuable development and exploration tool to understand tradeoffs of numerous controls and combustion parameters
- Many technical and commercial challenges remain