Heavy Duty HCCI Development Activities

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ExxonMobil

DOE Contract DE-FC05-00OR22806

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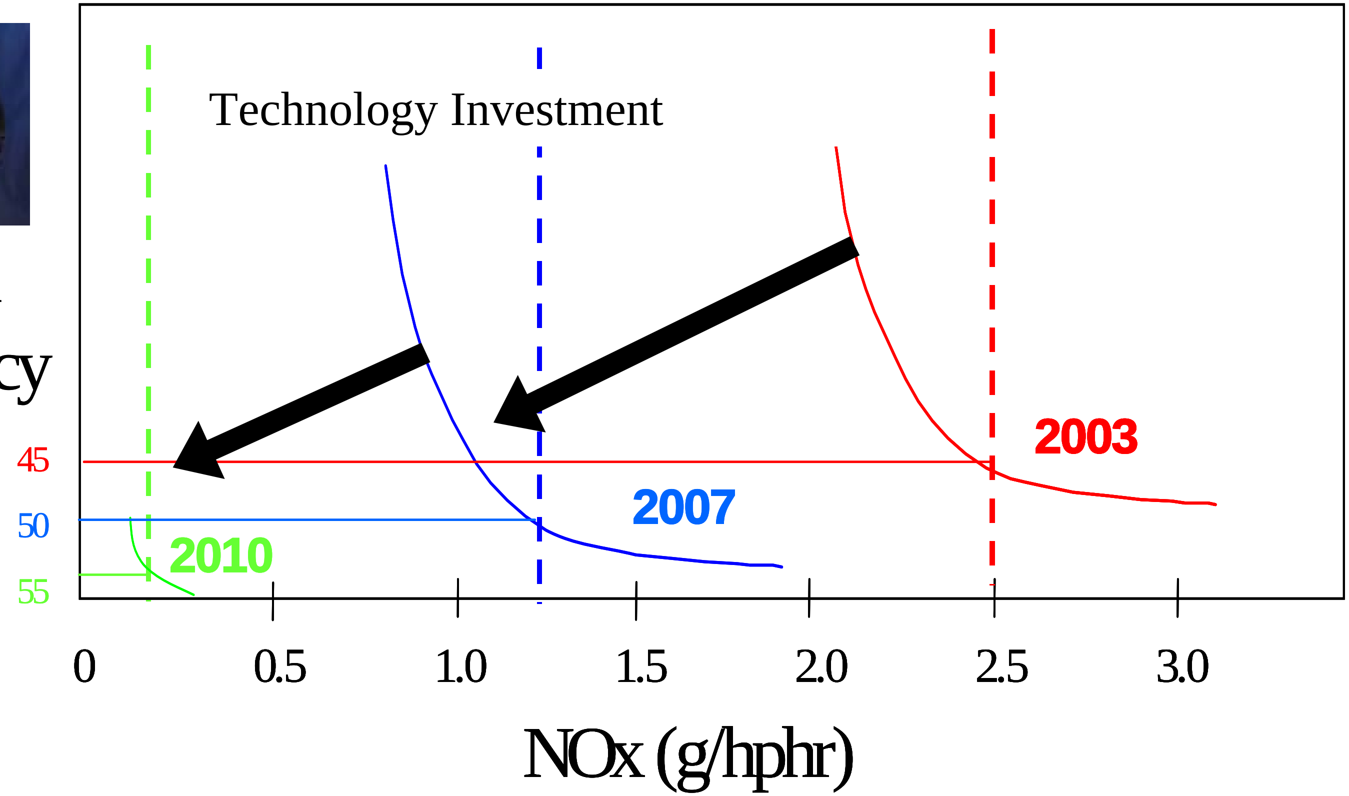
Agenda

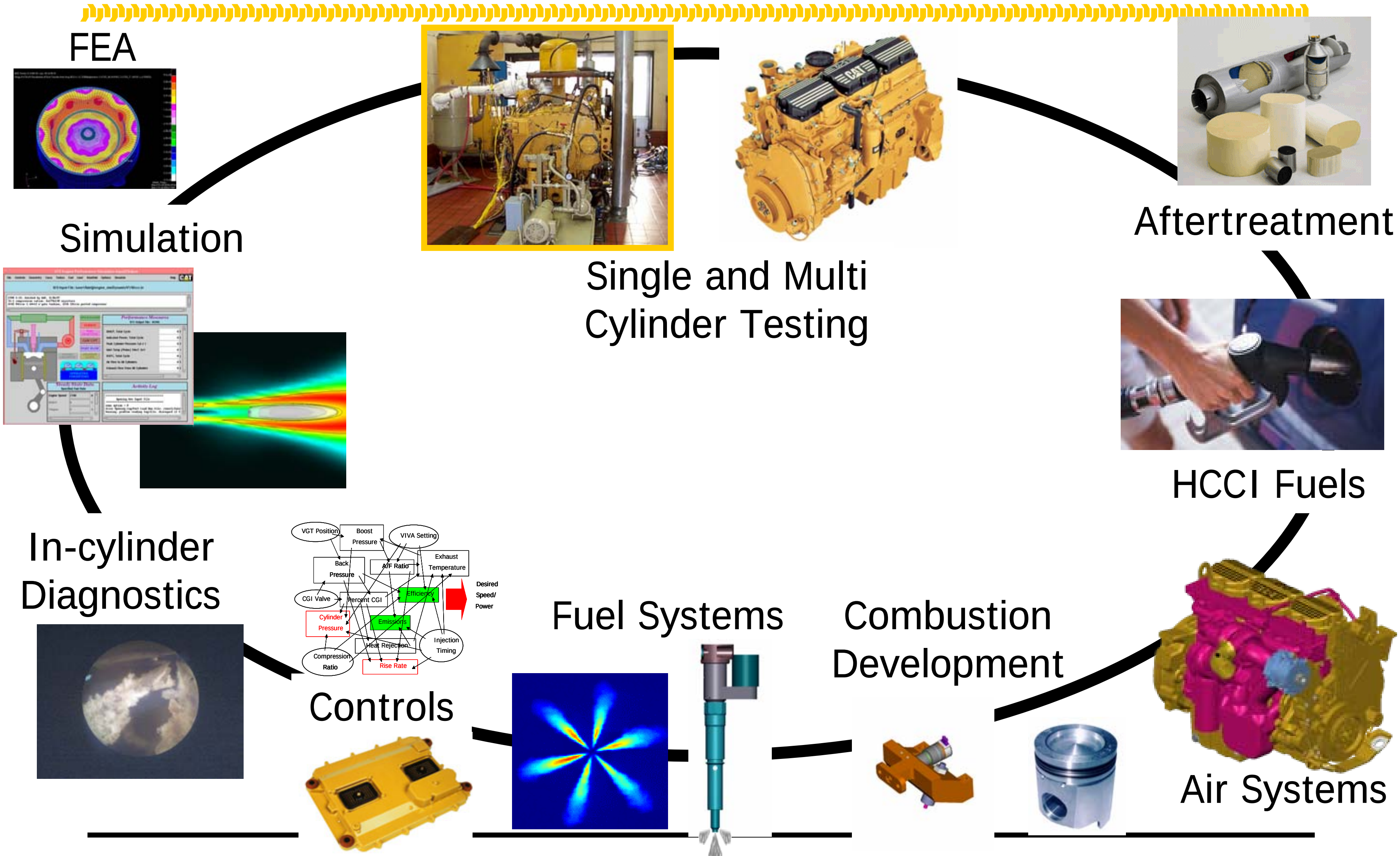
- Background
- Systems approach
- Controls Development
- Heat Flux Measurements
- Optical Engine Results
- HCCI fuel effects
- Conclusions

Engine Industry Challenges



- Improving fuel efficiency while meeting much more stringent emissions standards is a tremendous <u>technical</u> challenge.

Systems Approach to HCCI Development



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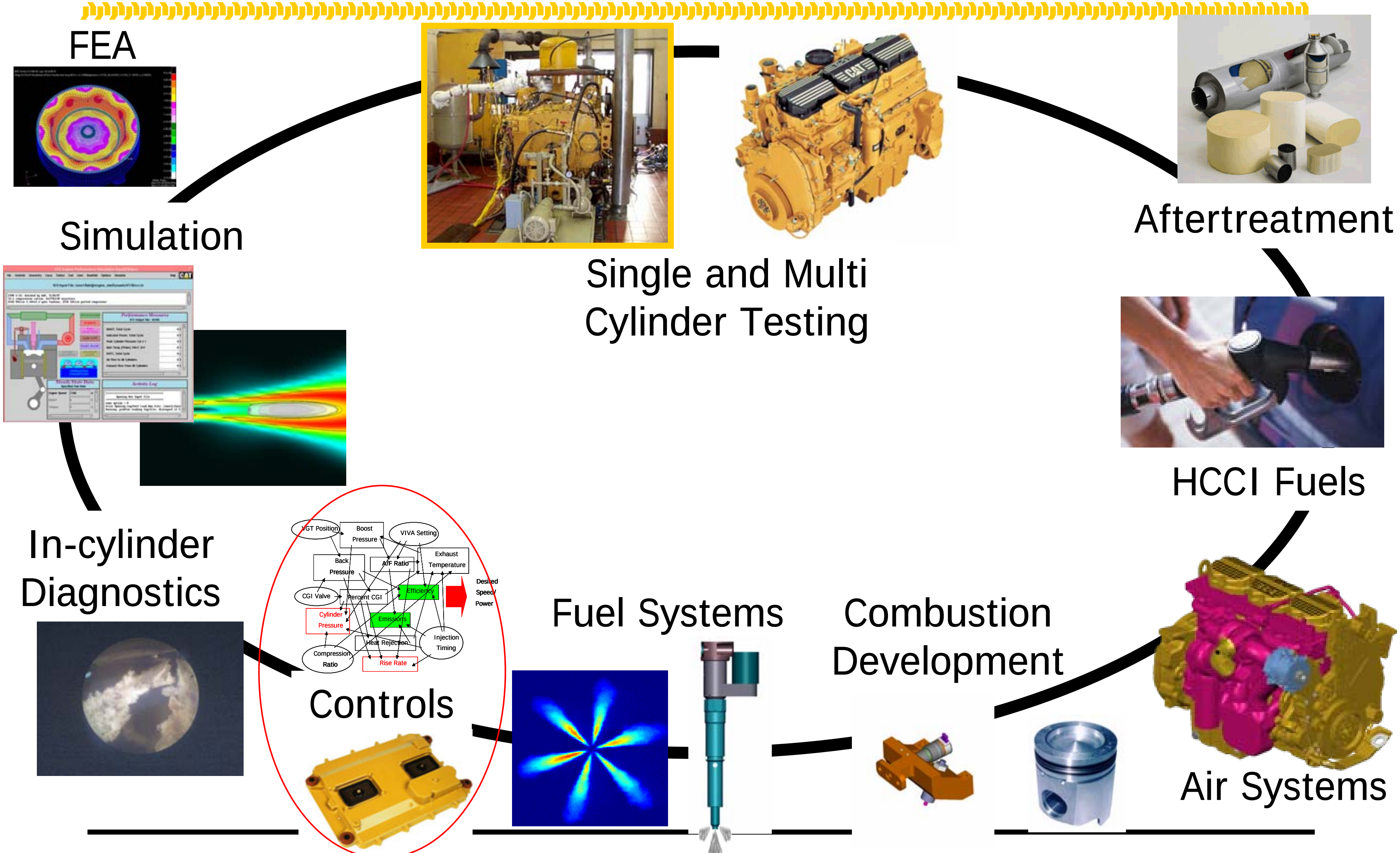
Systems Approach to HCCI Development



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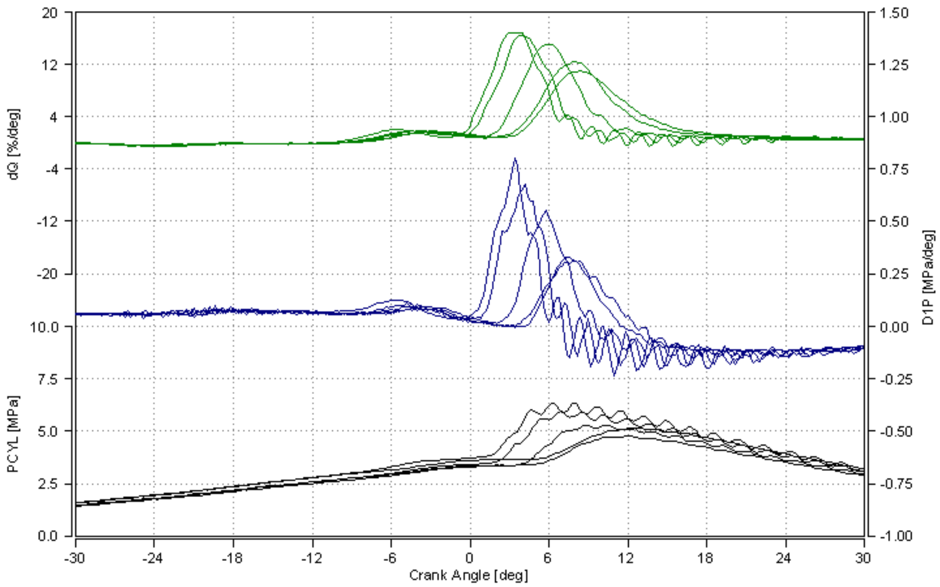
Controls Challenges

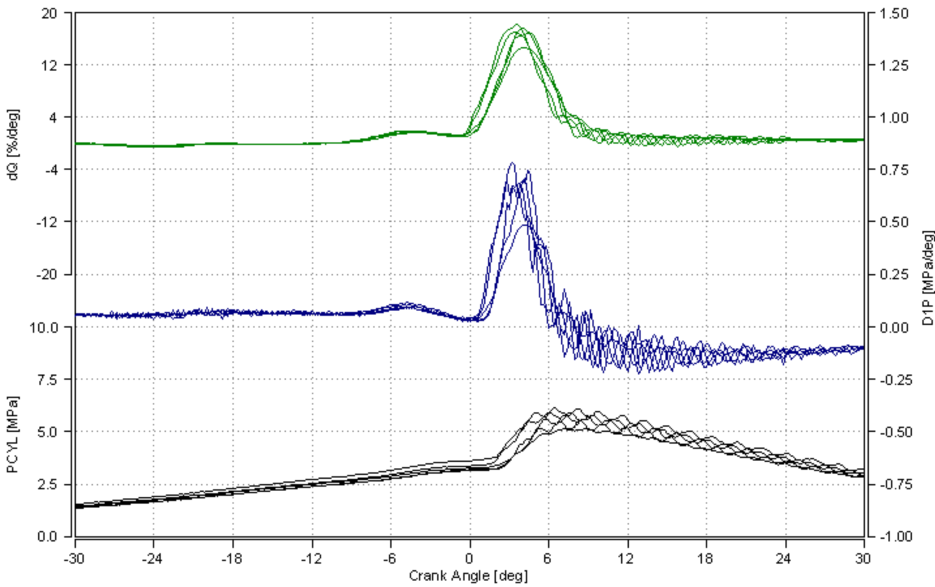
- Need robust method for detecting start of combustion (cylinder pressure sensor, ion sensor, torque fluctuation on crank, knock sensor, strain gauged head bolts, microphones, etc.)
- Transient operation, transitioning to different speed/load points
- Activities:
  - Sensor evaluation
  - RPAC installation, feedback control capability on multi
  - Preliminary controls architecture developed
  - Cylinder pressure feedback implemented
  - Basic phasing control demonstrated using intake valve actuation (IVA) to balance cylinders
  - Speed and load step tests demonstrated

VVA for Cylinder Balancing

Feedback off



Feedback on



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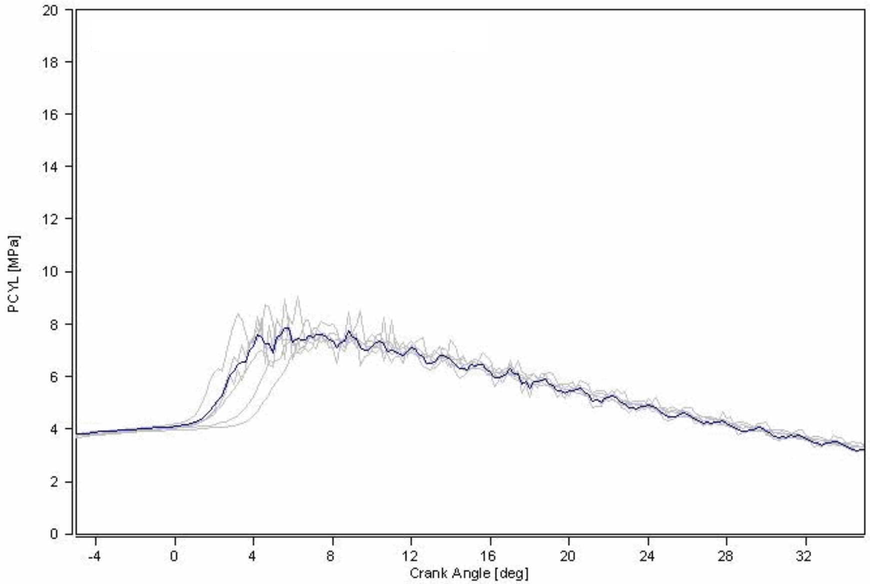
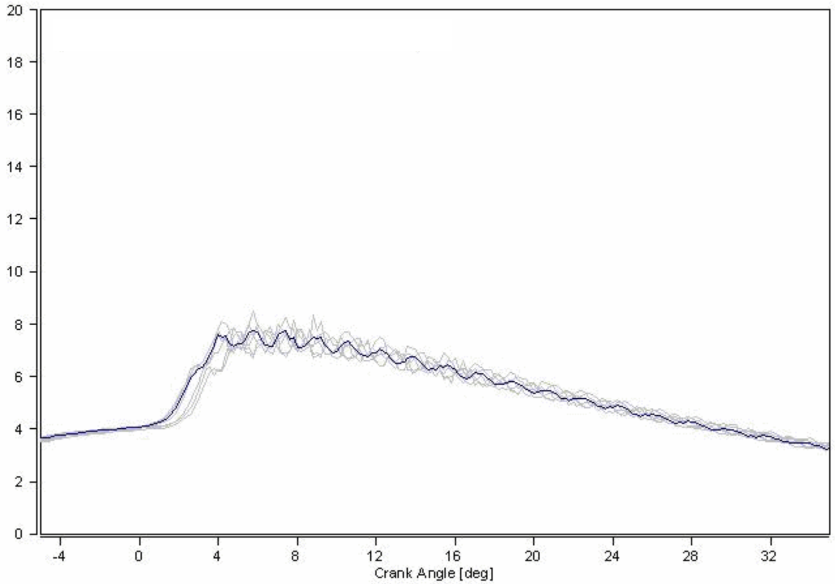
300 RPM Transition, Constant Load

Baseline transition strategy



Optimized transition strategy



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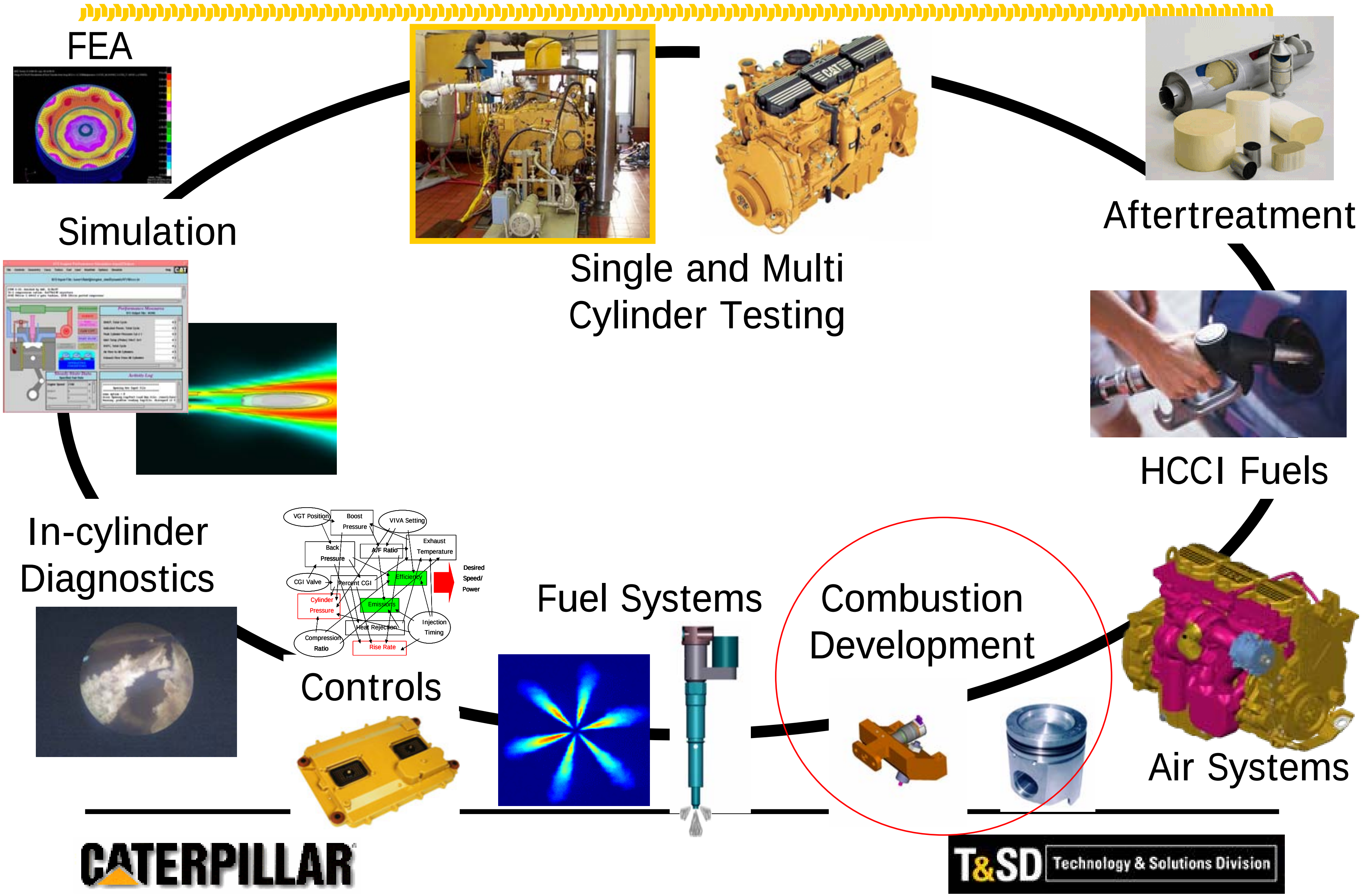
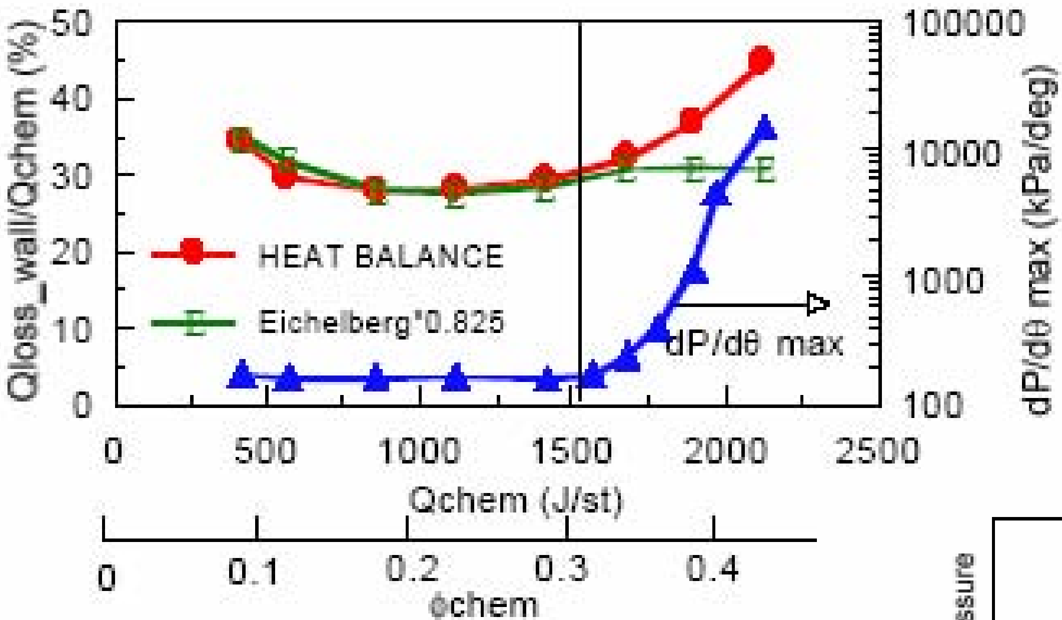


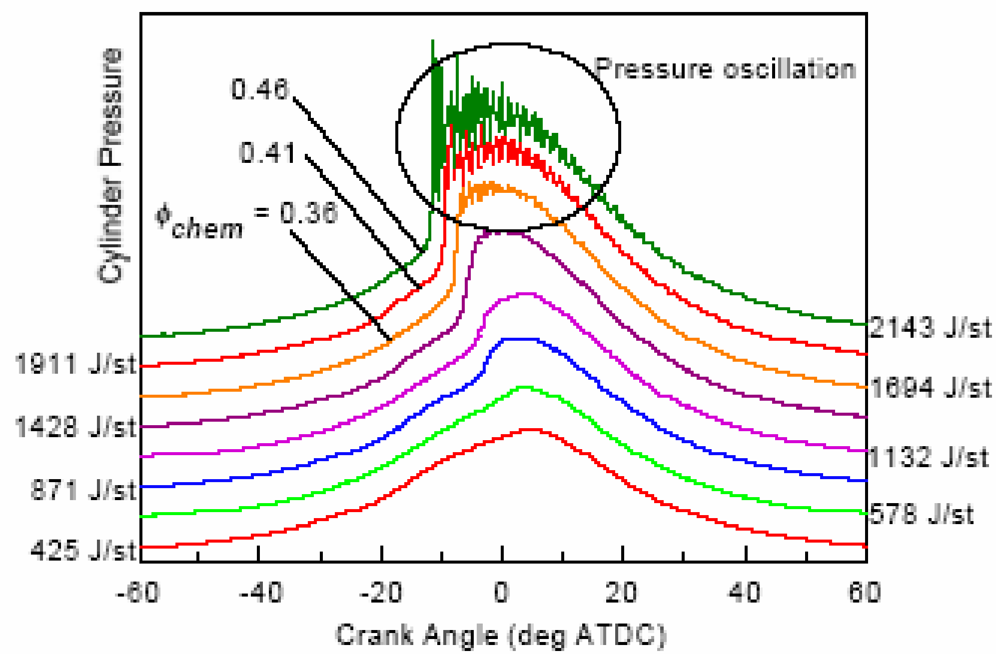
Heat Rejection Comparison

- Compared HCCI and conventional combustion with CGI (clean gas induction) at a part load operating condition
- For same CGI rate, NOx and BSFC, the engine block jacket water heat rejection was >50% higher for HCCI compared to conventional combustion (other heat rejection values similar)
- Is there significantly higher in-cylinder heat transfer to block/head/piston? (due to hotter bulk gas combustion near walls, short burn duration?)

Related Research



- Tsurushima et al. premixed DME/Propane HCCI (SAE 2002-01-0108)
- Chang et al. gasoline HCCI (SAE 2004-01-2996)



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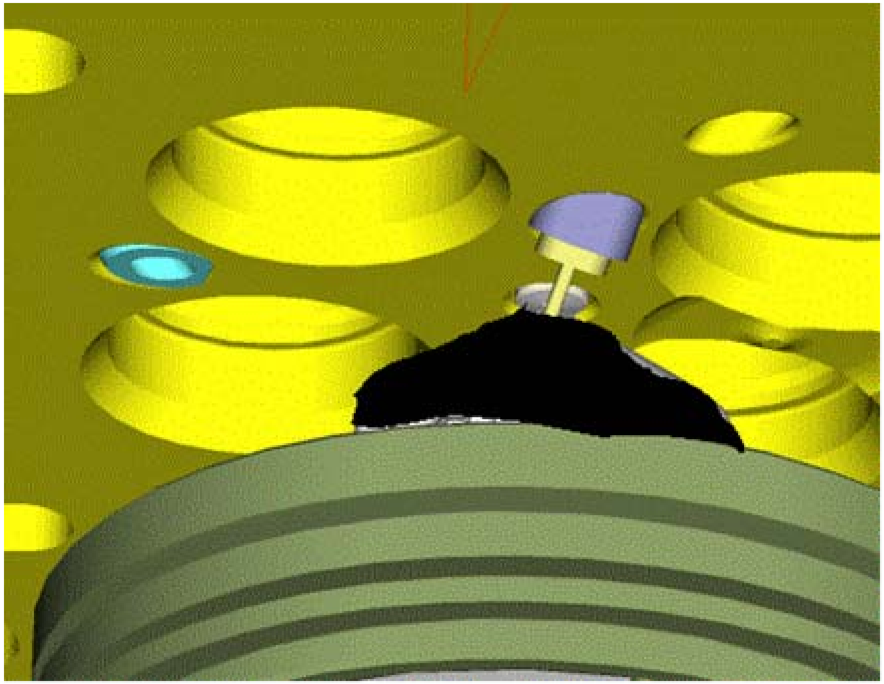
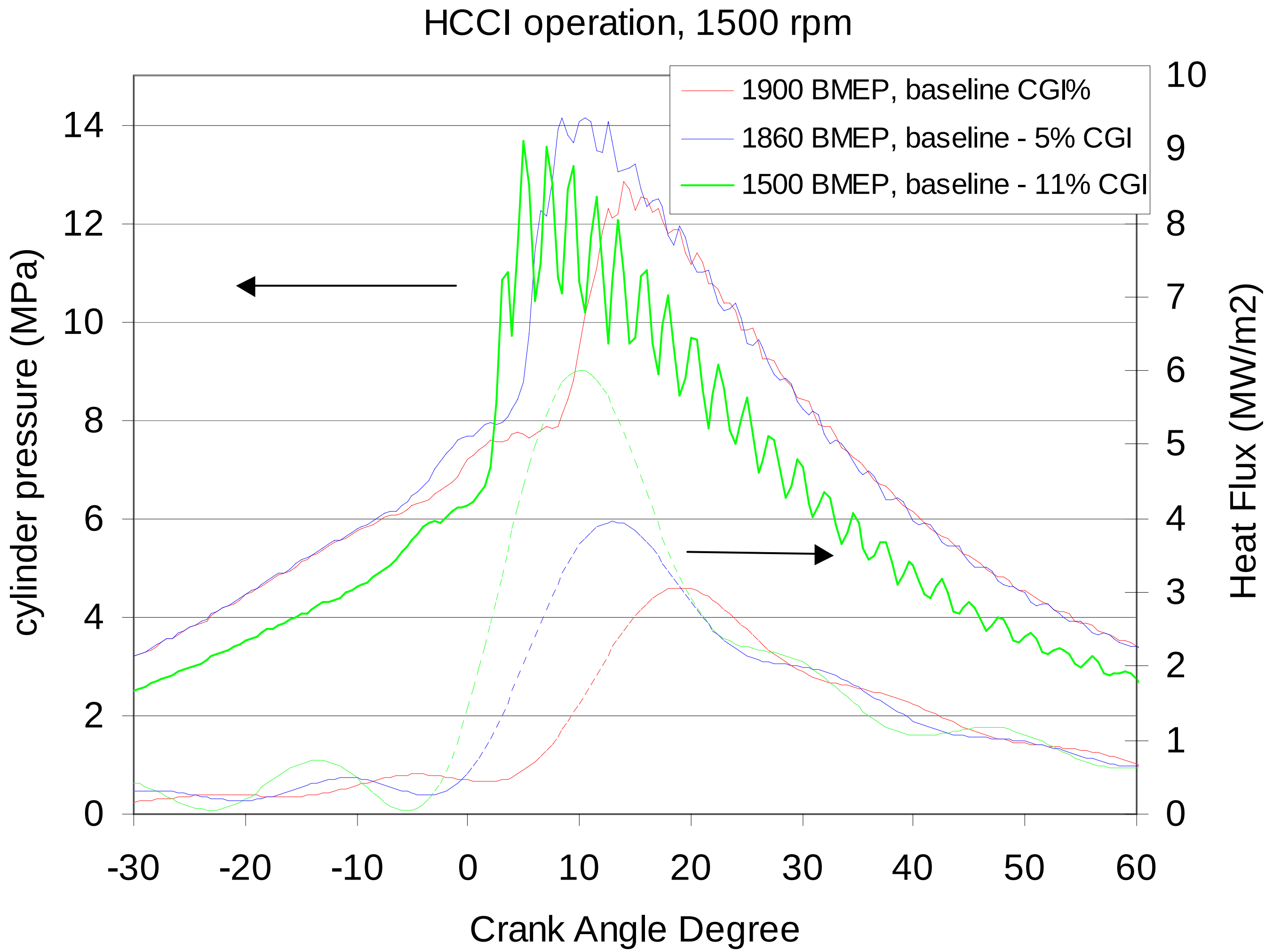
Heat Flux Measurement

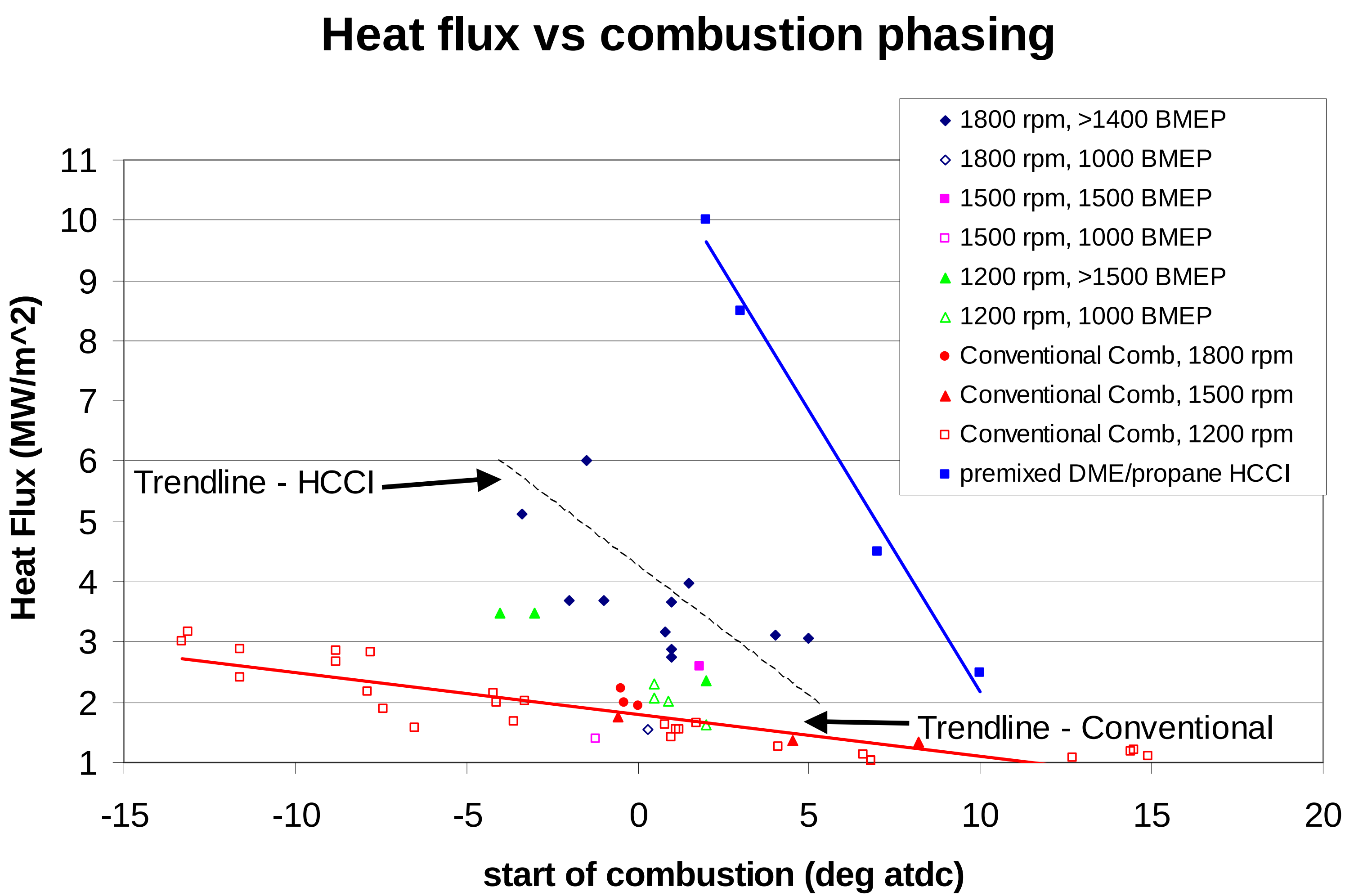
- Medtherm-heat flux probe
  - Two j-type TC, front side and back side
  - Front side has micro-second response time
  - Installed in head between exhaust valves
- Instrumented liner
  - 20 k-type TC radially
  - ~ 15 mm from liner top
  - Results showed no major difference in liner temps between HCCI and conventional combustion



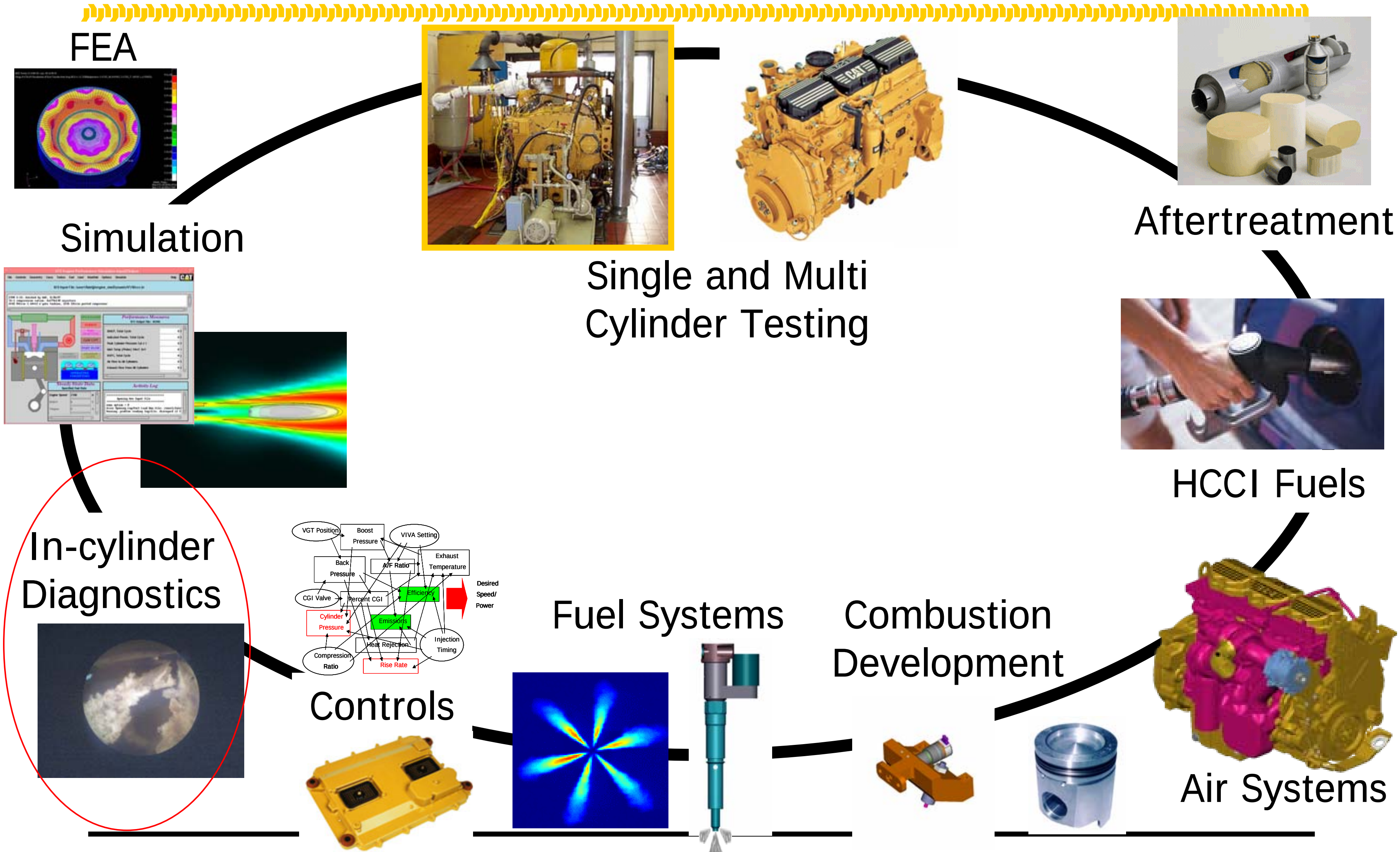
Knock Effect on Heat Flux



Effect of Partial Stratification



Systems Approach to HCCI Development



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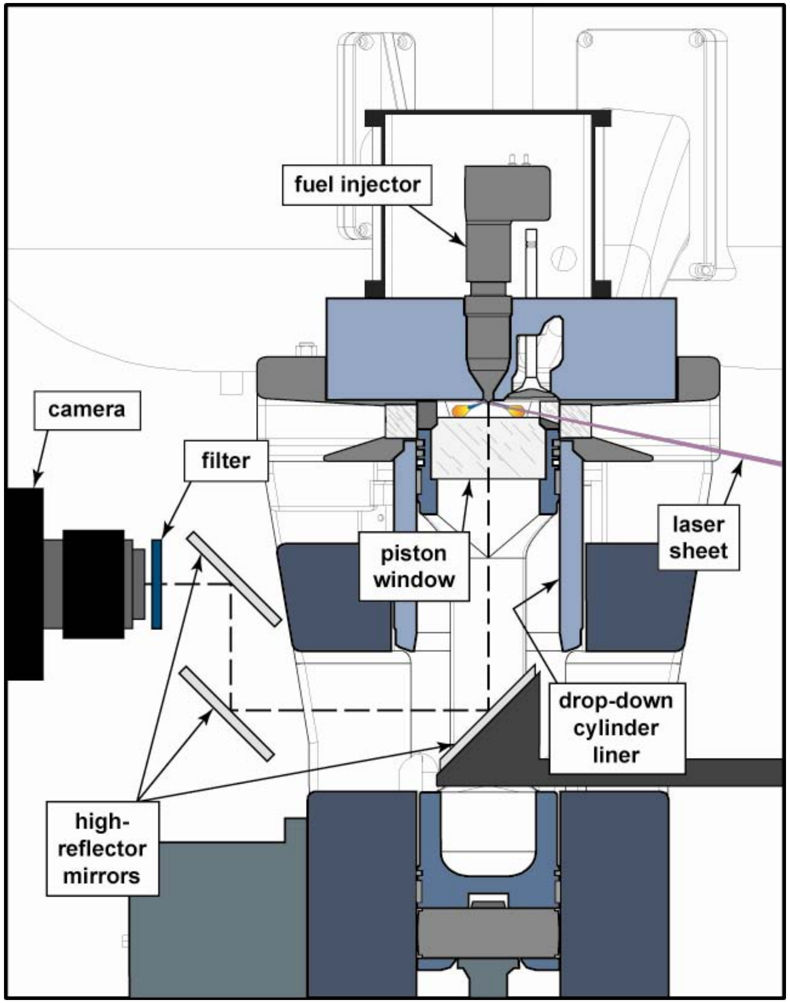
Optical Engine Testing with Sandia National Lab

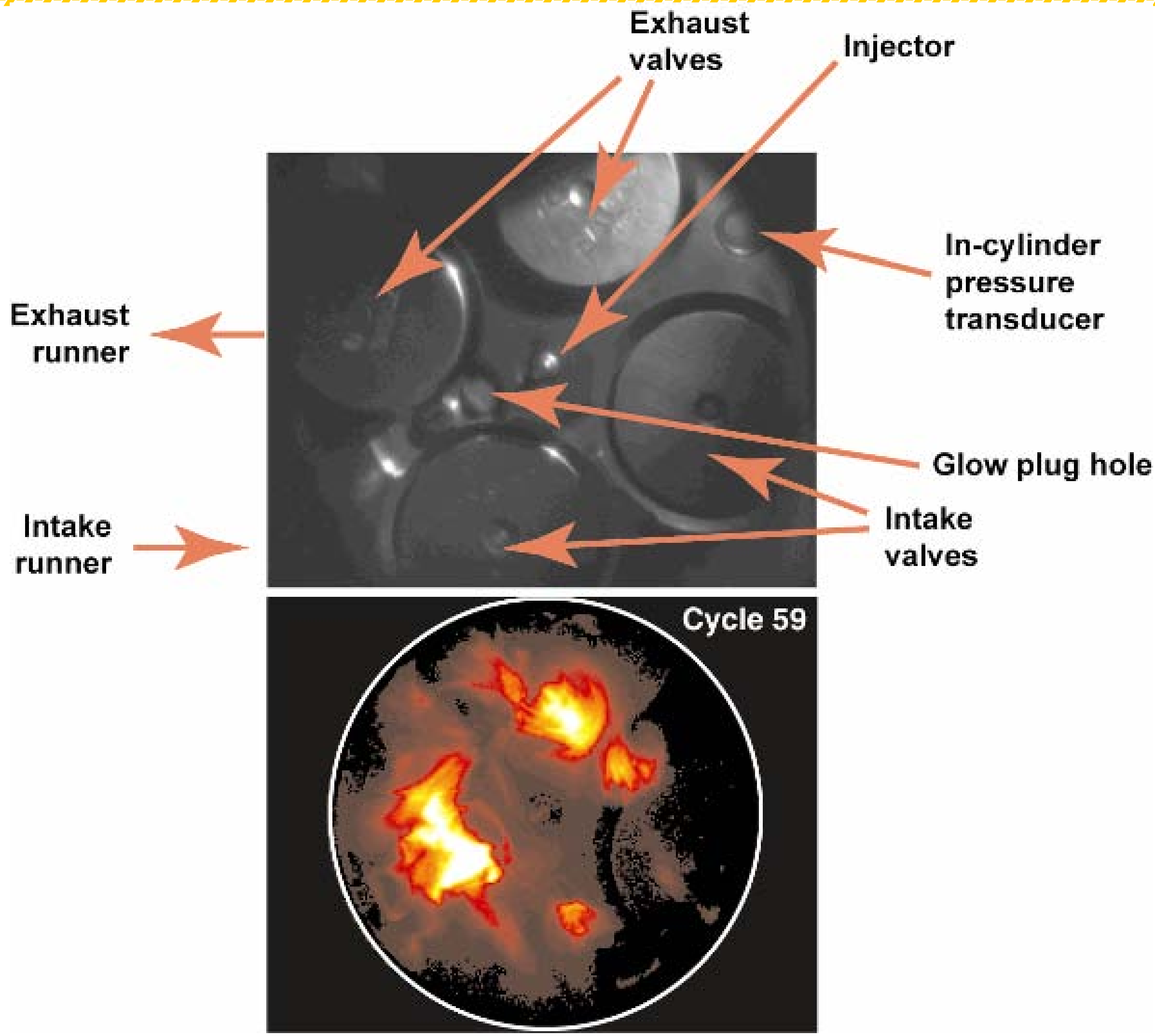
- Goal of Project: use optical diagnostic techniques to supply a knowledge base of in-cylinder processes under LTC operating conditions
  - To understand reasons underlying observed emissions levels
  - To gain insight into approaches to implement fuel or hardware changes that ameliorate the problems
  - To help validate simulations of in-cylinder mixing and LTC
- Partnering with Chuck Mueller and Glen Martin at Sandia on the Caterpillar/Sandia 3171 optical engine
- Optical diagnostics techniques used include natural luminosity, liquid and vapor phase spray imaging, soot imaging, PLIF

Sandia Compression-ignition Optical Research Engine (SCORE)

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

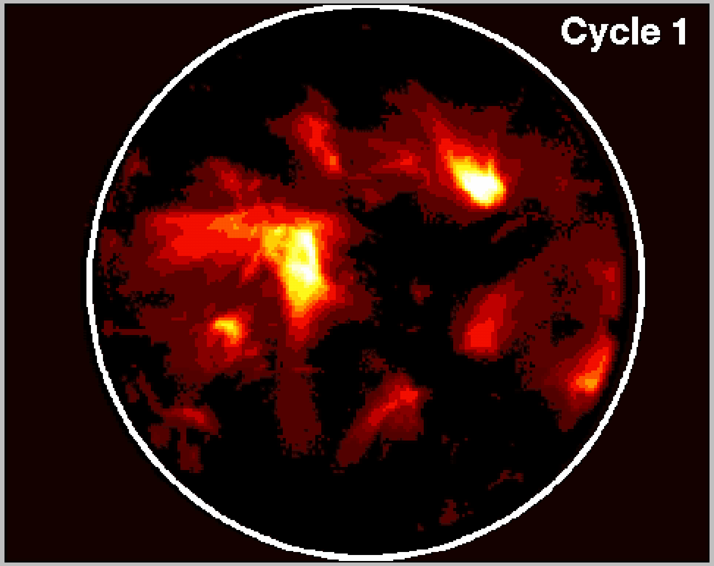


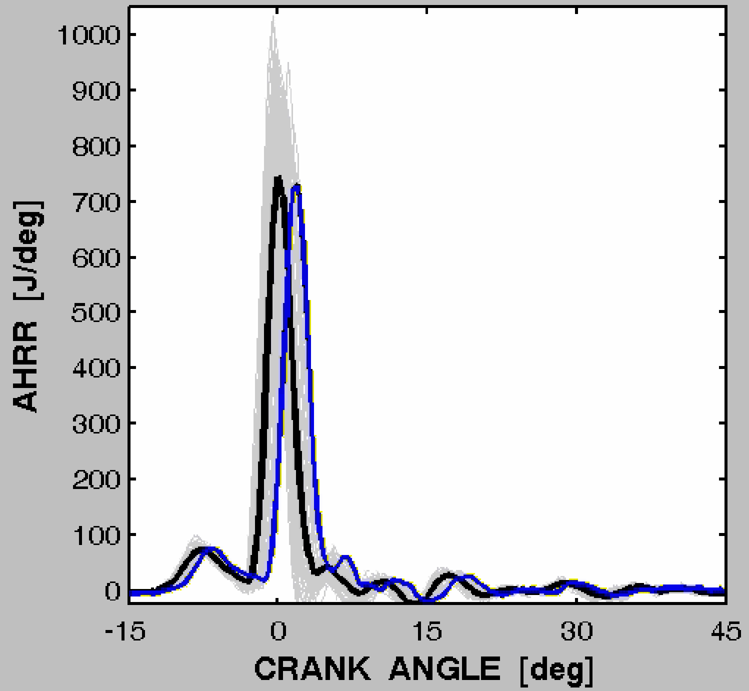
Camera View Orientation for Cycle Integrated Natural Luminosity (CINL) Movies



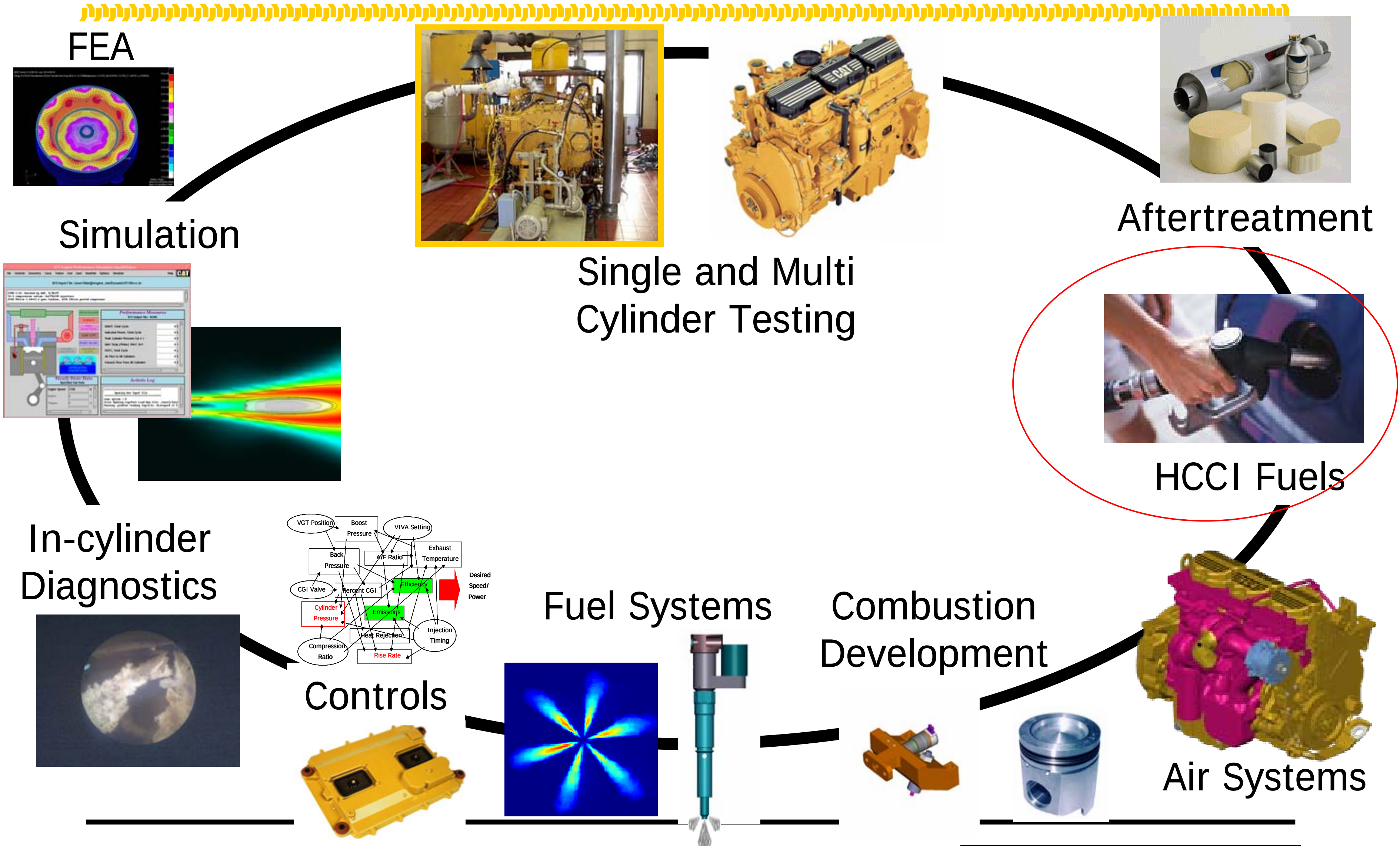
CINL Movie of HCCI Combustion

Full-Cycle Soot Incandescence with Apparent Heat-Release Rate 1200 rpm, 9.1 bar IMEP





Systems Approach to HCCI Development



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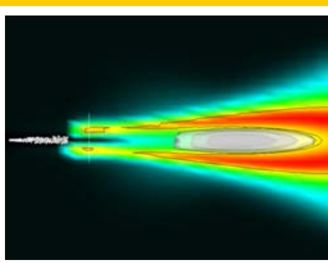
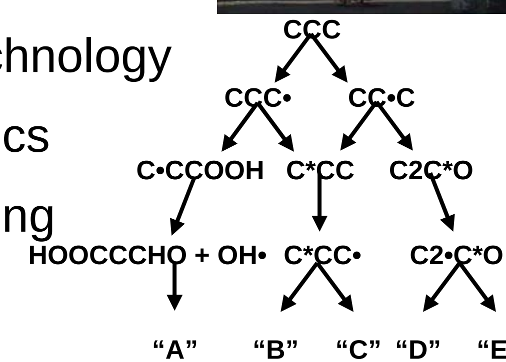
Fuel / Engine Systems Approach

CATERPILLAR + ExxonMobil → **Optimized Systems** →

Benefits For:
- **Consumer**
- **Environment**
- **Industry**



CAT	ExxonMobil
Hardware	Fuel
Engine Testing	Advanced Characterization
Systems Integration	Refining Process Technology
Combustion Modeling	Chemical Kinetics
Fluid Dynamics	Systems Modeling



Preliminary Fuel Effects Study

- Study parameters:
  - Ignitability
    - Cetane number: 39 - 55
    - Octane number (R+M)/2: 63 - 91
  - Aromatic content
    - 28 - 45%
  - Volatility
    - Gasoline
    - No.1 diesel fuel
    - No.2 diesel fuel
- Other fuel parameters generally well matched when varying single property

DIESEL FUELS

Cetane Number	39	>>>	Cetane Number	46
Aromatics %	43		Aromatics %	45
T90, °F	625		T90, °F	615

Aromatics >>> (from the middle fuel below up to the fuel with Cetane Number 46)

Cetane Number	47		Cetane Number	47	>>>	Cetane Number	55
Aromatics %	28		Aromatics %	28		Aromatics %	28
T90, °F	495	>>>	T90, °F	596		T90, °F	618

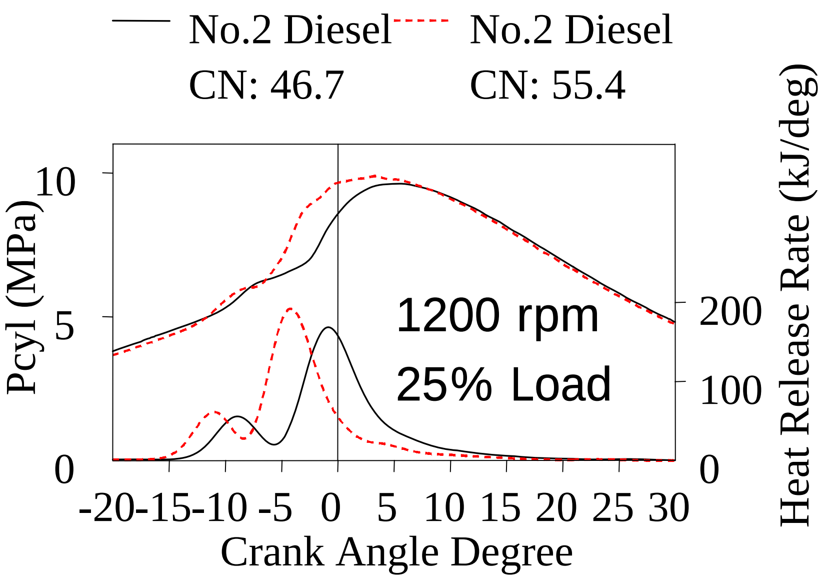
GASOLINES

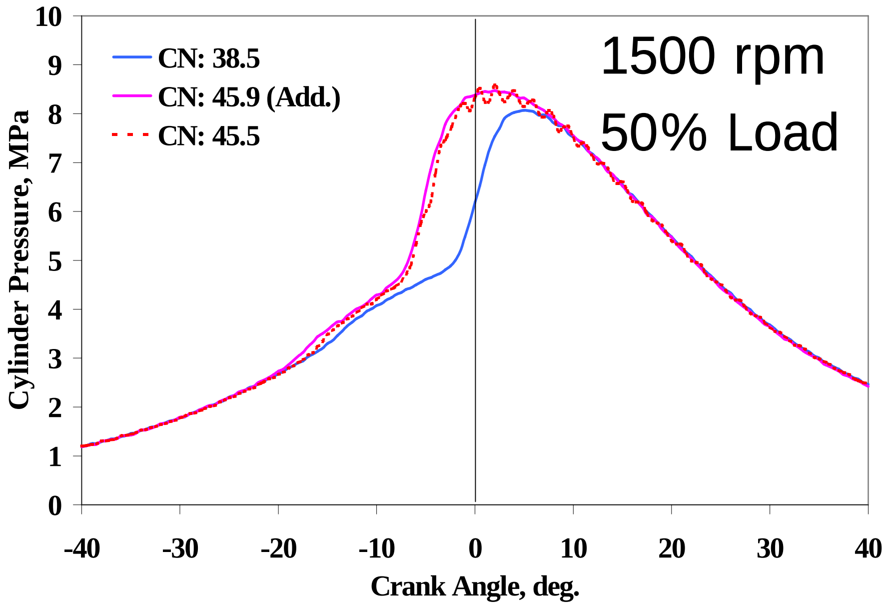
(R+M)/2	63	>>>	(R+M)/2	81	>>>	(R+M)/2	91
Aromatics %	15		Aromatics %	26		Aromatics %	27
T90, °F	315		T90, °F	309		T90, °F	299

Test Engine

- Single-cylinder Caterpillar 3401 engine
- Cylinder displacement: 2.44 liters
- Bore/Stroke: 137/165 mm
- Valves/cylinder: 4
- Swirl ratio: 0.4
- Hydraulically intensified fuel injection system. Multi-hole nozzle
- All emissions engine-out
- Main control variables: fuel injection timing, boost/backpressure
- Careful engine control to identify fuel effects

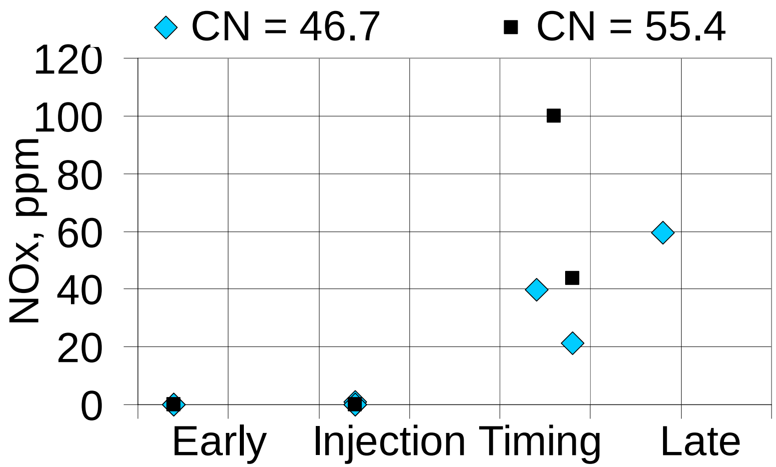
No Benefit for Increased Cetane in Expanding High Load Operability

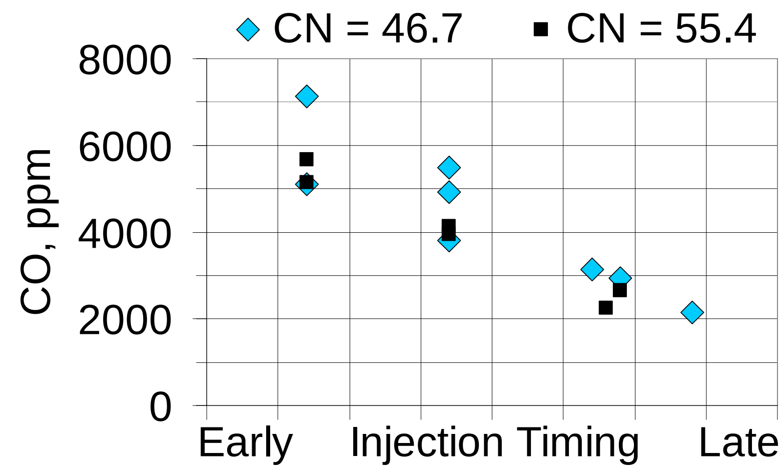




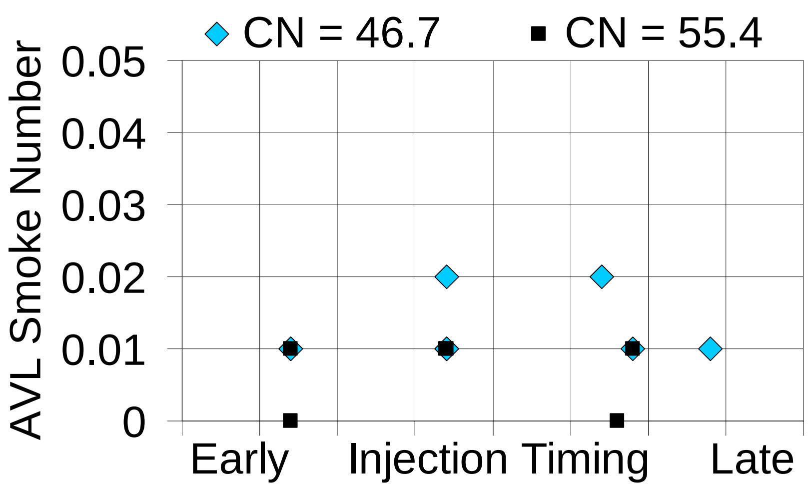
- Increasing cetane # produced <u>undesirable</u> advance in combustion phasing
- Cylinder pressure rise rate and increase in peak cylinder pressure result in lower load capability
- Similar behavior for natural and additized cetane

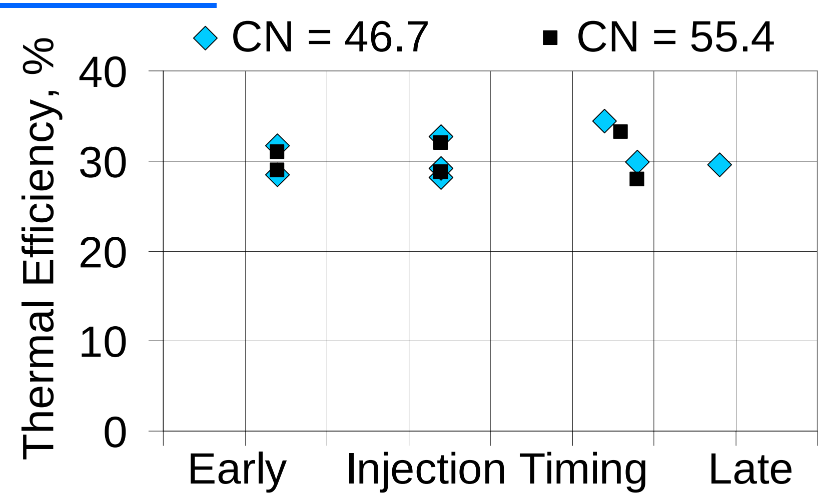
Cetane Number Had Small Effect on Emissions





1800 rpm, 25% load





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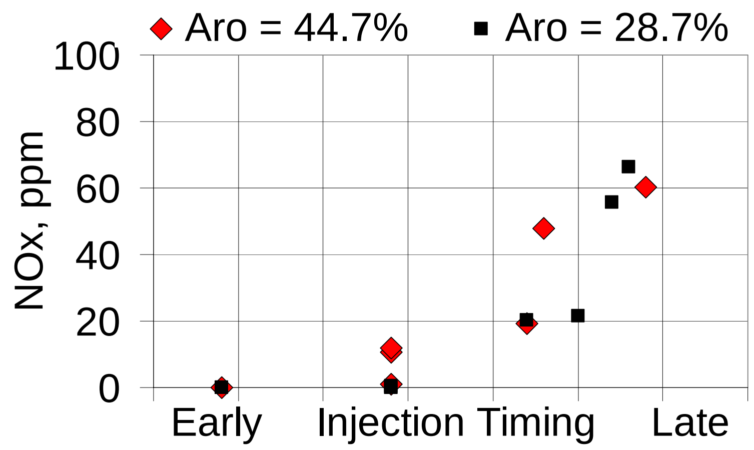
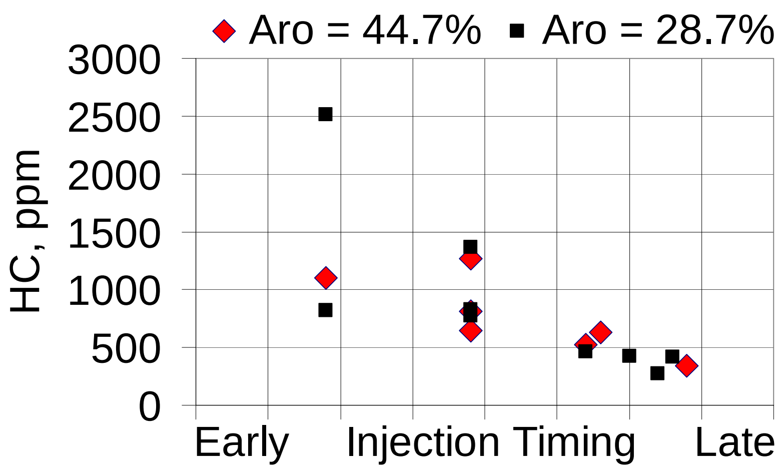
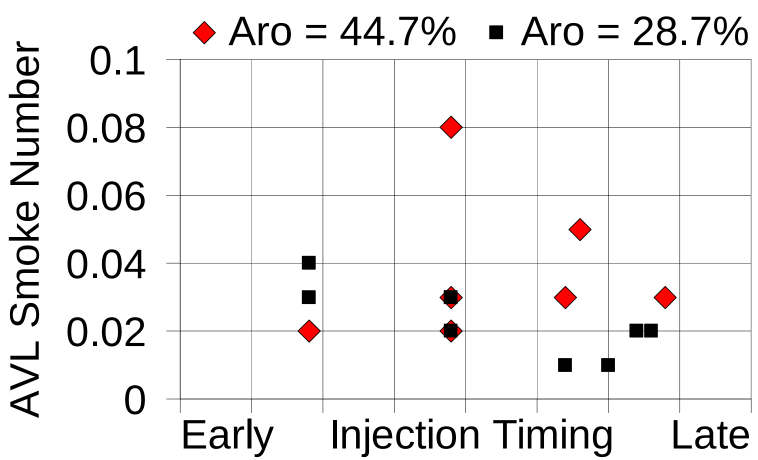
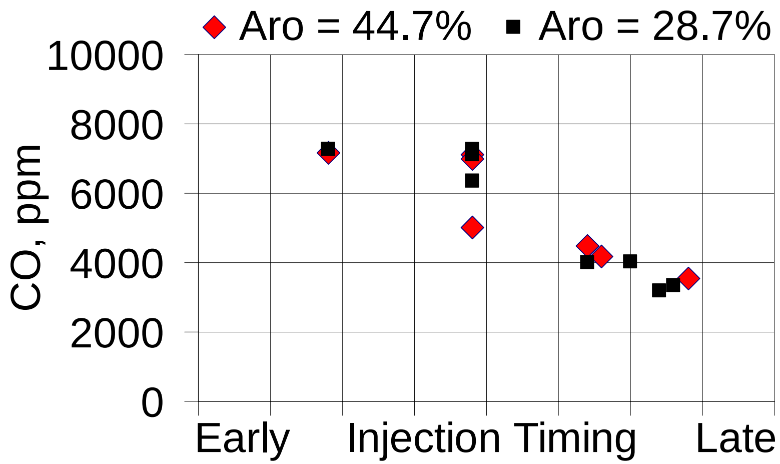
Aromatics Has Small Impact on Emissions



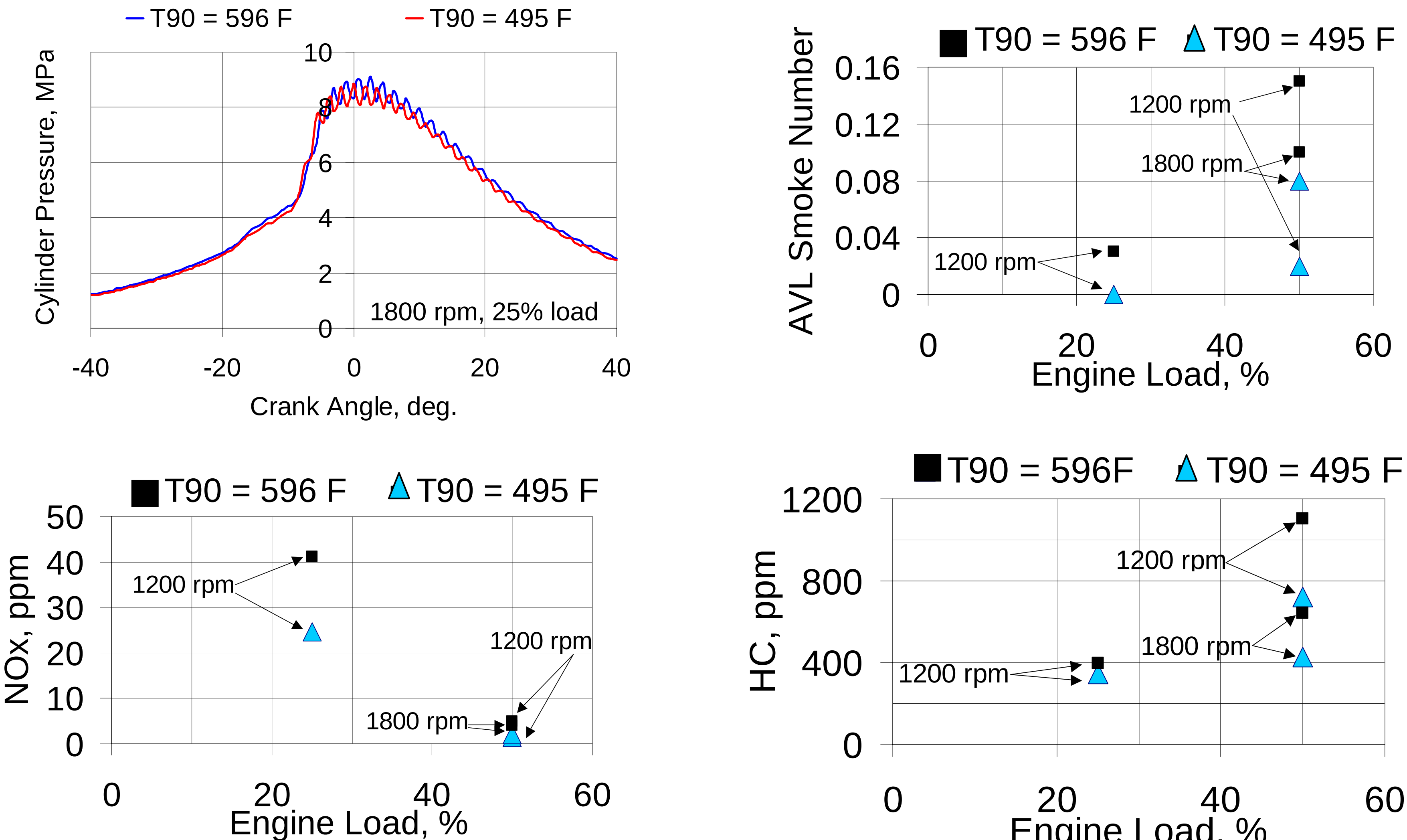


1500 rpm, 25% load





Increased Volatility Generally Reduces Emissions



Gasoline Can Also Achieve High HCCI Engine Loads

- Reduced octane rating enabled operation over a broader speed/load range

	(R+M)/2 = 63.2		(R+M)/2 = 81.2		(R+M)/2 = 91.2	
	1200 rpm	1800 rpm	1200 rpm	1800 rpm	1200 rpm	1800 rpm
Maximum Load Achieved	70%	82%	75%	HCCI operation was only achieved at 71%.	75%	HCCI operation was not achieved at any engine load
Minimum Load Achieved	25%	25%	50%		50%	

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Numerous Challenges Remain For HCCI

- Cold start with lower compression ratios
- Air system development requirements
- Light load HC/CO cleanup
- Controlling combustion phasing and transient operation
- Cylinder to cylinder variability
- Structural reliability with higher cylinder pressure and rise rates
- Small hole production related issues
- Noise/vibration

New DOE Program for Continued High Efficiency Clean Combustion Development

ExxonMobil Research and Engineering

- Fuels effects
- Combustion Chemistry/modeling

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- Program coordination
- Test/Analysis
- Truck/Machine system integration and packaging
- Combustion

AVL

- Closed loop control
- Transient controls
- Vehicle calibration
- Sensors

Sandia National Laboratories

- Optical diagnostics
- Fuel spray and combustion
- Fuels effects

Summary

- Significant progress made on expanding operating range for HD HCCI engine
- Full load HCCI is extremely challenging
- Fuels effects can have positive/negative impacts on performance and emissions
- Much work still needed to determine production feasibility of HCCI as a 2010 emissions strategy
- Advanced technology Diesel engines should continue to have long term viability as a prime power source for on and off-highway markets