Combustion Targets for Low Emissions and High Efficiency

Tom Ryan

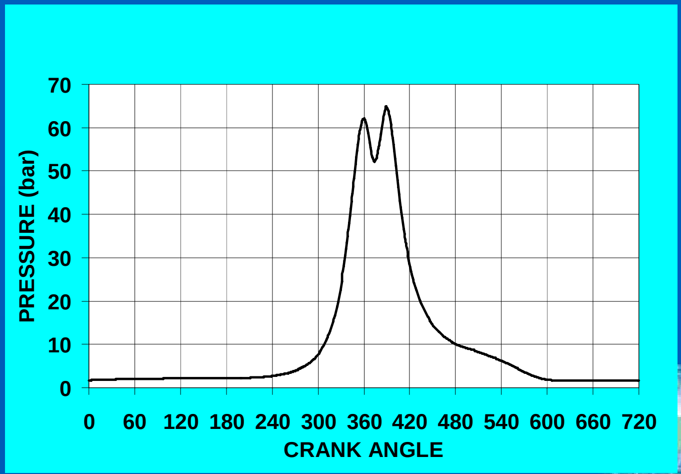
September, 2005

Three Combustion Modes

- Flame Propagation (SI Gasoline)
  - Stoichiometric Combustion
  - Thin Reaction Zone
  - High Temperature and High NOx
- Diffusion Burning (Conventional Diesel)
  - Stoichiometric Reaction Zone
  - Thin Reaction Zone
  - High Temperature and High NOx
  - Rich Zones at High T Leading to Soot Formation
- Homogeneous Reaction (HCCI)
  - Dilute Mixtures
  - Low Temperature Reactions and Low NOx
  - Homogeneous Mixture at Low Temperature

Background

- Engine Combustion Technologies are Apparently Converging to the same General Characteristics
  - Delayed Ignition and Rapid Burn Rate
- Engine Technologies are also Converging
  - Highly Boosted
  - High BMEP
  - High EGR



New Combustion Modes

- HEDGE, HCCI, CAI, PCCI, LTC, PCI, and CSI are some of the Acronyms used to Describe the Recent Developments for Modified Fuel Reaction Approaches
  - HEDGE - High Efficiency Dilute Gasoline Engine
  - HCCI - Homogeneous Charge Compression Ignition
  - CAI - Controlled Auto Ignition
  - PCCI - Premixed Charge Compression Ignition
  - LTC - Low Temperature Combustion
  - PCI - Premixed Compression Ignition
  - CSI - Compression and Spark Ignition

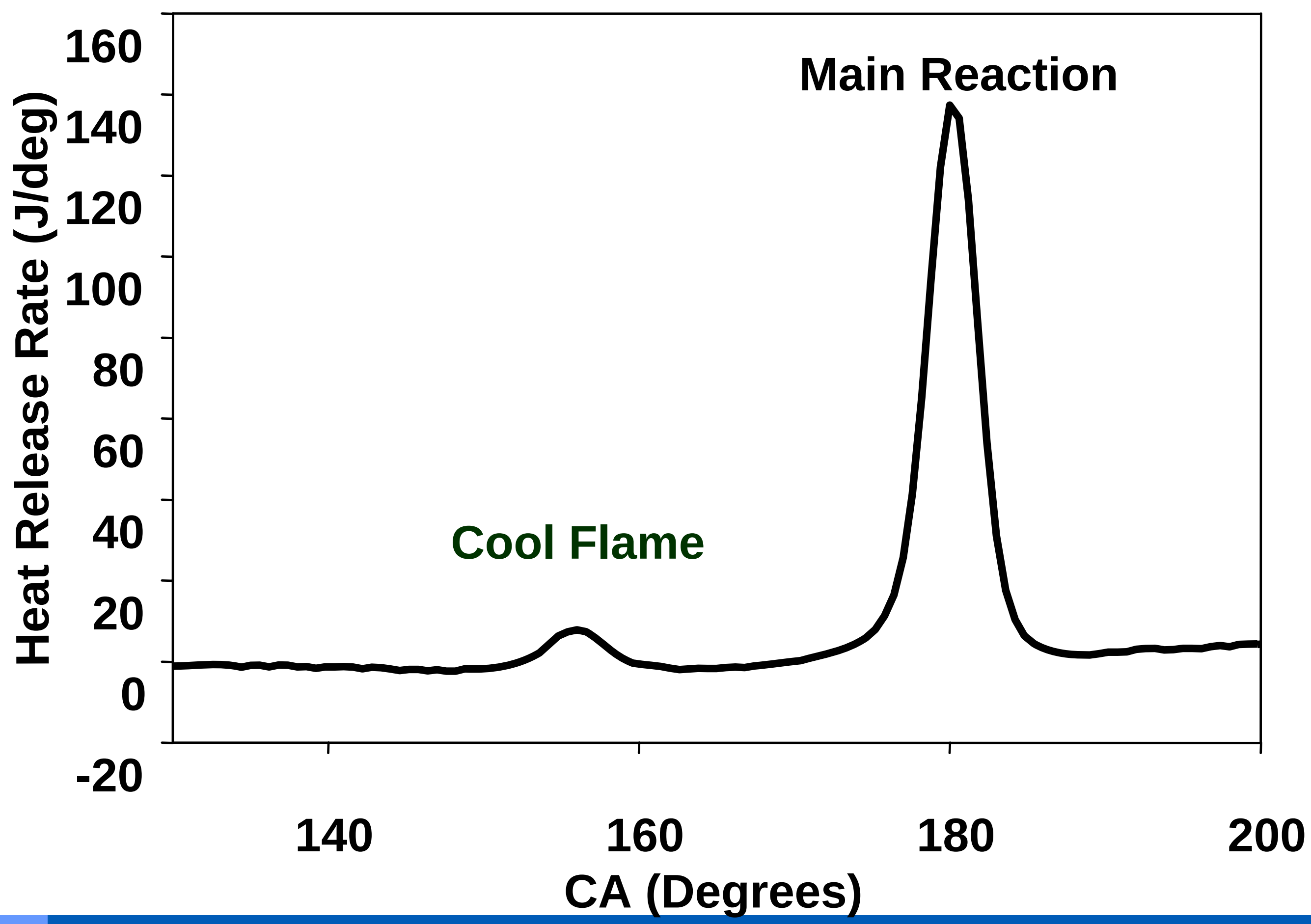
HEDGE, HCCI, CAI, PCCI, LTC, PCI, and CSI

- Common Factors include:
  - Thick Flames
  - Part or all of the Fuel is Premixed
  - All Use EGR
  - All have Lower NOx
  - All have Higher HC and CO
- Differences Include:
  - Degree of Premixing
  - PM Emissions
  - Overall Equivalence Ratio
  - Initiation of Reaction
  - Purpose/Application
    - Low Emissions
    - Exhaust Gas Composition and Temperature Control

Best Combustion Phasing - Theoretical vs Practical

- Thermodynamically Ideal Cycles Produce Highest Efficiency with Instantaneous Heat Release at TDC
- Practical Limitations Include
  - Noise due to Rapid Rates of Heat Release
  - Increases in Friction due to Higher Bearing Loads and Small $dV/d\theta$ Effects
  - Peak Firing Pressure Limits
  - Pressure Oscillations (maybe Knock)

Typical Advanced Heat Release Rate



Approach

- Use Cycle Simulation to Determine the Effects of Changing the Heat Release Rate Characteristics on the Emissions and the Efficiency
  - Mainly Concerned with NOx and BTE

HEDGE Performance Predictions Tools

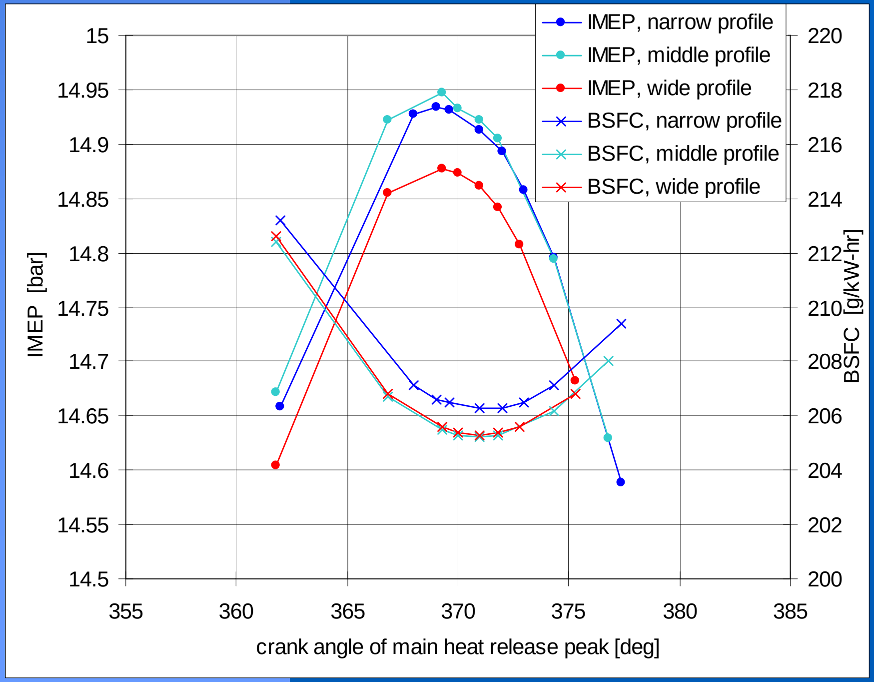
- Alamo Engine (A_E)
  - Phenomenological, Zero Dimensional Models
  - Gas Exchange
    - Steady State Emptying & Filling (Checks With Steady State 1D Flow Code)
  - TC
    - Energy and Flow Balance for Selected Efficiencies, Wastegating (Vs Engine Speed)
  - Combustion
    - Watson and Wiebe
  - Friction
    - Chenn-flynn
  - Aftertreatment
    - Fixed Converter Efficiencies

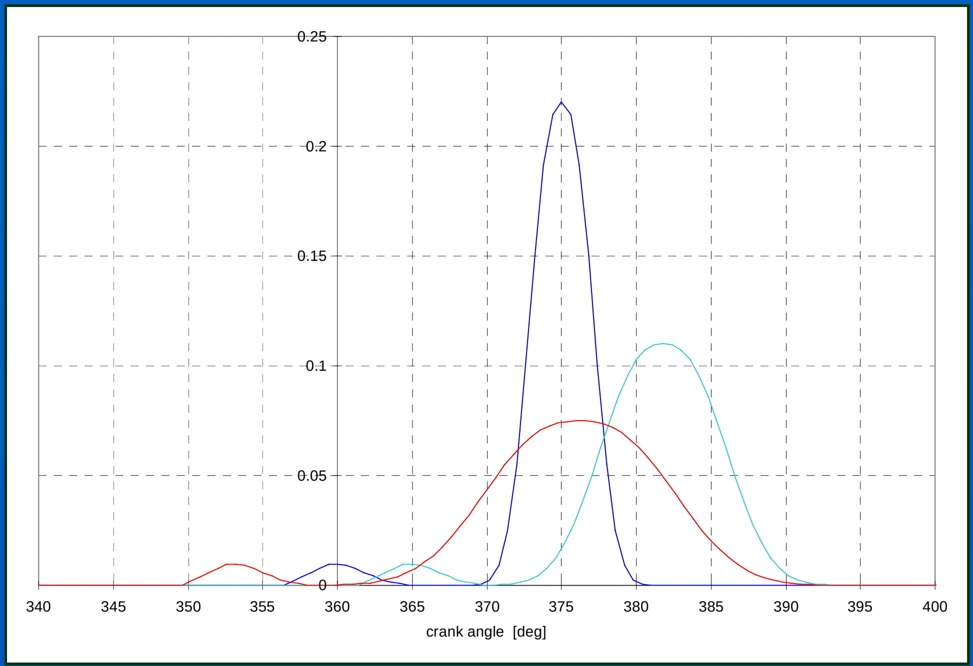
Assumption for All Calculations

- Engine Configuration
  - **130X160 mm BoreXStroke**
  - **16:1 CR**
  - **Turbocharged**
- Engine Conditions
  - **1800 rpm**
  - **A/F 24:1**
  - **40% EGR**
  - **240 kPa MAP**
- Only Changes, Shape and Timing of the HRR Diagrams

Details on Shape and Timing Effect

- Peak Efficiency Occurs in All Cases as 12º ATDC
- Rapid to Slow Heat Release (Duration 10 to 30º) Results in 0.5% Change in BSFC
- Corresponding IMEP Drop of 0.5%





Future Diesel Engines

Areas of Greatest Potential

- Fuel Management
  - High Pressure Injection Essential
  - Injection Rate Control Essential
  - Air Utilization Essential
  - Liquid Fuel Wall Interactions must be Avoided
- Gas Management
  - High Density Essential
  - High EGR Levels Essential
    - Outcome is High Boost Pressure
  - Uniform EGR Distribution Essential
  - Intake Cooling is Desirable
  - High Efficiency Turbocharger Systems Essential
  - In-Cylinder Flow Management Essential
- Combustion Chambers
  - Matched to Nozzle Spray Capabilities
  - Design for Maximum Mixing Rates
  - Premixed Combustion Considerations
    - Surface-to-Volume Ratio Minimized
    - Quench Volume Minimized

Premise

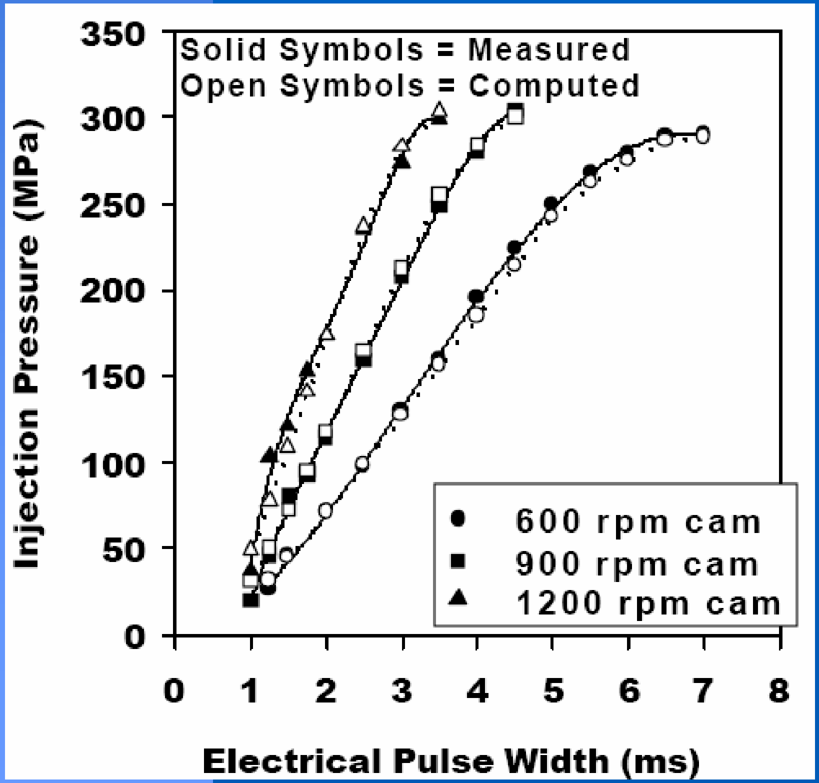
- Lowest Possible Emissions and Highest Efficiency in Diesel Engines Achieved Using:
  - Ultra High Injection Pressure and Small Holes
  - Massive EGR
  - Ultra High Boost
  - Well Designed Pistons and Intake

High Injection Pressure and Small Holes

Fuel Injection - High Pressure

SwRI Results SAE 2002-01-0494

High Pressure Electronic Unit Injector Operating on a Fixed Cam at Constant Speeds



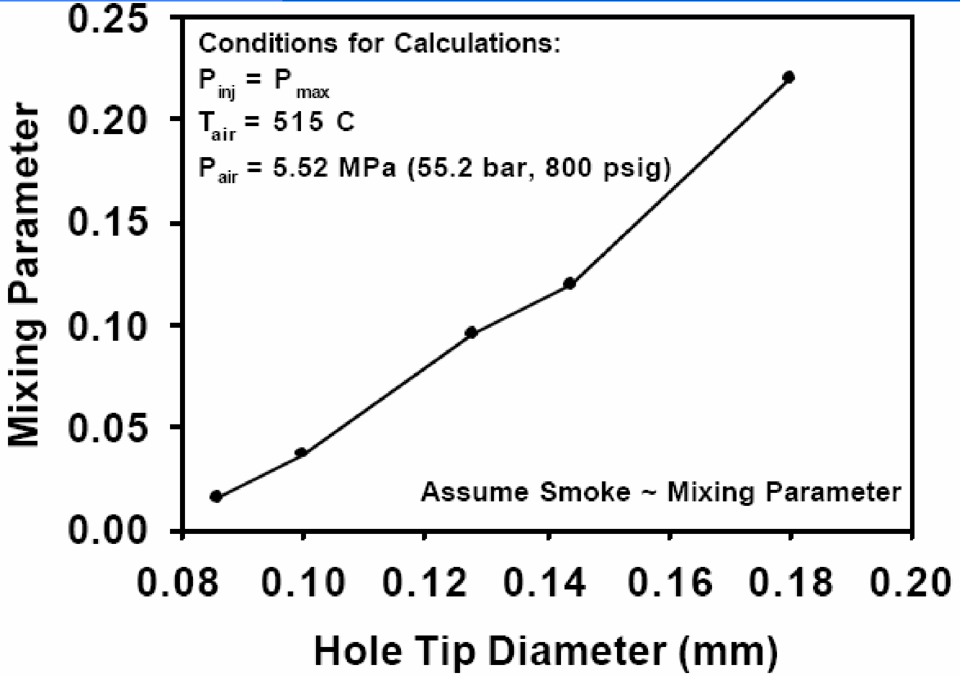
- Single Hole Nozzles 0.086 to 0.18 mm Dia
- Peak Injection Pressures from 254 to 283 MPa
- Higher Mixing Rates and Smaller Drops

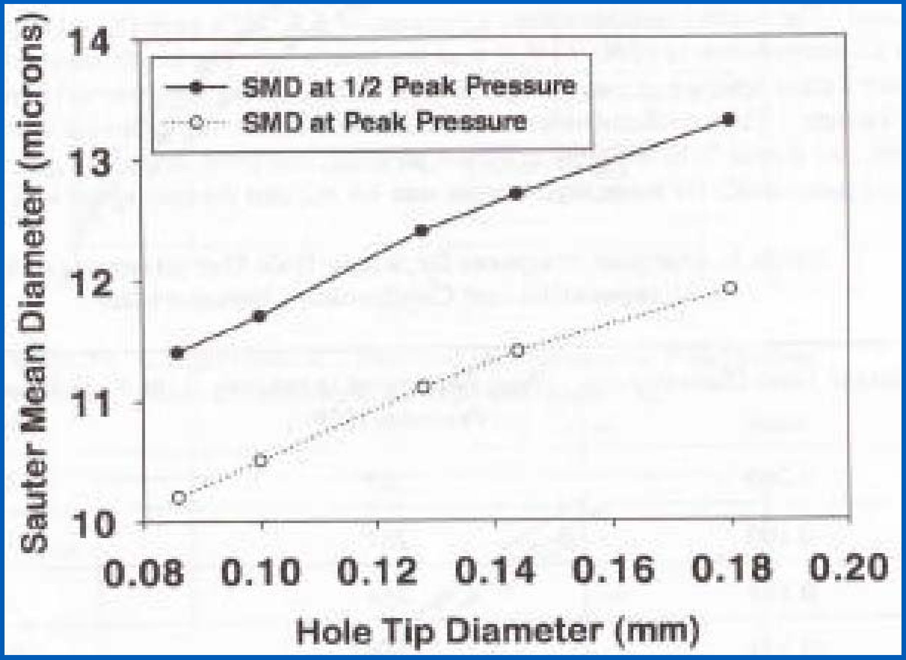
Injection Hole Diameter (mm)	Peak Injection Pressure (MPa)	½ Peak Injection Pressure (MPa)
0.086	283	142
0.100	281	141
0.128	266	133
0.144	267	134
0.18	254	127

Fuel Injection - High Pressure

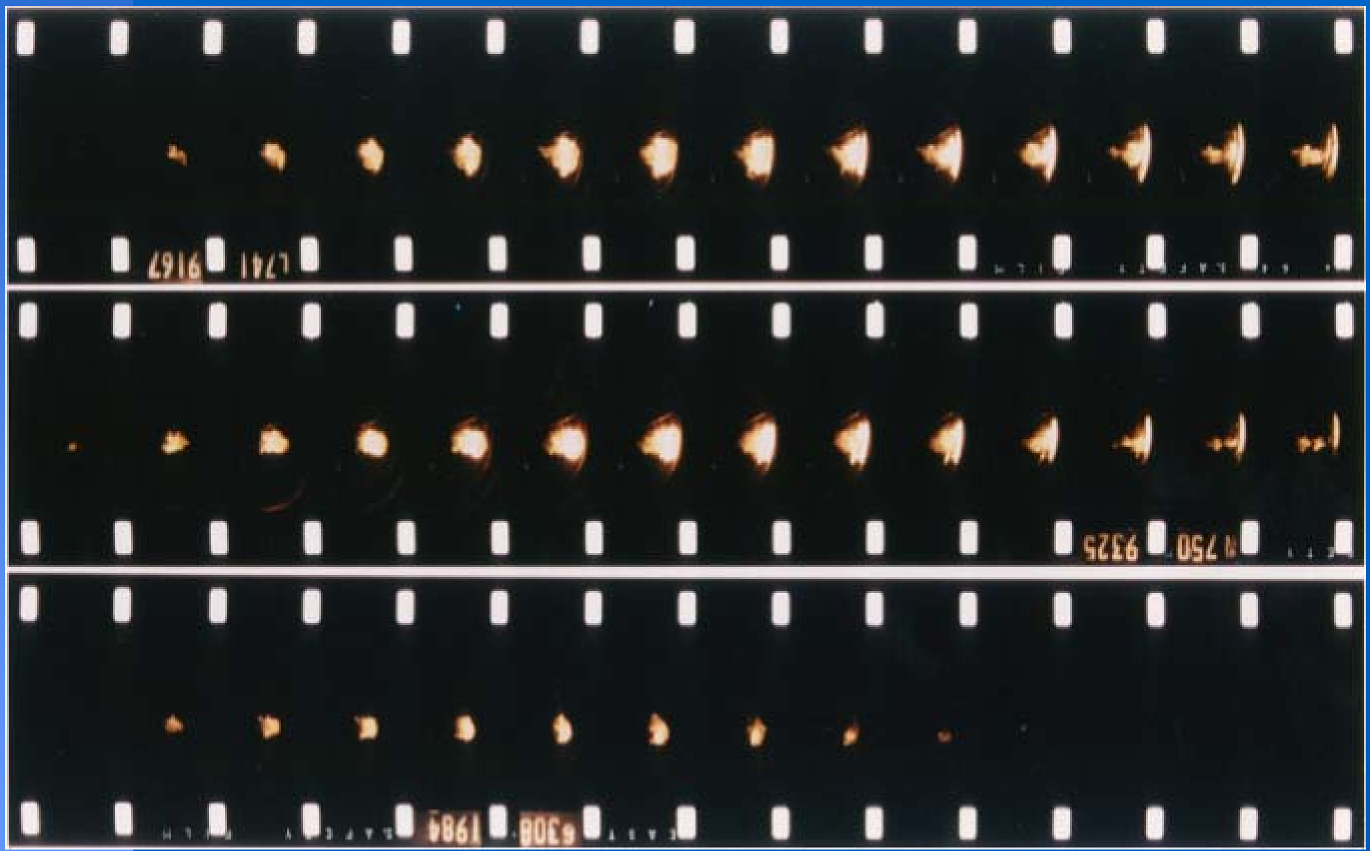
1. Mixing Rates Quantified in Terms of SwRI Defined Mixing Parameter
2. Mixing Parameter Defines the Mass of Fuel at Phi Greater Than 1.0 for than 0.6 ms
3. Rich Regions Mean More Soot

- Mixing Parameter and Drop Size both Decrease with Smaller Holes
- P_{inj} Increases with Smaller Holes





Fuel Injection - High Pressure



0.144 mm

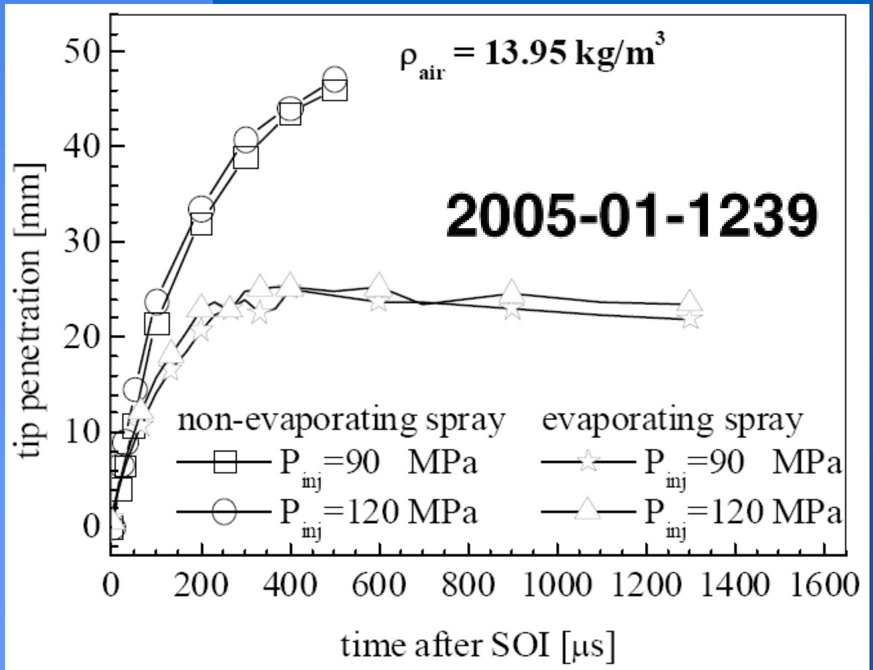
0.128 mm

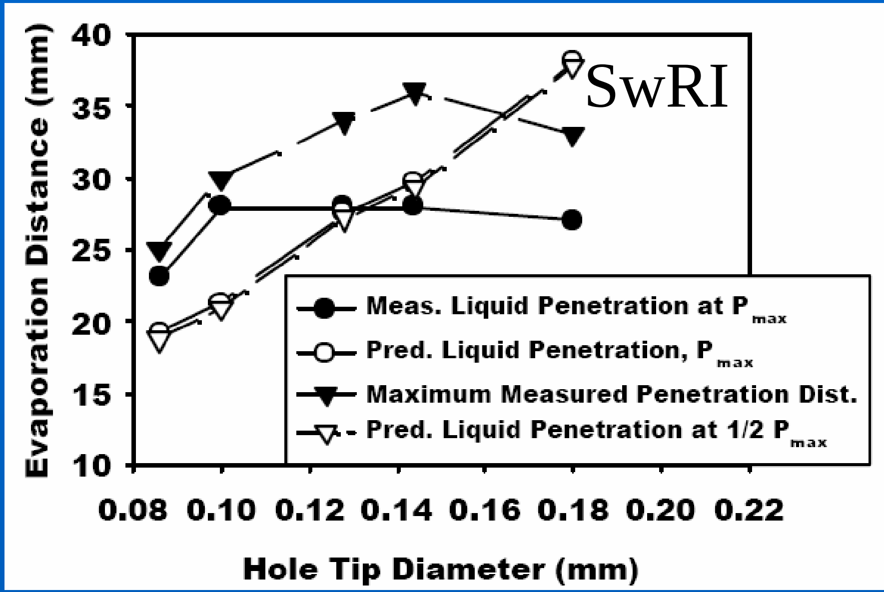
0.086 mm

- Small Holes Produce High Pressure, Small SMD, High Mixing Rates and Low Soot Formation Rates

Fuel Injection - High Pressure

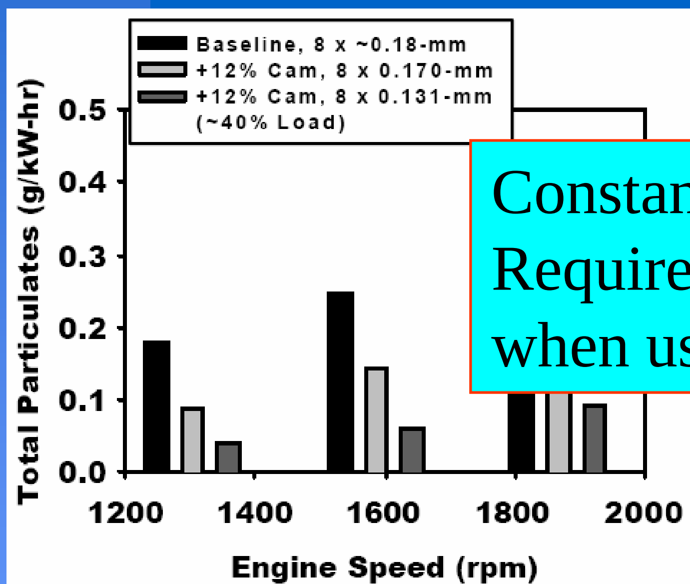
- High Pressure does not Affect the Jet Penetration Rate in either Evaporating on Non-Evaporating Sprays





- Small Holes do Affect the Evaporation Rate and the Liquid Length in Evaporating Sprays

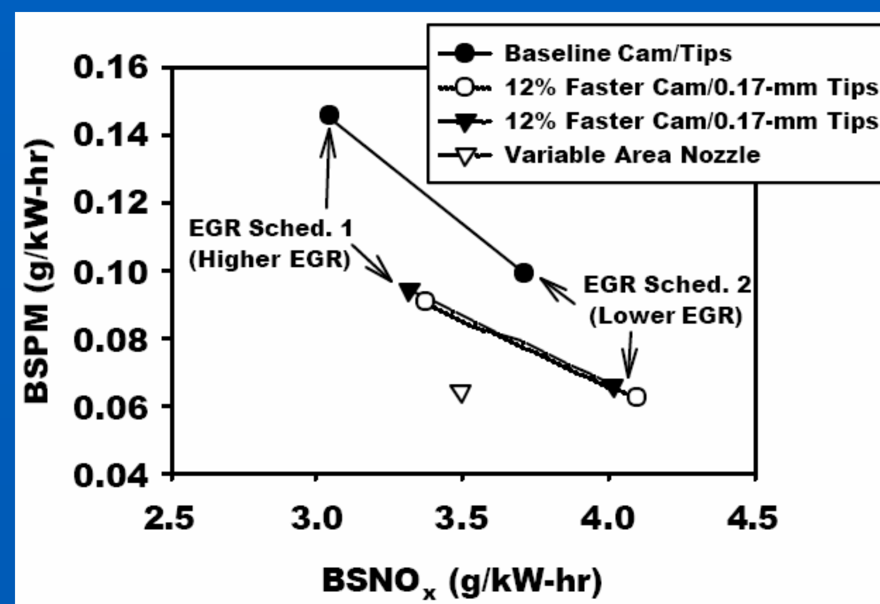
Fuel Injection - High Pressure



- Variable Area Nozzle (0.17 to 0.131 mm) Gives a Significant Improvement
  - ...sed for Light Loads
  - ...ed for High Loads
  - ...Liquid Length, and
  - ...e are Important

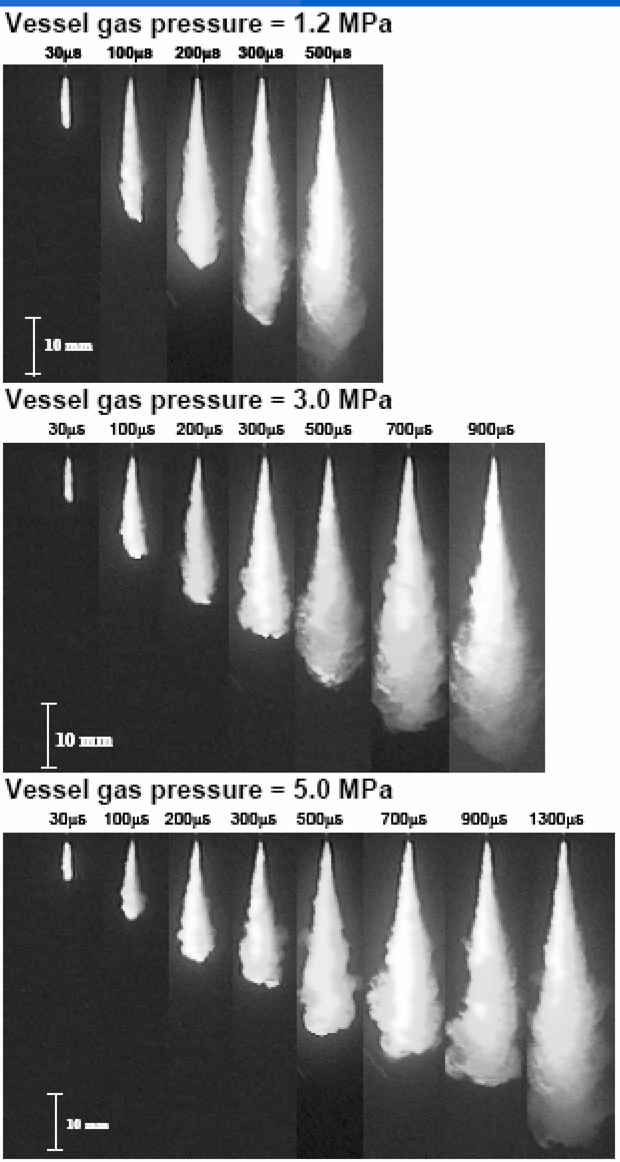
Constant Injection Duration Requires Higher Pressure when using Small Holes

- 12% Cam and 0.17 mm Nozzle Give same Duration as Baseline
- 12% Cam and 0.131 mm Nozzle Give Higher Rates

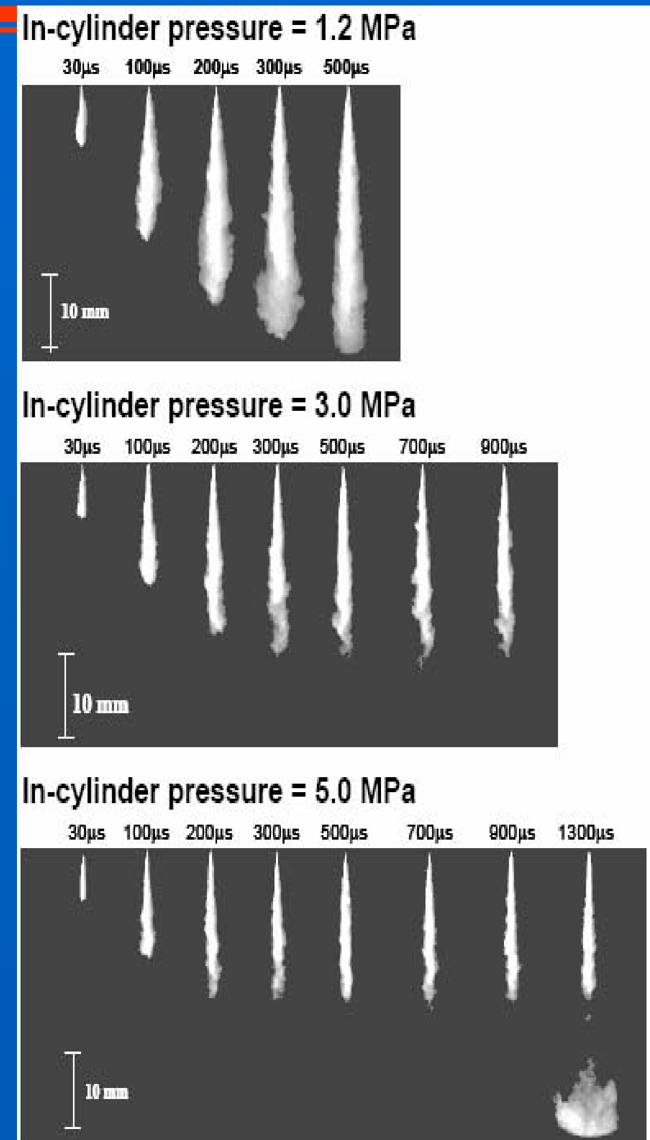


High Boost

Fuel Injection - High Density

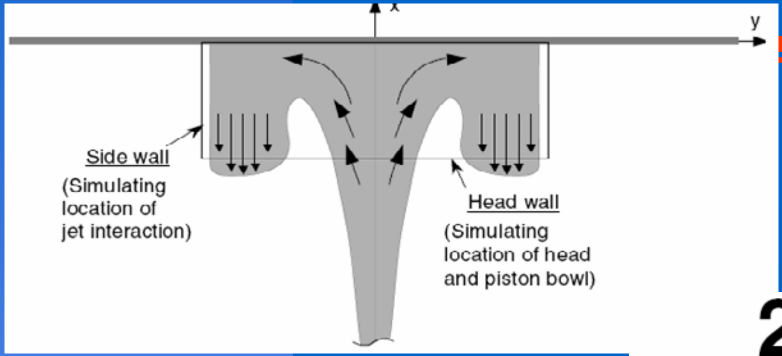


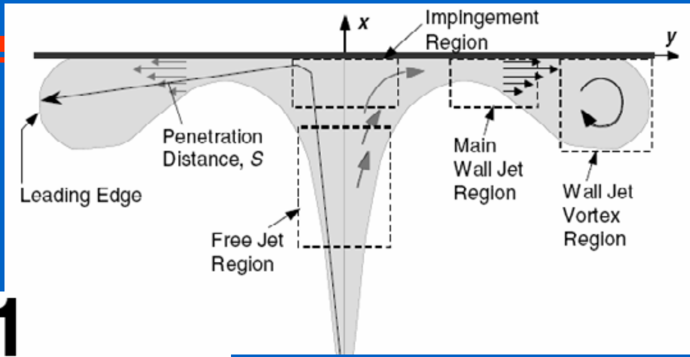
- Liquid Length Affected most Strongly by Hole Size and the Ambient Density
  - Smaller Holes
  - Higher Density
- Gas Jet Always Interacts with Combustion Chamber
  - Wall Jet Mixing Important
    - Air Motion



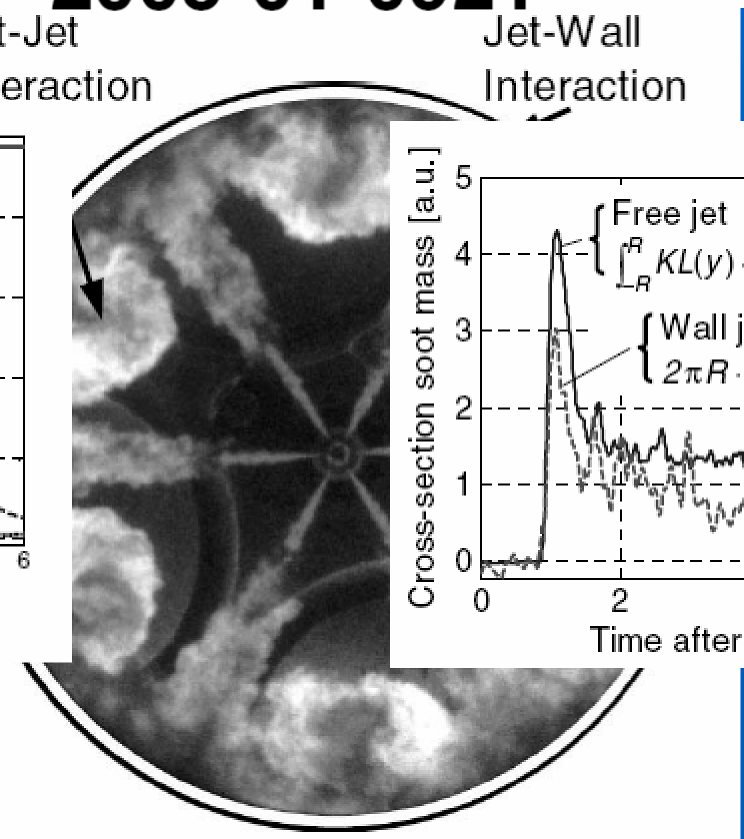
Combustion Chamber Design

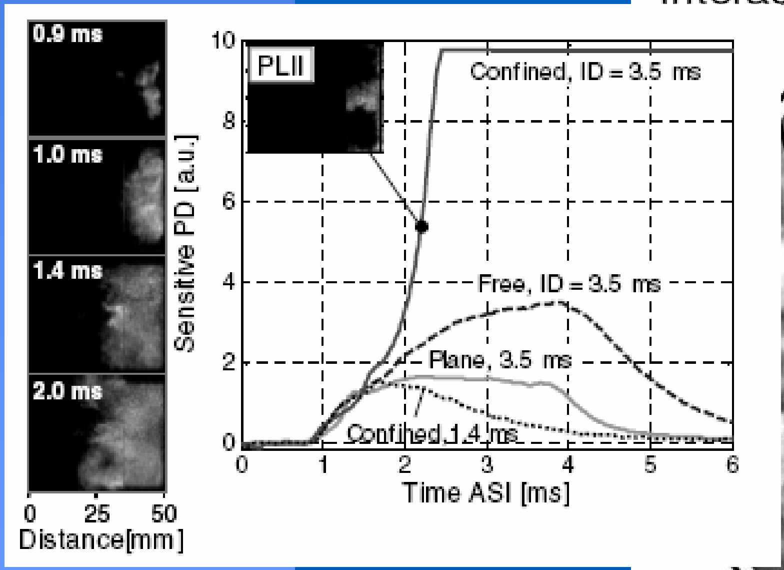
Fuel Injection - Jet-Wall Interaction

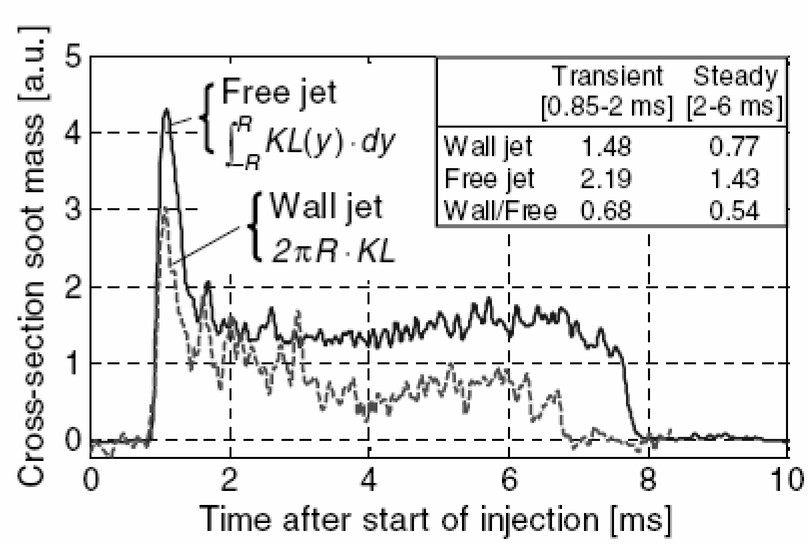




2005-01-0921







Combustion Chamber Design

Man D20

Cat C9

Cat C15

Volvo D12

ISX

DDC S60

- Spray Wall Interactions are Unavoidable
  - Avoid Liquid Impingement
  - Take Advantage of Jet Break-up and Wall Jet Opportunities
- Pilot and Post Injections Change the Bowl Shape and Spray Angle Requirements
  - Cat uses Pilot at Almost all Conditions
    - Spray Angle Narrower

Fuel Injection Wall-Wetting Issues

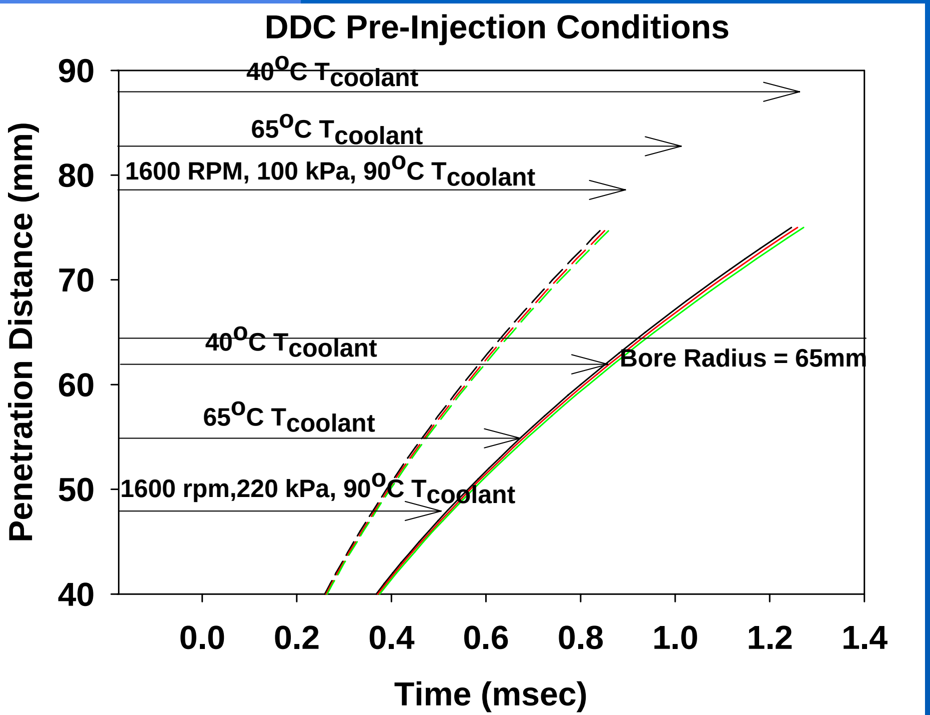
Background Is Liquid Impingement and Oil Dilution a Concern?

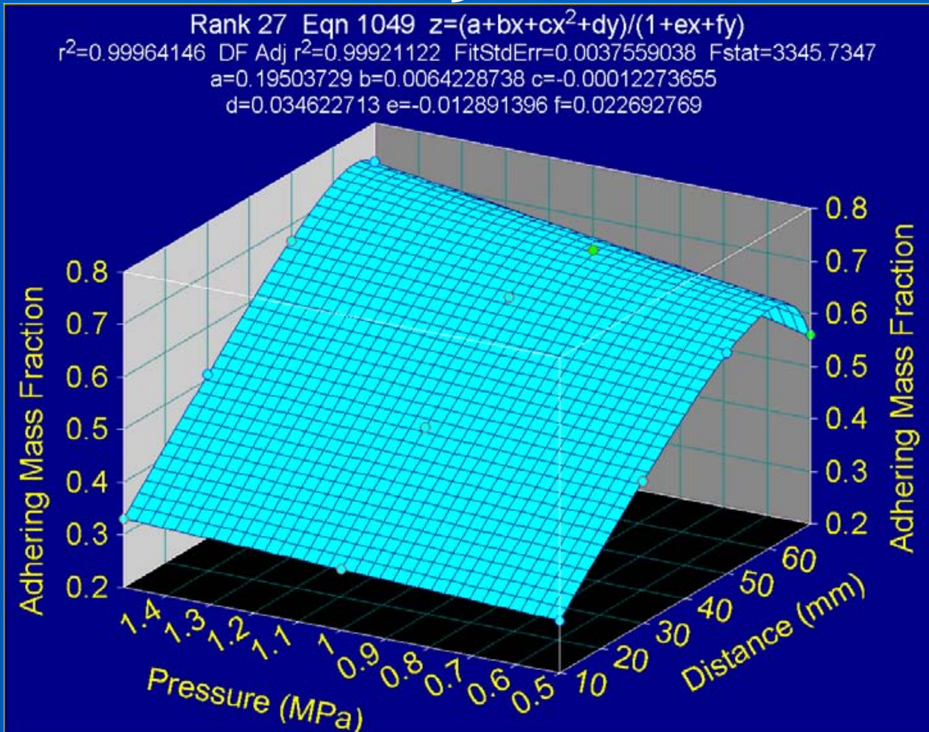
- Concerned with both Early Pre- Injection for Emissions and Noise Control and Late Post - Injection Strategies for DPF and LNT Regeneration
  - Fuel Jet Penetration Increases during Late Injection Due to the Lower Density
    - Decreasing Pressure and High Temperature
  - Liquid Fuel can Impinge on the Wall and Some can Adhere and Enter the Lubricant
- Approach
    - Developed an empirical based model for estimation of the relative quantity of injected fuel that becomes associated with, or adheres, to the combustion chamber walls

DDC Series 60, 1600 rpm, Pilot

- Liquid Mass Fractions at Bore
  - 90ºC = 31% Liquid
  - 65ºC = 37% Liquid
  - 40ºC = 43% Liquid
- Adhering Mass Fraction on Bore is 71%
  - 90ºC = 22%
  - 65ºC = 26%
  - 40ºC = 31%

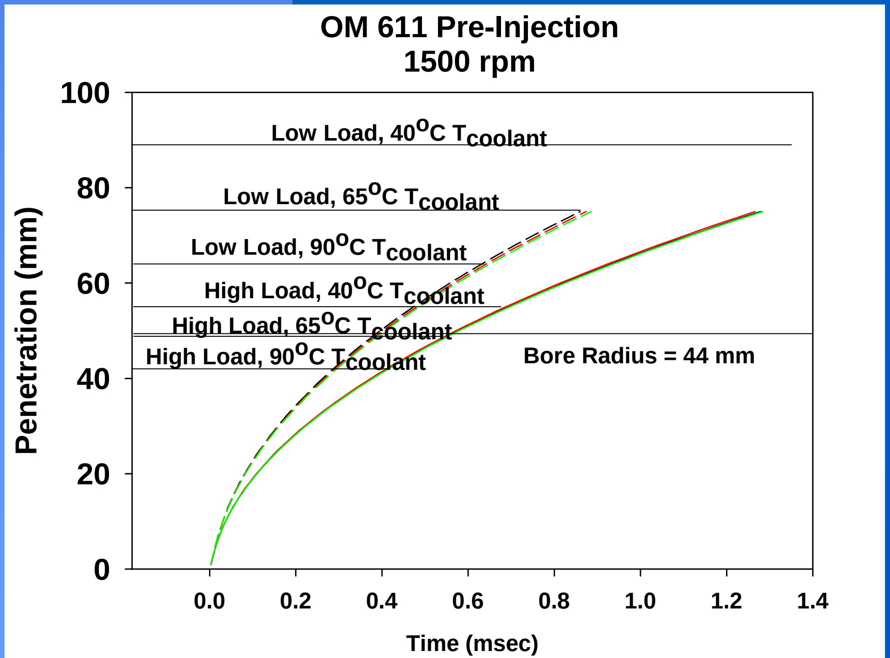
  } Liquid

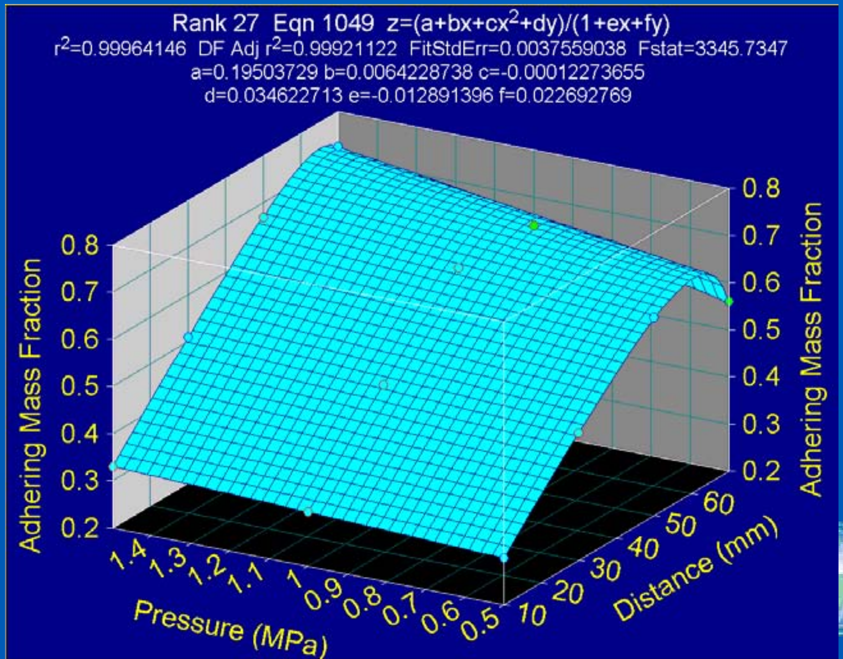




OM 611, 1500 rpm, Pilot

- Liquid Mass Fractions at Bore
  - High Load
    - 65°C = 22% Liquid
    - 40°C = 34% Liquid
  - Low Load
    - 90°C = 50% Liquid
    - 65°C = 64% Liquid
    - 40°C = 76% Liquid
- Adhering Mass Fraction 71%
  - High Load
    - 65°C = 16% Liquid
    - 40°C = 24% Liquid
  - Low Load
    - 90°C = 36% Liquid
    - 65°C = 45% Liquid
    - 40°C = 54% Liquid

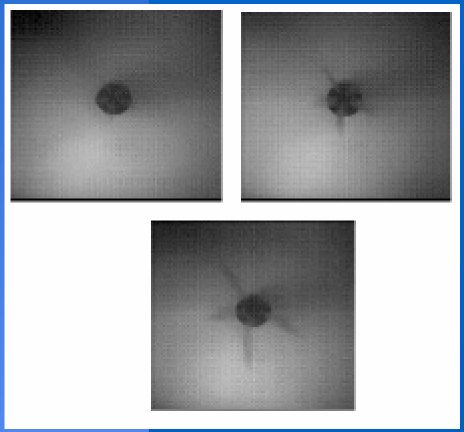




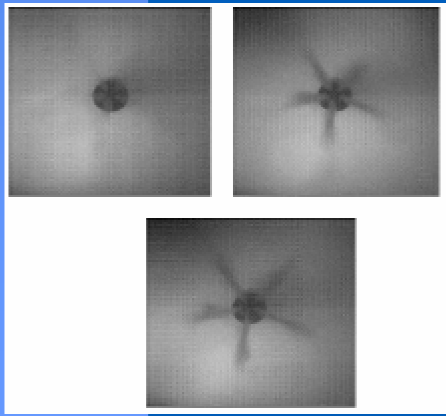
Fuel Injection - Pilot and Post

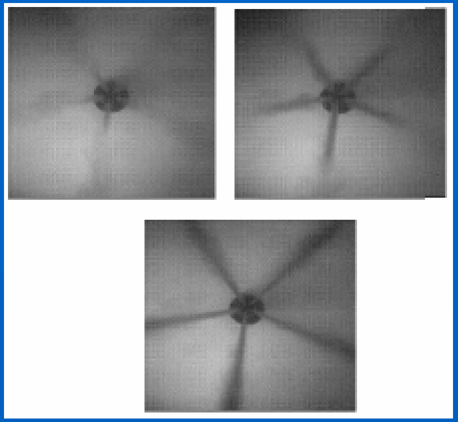
2002-01-1150

First Pilot, 0.17 ms



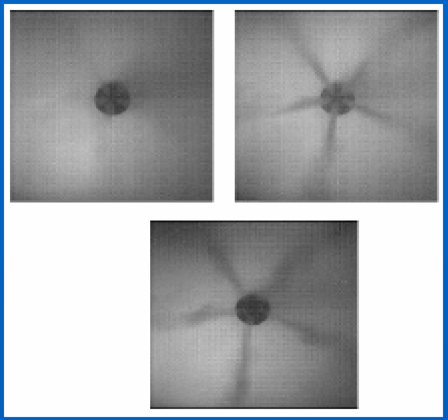
Second Pilot, 0.17 ms



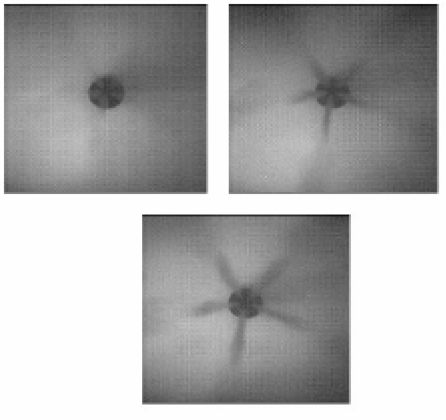


Main, 0.45 ms

First Post, 0.17 ms



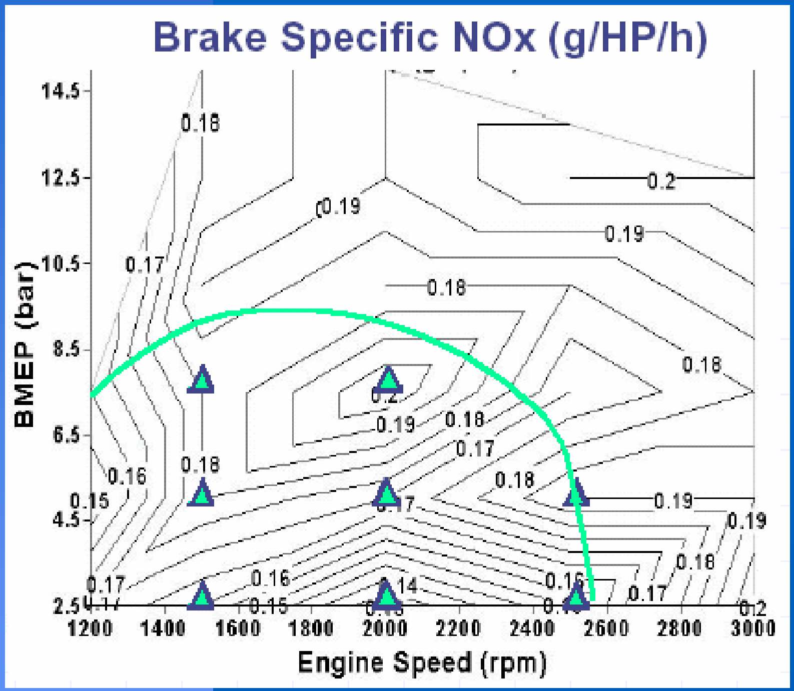
Second Post, 0.17 ms

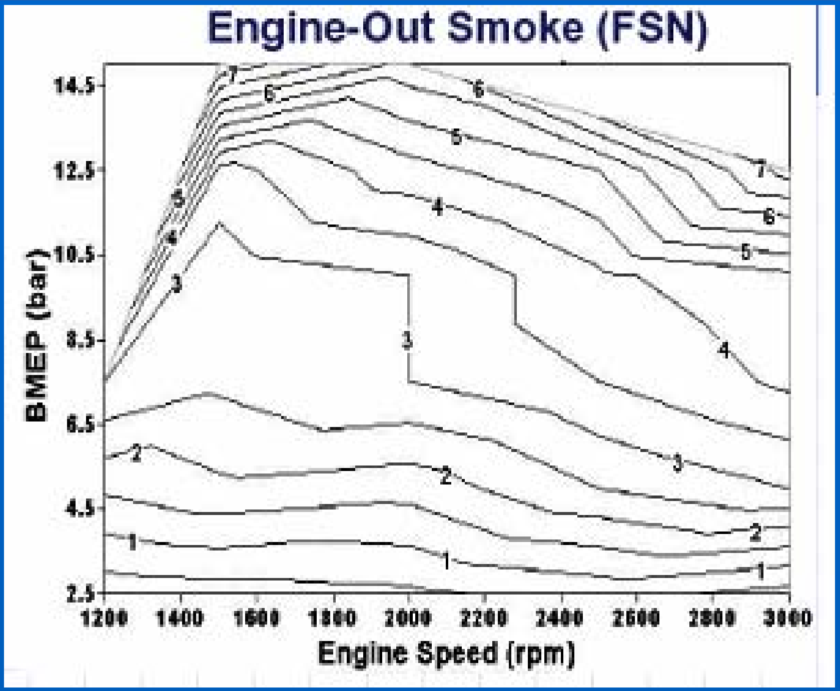


- Split Injection Offers Opportunity to Reduce Liquid Length and Liquid Impingement
- Benefits for both Pre and Post Injection

Massive EGR

Massive EGR Background - EPA-Ford Data





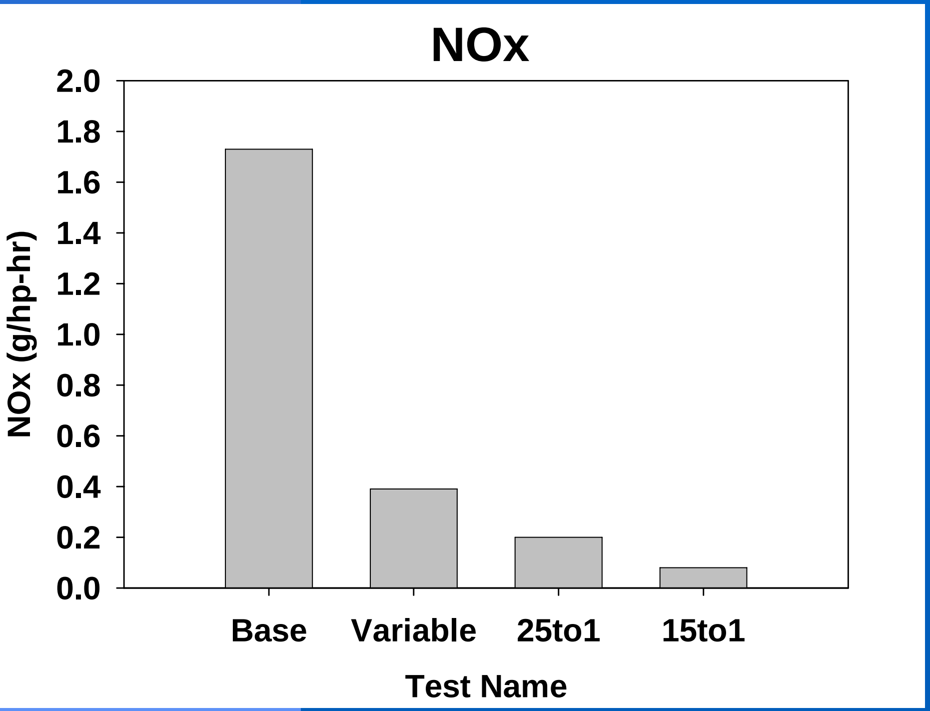
Type	4-cylinder, 2 valve/cyl OHC
Displacement	1896 cm^3
Bore	79.5 mm
Stroke	95.5 mm
Comp. Ratio	19.5:1

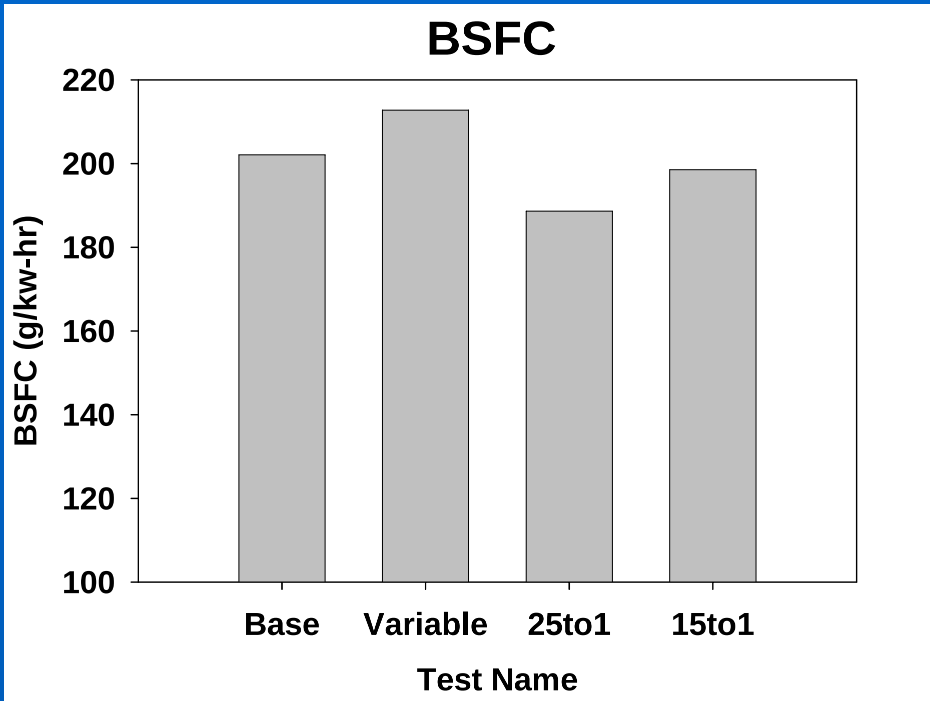
EPA Fuel System - Hydraulically Intensified
Injector Location - 7mm offset w/ 26° Inclin.
Boost Systems - externally supplemented ($P_{exh} = P_{int} + 0.1Bar$)
- partial map TC matched (Initial effort)

Massive EGR Background - Diffusion Burn Engine (Alternative to NOx After treatment)

- SwRI Has Extensive Data Base of 8-Mode Data for Cat 3176 2.5 g/hp-hr NOx + HC Engine
- Use Cycle Simulation to Model Different Levels of EGR
- Assumed LP Loop EGR After DPF
- Conditions Examined
  - Baseline - Good Prediction of Existing Data
  - Baseline A/F and Timing + EGR + Boost
  - Baseline Timing + A/F=25:1 + EGR + Boost
  - A/F=15:1 + EGR + Boost + Timing Advance

Massive EGR

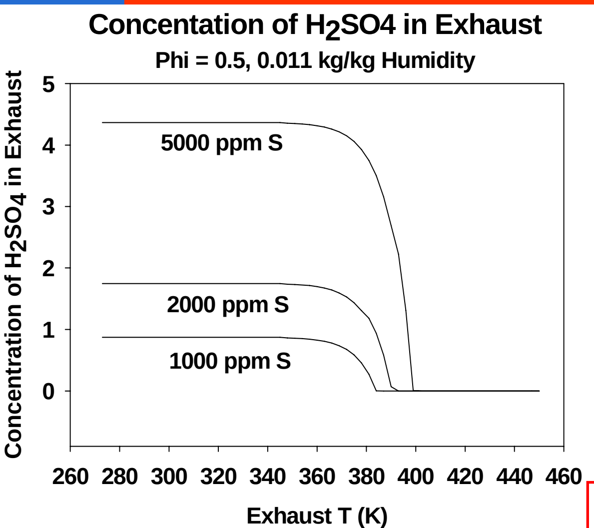




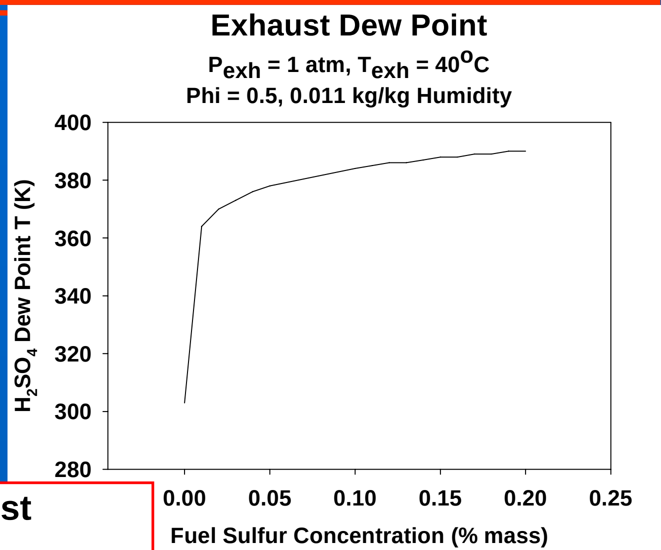
- Baseline Engine Around 2 g/hp-hr
- BSFC Penalty with Variable Due to Back Pressure Increases
- 25:1 A/F Produced Lots of Turbine Energy
- 15:1 A/F Lowered the Air Flow and Boost Requirements

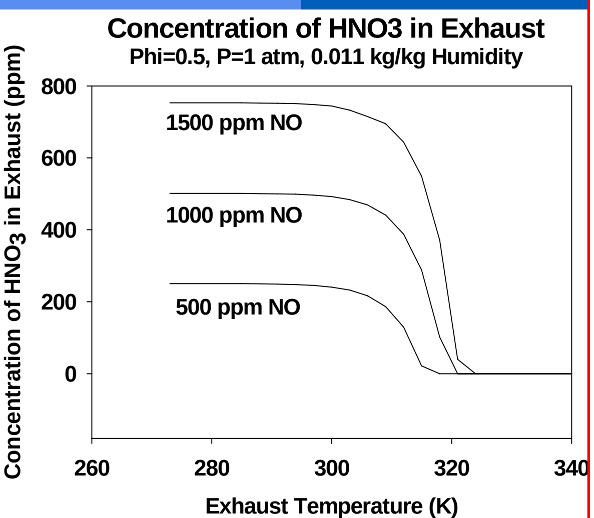
Massive EGR Issue

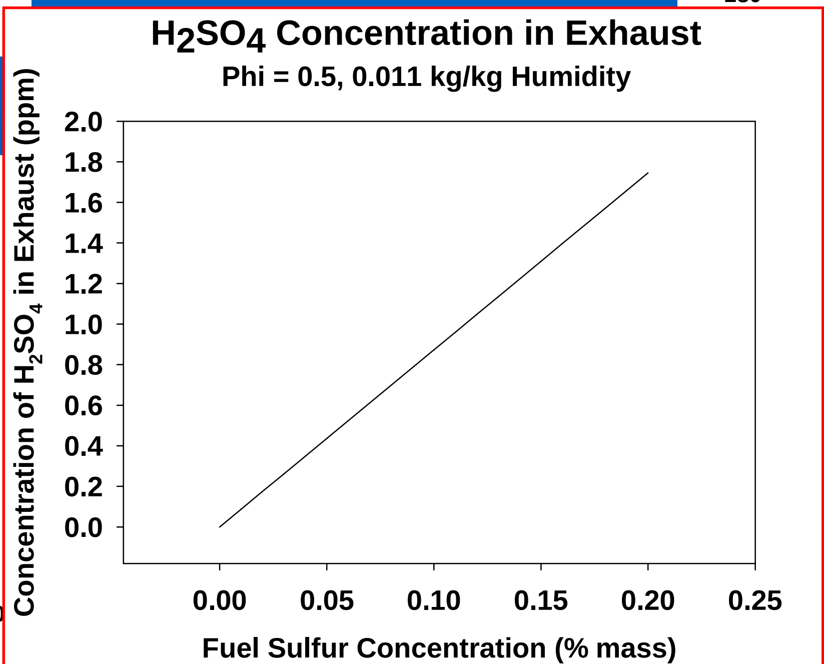
Cooled EGR

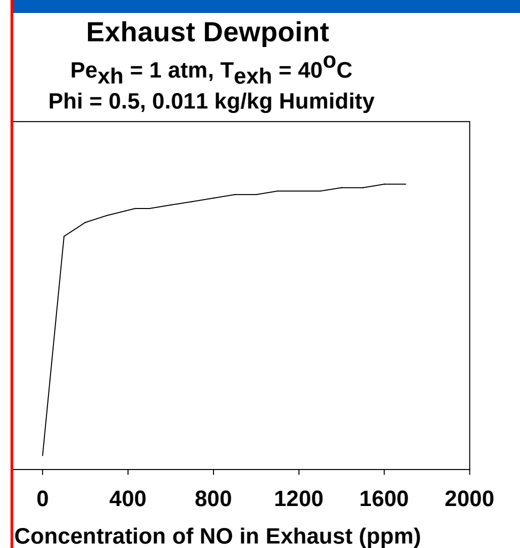


- S in the Fuel Raises the Exhaust Dewpoint
  - Concentration Determines the Concentration of H_2SO_4 in the Exhaust
- NO in the Exhaust Raises the Exhaust Dewpoint
  - Concentration Determine the Concentration of HNO_3 in the Exhaust
- H_2SO_4 in the Exhaust is Directly Related to Fuel S Concentration









Diffusion Burn Engine Fuel

- Conventional Current Diesel Engine Fuel Appetite
  - Low Aromatics (high H/C Ratio)
    - Lower Flame T and Lower NOx
    - Lower Propensity for Soot Formation
  - High Cetane Number
- Advanced Diesel Engine Fuel Appetite
  - Mixed Mode (Part Time HCCI and LTC)
    - Low Aromatic
    - High Cetane Number (at least consistent)

So, Best Diffusion Burn System

- Ultra High Injection Pressure and Small Holes
- Massive EGR
- Ultra High Boost
- Well Designed Pistons and Intake
- High Quality Diesel Fuel

Alternative Approaches

- Full Time HCCI
  - New Fuel Required
- HEDGE
  - Could be the Lowest Cost Alternative

Thank You