Effect of Compression Ratio and Piston Geometry on RCCI load limit

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Improve Engine Fuel Efficiency

Brake efficiency=F(gross efficiency, gas exchange, friction)

What can we do about efficiency?

Optimal combustion timing & duration → **Approach ideal cycle**

volumetric at/near TDC

Improve combustion efficiency → **Combust all fuel**

reduce losses (HC and CO)

Improve thermal management → **Keep energy in**

reduce thermal losses

Improve gas exchange → **Lower negative work**

reduce pumping pressure

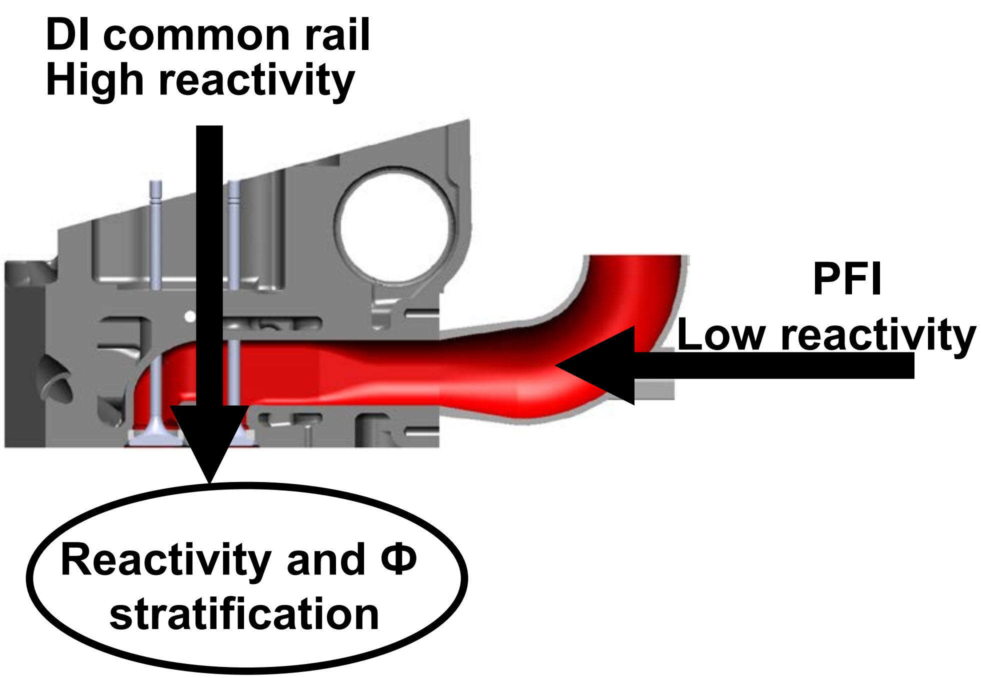
Improve friction → **Throw less away**

reduce bearing loads

RCCI Fueling Strategy

Kokjohn et al. SAE 2009-01-2647
Hanson et al. SAE 2010-01-0864

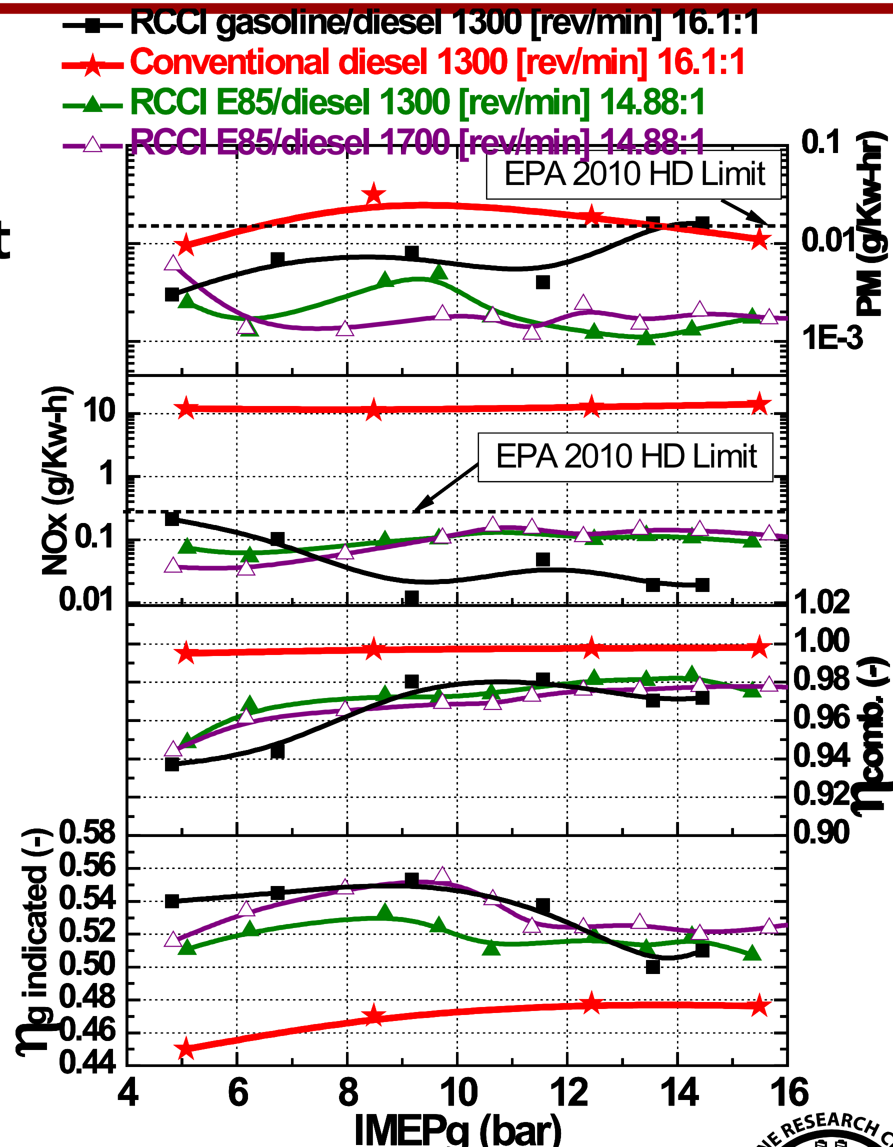
- **Retrofitted conventional (SI type) PFI system**
  - Delivers low reactivity fuel (gasoline, E85, hydrous ethanol)
- **Conventional DI common rail operated at low pressure**
  - Early Direct injection(s) of reactive fuel (diesel, bio diesel), at ~500 bar



- **Result:**
  - **Stratified in both reactivity and equivalence ratio**
  - **Significant combustion control gained through injection timing and fueling ratios**
  - **Global and local reactivity blend can be altered through injection timings**

RCCI Load Sweep

- **DEER 2010 RCCI data**
  - SAE 2011-01-0363
- **Overall turbo eff. 50% without EGR, 40% with (RCCI 9bar+)**
- **Conventional diesel**
  - Single injection (high η)
  - High NOx and PM (SCR?)
  - Gross efficiency ~47-48%
- **E85/diesel RCCI reduced Cr**
  - Cr reduced to 14.88 from 16.1
  - Intake temp raised (32° to 55°C)
  - Bathtub piston (~no squish)
- **Increased engine speed**
  - Reduced heat transfer time



Clean, efficient, wide load RCCI possible

Optimizing Piston Shape for Premixed Fuel

- **Different from CDC**
- **Fix Cr and bowl ø**
  - change bowl and squish depths
- **High eff. has low losses**
  - **Reduce heat transfer**
    - Decrease surface to vol. ratio

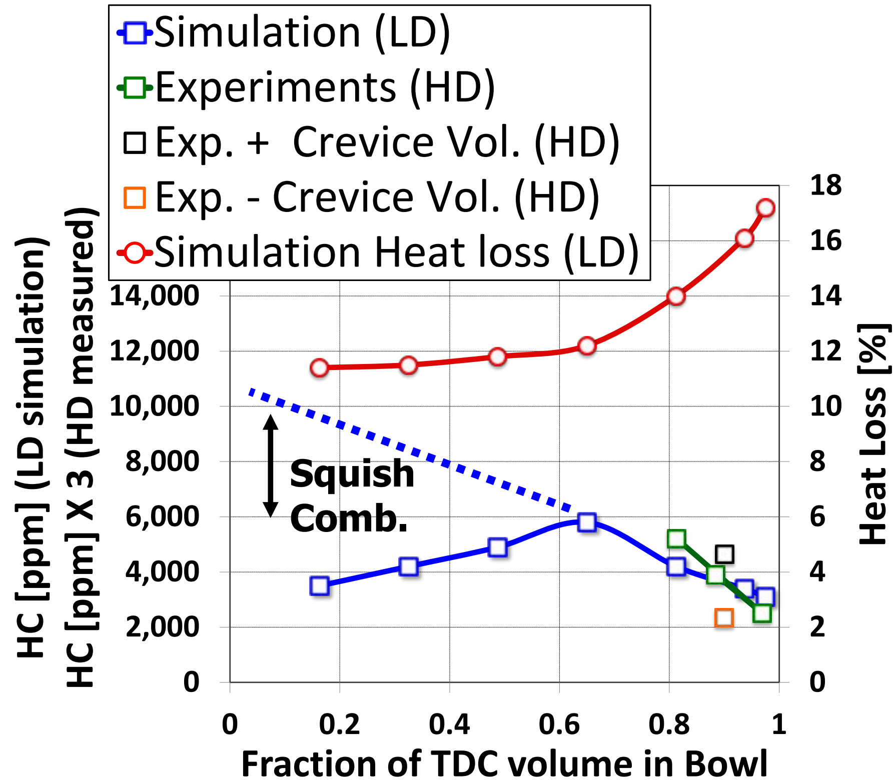
Flatter piston reduces surface area for HX

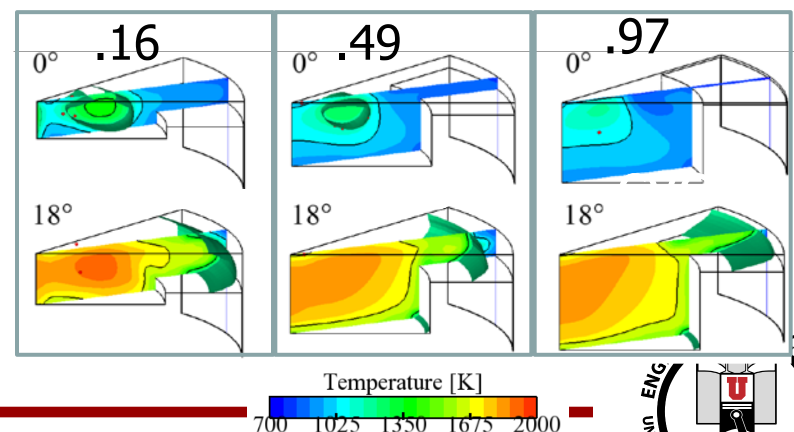
  - **Reduce HC and CO**
    - Lose less charge to crevices

Small squish height

    - Better oxidize trapped and outgassing crevice charge

Best with large squish height

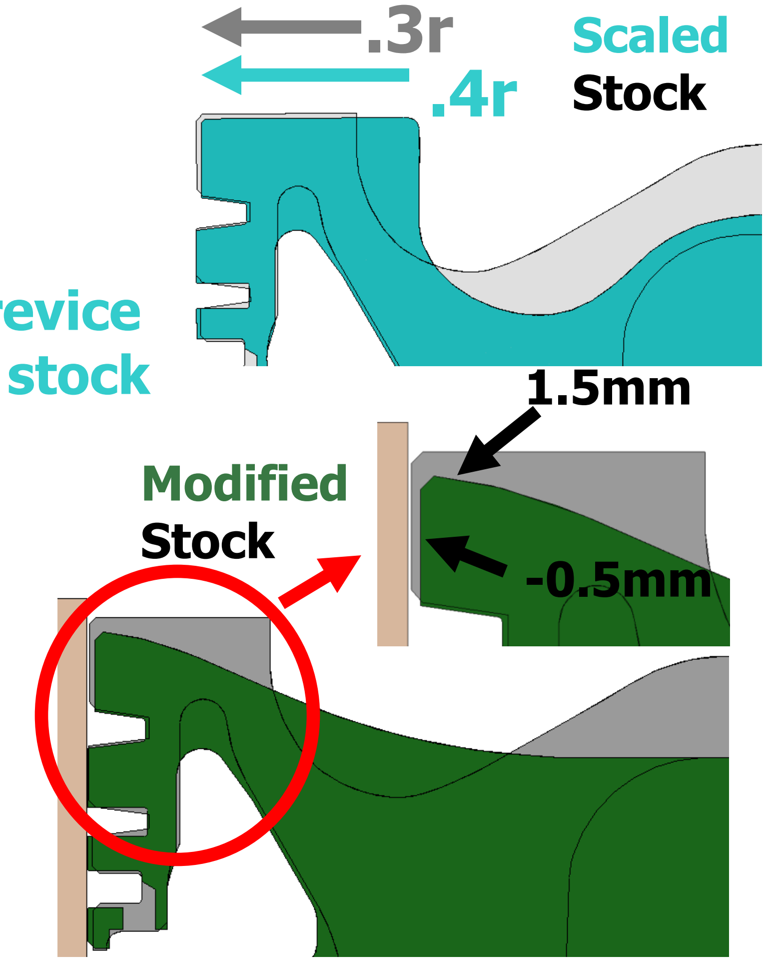




Tested Piston Shapes

- **Examine 3 piston shapes**
- **Stock**
  - Piston optimized for diesel, Cr 16.1:1
- **Scaled to UW LD**
  - Cr reduced to 15.5:1
  - Longer squish (.4r vs. .3r)
  - Cut from blank 1mm ø undercut
- **New piston design**
  - Bathtub shape (~no squish)
  - Piston surface area reduced by 4.15%
  - Cr reduced to 14.88:1
  - Top ring crevice 1.5mm shorter
  - Cut from blank 1mm ø undercut

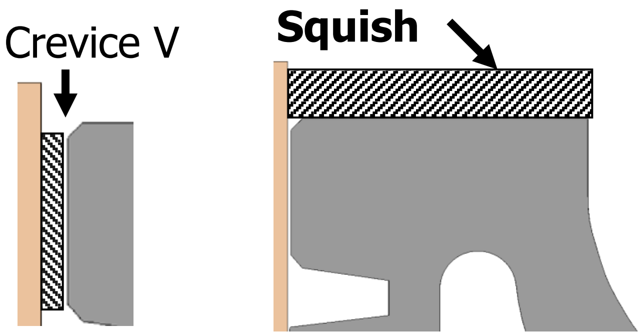
Top crevice 2.48X stock



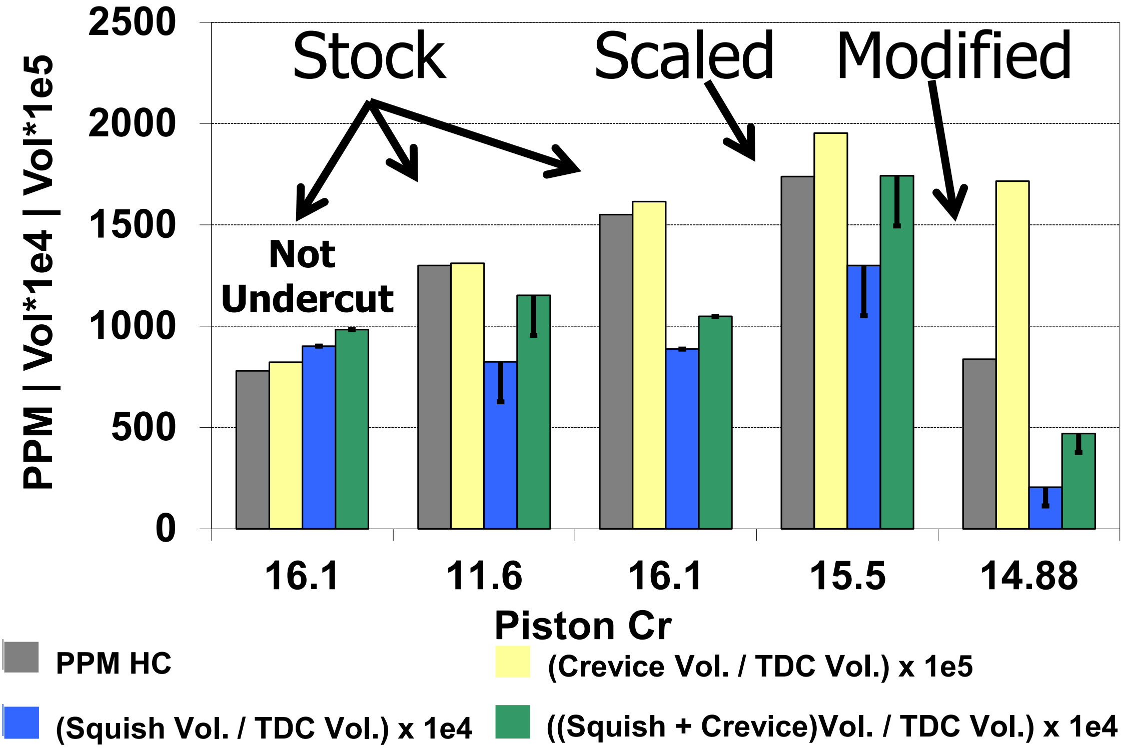
Top crevice 2.27X stock volume

Tested Piston Designs

- **RCCI Operated with 5 pistons**
  - Designs varied in Cr, bowl diameter, crevice volume, and squish heights
  - All but stock 16.1 cut from blanks
  - Blanks ø undercut -.5 to -1 mm
- **Measured engine out HC**
- **Calculated**
  - crevice V / VTDC
  - squish V / VTDC
  - crevice + squish V / VTDC



Error bars , only BL vol. Dec et al. SAE 2009-01-0650



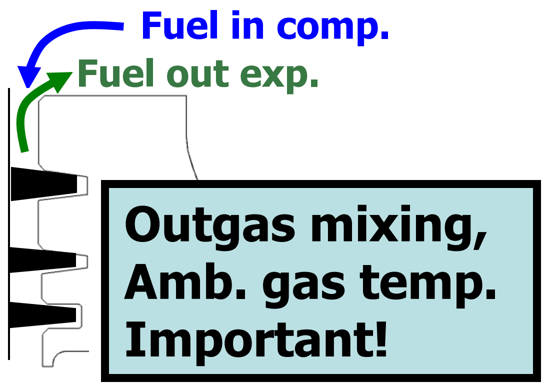
<u>Engine out HC dependencies</u>
- **crevice volume**
  - **smaller=better**
- **squish geometry**
  - **squish optimization**
    - **reduce HC**
    - **even with large crevice**

HC Conversion Efficiency vs. Geometry

- **HC crevice dependent**
- **Modeled crevice flow**

  Reitz et al. SAE 892085

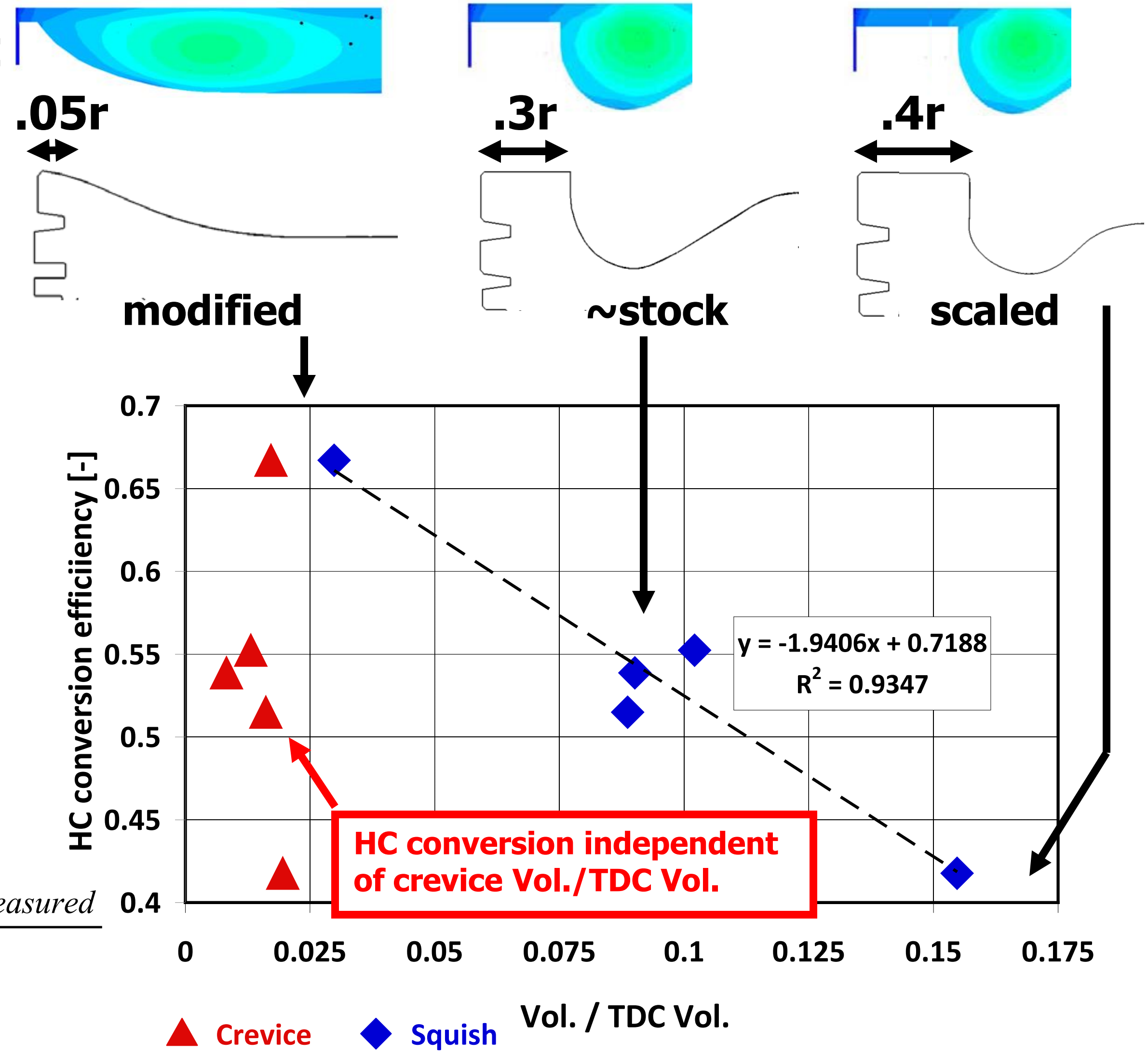
  - F (Cr, Φ, speed, size)



  - predict trapped fuel

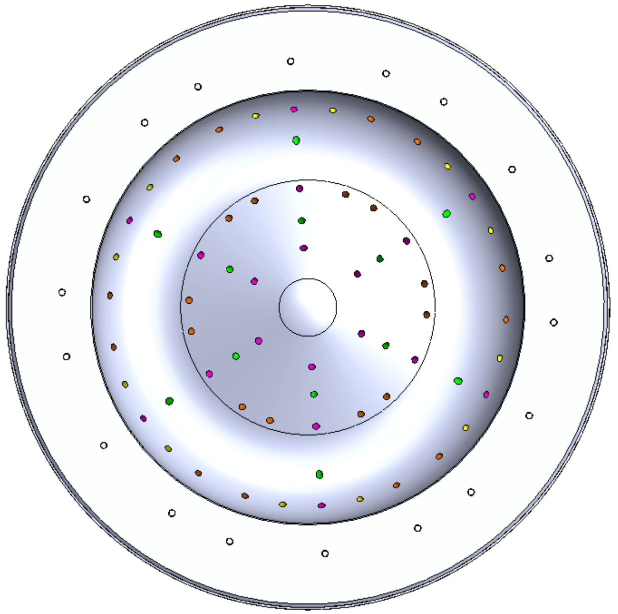
- **Defined HC** $\eta_{conversion}$

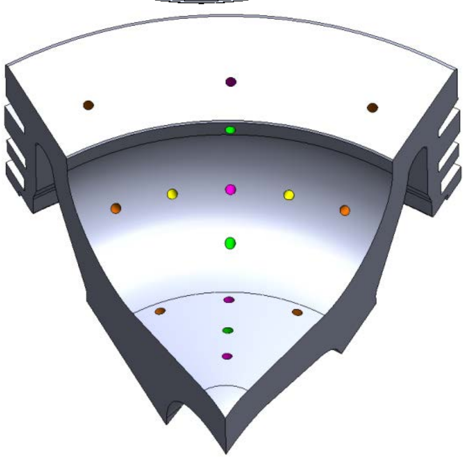
$$\eta_{conversion} = \frac{M_{prediced} - M_{measured}}{M_{prediced}}$$



Thermal Losses

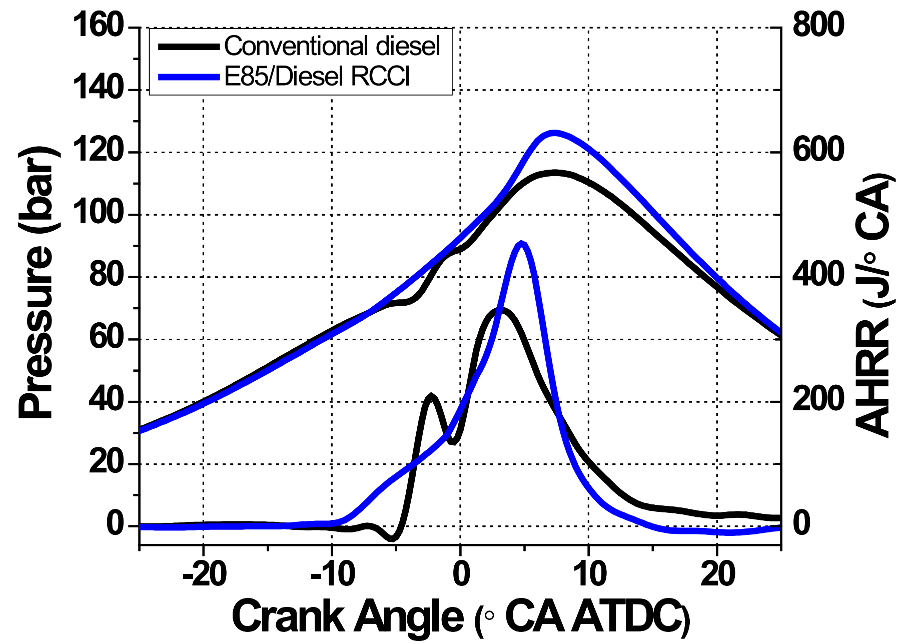
- **Stock type piston instrumented with 15 thermocouples**
  - 11 on piston face, 1 top ring land
  - 2 in oil gallery (in/out), 1 backside
- **By symmetry 15 thermocouple "60°sector"**
- **Mirror sector 360°(6 plumes)**
  - 90 measurement locations
  - **<u>Error:</u>** does not capture gradient in oil galley (thus surface) temperatures across piston





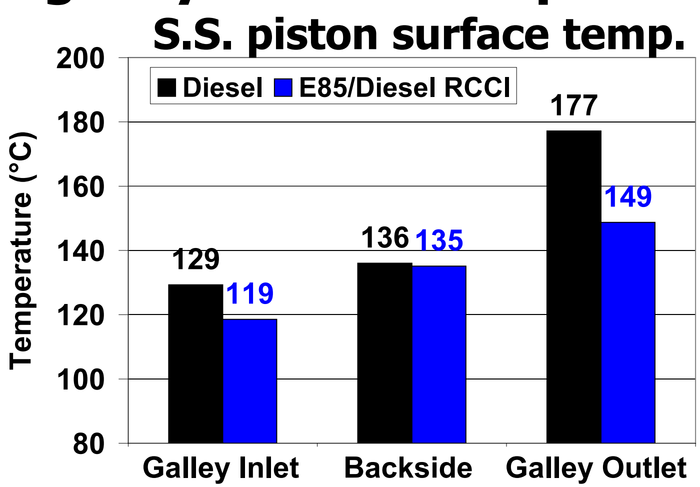
Thermal Differences

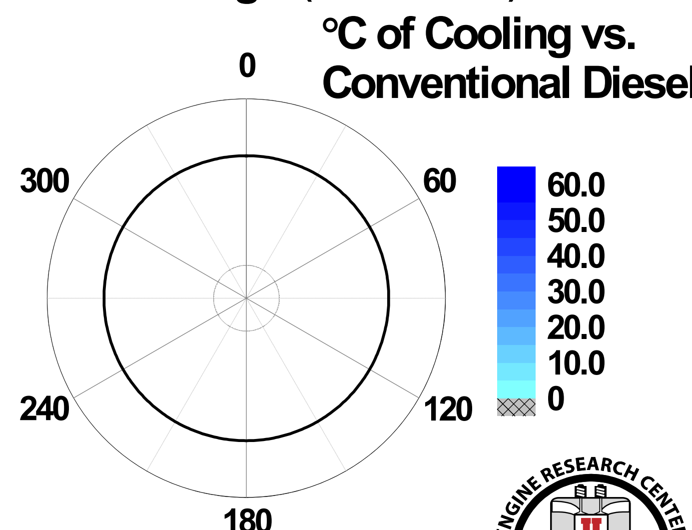
- **Diesel operation**
  - Single injection 1500 bar
  - No egr, ~50% turbo eff., Φ=.38
- **RCCI operation**
  - Same conditions as diesel, Φ=.34
  - Comb. η ~95%, GTE 54% vs. 50%
    - Piston ø undercut 0.5mm
- **Defined °Cooling**
  - ≡ (temp. diesel) – (temp. RCCI)
- **Measured oil galley surface temp.**



Up to 60°C cooler piston T

~37% lower piston oil surface ΔT





How do Brake Efficiencies Compare?

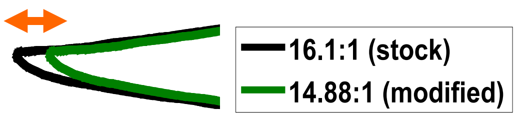
- **Apply Chen-Flynn model**
- **CDC, stock piston**
- **Assume stock crevice gap**
- **Apply HC conversion η**
  - **RCCI, stock piston**
  - **RCCI with modified piston**
  - ~NTE, +.8 BTE (lower Pmax)
  - More pumping losses with 16.1:1

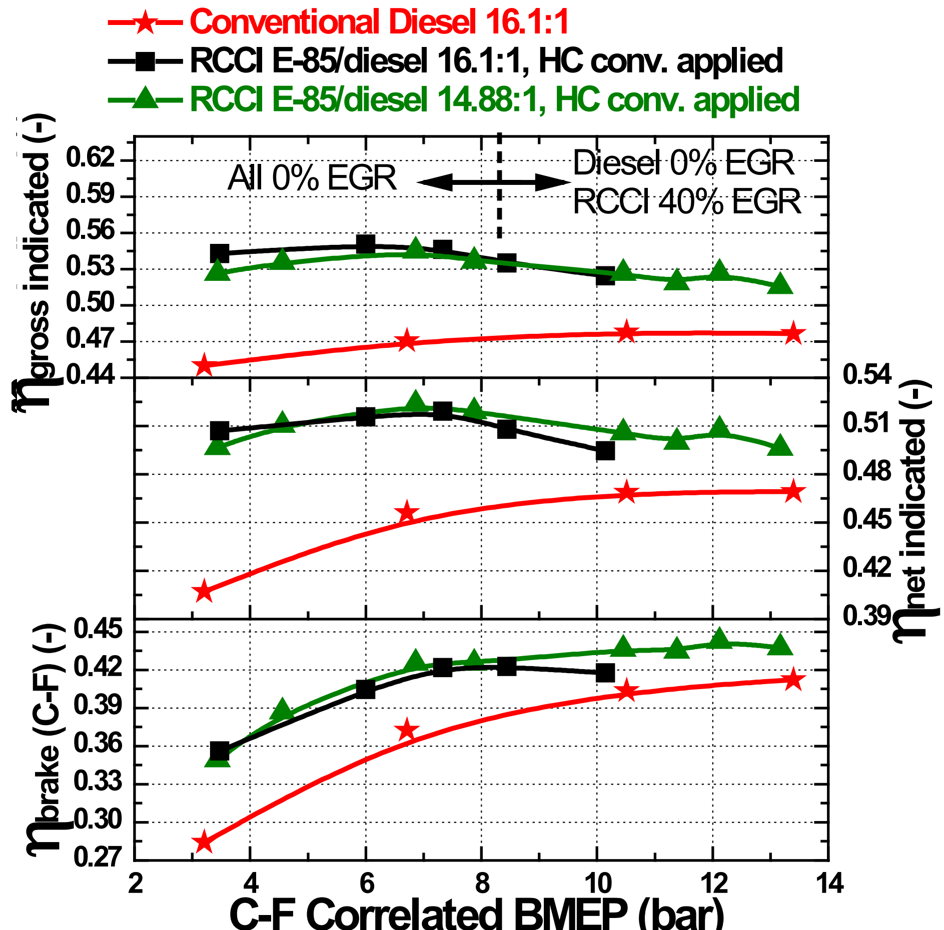
$$FMEP = C_1 + (C_2 * P_{max}) + (C_3 * \overline{S_p}) + (C_4 * \overline{S_p}^2)$$

$$P_{max} = \text{Peak Cylinder Pressure} \quad \overline{S_p} = \text{Mean Piston Speed}$$

Used same constants (C1-C4) as GT Power

same P more ΔV
20% less - work





- **To increase brake values must**
  - Increase net without + Pmax
  - Limit/optimize EGR delivery/rate

RCCI ~5-15% +η vs. CDC

RCCI meets EPA 2010 HD NOx and PM mandates in-cylinder!

Conclusions

- **By mixing of fuels of varied reactivity in-cylinder (RCCI), high efficiency and low emissions were realized across a wide range of loads.**
- **Computational simulations suggested that piston shape was important**
  - Improved squish geometry has potential to reduce sources of HC
  - Improved bowl shape has potential to reduce heat transfer losses
- **HD engine experiments with three piston shapes confirmed simulation**
  - Optimal shape for RCCI like strategies has wide bowl with reduced squish
  - Reduced compression ratio found to offer wide intake temperature range
- **Best tested bowl shape found to improve crevice outgas oxidation rate**
  - Major HC source from non-participating fuel located in crevice (η loss)
  - Small squish improved oxidation of crevice fuel outgassing (η increase)
    - With identical crevice, low Cr predicted to match high Cr performance
- **Thermal losses with RCCI found to be reduced vs. CDC**
  - Increased potential for increased expansion work (keep more energy in)
  - Reduced thermal => further ring pack optimization (reduce HC further)
- **Correlated brake efficiency high for both tested piston shapes**
  - low Cr matched brake η, or slight improvement, more optimization possible
  - Compared to CDC RCCI offered ~5-15% + in BTE + NOx PM met in-cylinder
  - RCCI operates HP system at low pressure potential for further η+

Thank You for your attention

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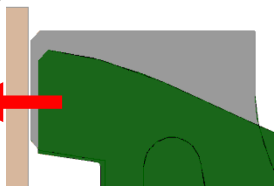
Estimated Improvements

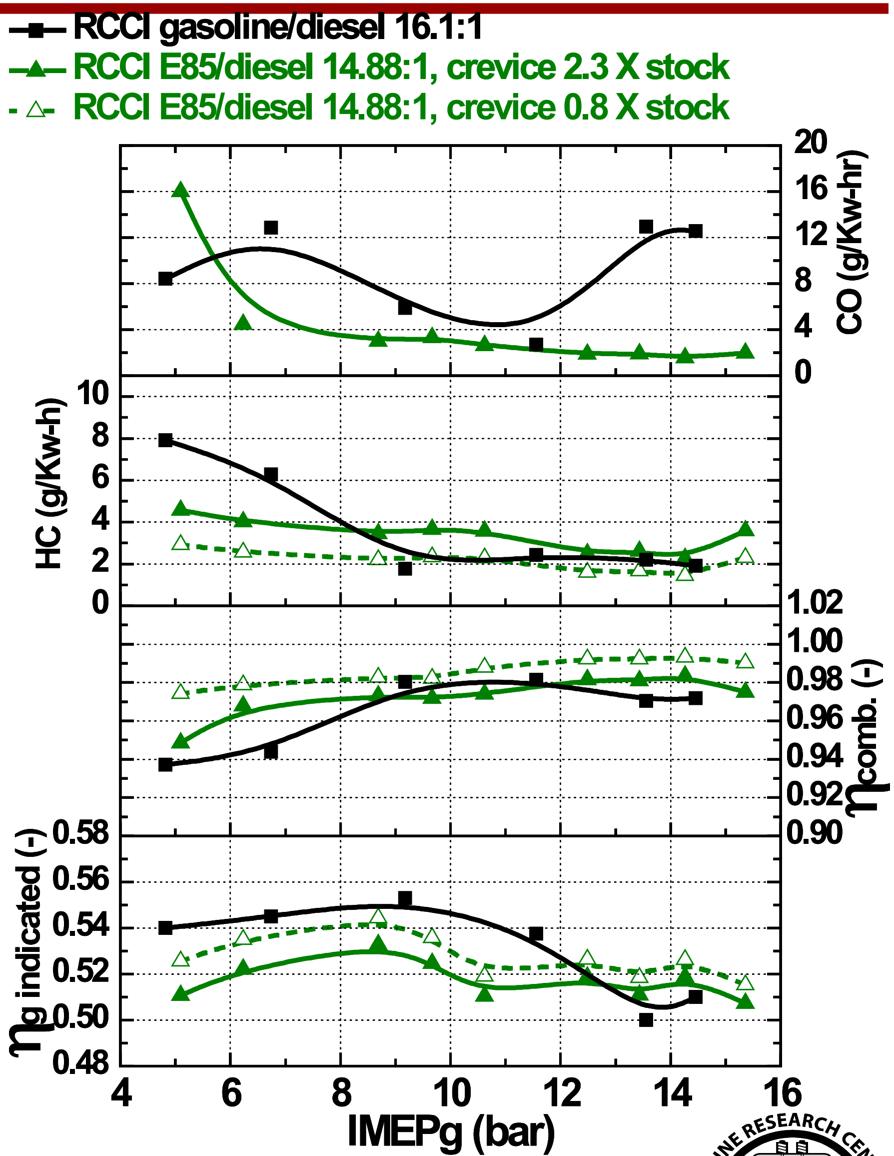
- **Crevice effects on η**
- **Stock piston**
  - Optimized for diesel CDC
    - Small crevice, long squish, tight squish clearance
- **Modified 2.3x crevice**
  - ~2pt loss in efficiency < 12bar
    - HC ~ same as stock
- **Use stock clearances**

Crevice reduced to +.5mm 0.8X stock!



- Assume same HC conv. eff.

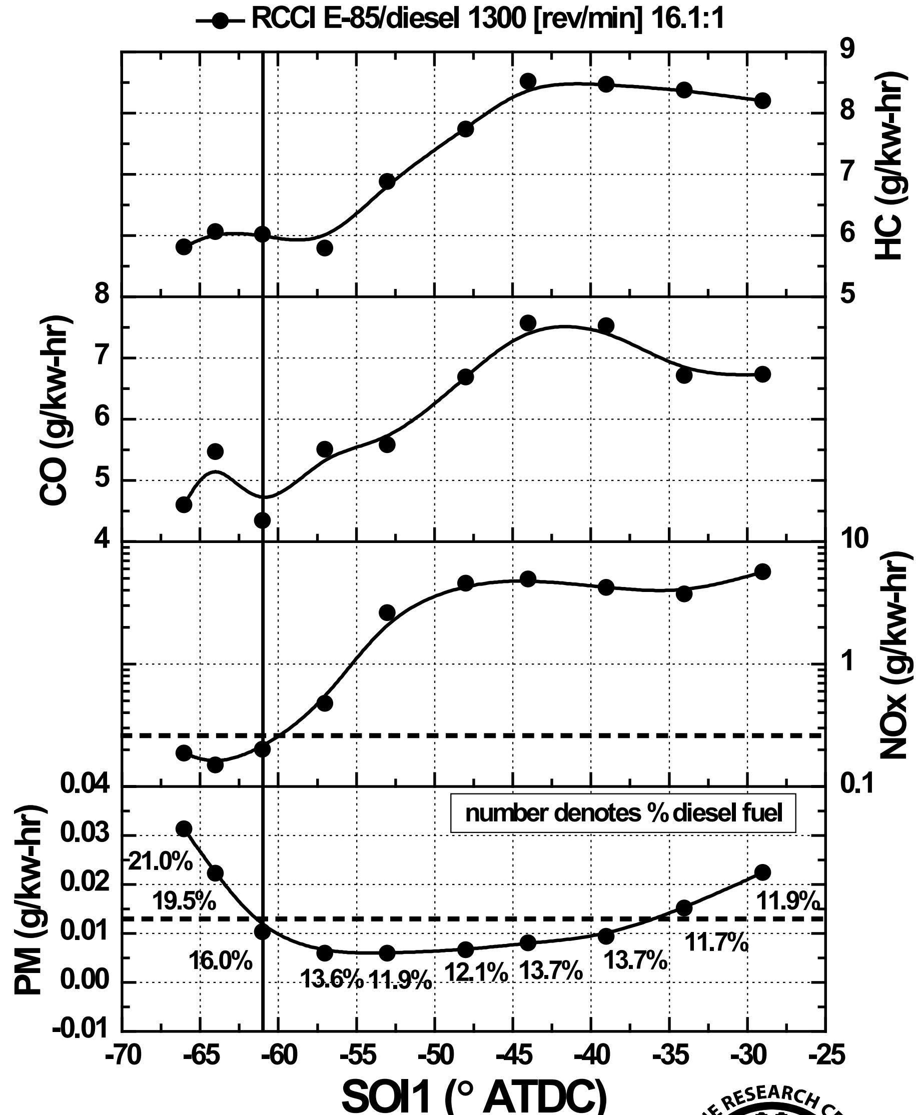
~60% reduction in HC
Converting HC at ~50%
~1 pt. increase in GTE



Charge Preparation is Critical

- **Double Injection**
- **60% of DI fuel in first pulse**
- **Constant 24°CA between pulses**
- **Constant load of 8 bar IMEPg**
- **Constant CA50 of -5°CA ATDC +- 1°CA**
- **Phased through intake temperature (boost adjusted)**

- **Small window for low emissions and maximum efficiency**
  - Low HC and CO required for high efficiency
  - Low NOx and PM required for emissions mandates (met in-cylinder)



Double Injection Sweep AHRR, Cyl. Press

- **Double Injection**
- **60% of DI fuel in first pulse**
- **Constant 24°CA between pulses**
- **Constant load of 8 bar IMEPg**
- **Constant CA50 of -5°CA ATDC +-1°CA**
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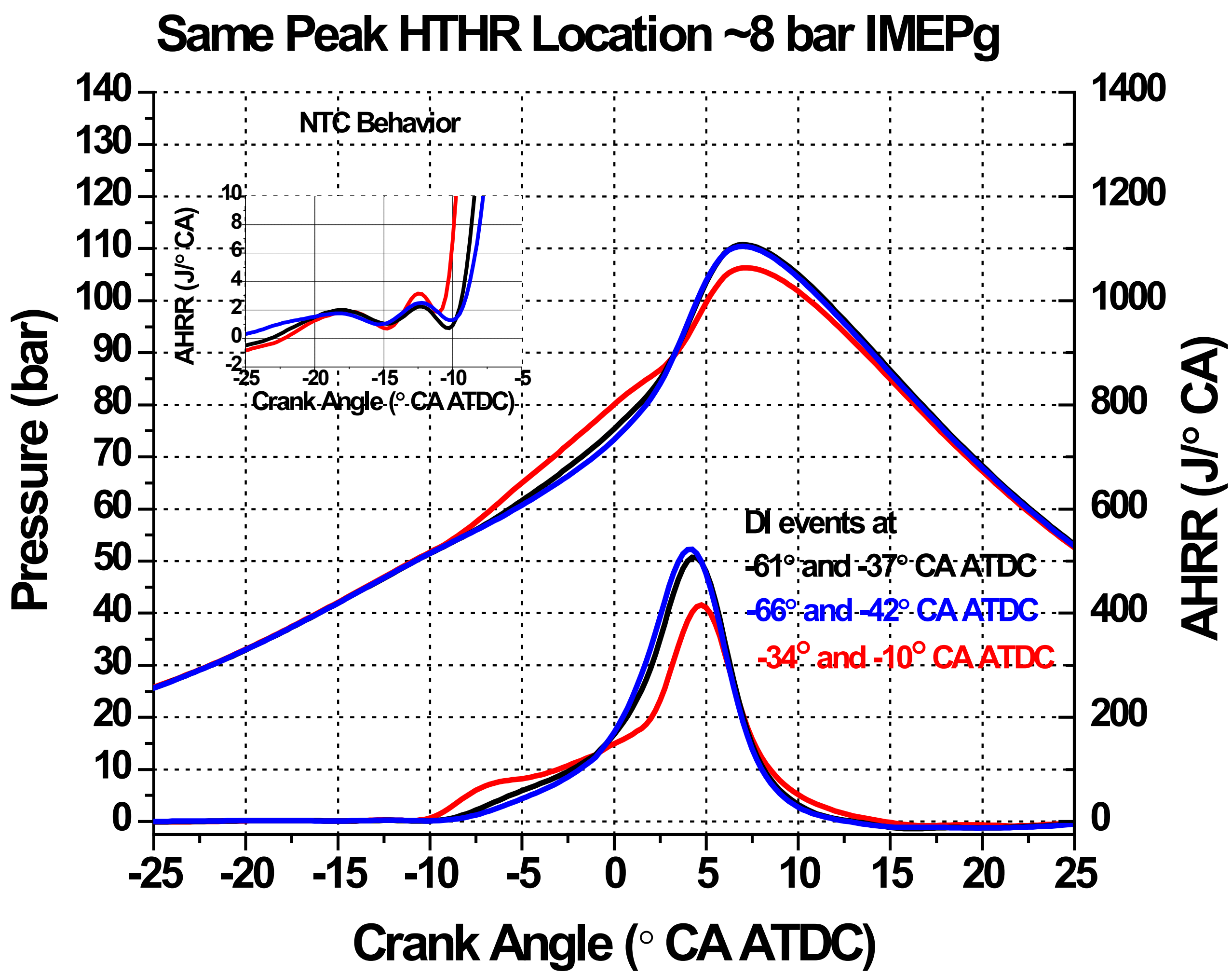
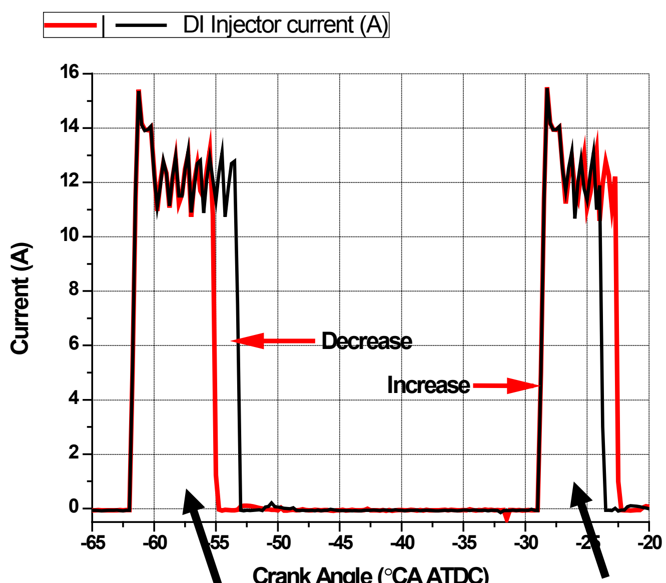


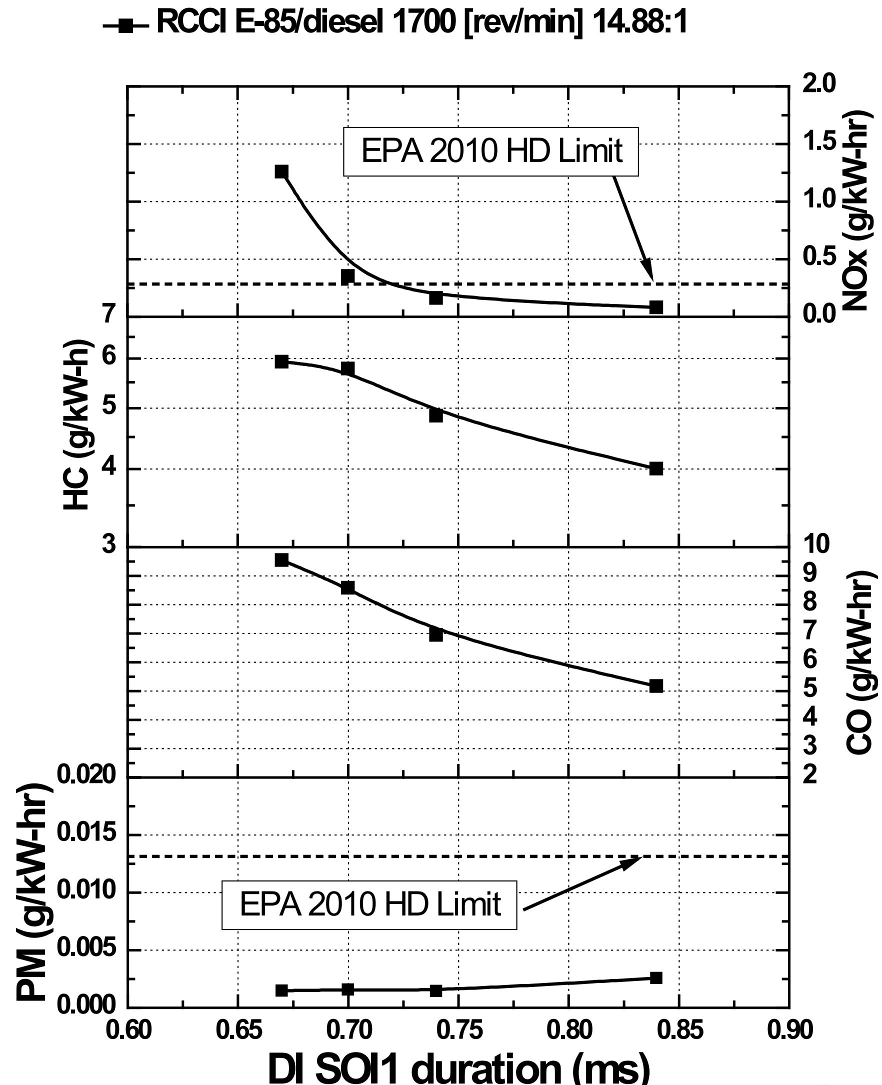
Redesigned piston injection effects

Bathtub piston bowl shape effects emissions trends

- Engine operated at 1700 [rev/min], 6 bar net nominal load, E85-diesel fueling
- Reactive fuel near liner reduces HC, CO, NOx, increases Soot
- Reactive fuel near center increases NOX, CO, and HC, reduces Soot



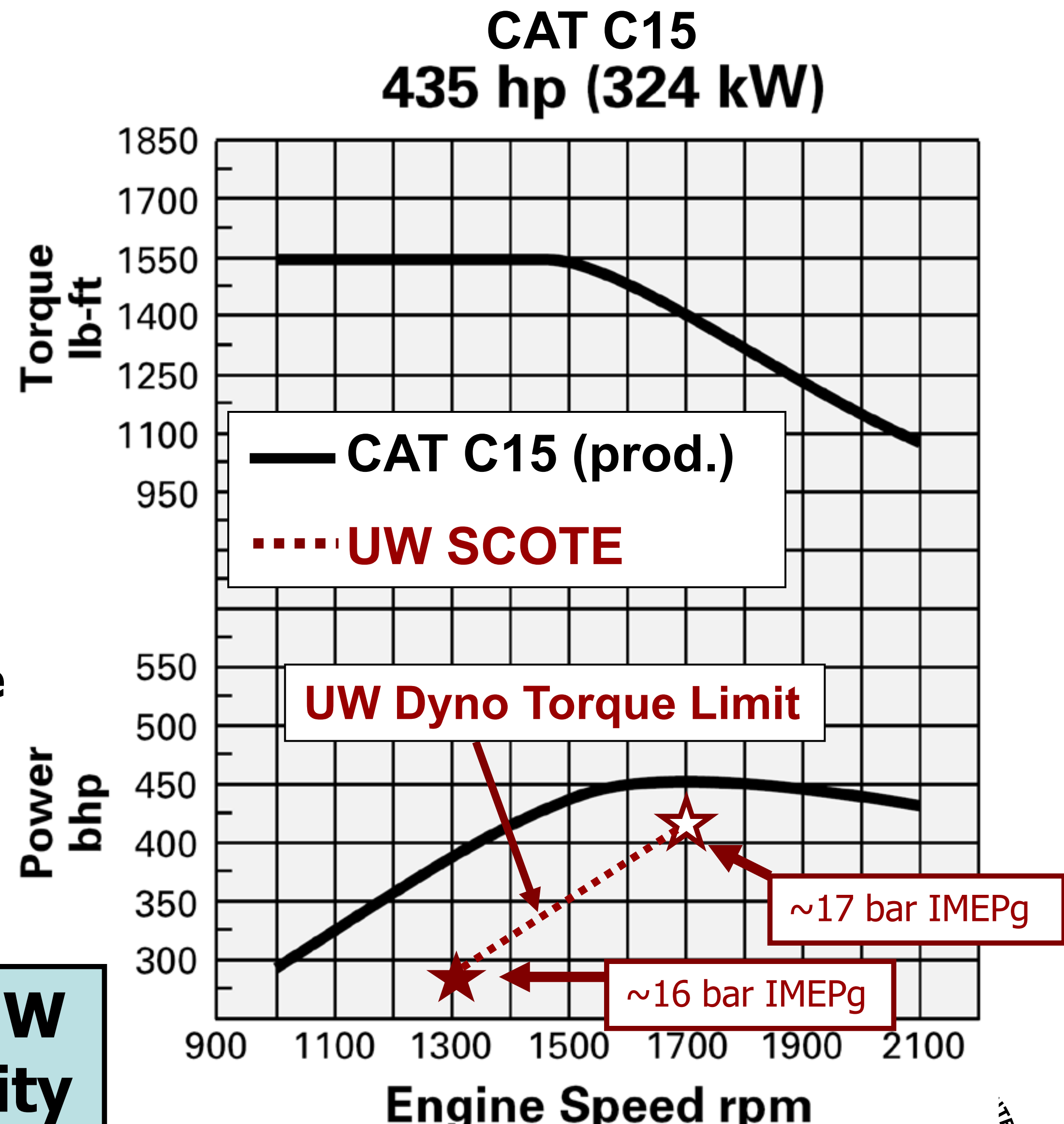
+Soot **+NOx +HC+CO**



RCCI E85/Diesel High Load

- **SCOTE ~ CAT C15 in geometry and displacement (per cylinder)**
- **C15 435 hp rating (450 hp developed)**
- **RCCI operated in SCOTE at two speeds**
  - **1700 RPM ~ rated power**
  - **1300 RPM ~ rated torque**
- **UW experiments limited in load by dyno capacity**
  - **(100 hp at 2000 RPM)**

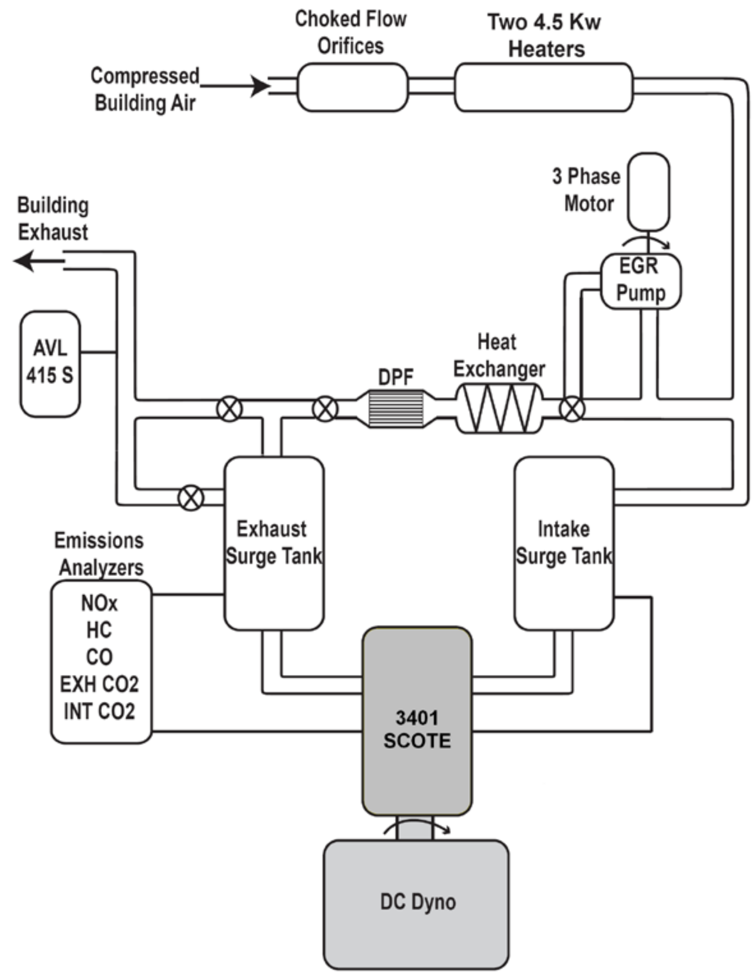
Tested RCCI to UW laboratory capacity



UW SCOTE Engine Laboratory

3401E SCOTE Geometry

Displacement (l)	**2.44**
Bore (mm)	137.20
Stroke (mm)	165.10
Connecting Rod Length (mm)	261.60
Squish Height (mm)	1.57
IVC (deg BTDC)	143.00
IVO (deg ATDC)	335.00
Swirl Ratio (stock)	0.7
Piston shape	Open crater (Stock) Bathtub (Modified)
Geometric Compression Ratio	**16.1:1 Stock Modified to 14.88:1**

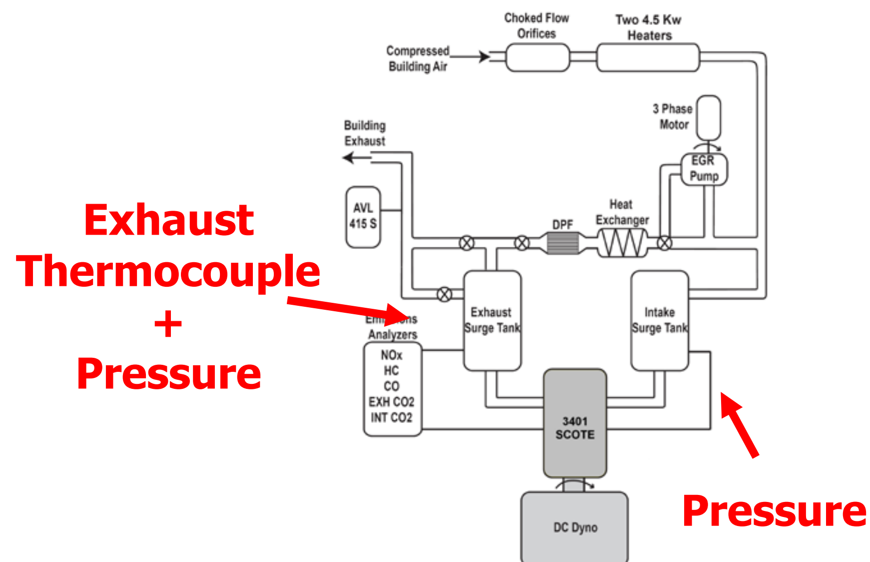


Load Sweep conditions

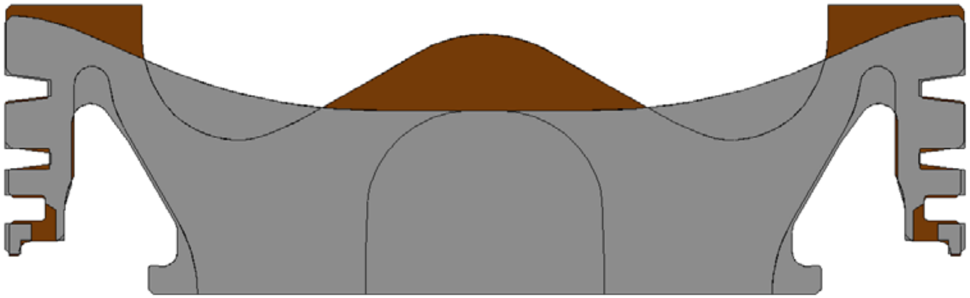
- **Overall Turbo charger efficiency calculated**
  - Used to determine boost

$$\frac{P_{intake}}{P_{ambient}} = \left[1 - \frac{cp_{exhaust} * T_{exhaust}}{cp_{ambient} * T_{ambient}} * \left(1 + \frac{1}{AFR}\right) * \eta_{overall} * \left(1 - \left(\frac{P_{exhasut\ pipe}}{P_{exhaust\ manifold}}\right)^{\left(\frac{\gamma_{exhaust}-1}{\gamma_{exhaust}}\right)}\right)\right]^{\left(\frac{\gamma_{amb}-1}{\gamma_{amb}}\right)}$$

- **Intake temperature**
  - Between 32°C and 70°C
- **EGR Temperature**
  - 60-120°C
- **Peak pressure rise rate of 10 bar/°**
- **Peak pressure limit of 150 bar**
- **Peak motor pressure @ -0.4 °ATDC**



Redesigned Piston



Why Change piston shape?

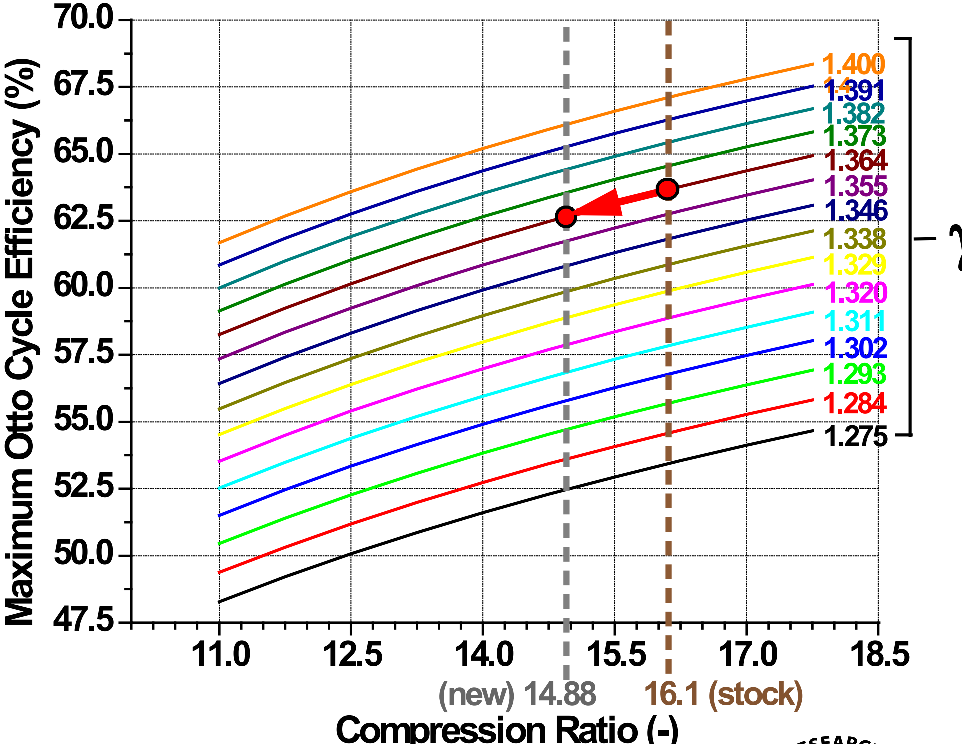
- **Improve piston shape for premixed fuel, and reduce heat transfer**
  - Reduced piston surface area 4.15%

Why Change Cr?

- **Enable increased intake and EGR temperatures**
  - Intake temperature increased ~40°C to ~70°C, EGR increased to 120°C

Penalty of Reduced Compression Ratio

- **Theoretical thermal efficiency reduced**
  - **Design Result**
    - 2.17% reduction in theoretical maximum thermal efficiency



Efficiency + Friction

- **Chen-Flynn Model for determination of FMEP**

$$FMEP = C_1 + (C_2 * P_{max}) + (C_3 * \overline{S_p}) + (C_4 * \overline{S_p}^2)$$

$$P_{max} = \text{Peak Cylinder Pressure}$$

$$\overline{S_p} = \text{Mean Piston Speed}$$

  - Used same constants as GT Power
  - Error bars in figure denote range of constants (C1-C4)
- **For a given compression ratio and engine speed**
  - RCCI operation yielded ~ 14% better ~brake eff. vs. CDC