Development of Low-Exergy-Loss, High-Efficiency Chemical Engines

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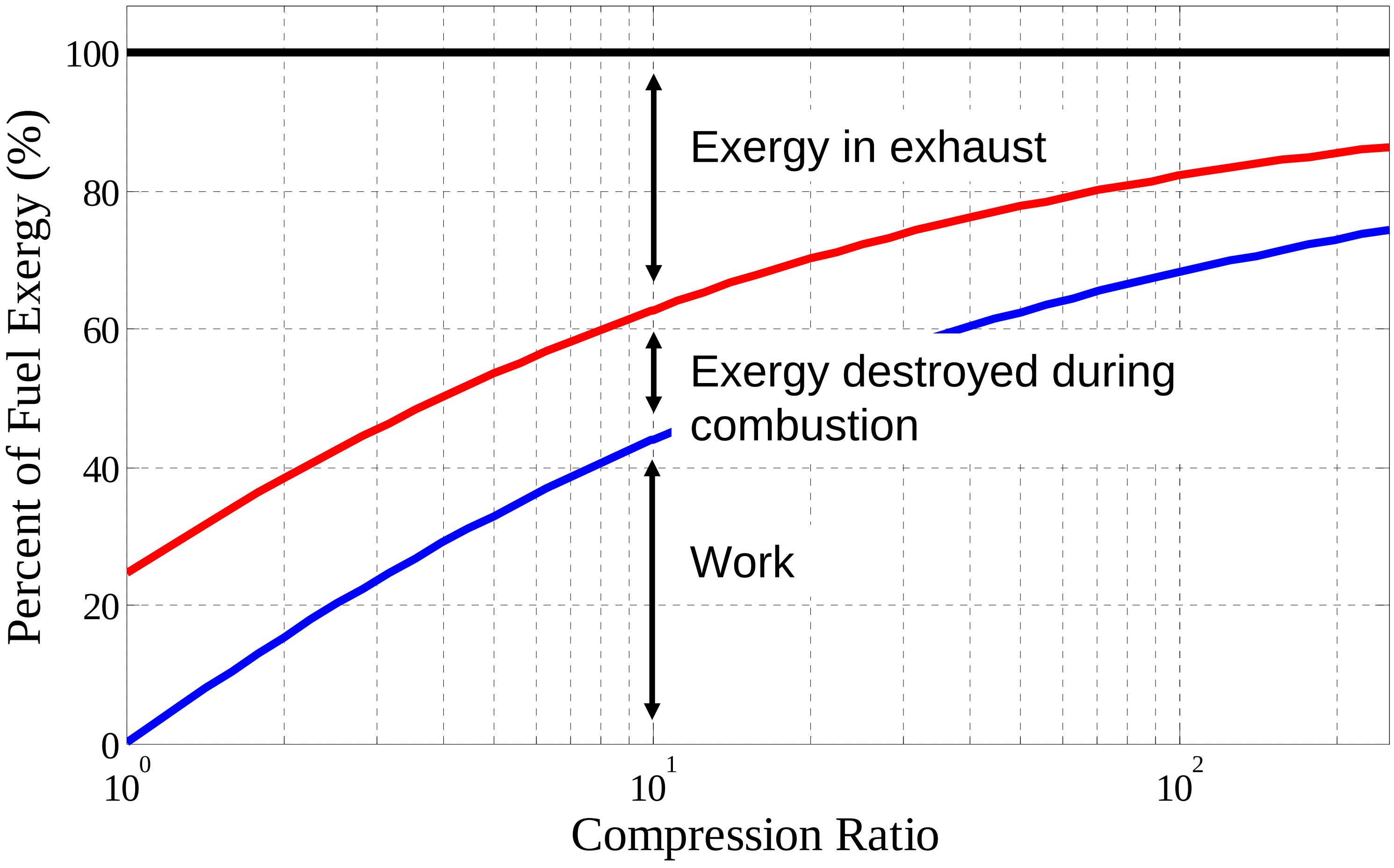
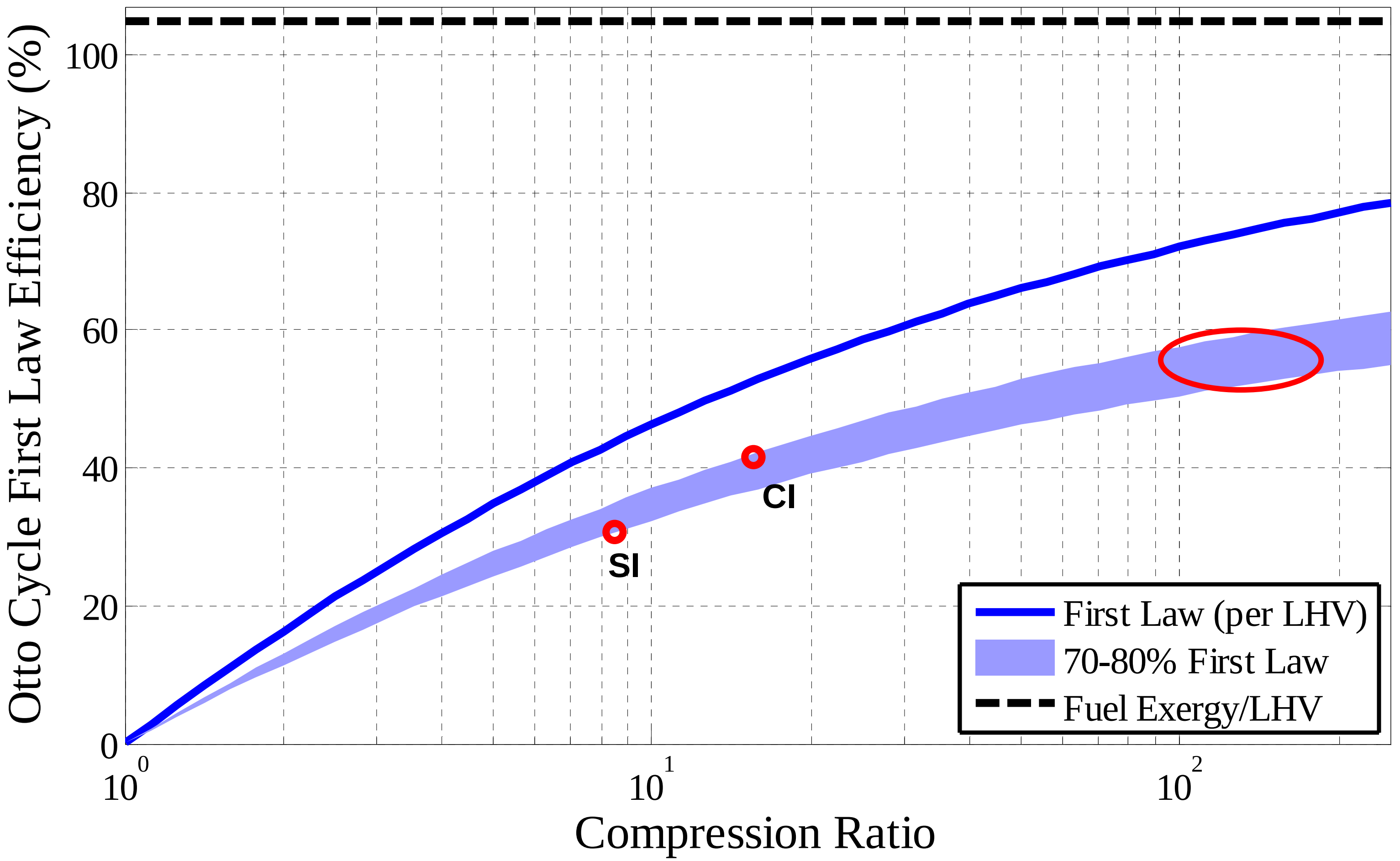
Fuel Exergy Distribution for Reactive Otto Cycle



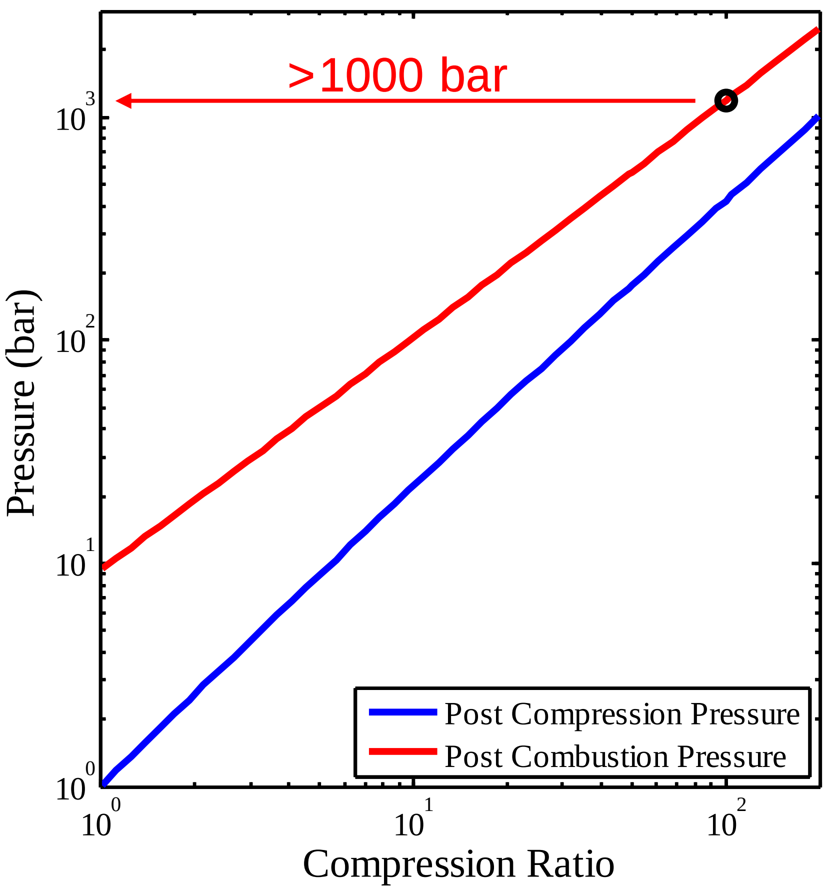
Stoichiometric propane/air modeled as ideal gases.

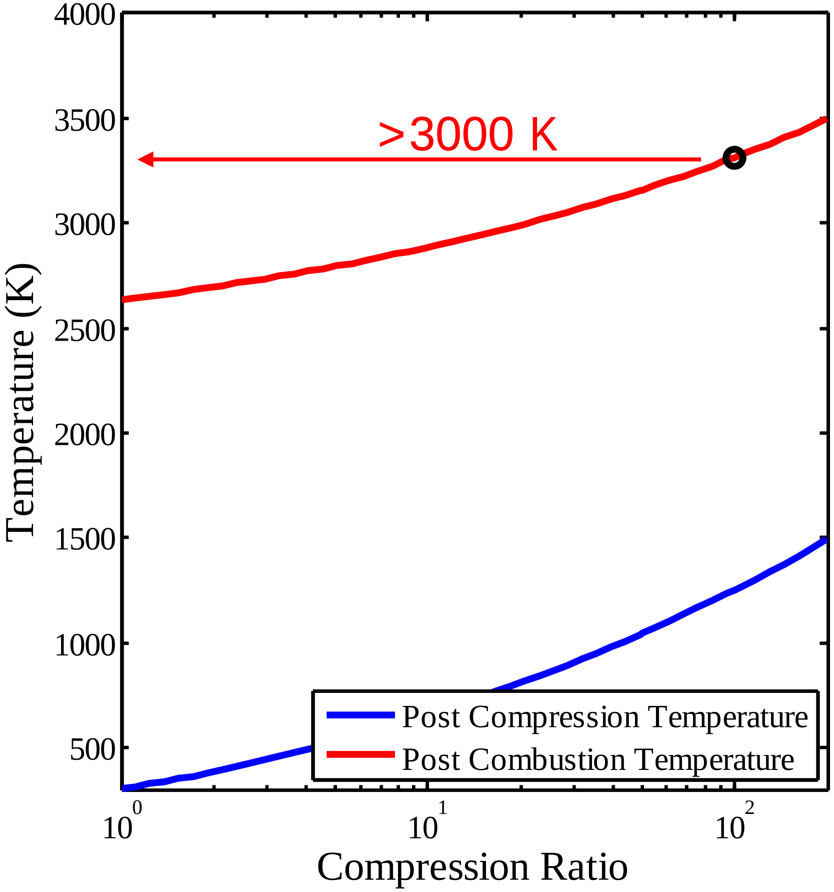
What fraction of theoretical efficiency might be achieved?



Stoichiometric propane/air modeled as ideal gases.

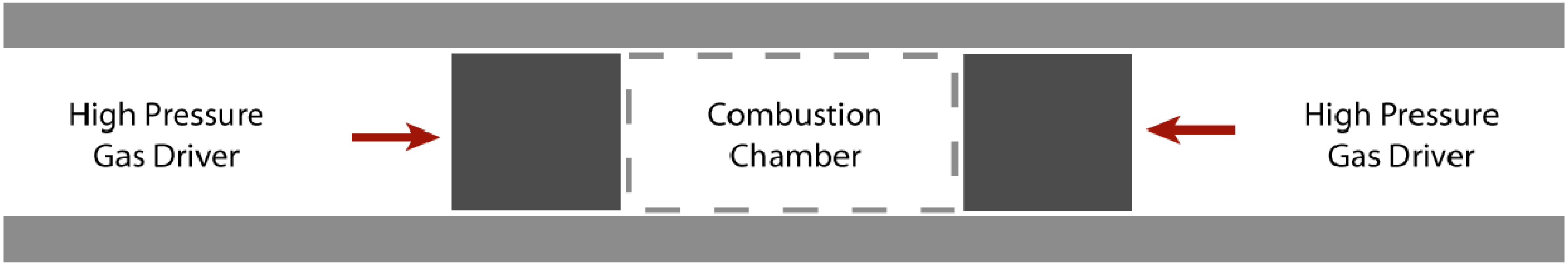
Extreme Compression Conditions





Stoichiometric propane/air mixture modeled as ideal gases.
Adiabatic, isentropic compression followed by adiabatic constant volume combustion

Achieving Extreme Compression



Basic Requirements:

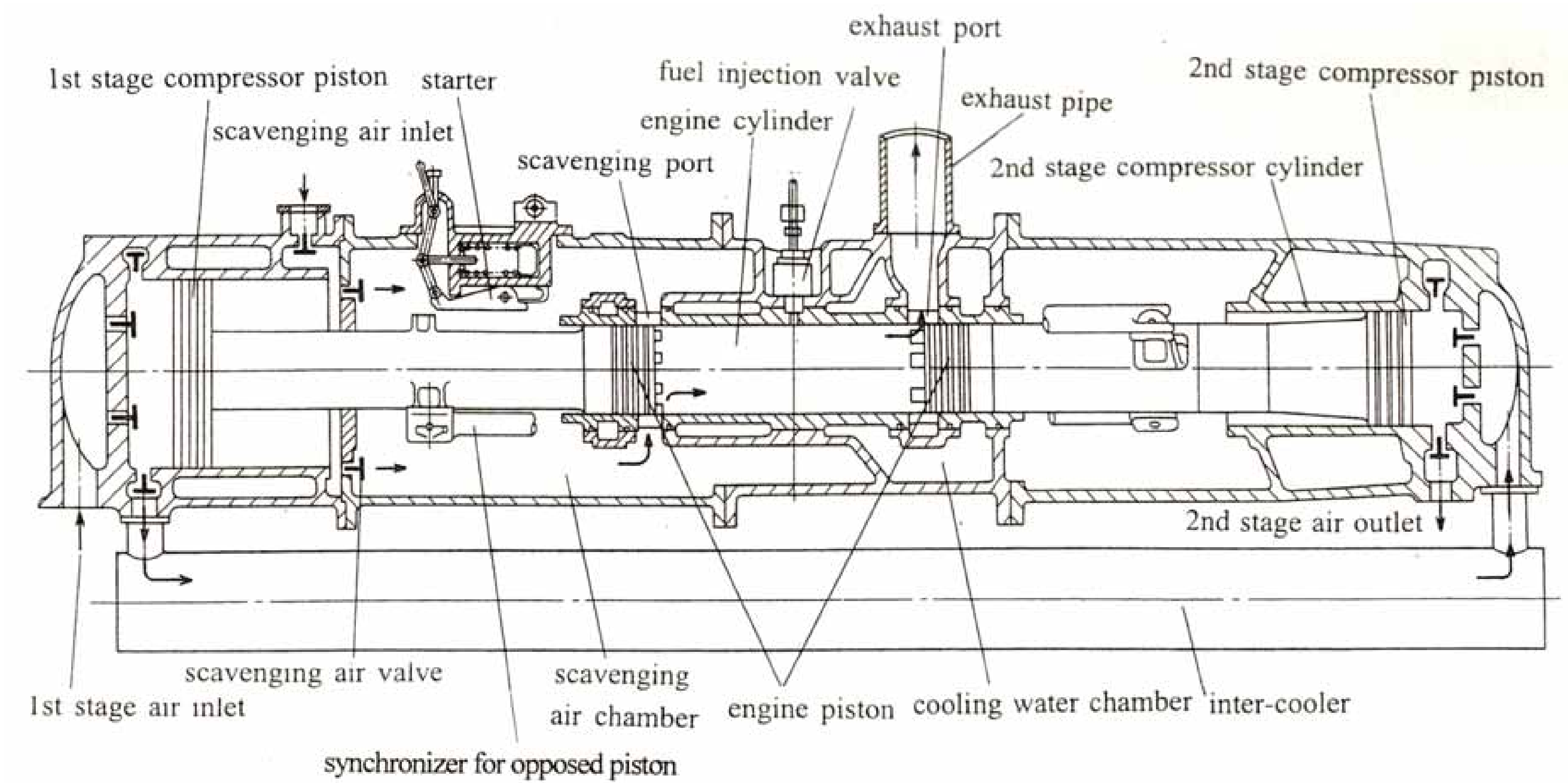
- High compression ratio (100:1 and higher)

- Approach for reducing heat transfer
  - Large TDC volume to reduce heat transfer
  - High piston speeds to reduce time available for heat transfer

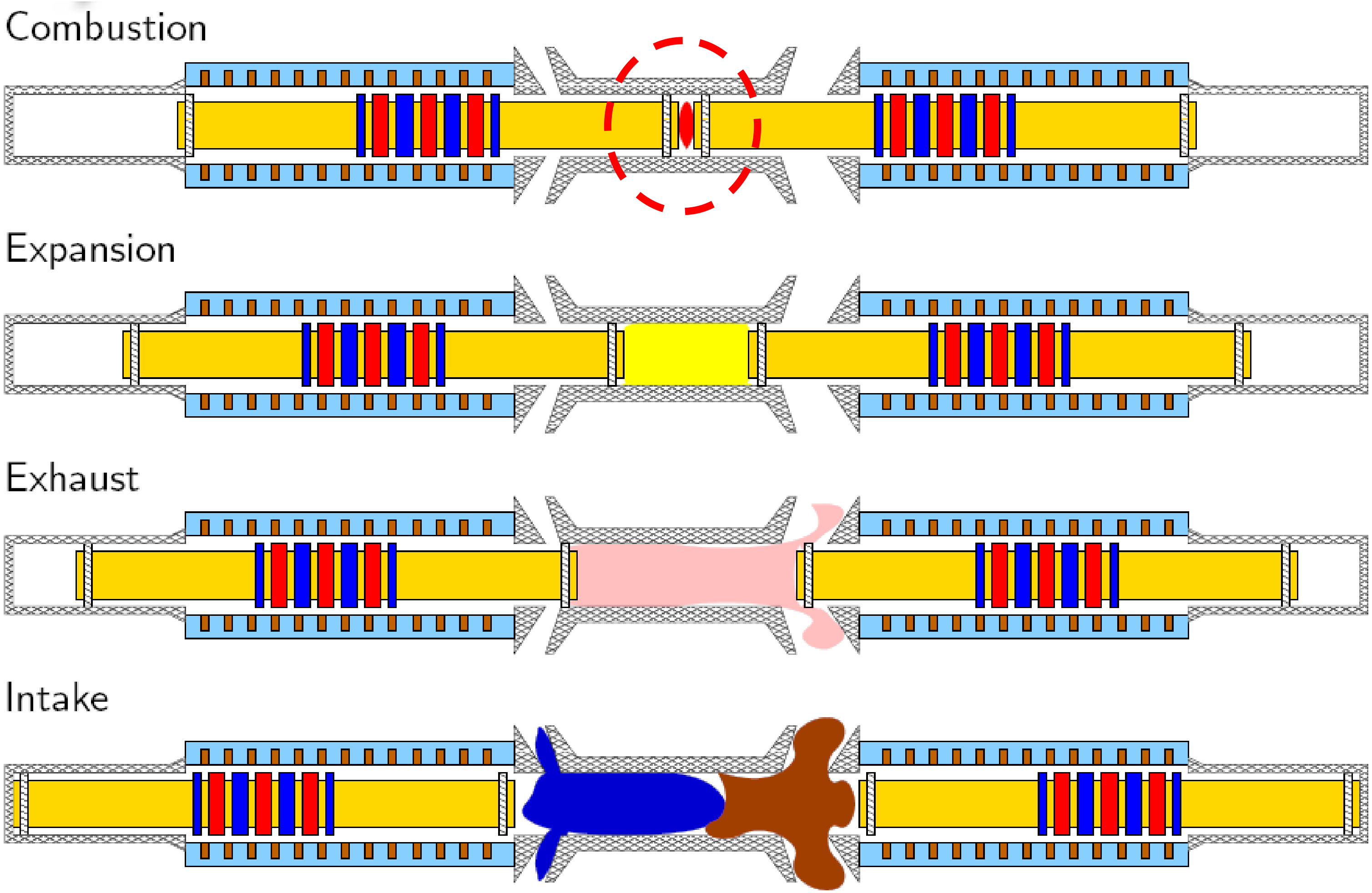
- Approach for high forces
  - Free pistons
  - Multiple pistons

Design apparatus for testing the Critical Questions

Junkers Free-Piston Compressor



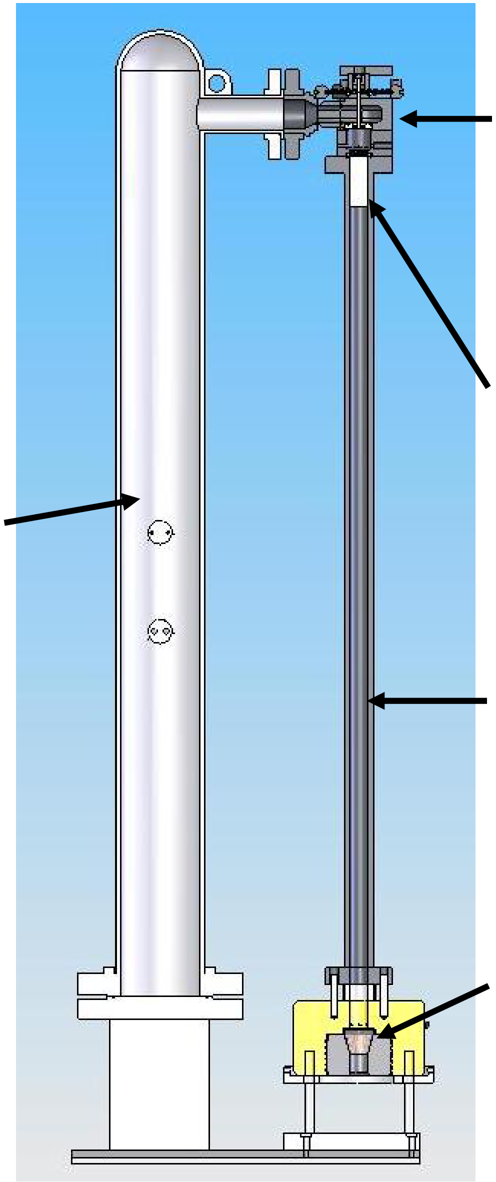
Van Blarigan/Aichlmayr Linear Alternator Concept



Critical Questions

1) Can an engine handle the high temperatures and pressures required for extreme-state combustion?
    1) Material stress
    2) Wall temperatures and heat transfer
    3) NOx
2) Can the rings withstand the pressure and piston speed?
    1) Seal survivability
    2) Sealing ability: Can we achieve <1% blowby?
3) Can we implement and control combustion?
    1) Ignition phasing
    2) Combustion control
    3) Rate and efficiency

Experimental Design



A fast-acting poppet valve for initiating compression

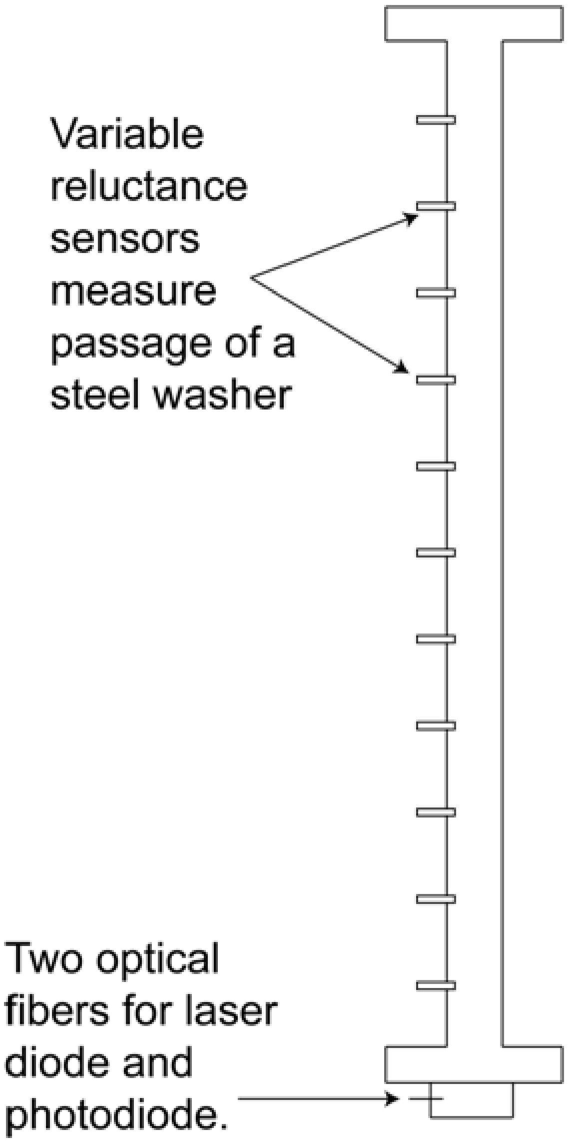
A single, free-piston design with the forces distributed over a large area

A large, high-pressure reservoir, capable of pressures up to ~70 bar

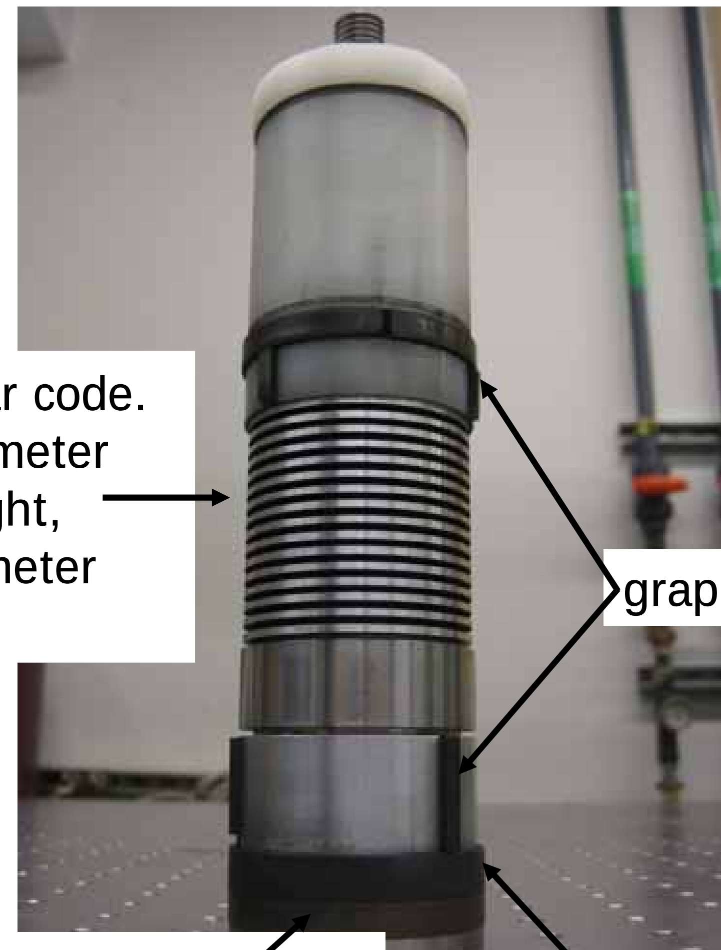
~2.5m cylinder for a low surface to volume ratio at TDC (~ 1:1 aspect ratio at CR = 50)

Optical access through a sapphire window in a high-strength, forged, steel combustor

Piston Position Sensing



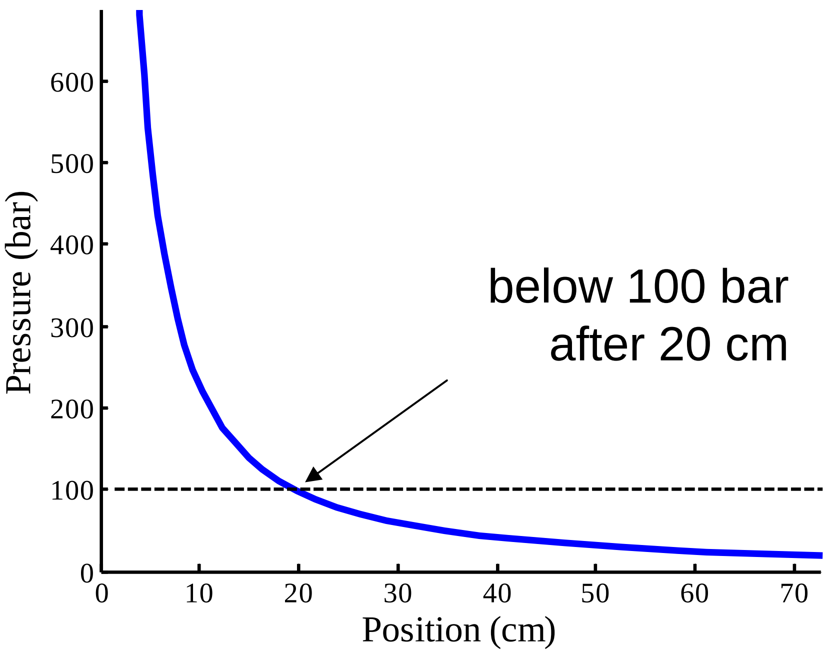
Current Piston Design

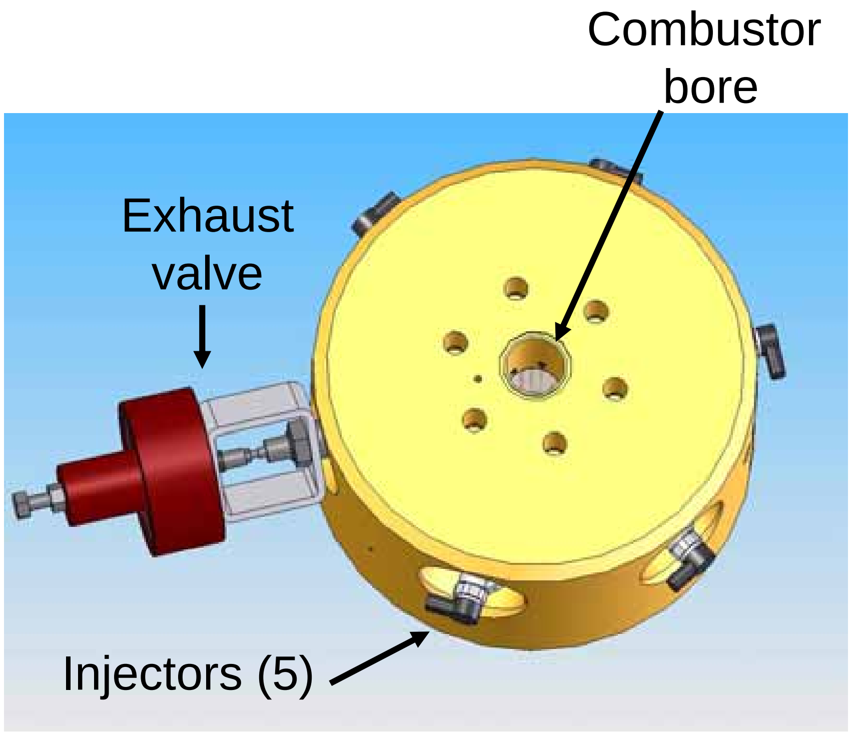


Combustor Design

Material stress strategy: Use pressure profile to our advantage

Injection strategy: Five Bosch high-pressure diesel injectors

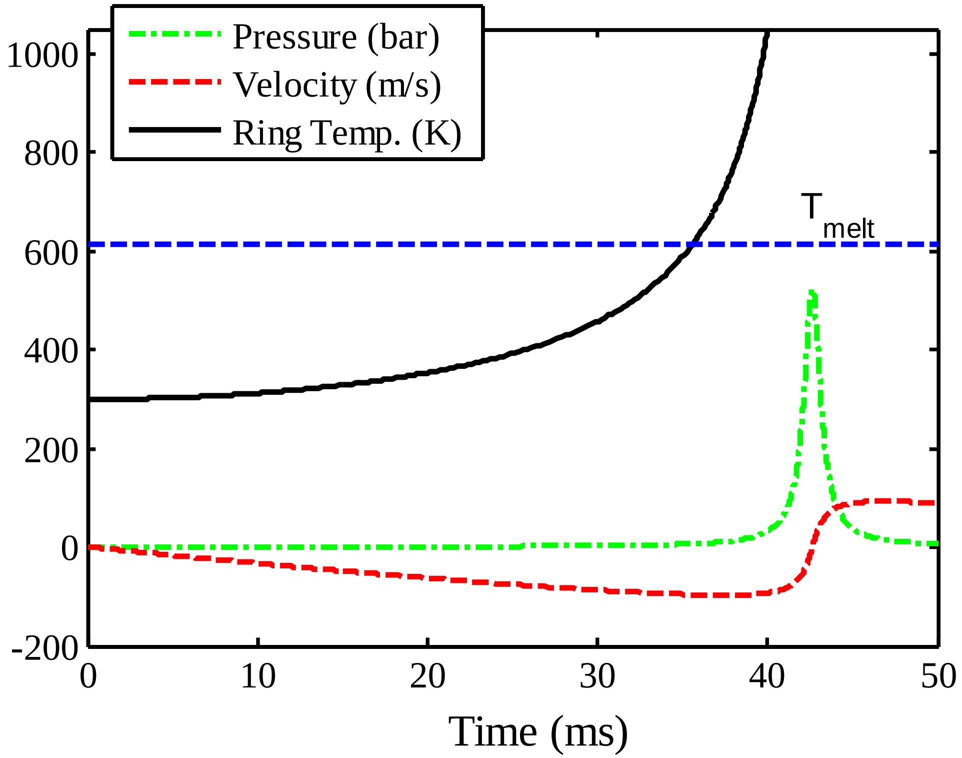


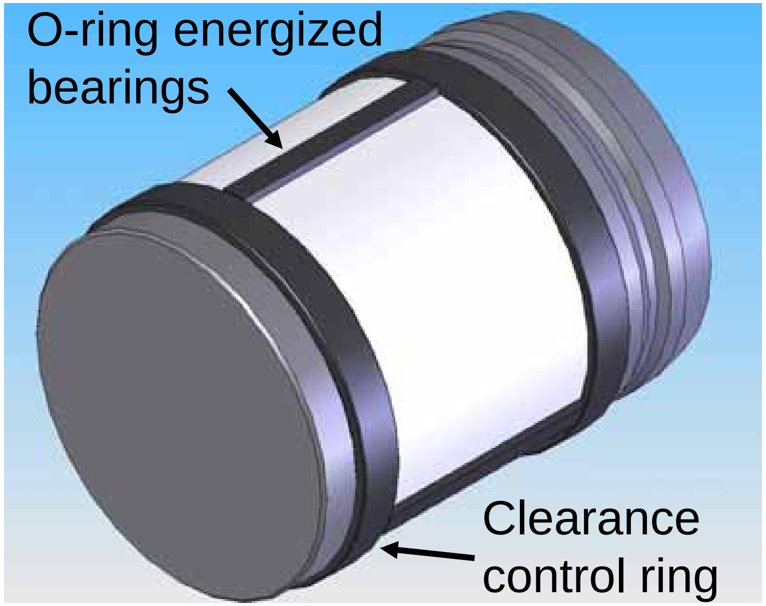


Combustor with 2000 bar working pressure

Piston Design

Sealing strategy: Use clearance control, rather than conventionally energized rings to reduce ring temperatures



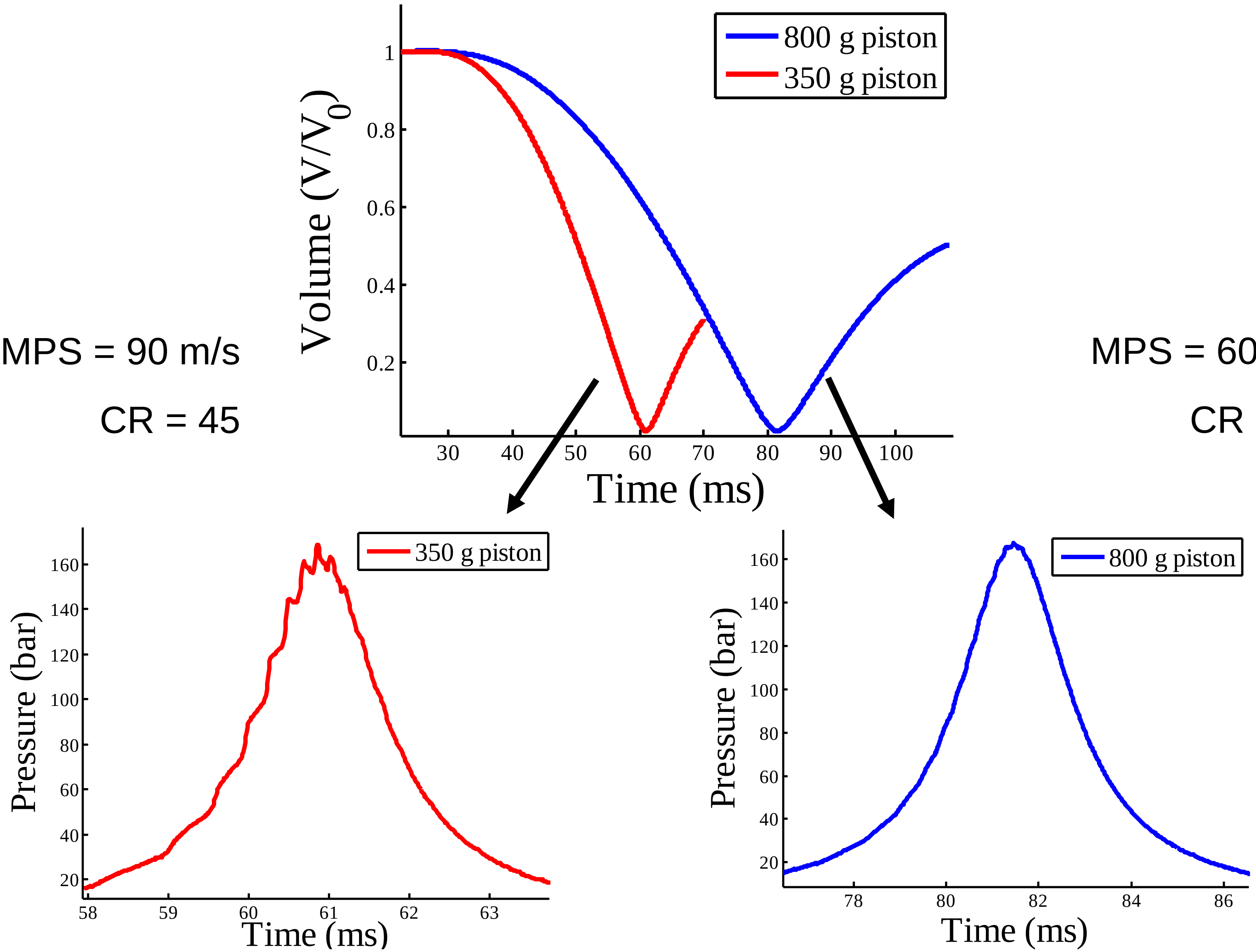


This low friction strategy also gives high experimental repeatability.

Air Compression: Initial Findings

MPS = 90 m/s

CR = 45

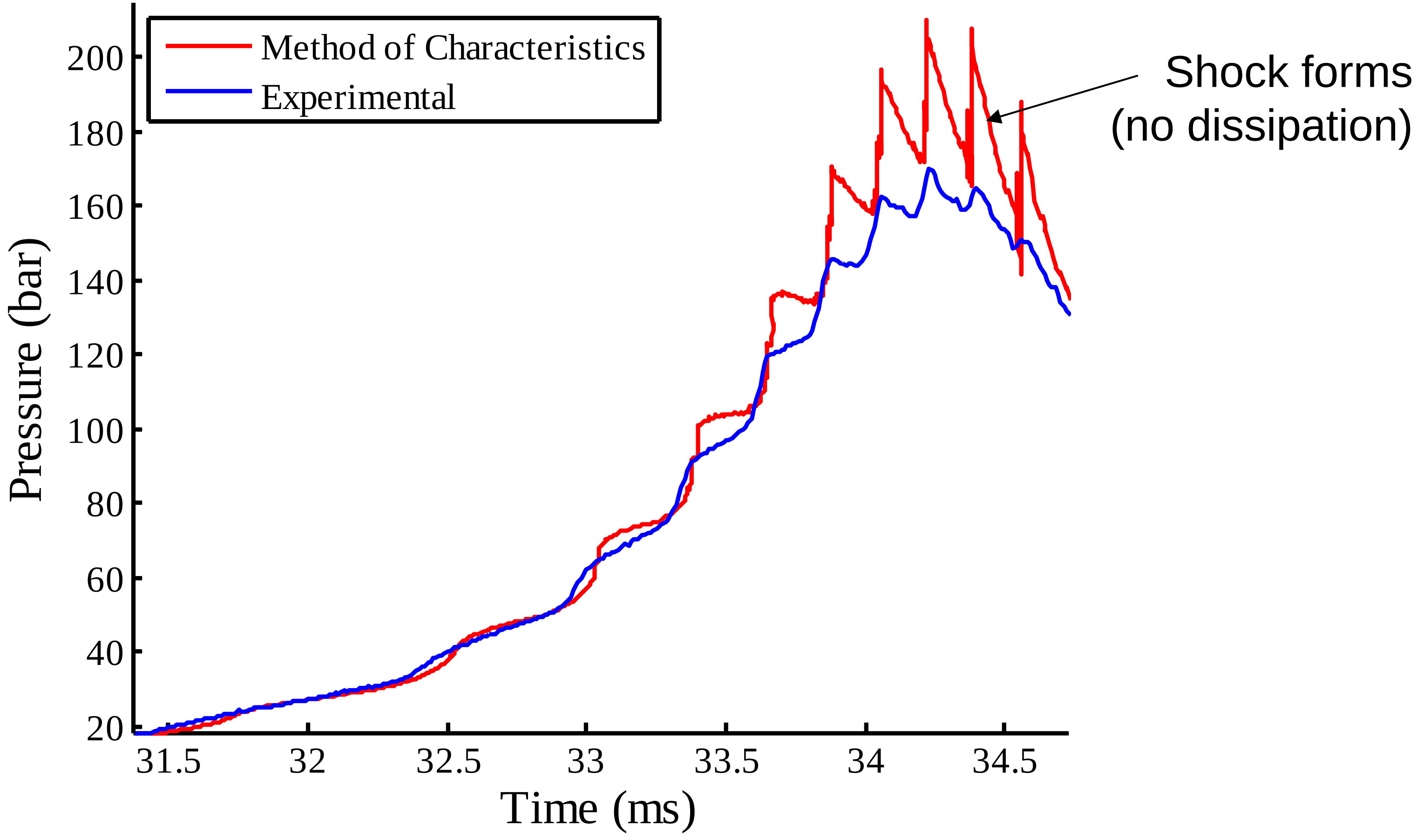


MPS = 60 m/s

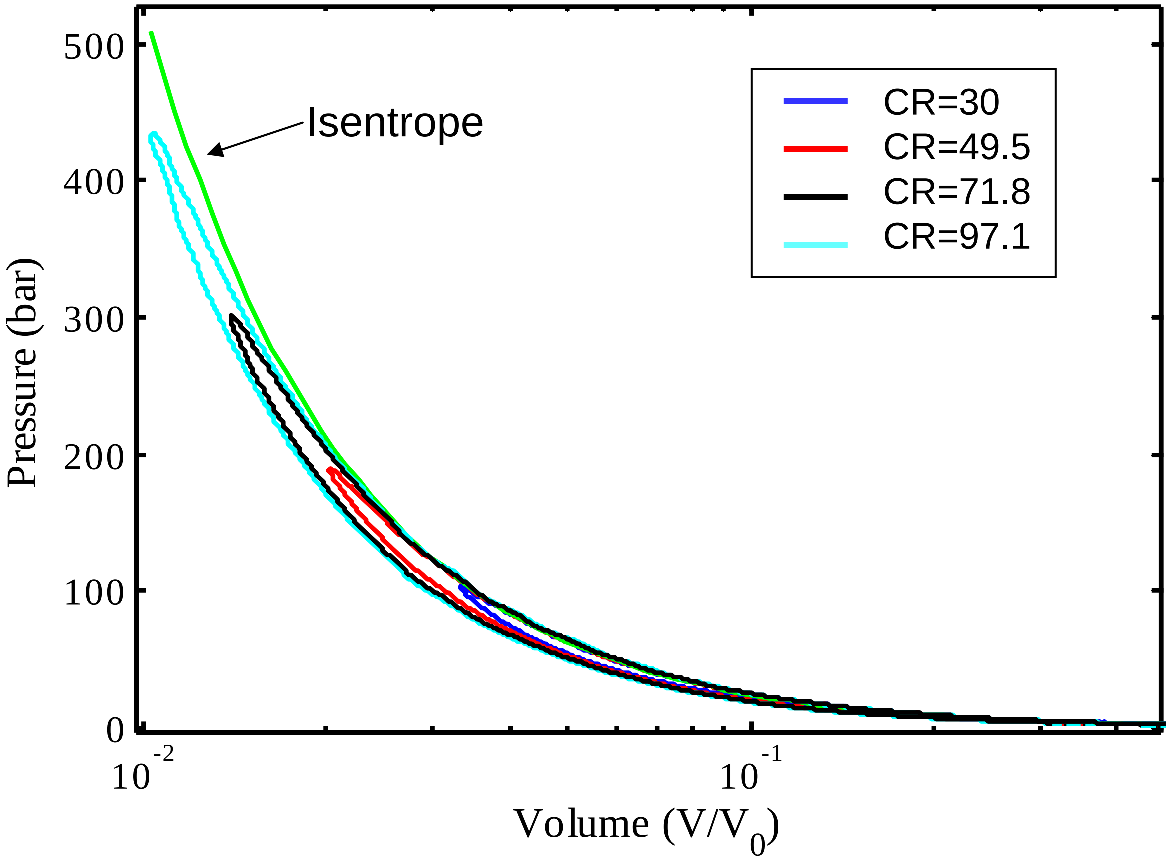
CR = 45

Acoustic Waves

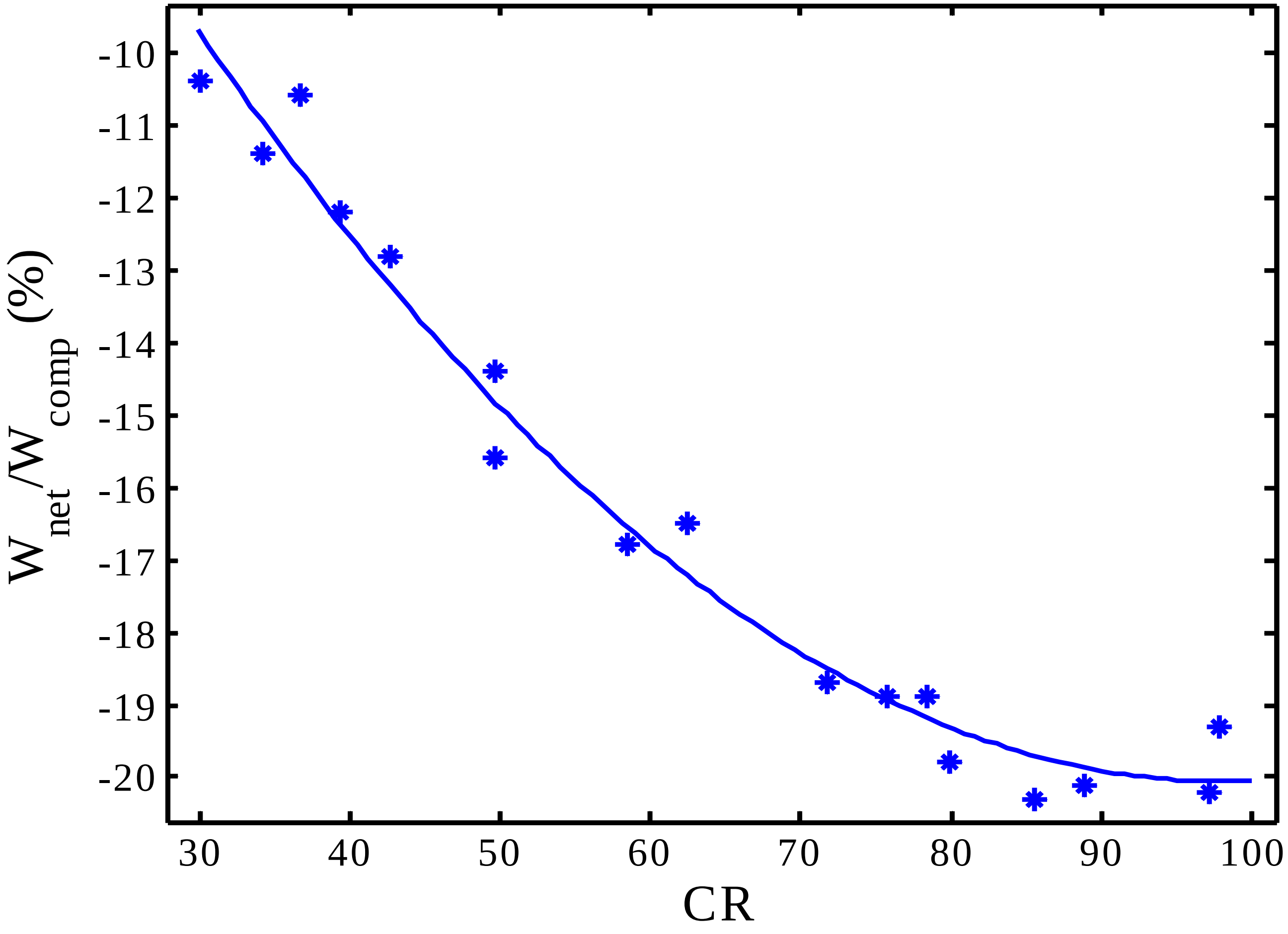
Method of characteristics simulations show that high piston accelerations cause acoustic waves.



P-V Plots: Air Data

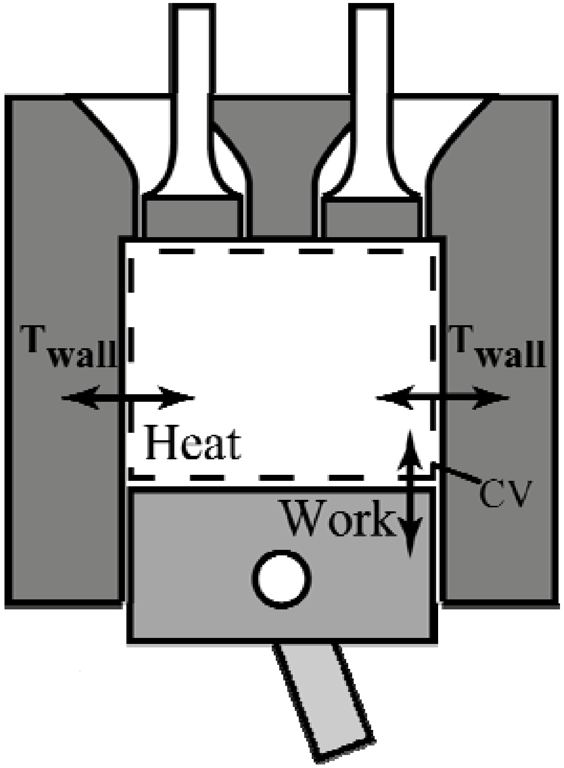


Total Losses Over an Air Cycle



Losses consist of heat and mass transfer.

Heat Loss on Compression



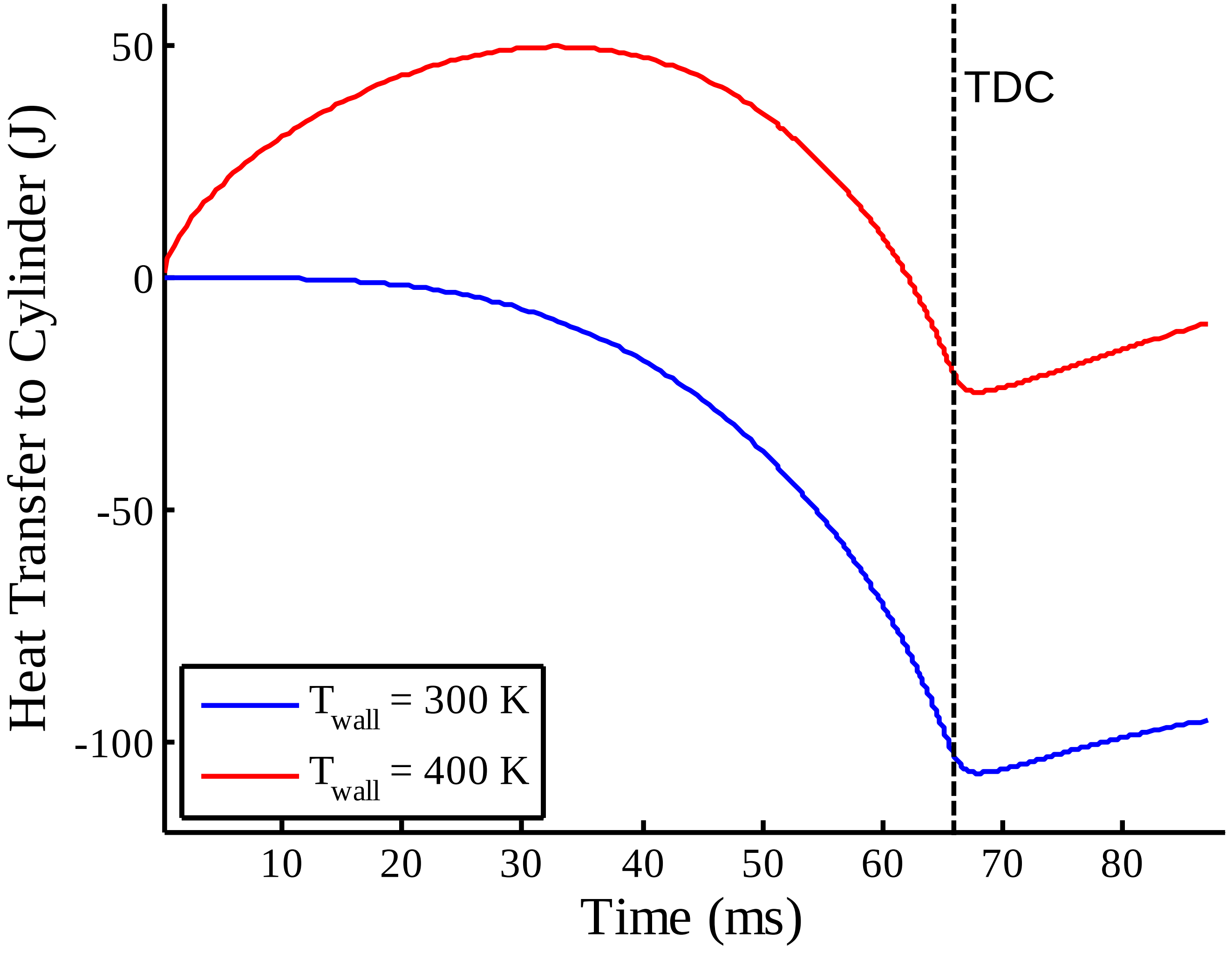
Model Assumptions

- simulates boundary layer formation assuming conduction as only form of heat transfer
- one dimensional
- constant wall temperature
- uniform pressure

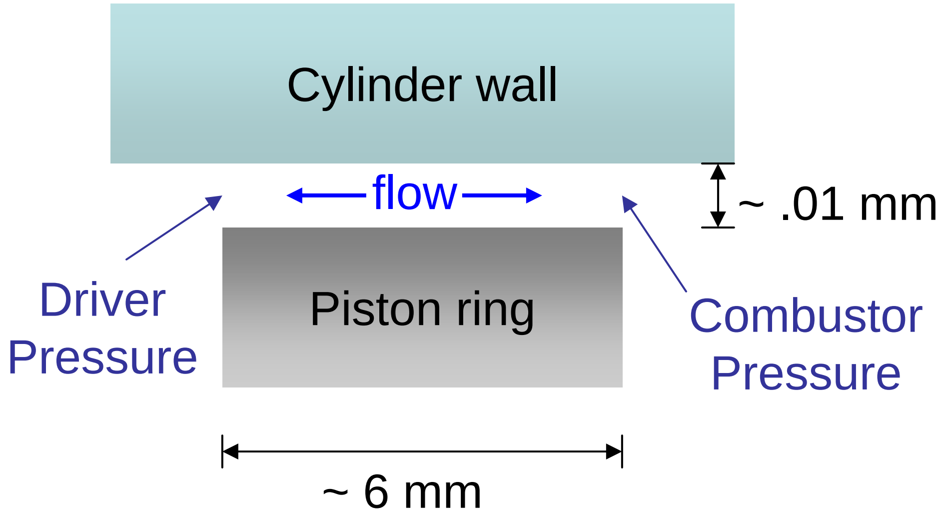
Modeled heat transfer losses for CR = 50 air data:

300 K →	~2% compression work lost to HT
	~3% drop in peak pressure from isentropic
400 K →	~0.2% compression work lost to HT
	negligible pressure drop from isentropic

Heat Transfer to Cylinder



Mass Loss Past Rings



Model Assumptions

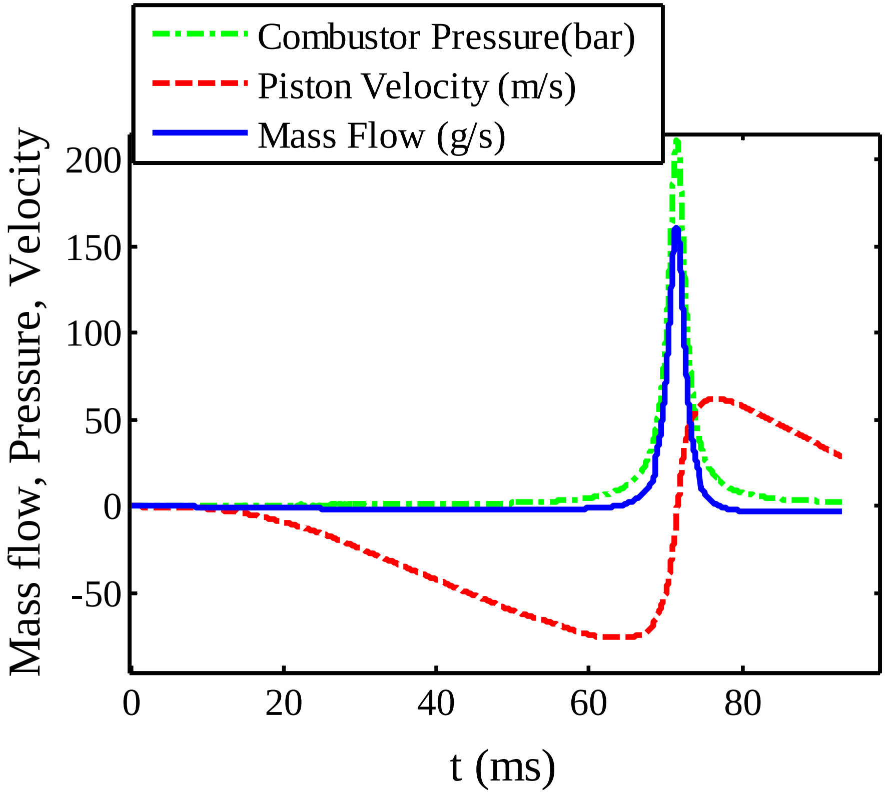
- 1D, isothermal flow through ring-wall gap driven by pressure drop and piston motion
- Viscous effects included via a friction factor
- Pressure and piston motion from experimental runs

Modeled losses for the CR = 50 air data:

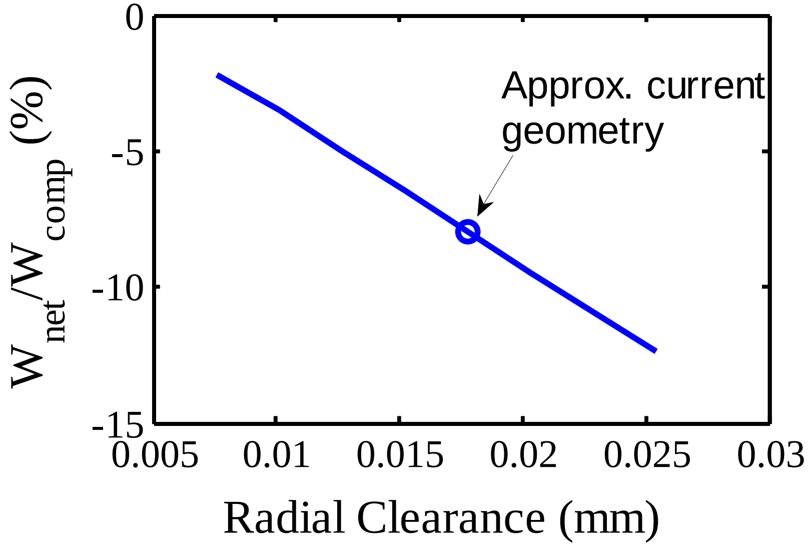
8% of compression work (W_{net} / W_{comp})
4% of peak pressure (P / P_S)

Mass Transfer to Cylinder

Mass flow profile for CR = 50



Effect of clearance gap on work loss for CR = 50

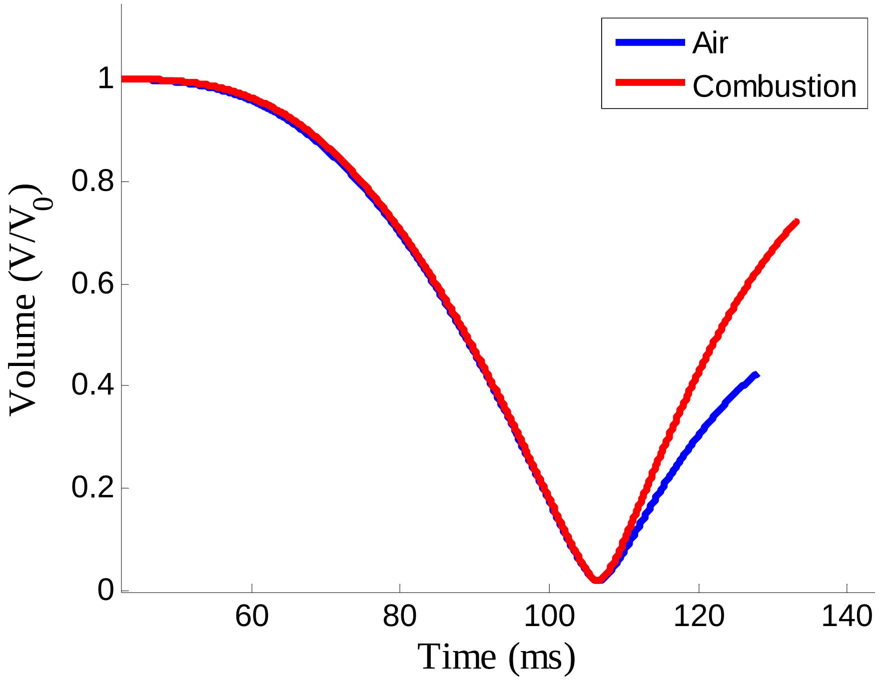


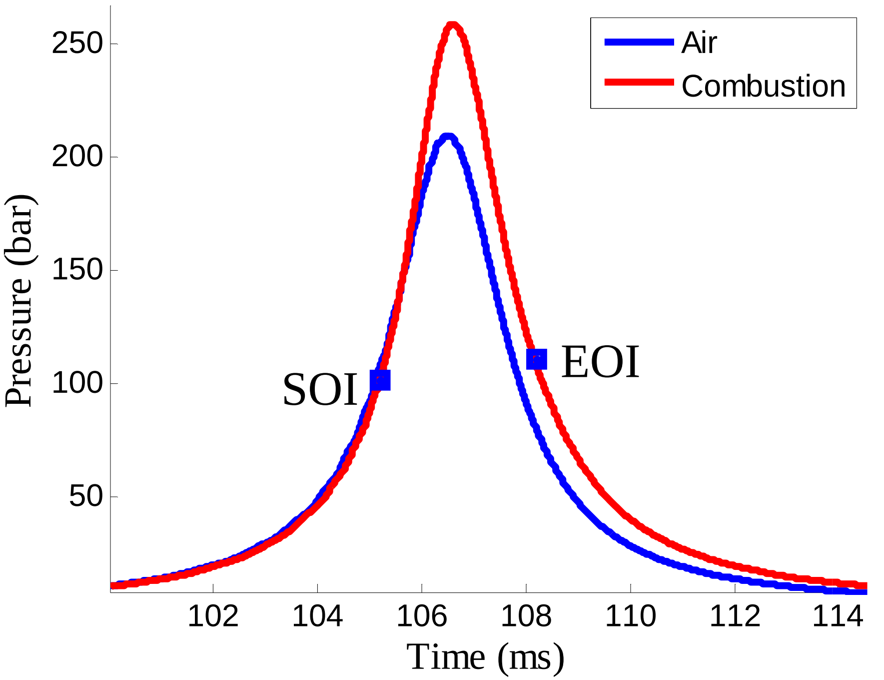
Radial bore tolerances:

combustor ± .0015 mm

cylinder ± .007 mm

Combustion Data: CR = 50





MPS ~ 40 m/s

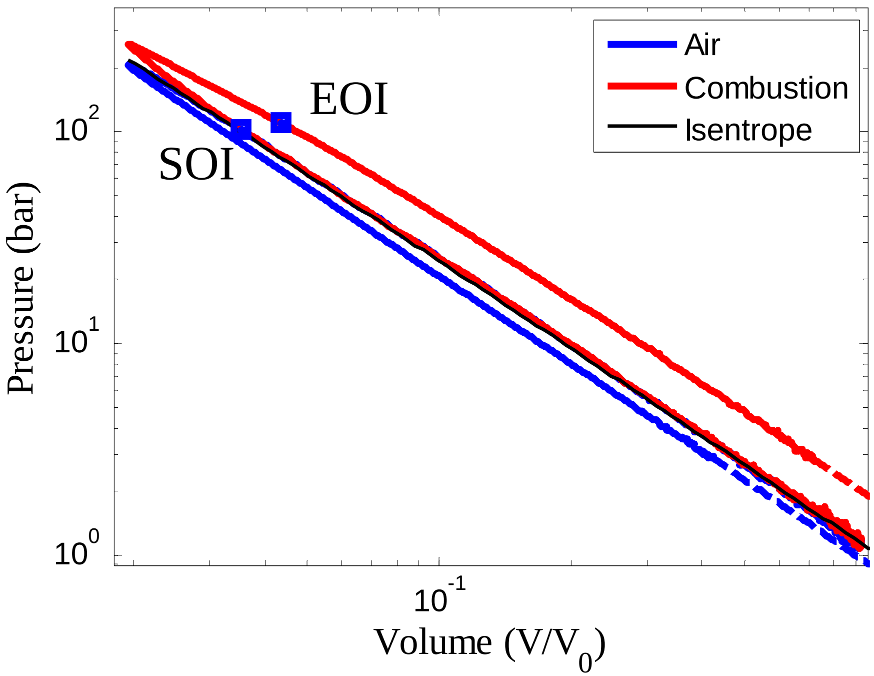
Peak Speed ~ 75 m/s

Piston mass = 1.03 kg

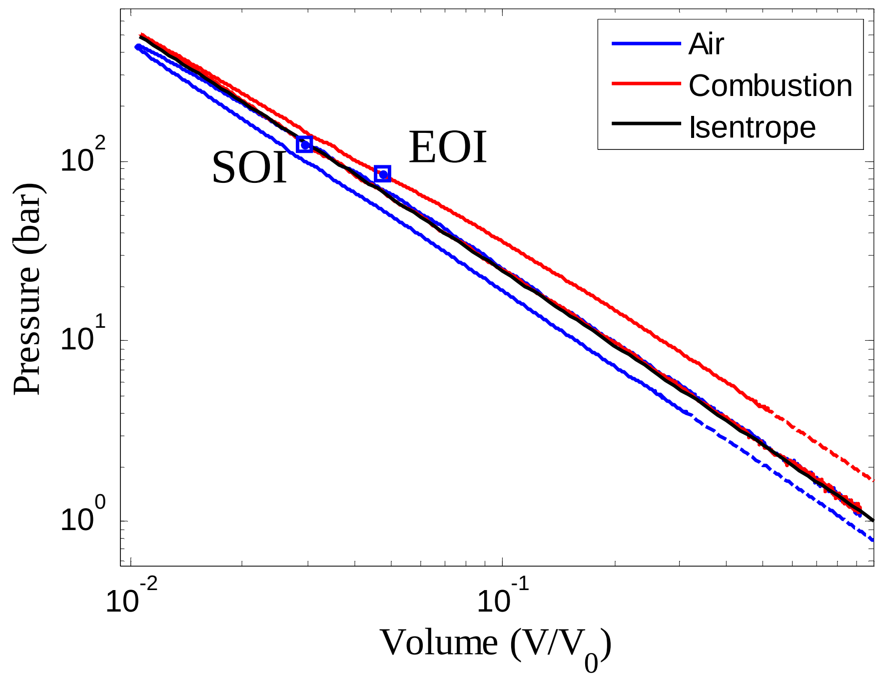
CR = 51.4

Driver Pressure = 10.2 bar

Comparison to Higher Compression

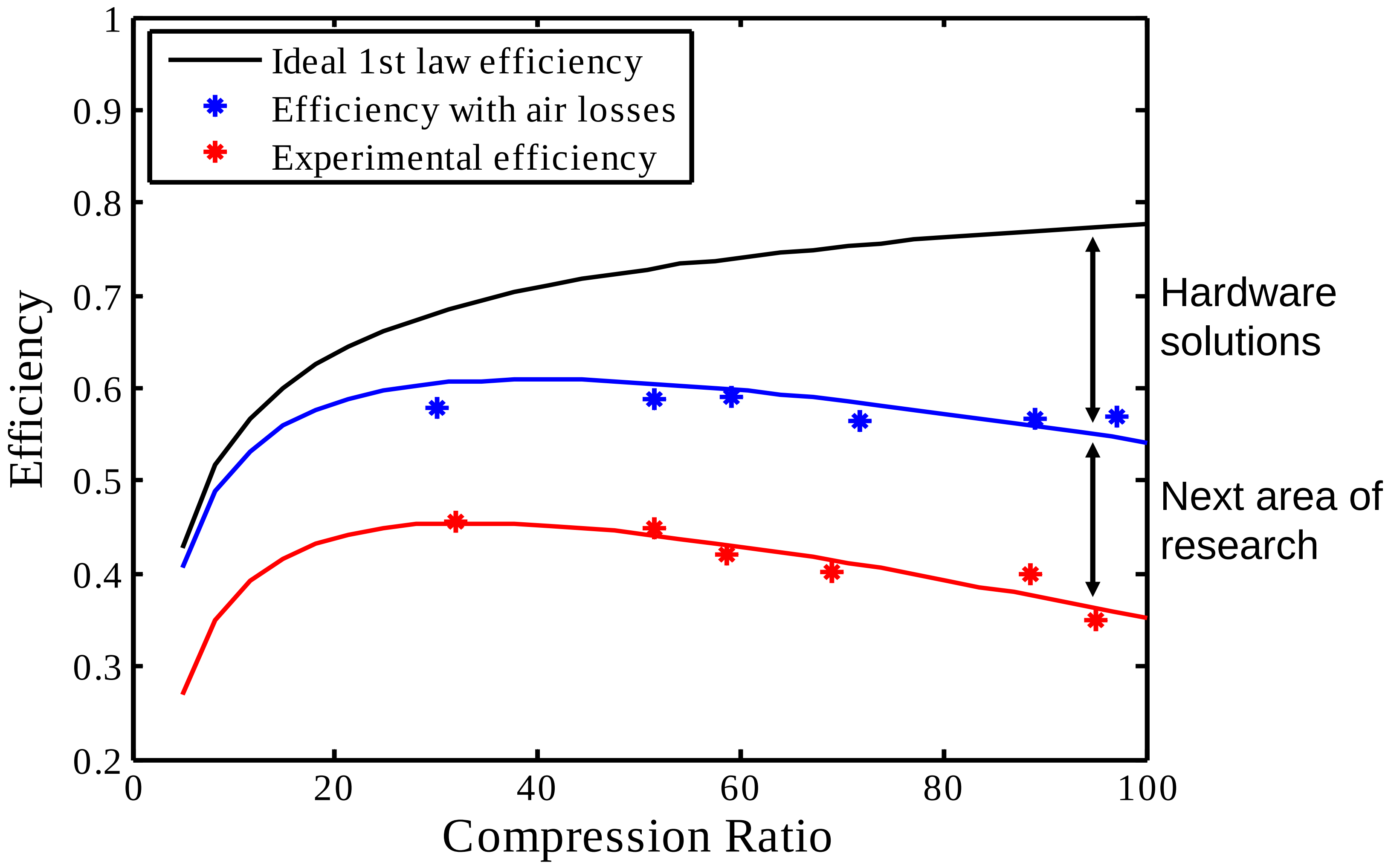


CR = 51.4 (Combustion)



CR = 95 (Combustion)

1st Law Efficiency vs. CR



Critical Questions Revisited

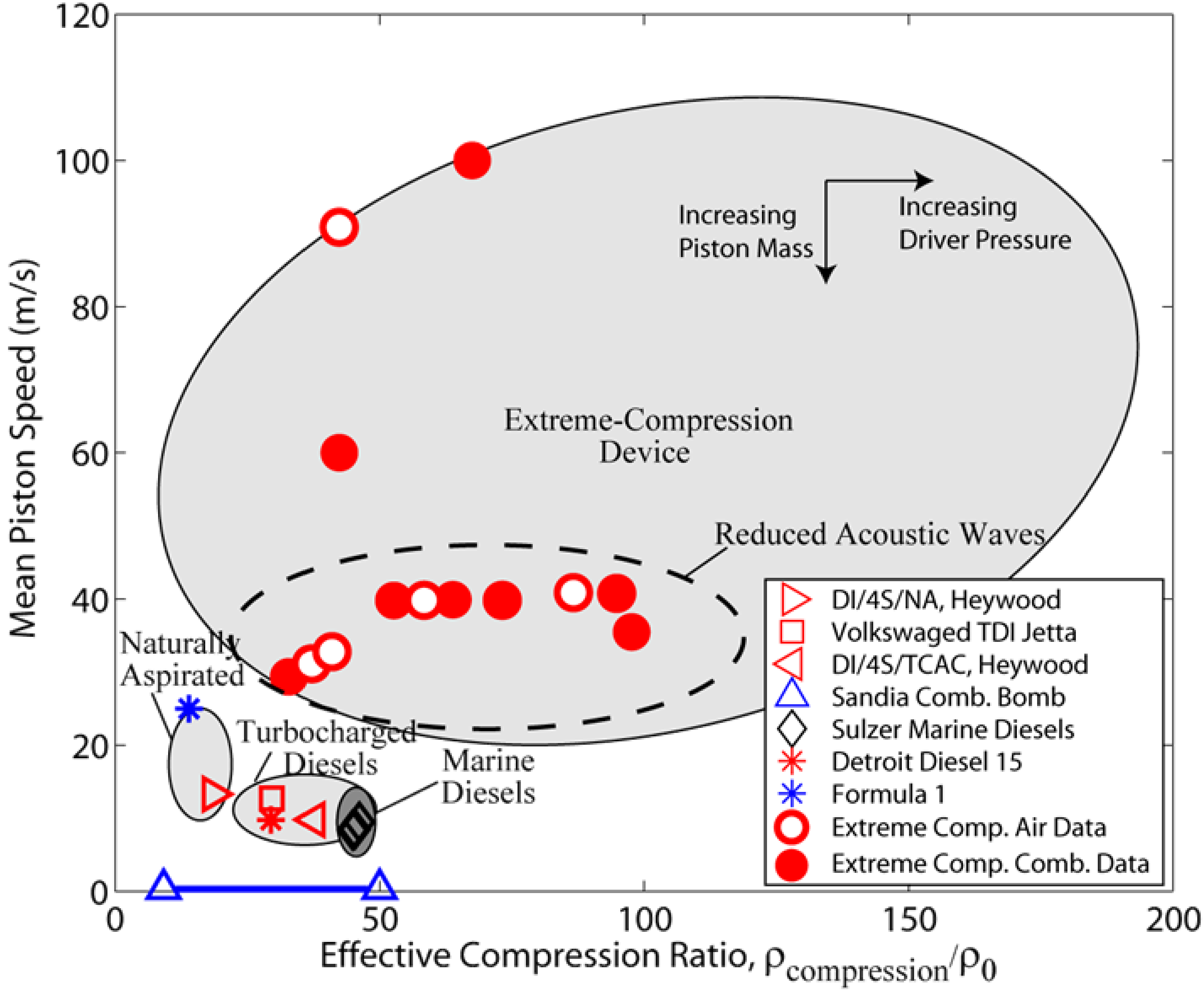
Critical Question	**Extreme Compression Apparatus**	**Extreme Compression Engine**
Material stress	✓	✓
Wall temperatures and heat transfer	■	■
NOx	■	■
Seal survivability	✓	■
Sealing ability	■	■
Ignition phasing	✓	✓
Combustion control	●	●

✓ solutions available and understood

■ more research required, but no obvious barriers

● high priority for research

Operating Space



Next Steps

- Assess Combustion Performance
  - Injection performance at high densities
  - Ignition delay timing
  - Ability to generate turbulent mixing
  - Combustion efficiency
  - Implications for heat loss
- Install window to visualize spray dynamics and combustion
- Analysis and experimental testing of ring design to quantify and reduce blowby
- Install exhaust gas analysis system for measuring NOx and combustion efficiency

Posters

- *Increasing Engine Efficiency through Extreme Compression:* S.L. Miller, M.N. Svrcek, K.-Y. Teh, O. Lacroix, J. Wilson, C.F. Edwards

- *Optimal Architecture for Efficient Steady-Flow Engines: S*. Ramakrishnan, K.-Y. Teh, S.L. Miller, C.F. Edwards