Thermodynamic Fuel Cell

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Sandia National Laboratories

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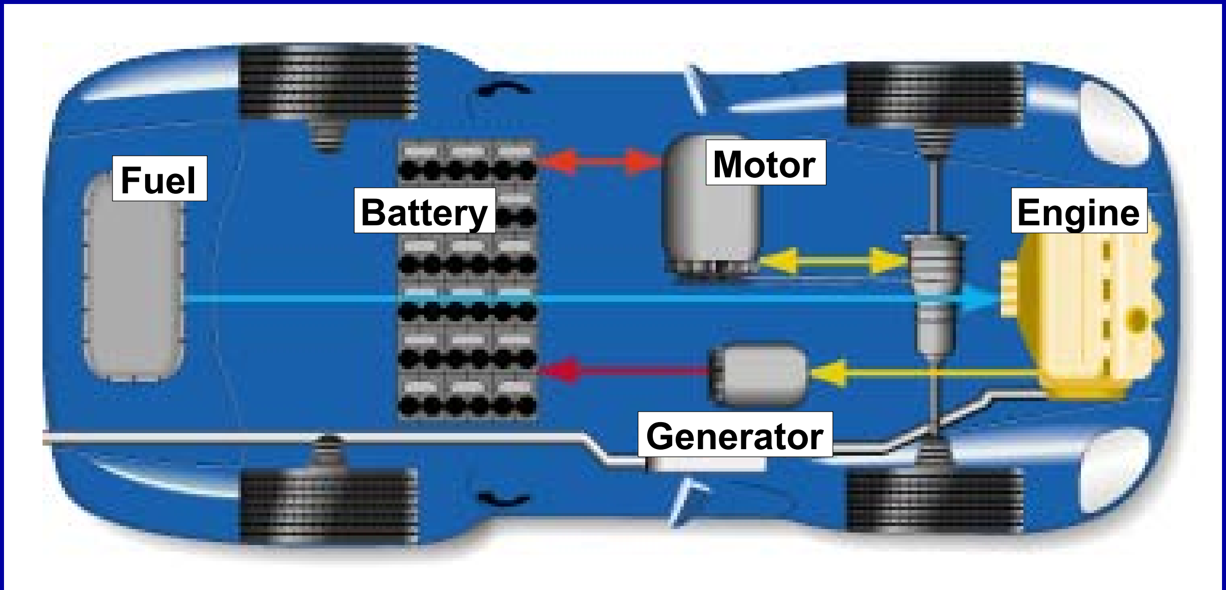
Background

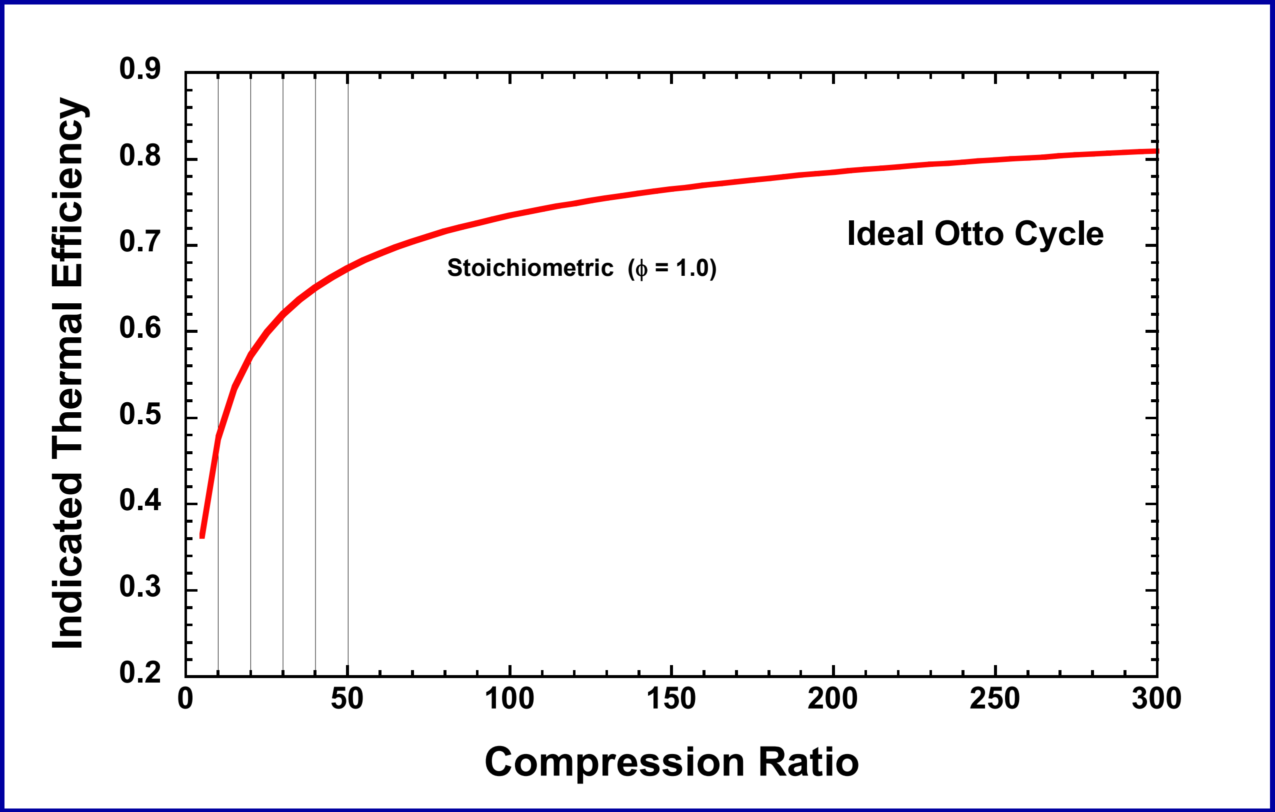
1995 – H_2 fueled genset for series hybrid vehicle

- On / Off Operation
- Single Power level → electricity output



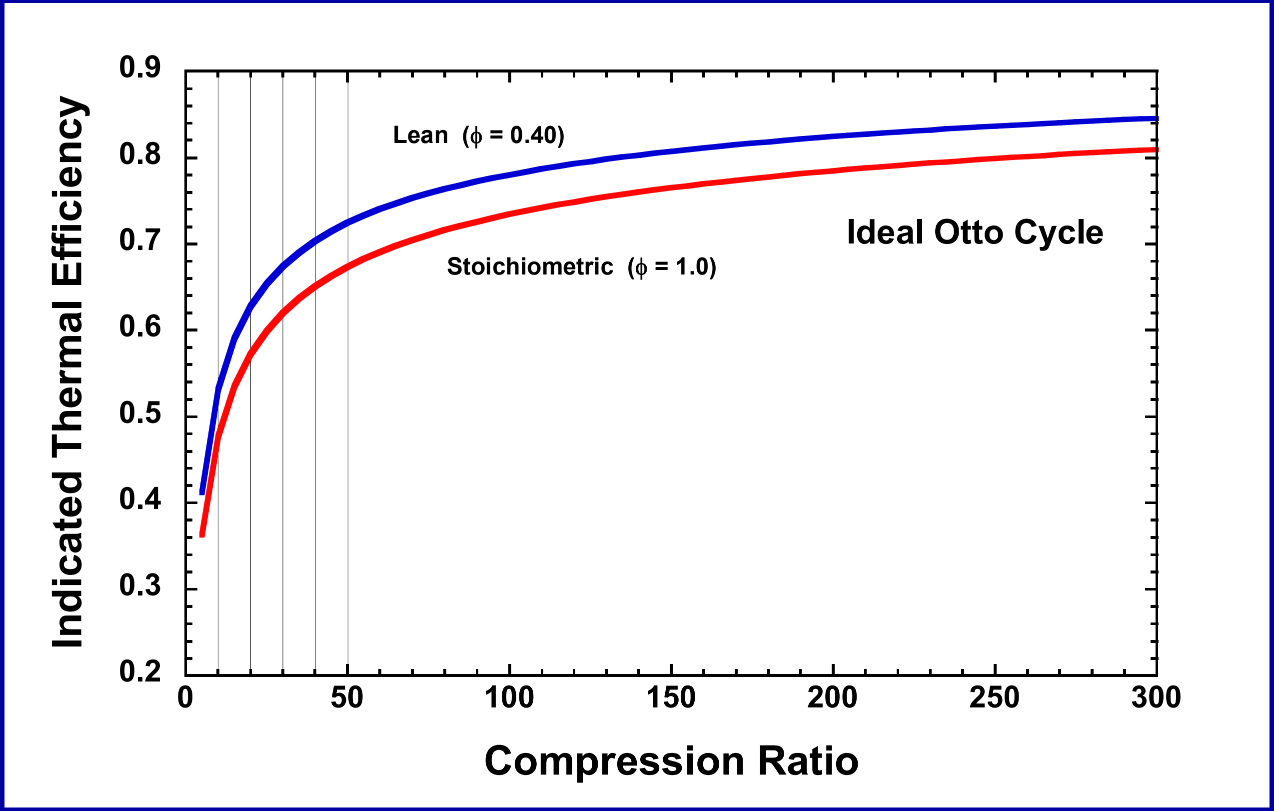
Hybrid electric vehicle platform

Constant Volume combustion based machine can be high efficiency



Otto cycle is fundamentally capable of high (>80%) conversion efficiency.

Constant Volume combustion based machine can be high efficiency



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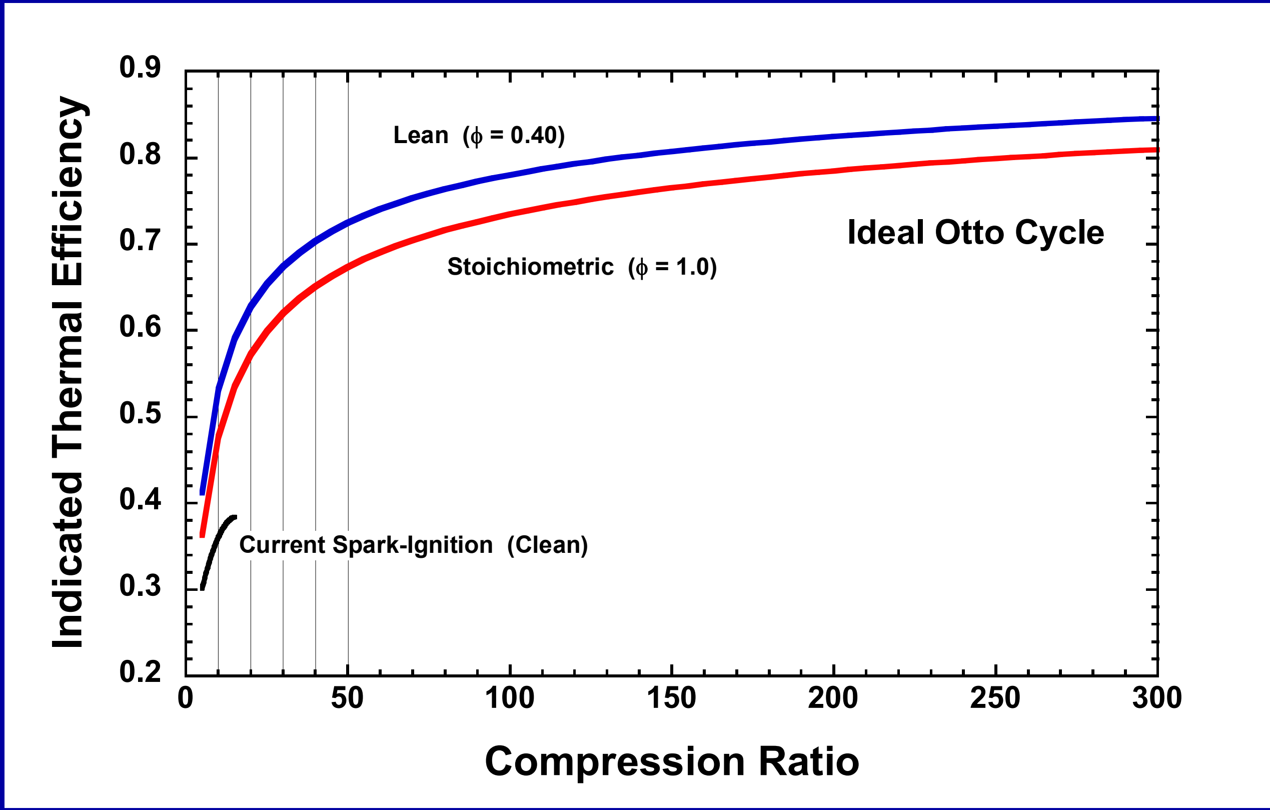

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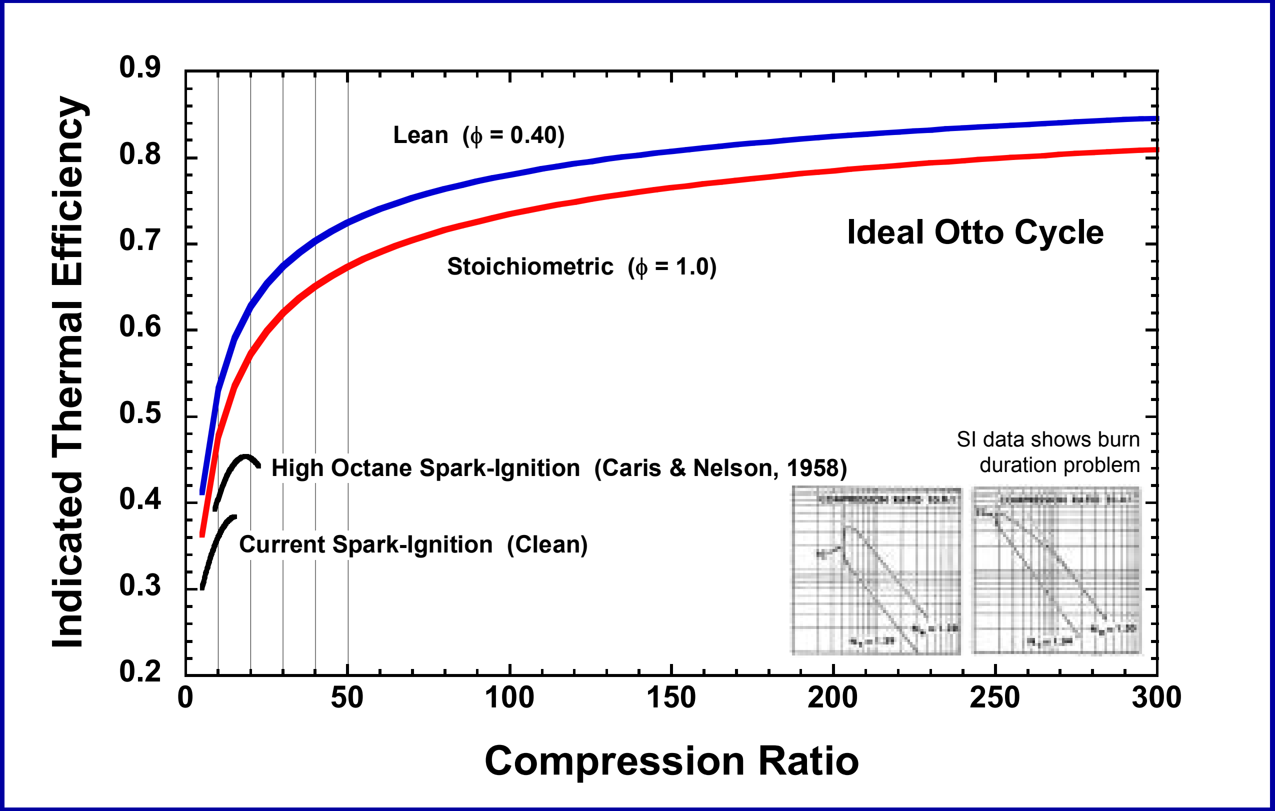

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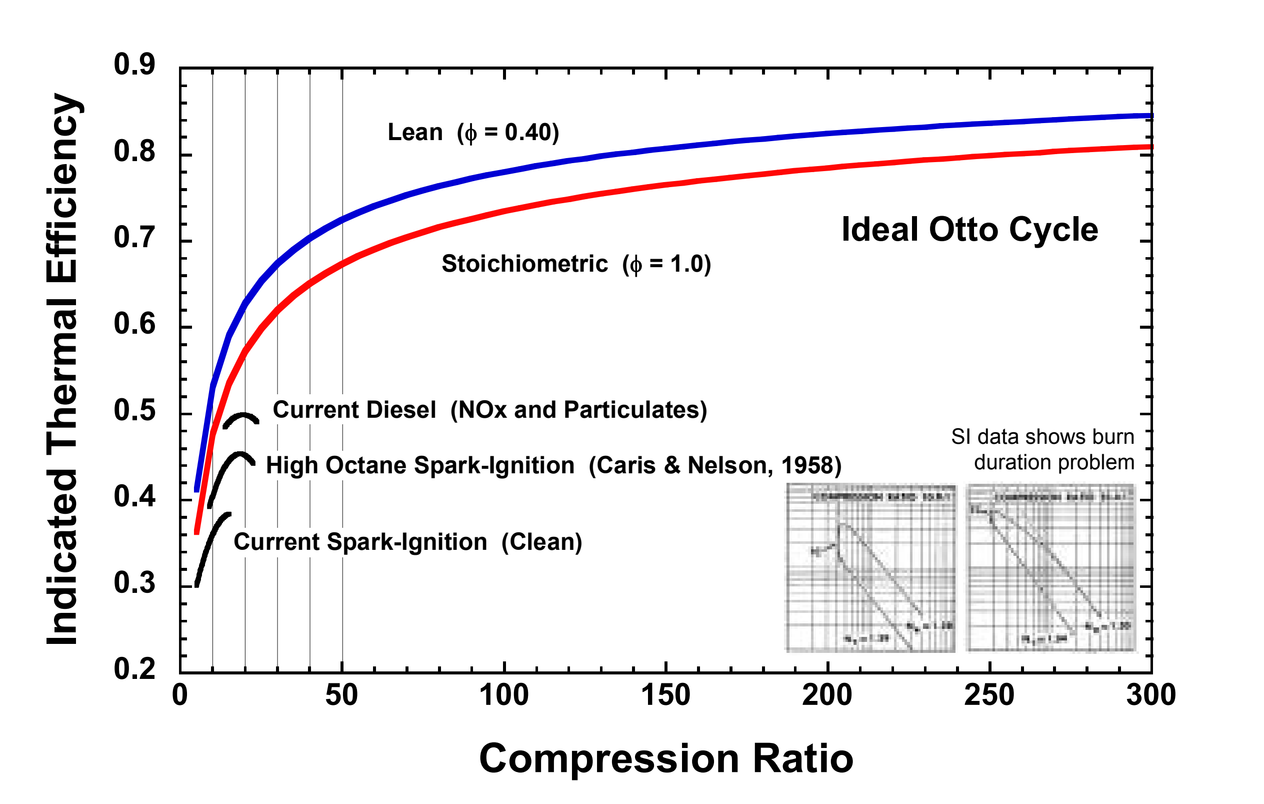

Otto cycle is fundamentally capable of high (>80%) conversion efficiency.

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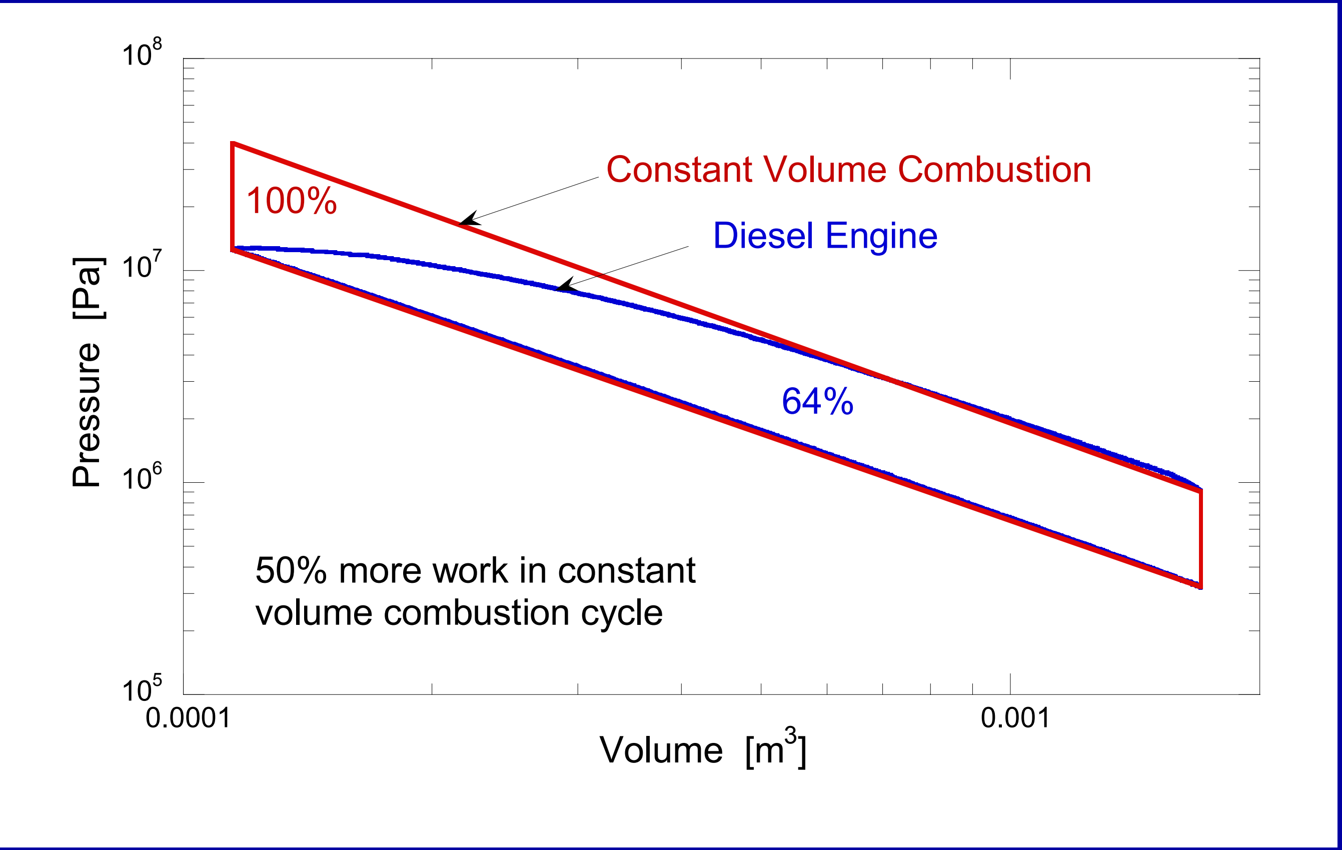
Illustration of burn duration penalty

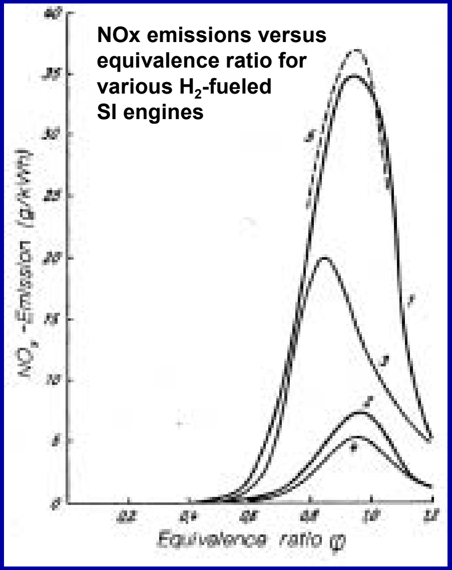


Modern 4 stroke Diesel is extreme case, pressure limitations control design.

Homogeneous Charge Compression Ignition

- Fuel / air premixed.
- Charge combusts due to compression heating.
  - No flame propagation / diffusion mixing required
  - Chemical kinetics dominate (VERY FAST!)
- Can achieve constant-volume combustion.
- Multi-fuel capable   no flammability limits.
- NOx control by dilution.

  limits combustion temperatures



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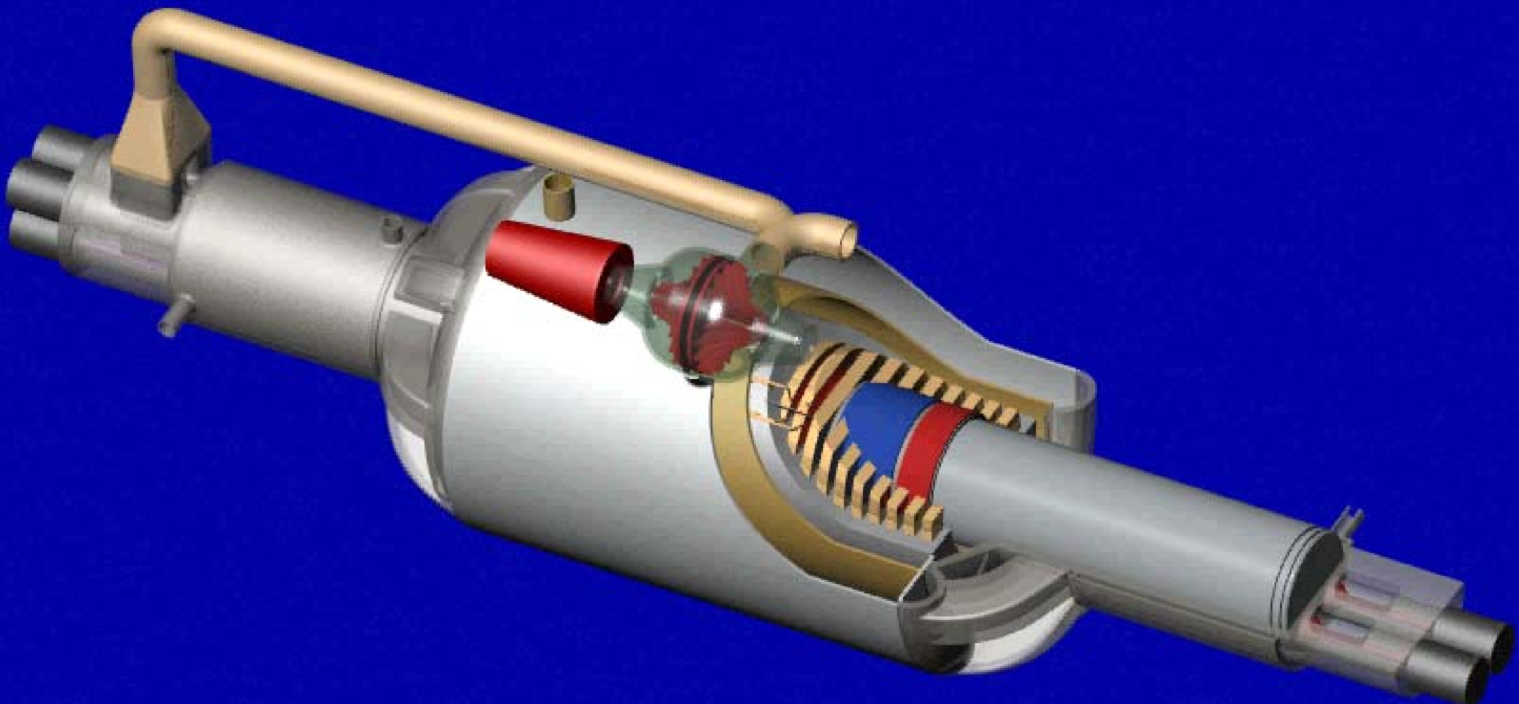
Harnessing HCCI's Potential

Characteristics of Thermodynamic Fuel Cell

- Electronic control of CR
- Rapid compression
- High pressure capability
- Mechanical simplicity
- Two-stroke scavenging
- Electrical output



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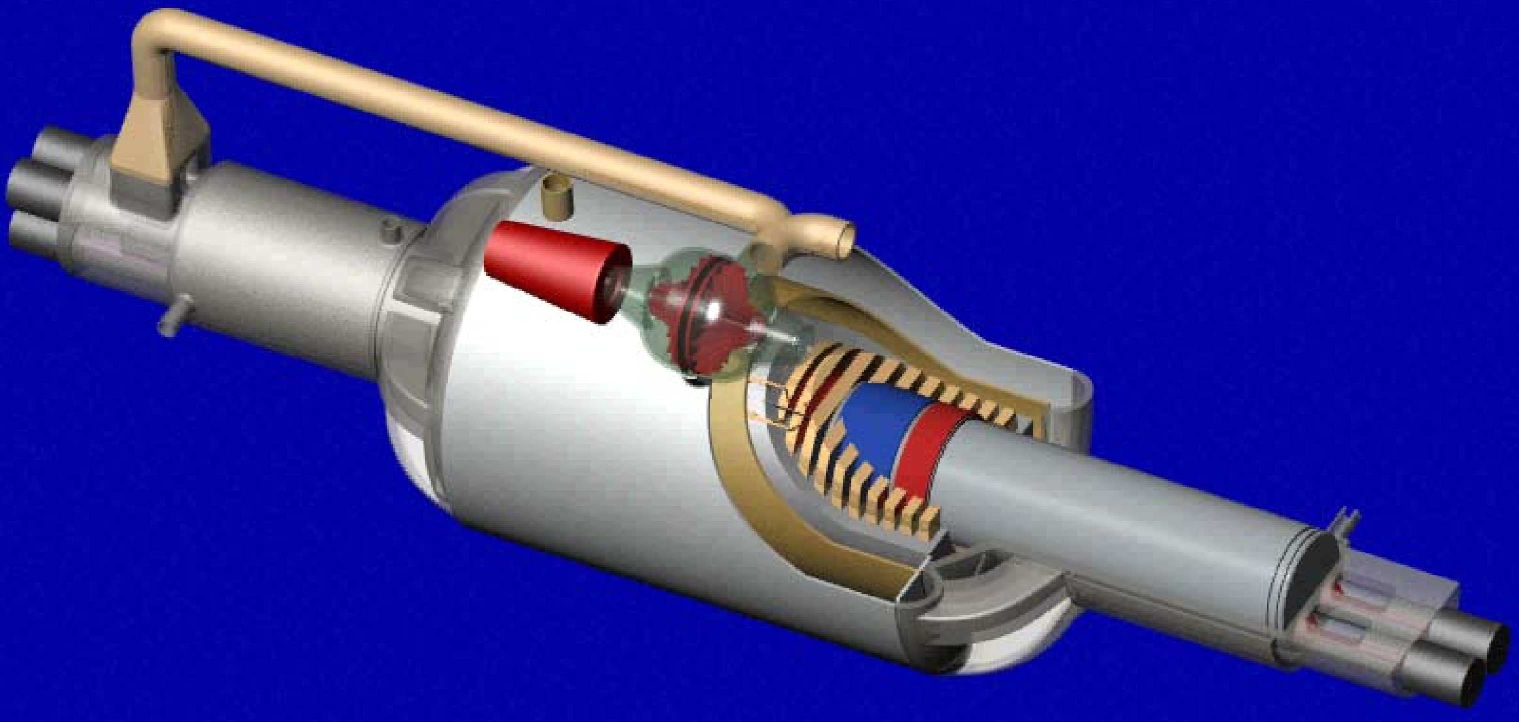

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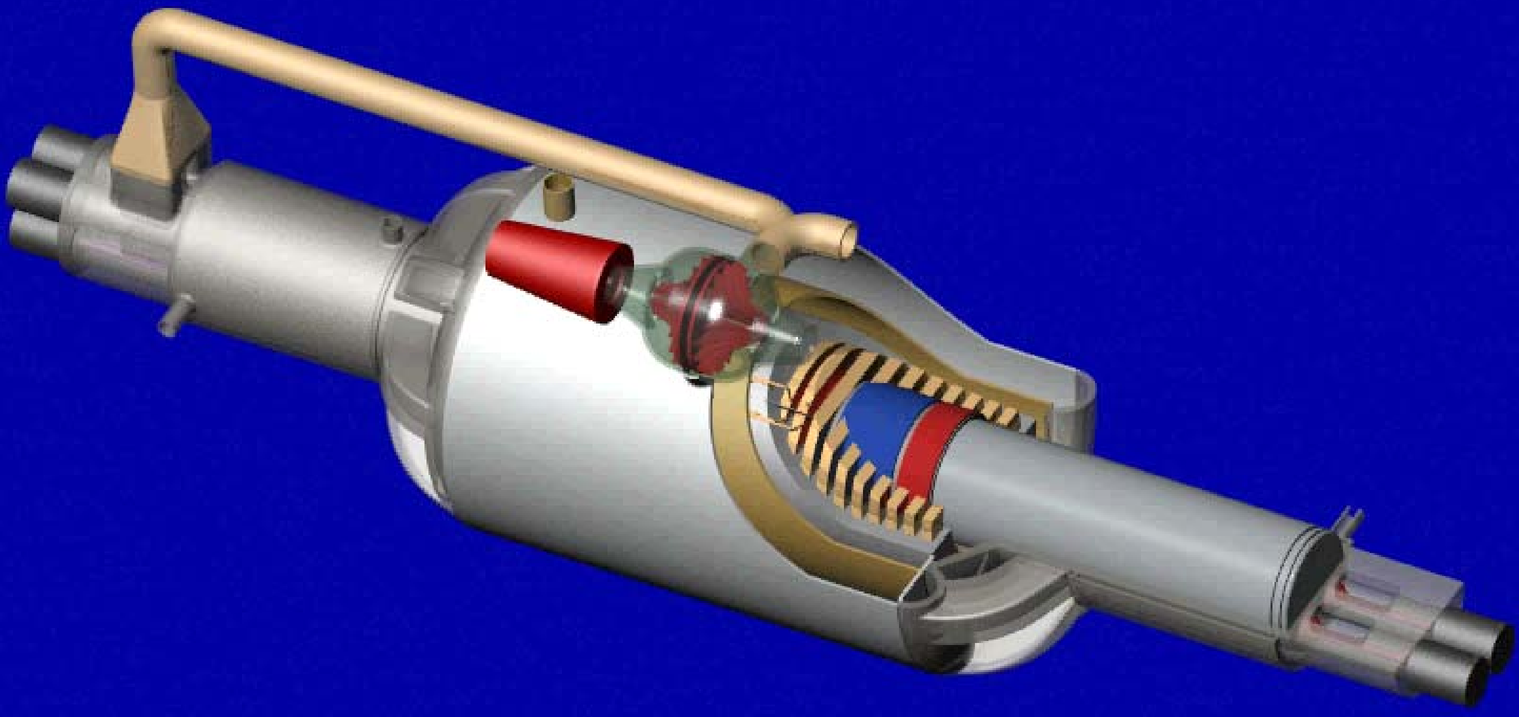

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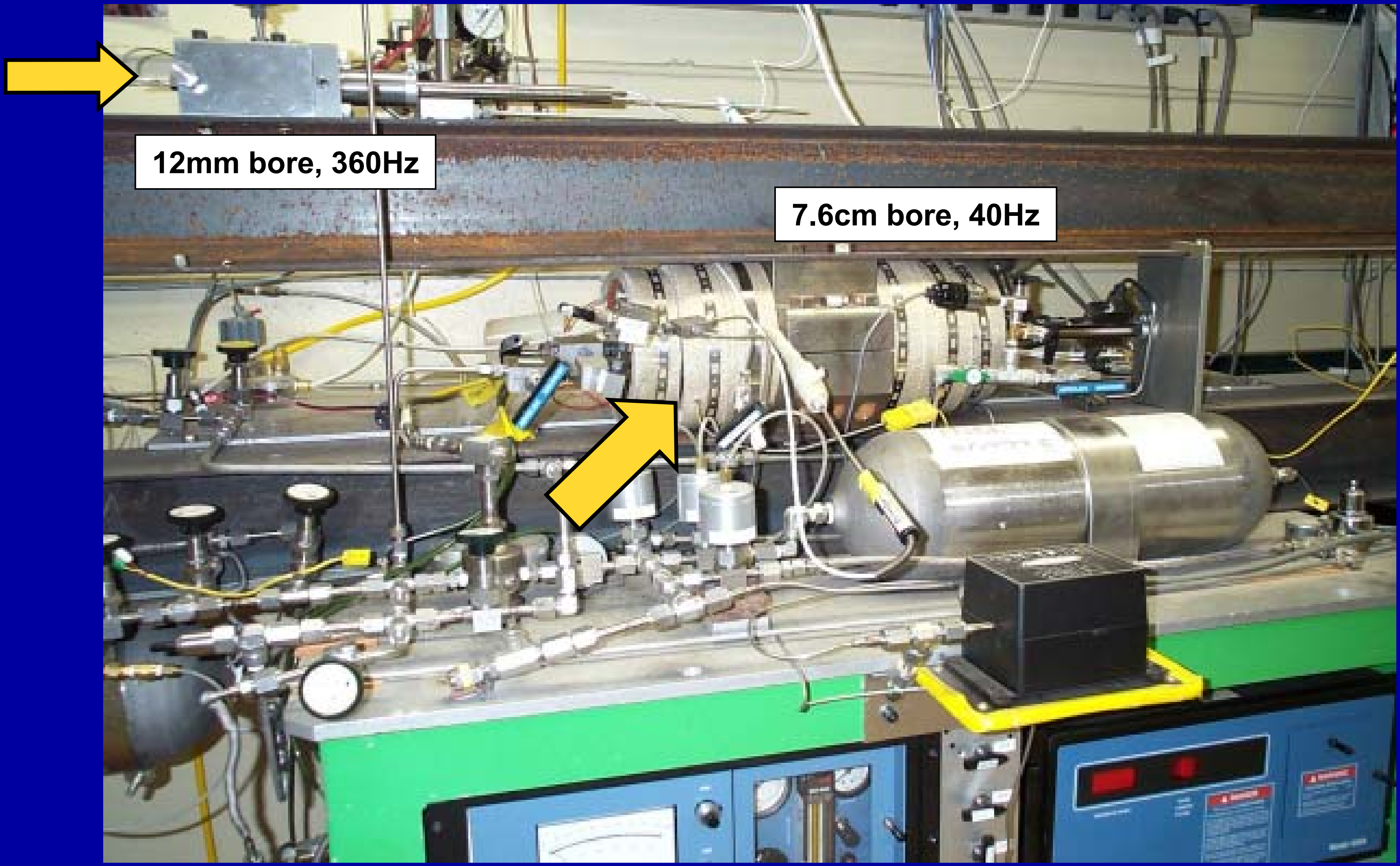
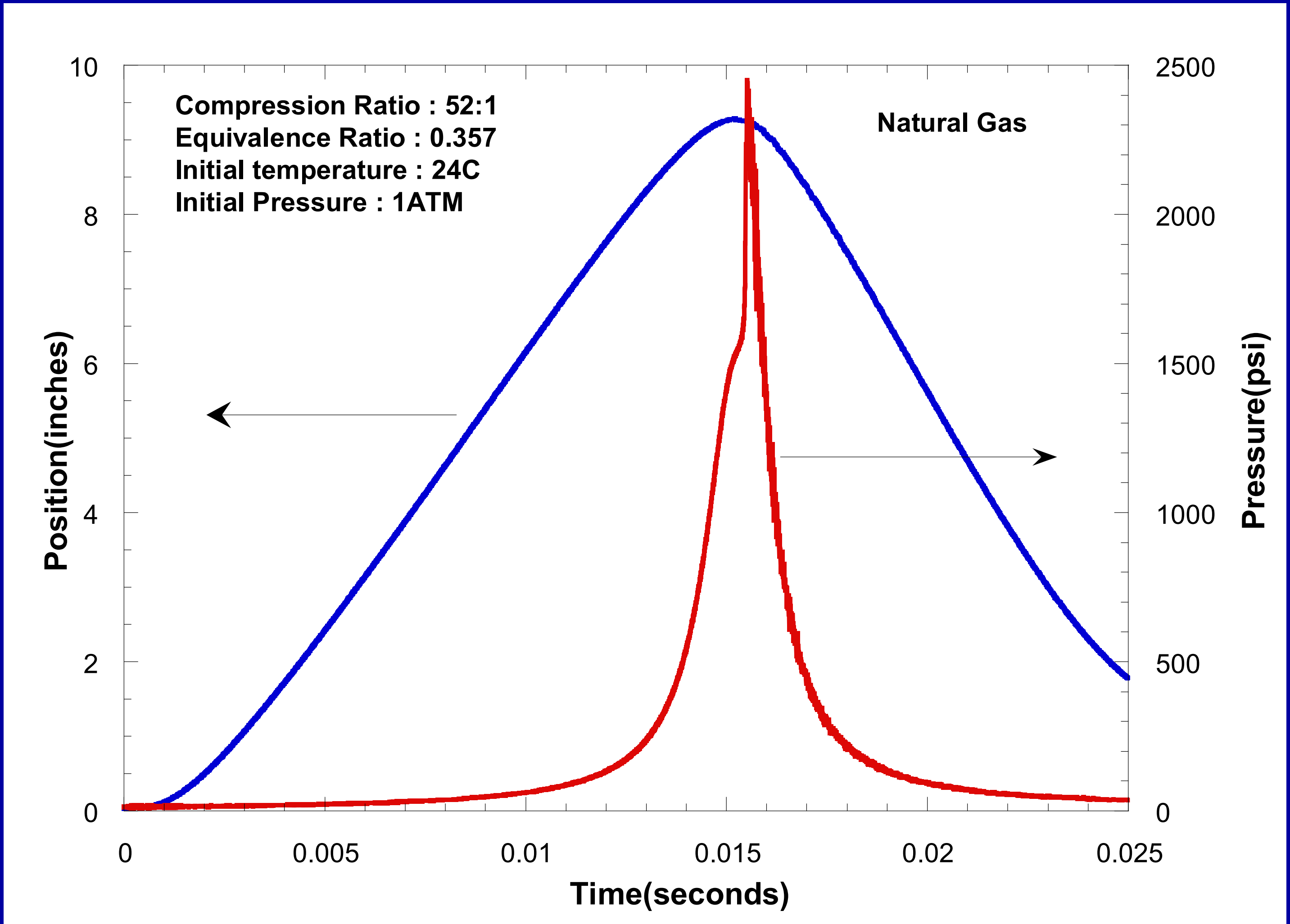
Approach to Development

- Demonstrate HCCI combustion potential
- Develop linear alternator
- Develop intake / exhaust process

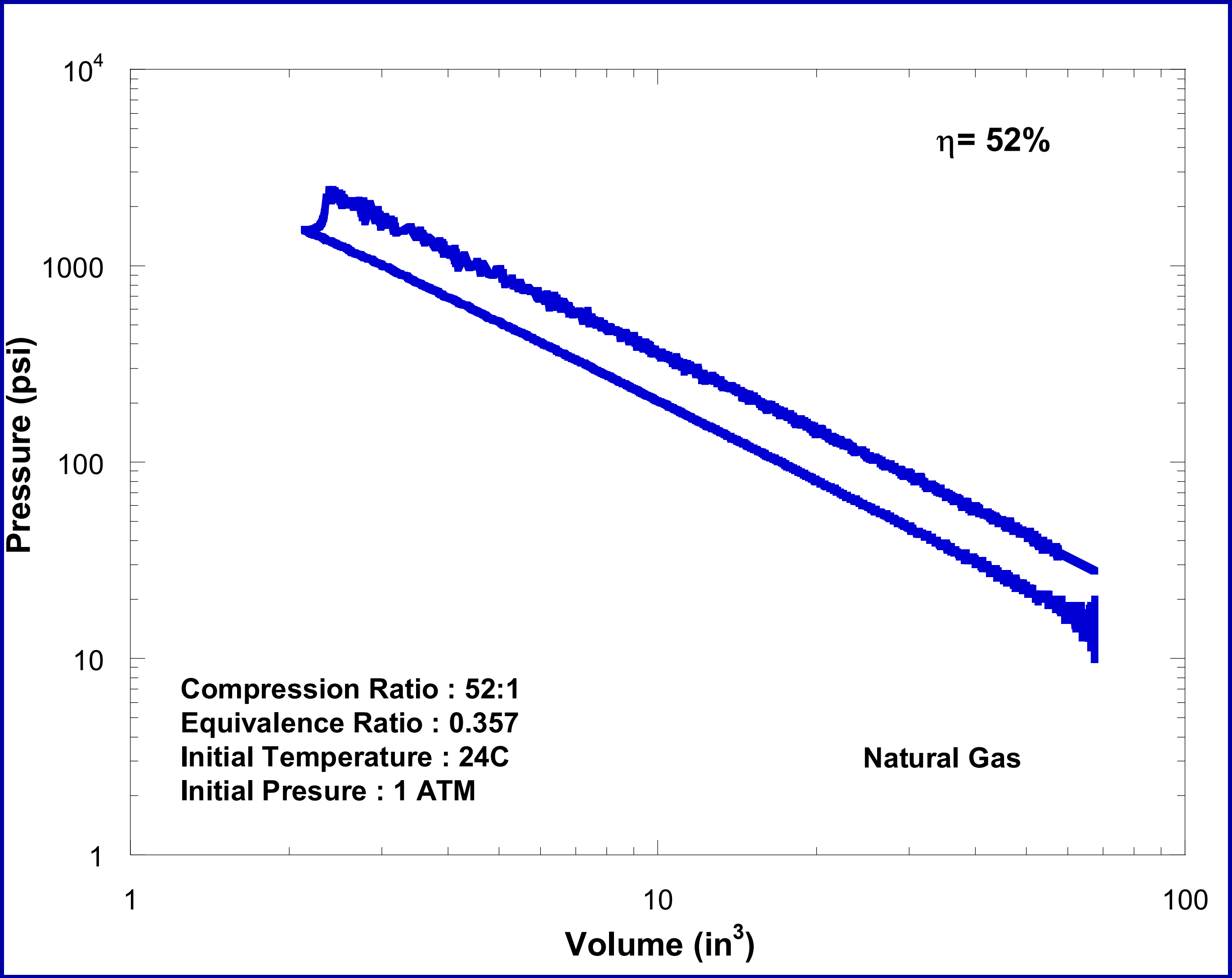
∴ Combine critical components into 30kW prototype research engine

RCEM Combustion Experiment





Typical free piston position, and cylinder pressure histories for RCEM



Typical pressure – volume data from a free piston, Rapid Compression Expansion Machine

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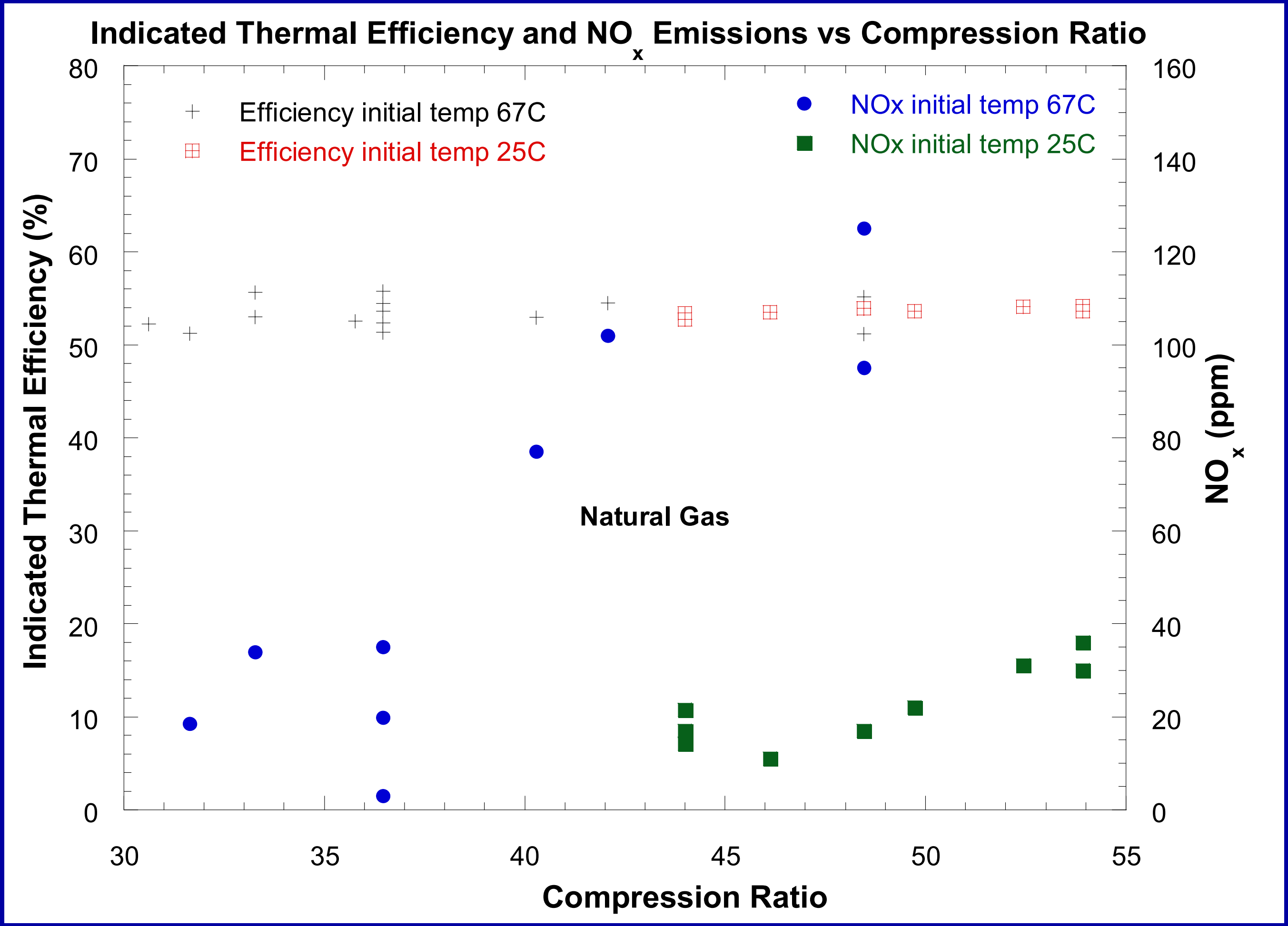
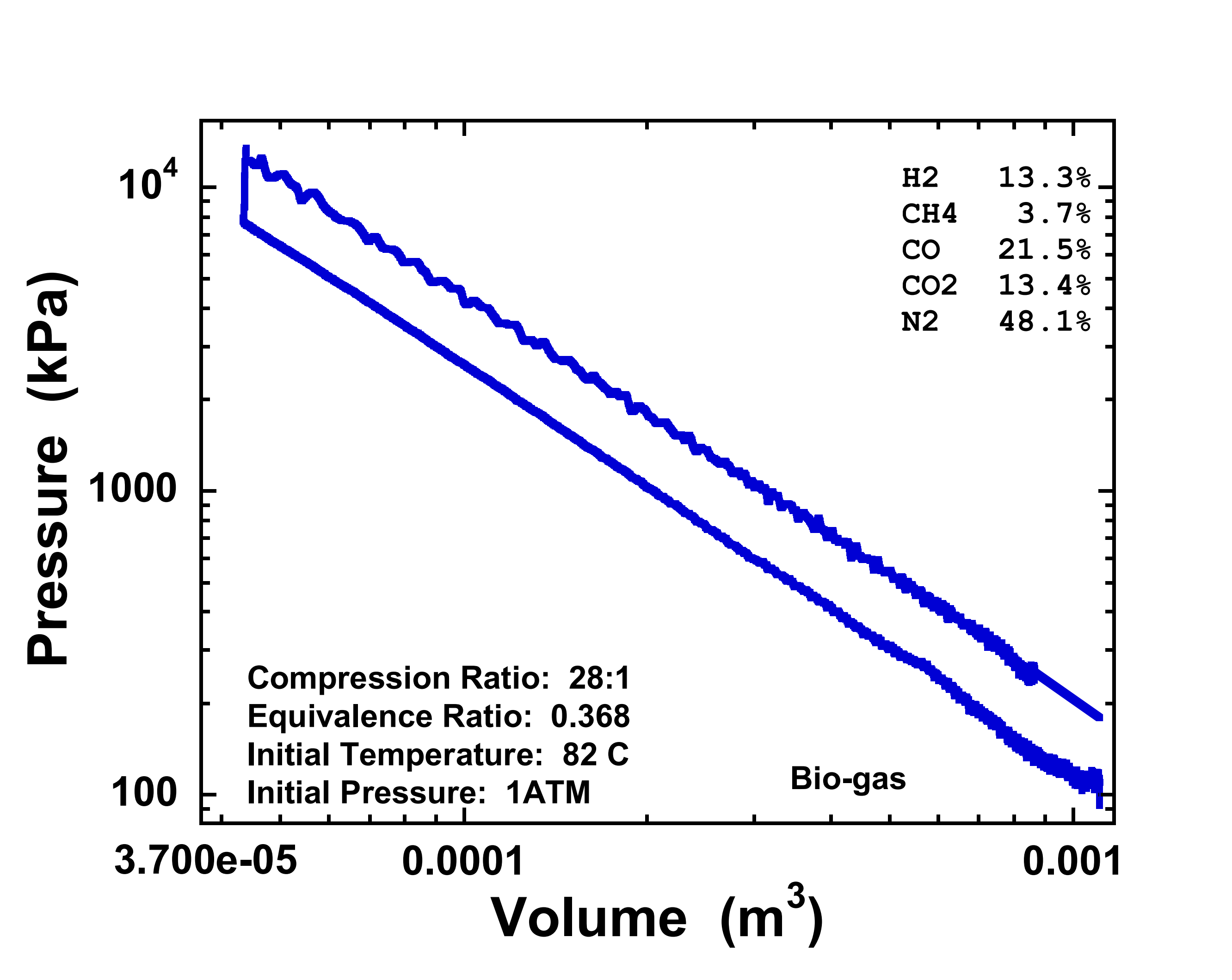


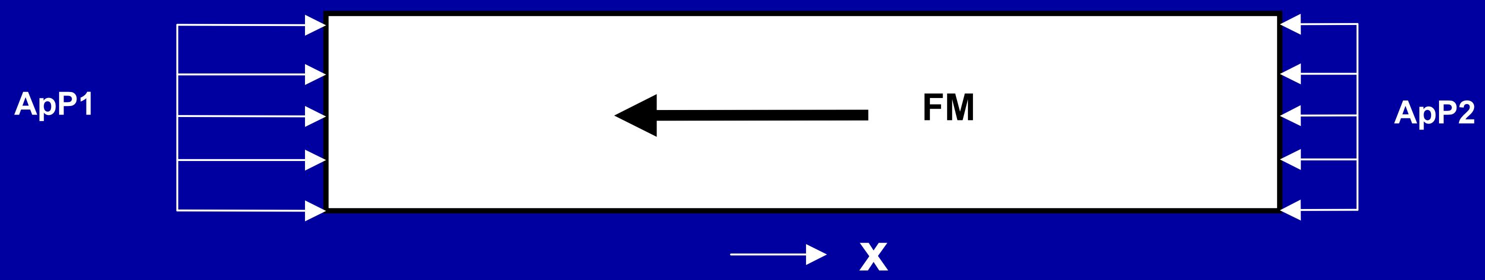
Efficiency and emissions performance for different initial temperatures, and single-shot compression ratios



Pressure – volume data using low BTU bio-gas

Linear Alternator

Piston Free-Body Diagram



$$\sum F_x = ApP1 - FM - ApP2 = mp\ddot{x}$$

- Key Component:
  - Crucial term in the force balance.
  - Converts piston kinetic energy into electricity.
  - Electromagnetically couples the piston motion to the electrical load.
  - Facilitates electronic control of the piston motion e.g., compression ratio.

Linear Alternator

Parallel development plan

In-house

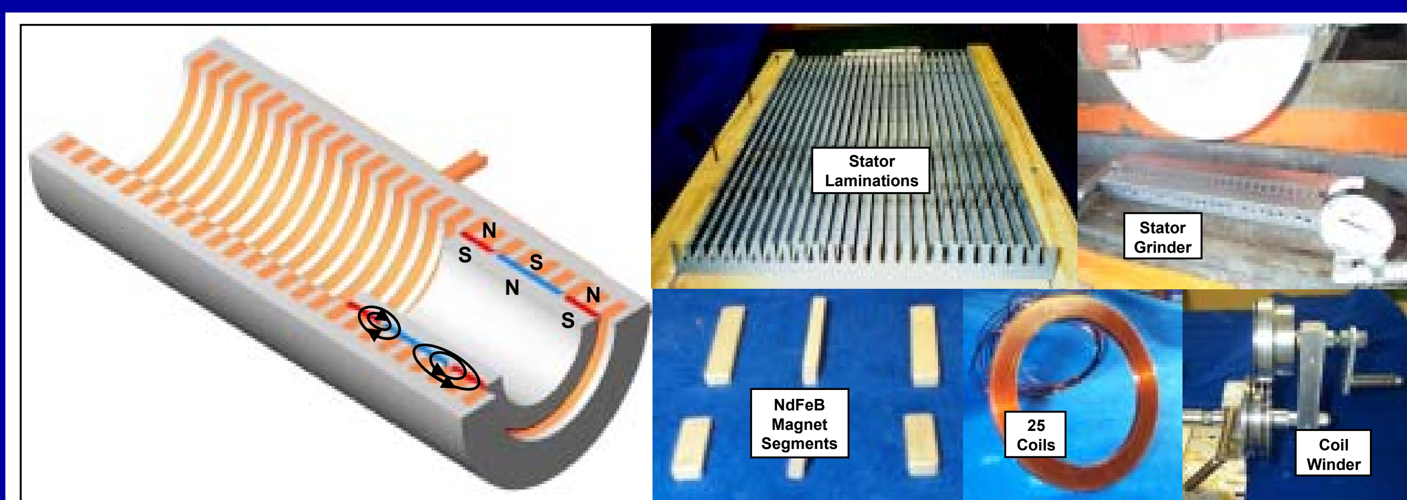
Electromagnetic modeling (FLUX2D)
- Describe velocity profile, anisotropic materials. Calculate I^2R losses.

Parametric variations to focus on optimal configuration.

Magnequench, International

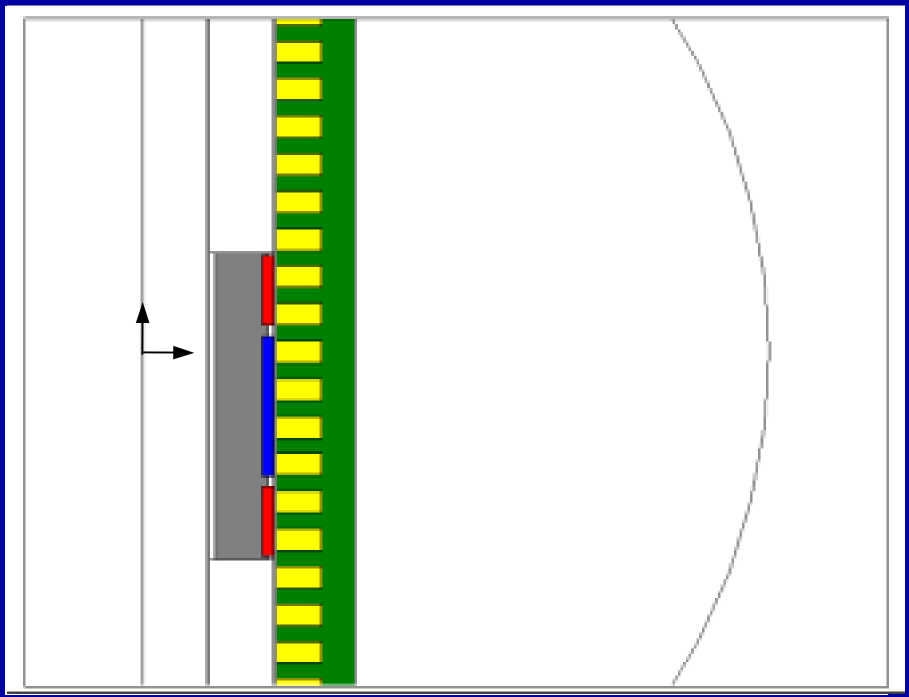
Design, fabricate and supply at no cost.

Magnequench Design

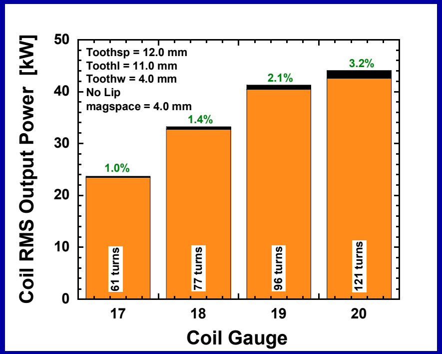


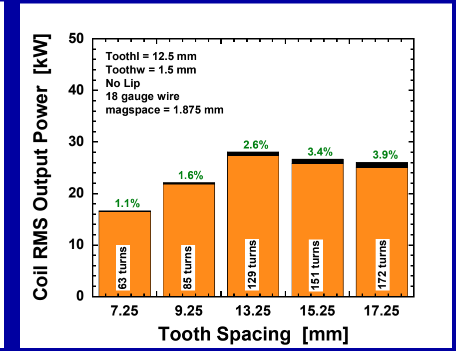
Sandia Design

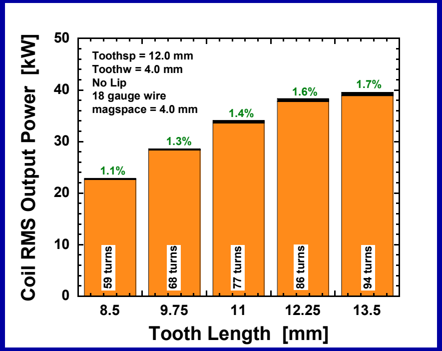
Computational modeling to develop design

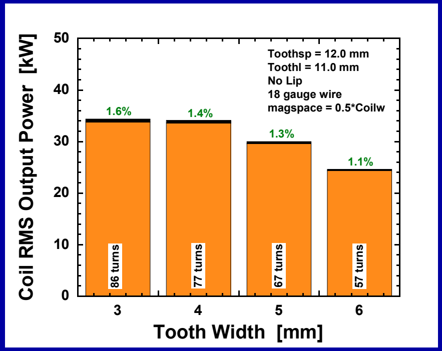


Sandia Design









Parameters investigated

- Number of magnets, magnet strength
- Number of teeth per magnet
- Tooth / stator geometry
- Coil configuration

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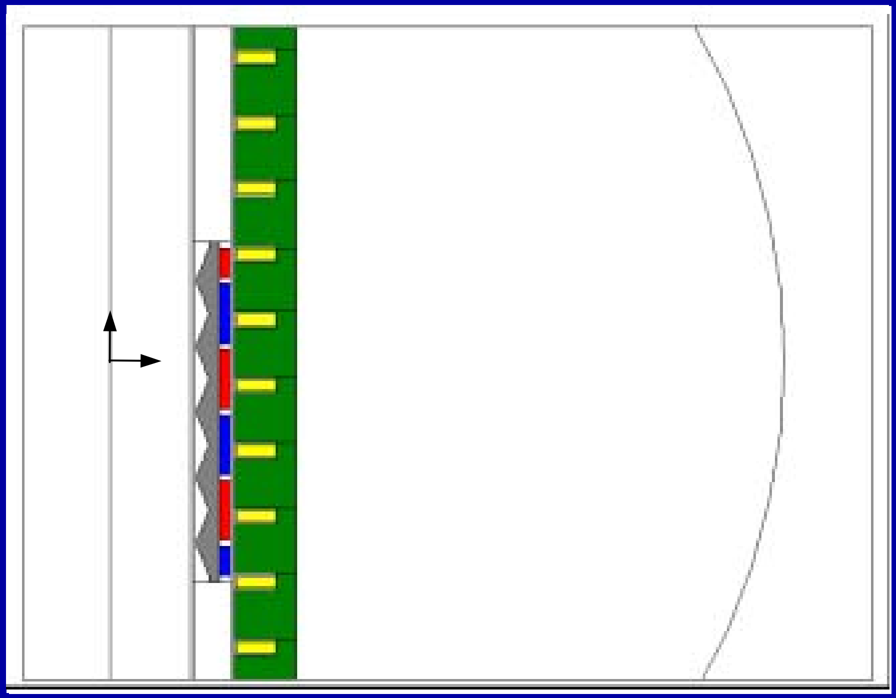
Simulate performance of Magnequench design



Magnequench Design

Experimentally verify computed results

Alternator Test Rig

Linear Alternator Test Program

- Objectives:
  - Verify Flux 2D performance predictions.
    - Measure power output and compute efficiency.
  - Characterize linear alternator dynamics
    - Determine reaction force vs. magnet position.
- Strategy:
    - Modify a Caterpillar 3304 Diesel engine to drive a linear alternator.
    - Disable two cylinders.
    - Magnets are attached to a “plunger” that is substituted for the fourth piston.
    - Mount the stator over the plunger.
    - Suspend the stator with six load cells.
    - Measure stator reaction forces and electrical output.
    - Piston position is determined from slider-crank kinematics and shaft encoder output.

Experimental Setup

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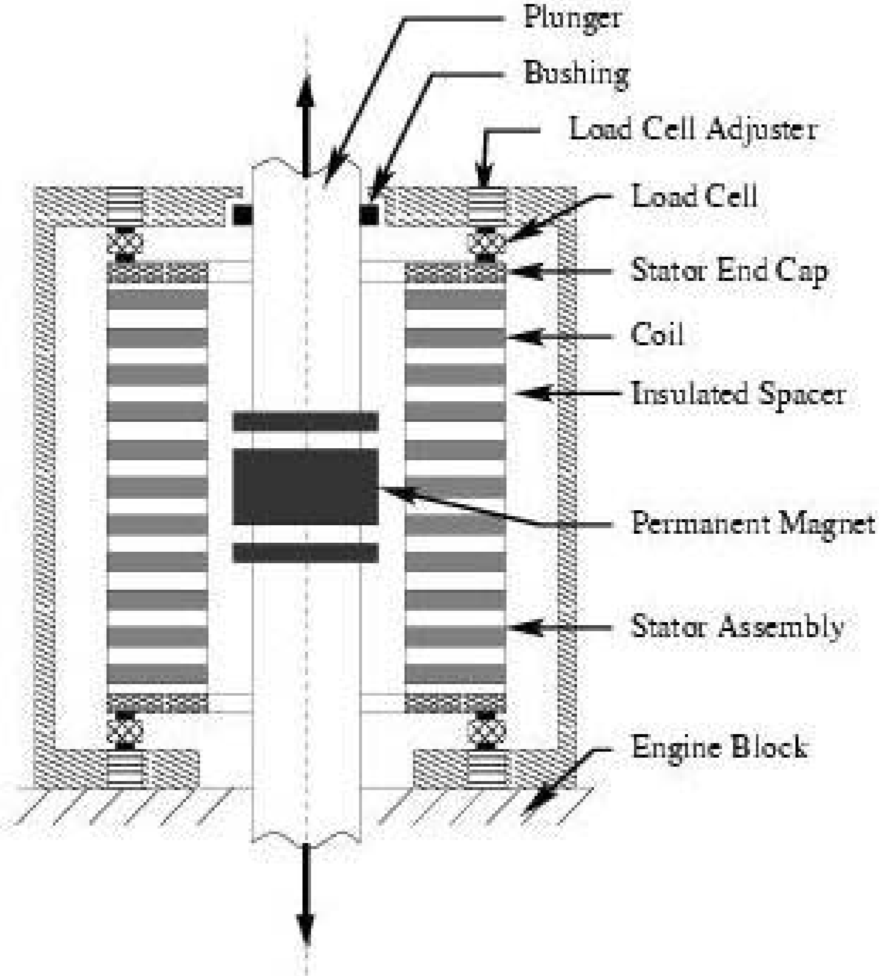
Experimental Setup

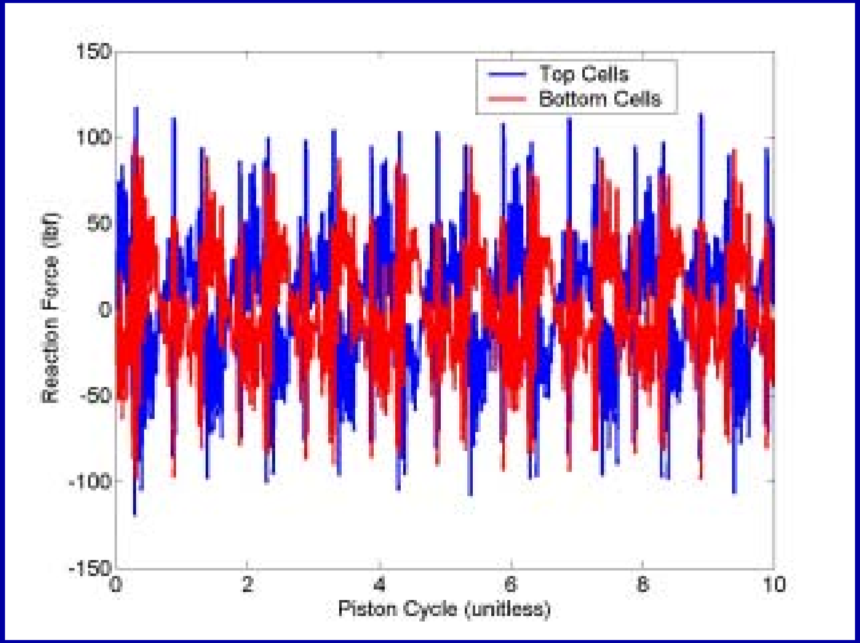
Linear Alternator Installed

Linear Alternator Schematic

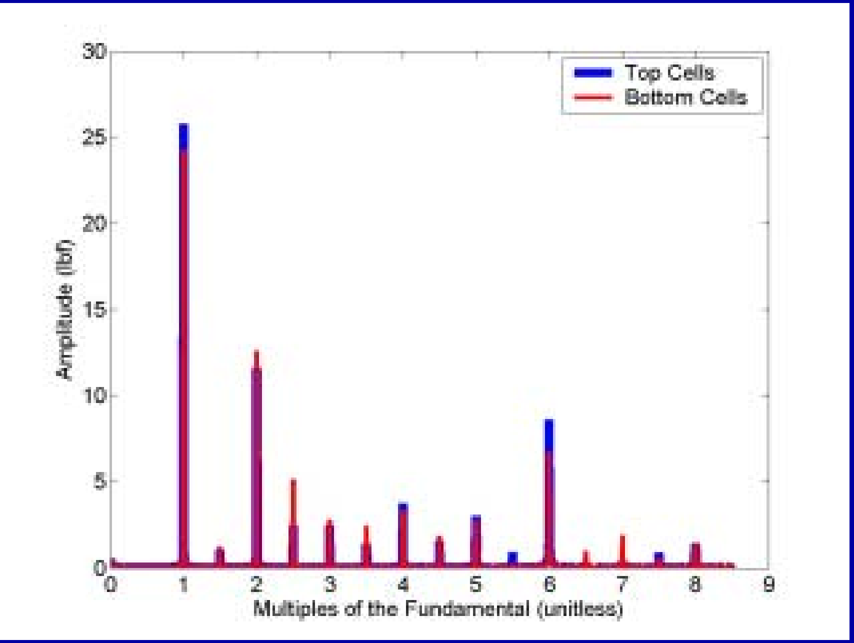


Data Reduction Challenges

Time Domain



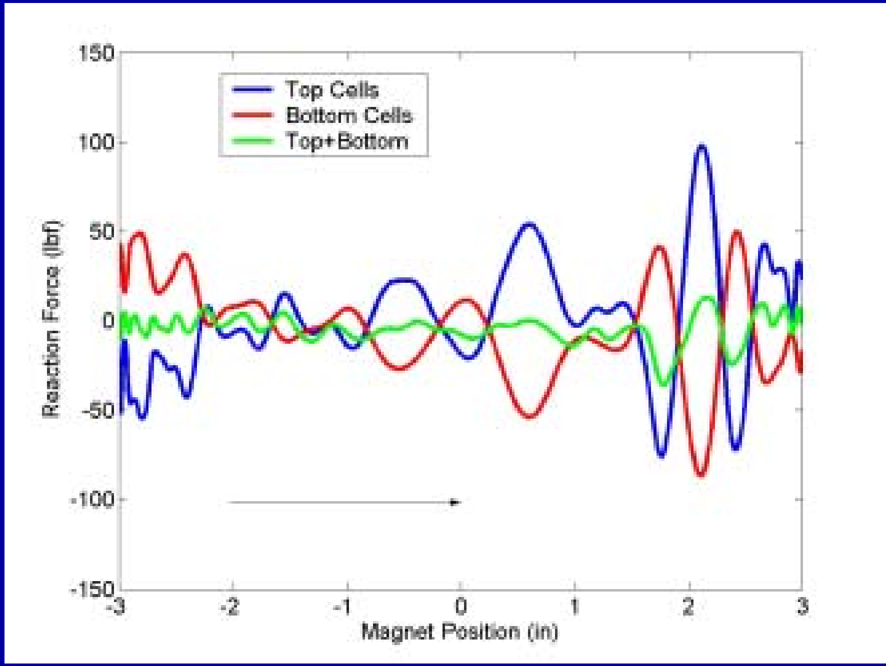
Frequency Domain



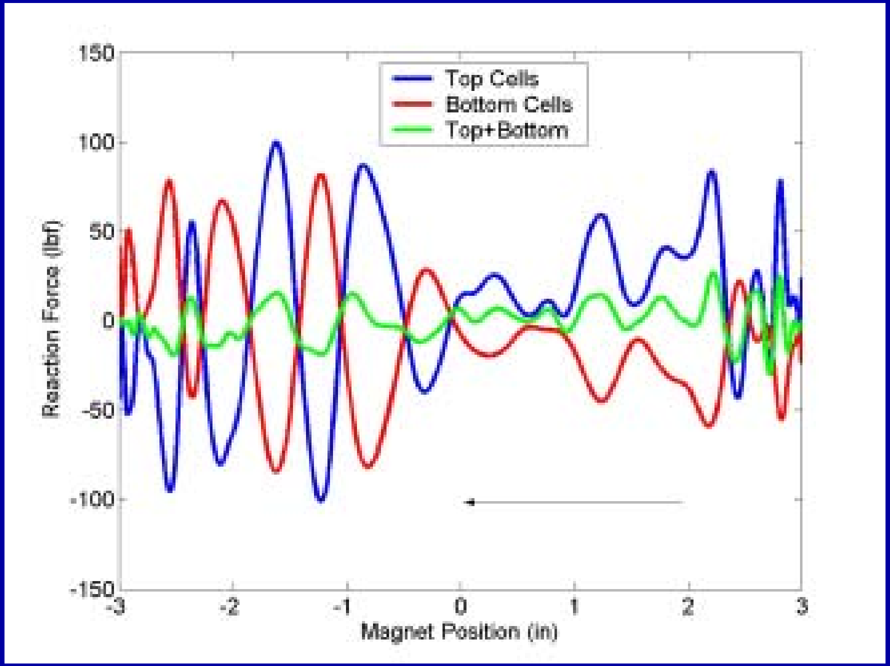
- Load cell signal is a complicated waveform---even without magnets.
- Multiple frequency components.
- Employing spectral analysis to determine optimal engine operating / test conditions.
- Load cell-stator system behaves like a spring-mass system subjected to base excitation.

Data Reduction Challenges

Ascending Plunger



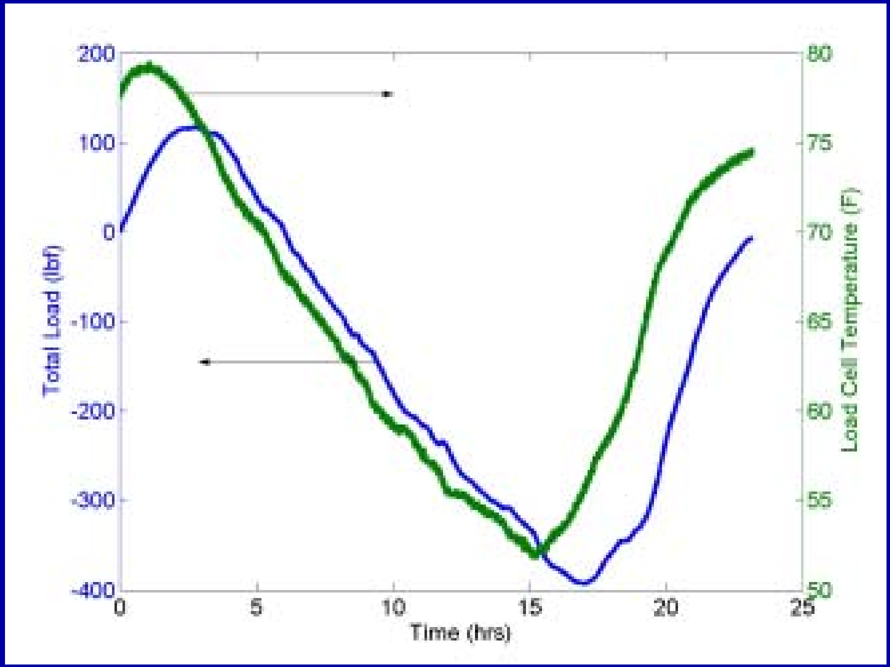
Descending Plunger



- Top and bottom load cell signals are complimentary.
- Reaction forces depend upon the direction of the piston motion---further complicates the force-position analysis.
- Developed a mathematical model to facilitate the interpretation of load cell signals.

Ancillary Difficulties

Stator Thermal Expansion



- Stator thermal expansion causes an apparent "static drift" in the load cell signals.
- Stator has considerable thermal inertia.
- Developed a mathematical model of the warm-up process.
- Devising experimental techniques to minimize thermal expansion effect.

Intake / Exhaust System

Critical for efficiency / emissions goals

- Charge preparation for HCCI combustion.
- Control of short-circuiting (fuel loss, HC emissions).
- Limit pumping power.

CFD modeling and visualization

- KIVA3V / Ensight; 0D pressurization; 1D friction
- Single step parametric optimization

  scavenging methods, charge delivery options, etc.

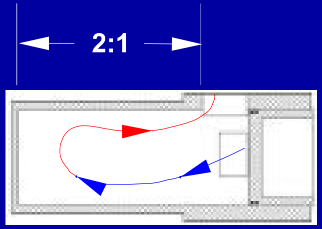
Turbocharging

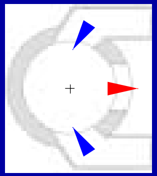
Experimental verification

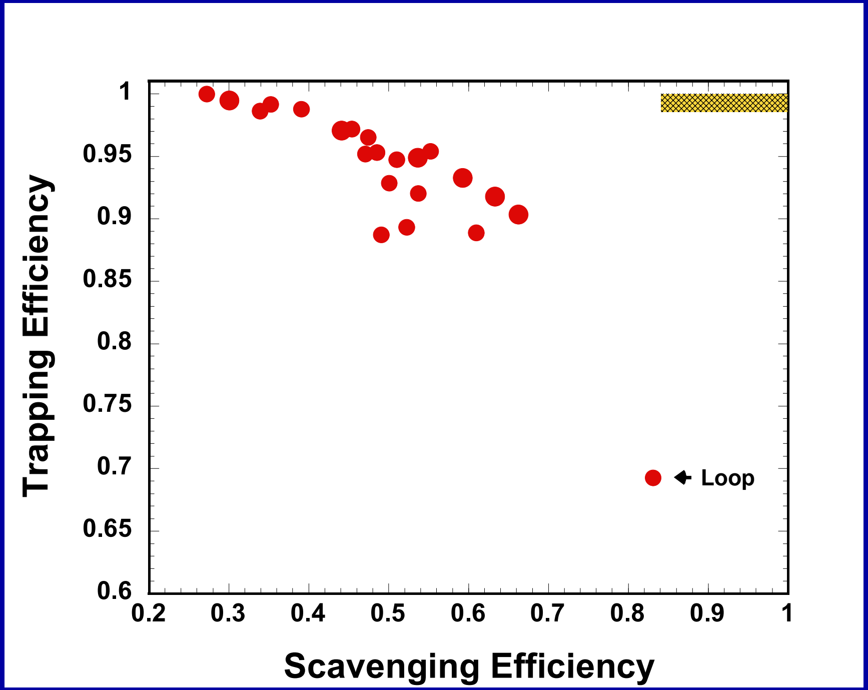
- Single-shot HCCI driven, free piston device.

Scavenging Methods

Loop



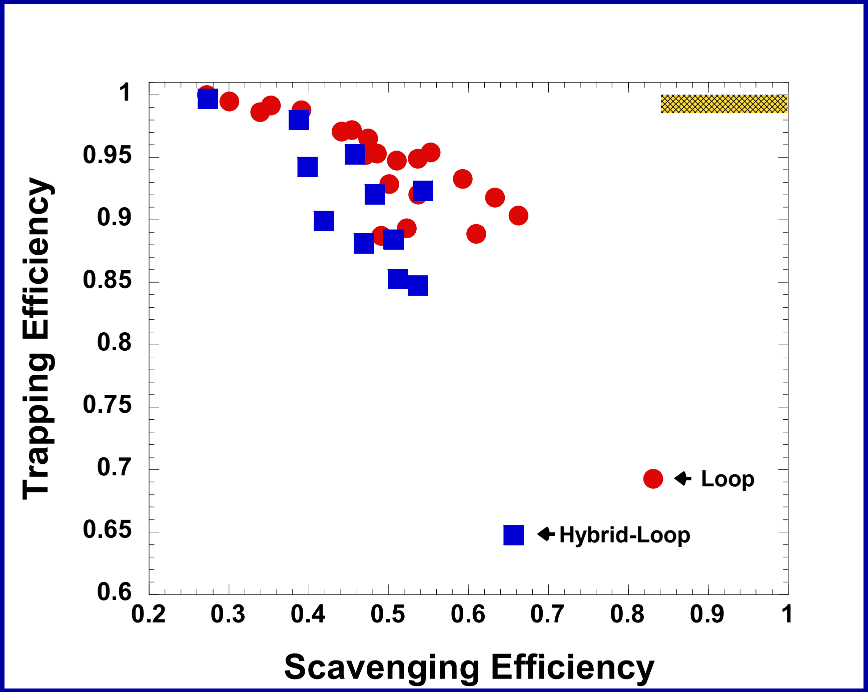




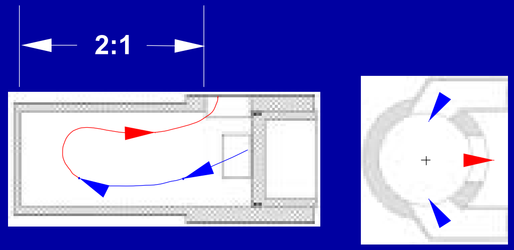
Parameters investigated

- Charging pressure
- Intake / exhaust port area and timing
- Operating frequency

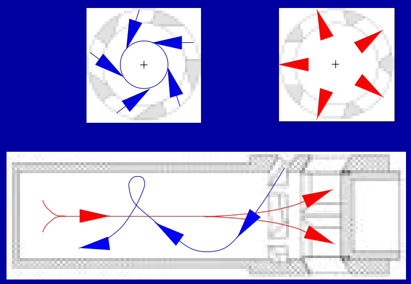
Scavenging Methods



Loop



Hybrid-loop

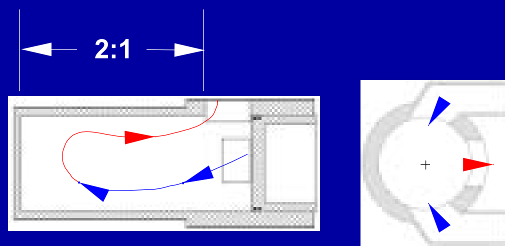


Parameters investigated

- Charging pressure
- Number & arrangement of intake / exhaust ports
- Operating frequency

Scavenging Methods

Loop



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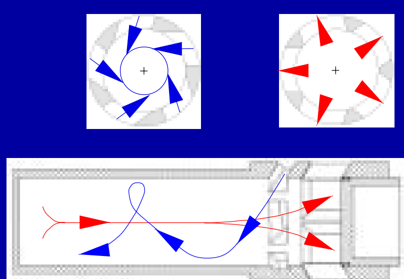
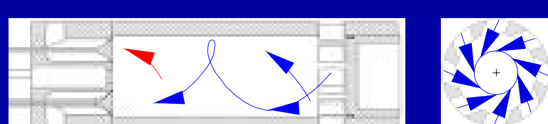
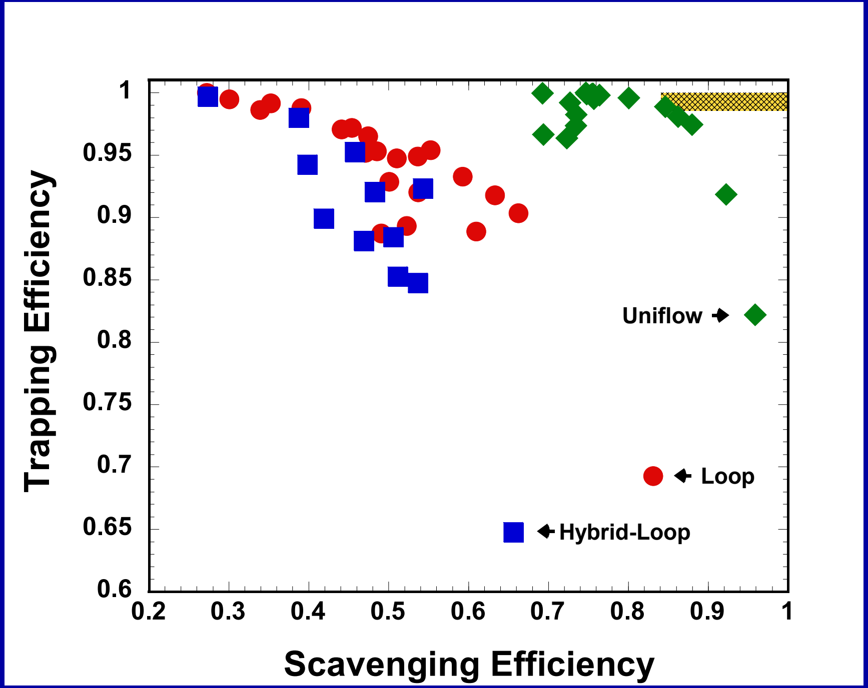


Uniflow

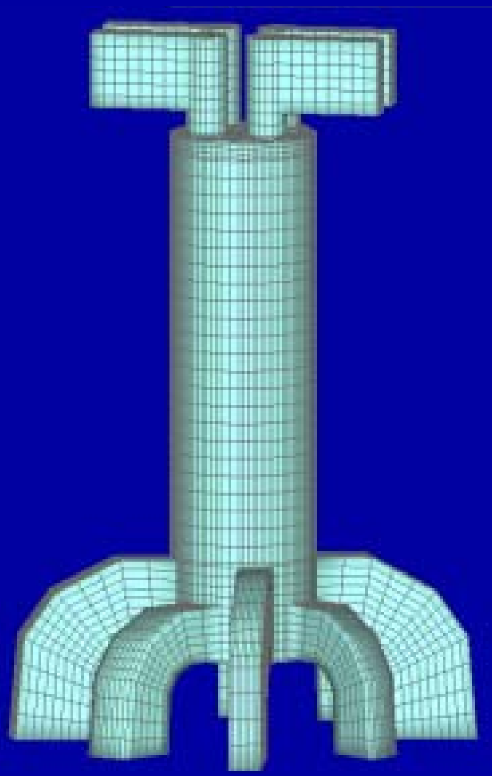




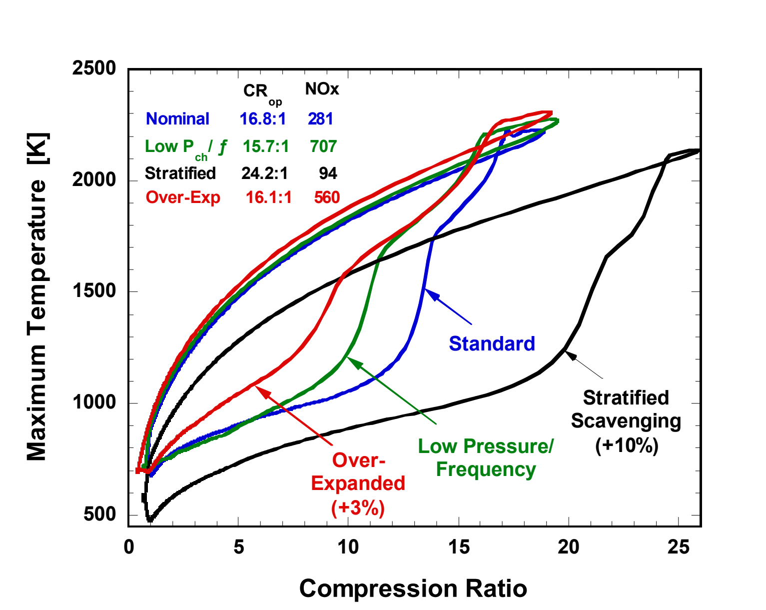
Parameters investigated

- Port / valve configuration
- Operating frequency
- Travel past port bottom

Improving the thermodynamic cycle



- Nominal uniflow configuration
- Low charging pressure / frequency
- Stratified scavenging
- Over-expanded (Atkinson) cycle



4 tall air-only ports / 4 short fuel-air ports

P_{ch} = 1.2bar, P_{ex} = 1.0bar	Bore = 7.24cm
Frequency = 45Hz	Stroke = 25.56cm
η_{sc}~0.93; η_{tr}~0.93/0.99; ϕ_{eff}~0.38	Swirl Angle = 15°

Stratified scavenging option

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Support / Collaborators

- DOE Support :

  Office of Transportation Technologies
  Hydrogen Program
  DER Program
  Sandia National Laboratory

- Government Support:

  NASA

- Collaborators:

  Caterpillar, Ricardo, Lotus, Delphi,
  UQM, Magnequench, LANL

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Summary

- Thermodynamic fuel cell provides electrochemical fuel cell like performance.
- Utilizes highly developed reciprocating engine technology.
- Near term cost will be low.
- Multi-fuel capability important.
- Provides an alternative, competitive path for hydrogen conversion.
- Meets FreedomCAR 2010 goals for internal combustion systems operating on hydrogen, or hydrocarbons.

	GOAL	Thermodynamic fuel cell
Efficiency	45%	50%
Cost	\$30 / kW	\$20 / kW
Emissions	Meet Standards	≈ 0

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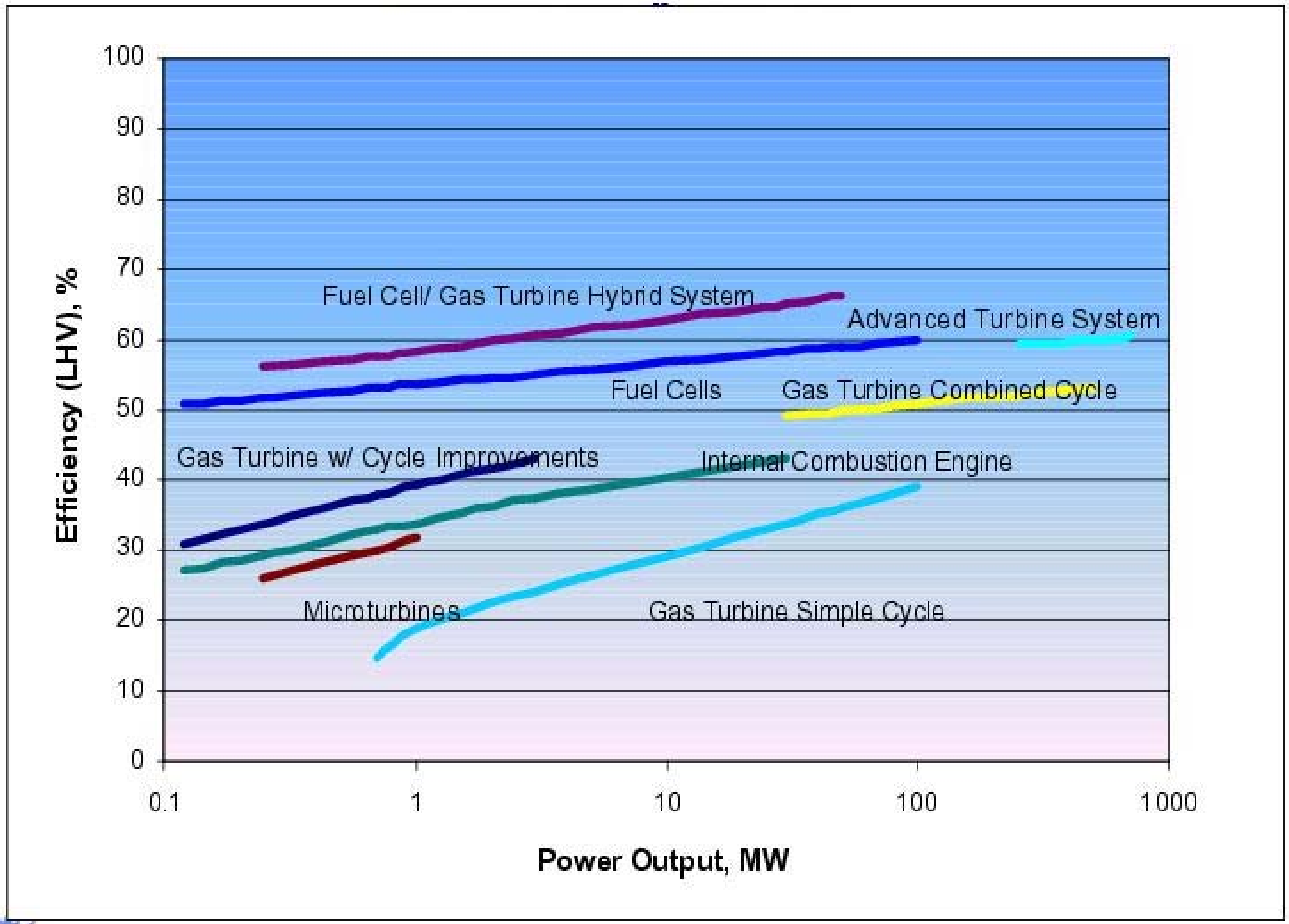
Summary – 50% fuel to electricity conversion efficiency at 30 kw is unique



David Tucker
2002

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