Argonne NATIONAL LABORATORY

Technologies for Gaseous Fueled Advanced Reciprocating Engine Systems

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Argonne National Laboratory/ ARES team
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U.S. DEPARTMENT OF ENERGY

Executive summary

Develop technologies to improve efficiency and reduce emissions of reciprocating engines that use natural gas/ opportunity fuels.

1 Distributed Energy Research Center (DERC):

- A user facility to develop/test technologies to improve DE performance.

2 Advanced Laser Ignition System (ALIS):

- Laser ignition was shown to extend lean ignitability of methane-air mixtures up to $\phi = 0.5$.
- Besides improving ignition probability, laser ignition enabled efficiency improvements up to 3% points, and/or NO_x emissions reductions up to 70%.
- Developed a prototype laser ignition system for a 6-cyl engine; demonstration pending completion of engine test cell.

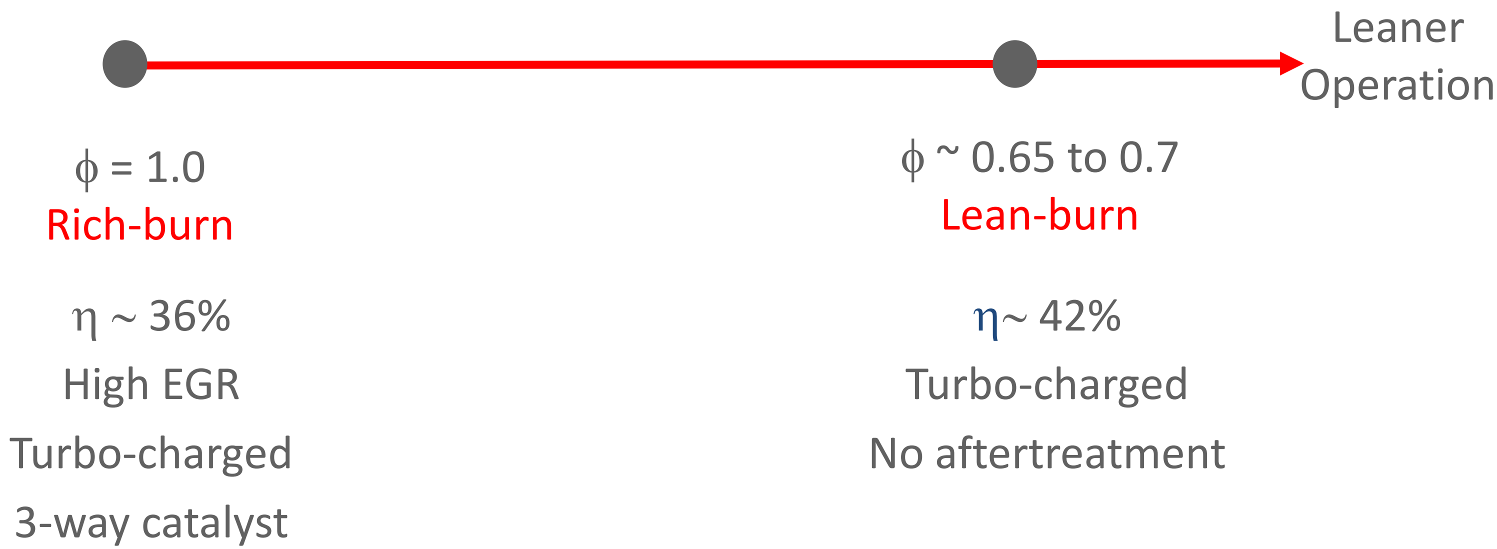
3 Nitrogen Enriched Air (NEA):

- NEA is a clean alternative to Exhaust Gas Recirculation; hardware durability is improved as obnoxious particulate and acidic species are avoided.
- NO_x emissions reduced up to 50% with modest efficiency penalty.

4 Diagnostics for engine metrics:

- Developed advanced diagnostics for in-cylinder temperature, rate of heat release, local equivalence ratio and in-cylinder EGR fraction.

Project objectives



- Develop in-cylinder technologies for emissions and performance improvement of natural gas fueled engines.
- Aim to improve performance of both existing as well as newer engines.
- Develop prototypes for high-risk high-return concepts for both lean-burn as well as rich-burn engines.
- Develop advanced diagnostics for combustion assessment in production engines.
- Research use of opportunity fuels – syngas, digester gas, landfill gas, etc.

1 Distributed Energy Research Center

- A user facility for advanced DE technologies

Capstone

Cummins

altronic
HOERBIGER Engine Solutions

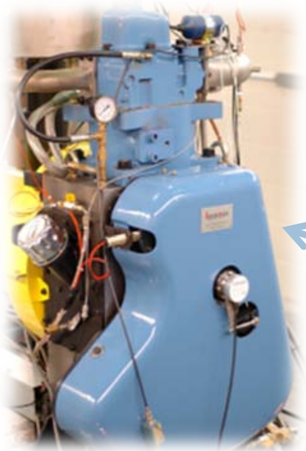
PACKER ENGINEERING Inc.

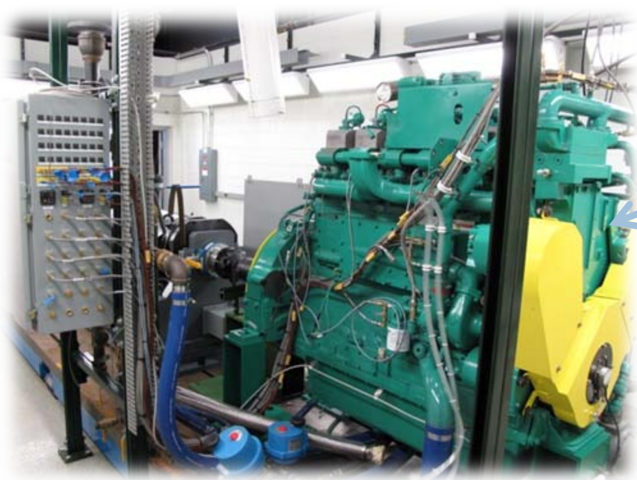
CMS Compact Membrane Systems, Inc.

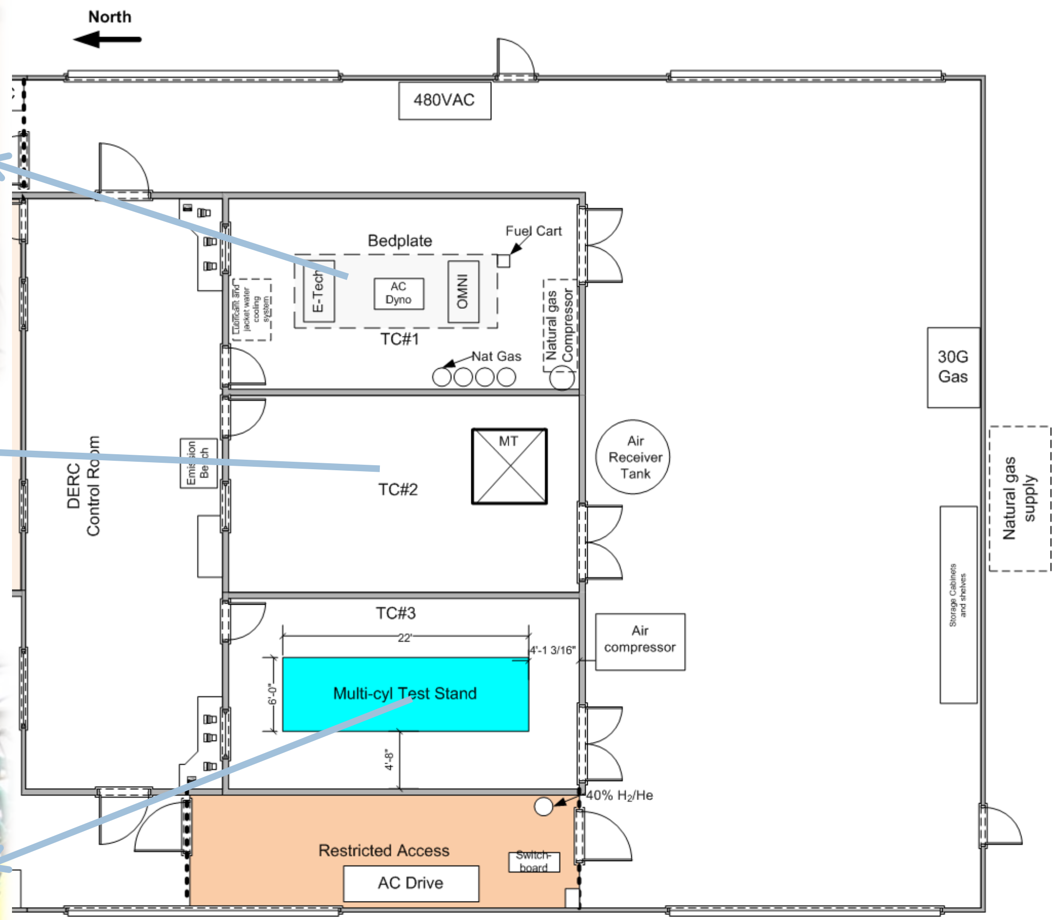
The University of Akron

PURDUE UNIVERSITY

DERC: A user facility for industry/ universities/ national labs to test/develop advanced DE technologies







Nov. 2010

2 Advanced Laser Ignition System

Current spark ignition systems cannot meet the demands of stationary natural gas engines

- Capacitance Discharge Ignition (CDI) Systems cannot generate the needed voltage across the spark gap

Current engine BMEP: ~ 18 Bar
(AVL, ASME ICES2005-1094)

Target BMEP: 25 Bar

Lean operation ($\phi < 0.65$)
High boost pressures
High BMEP levels

→ High in-cylinder densities require ignition voltages > 40 kV

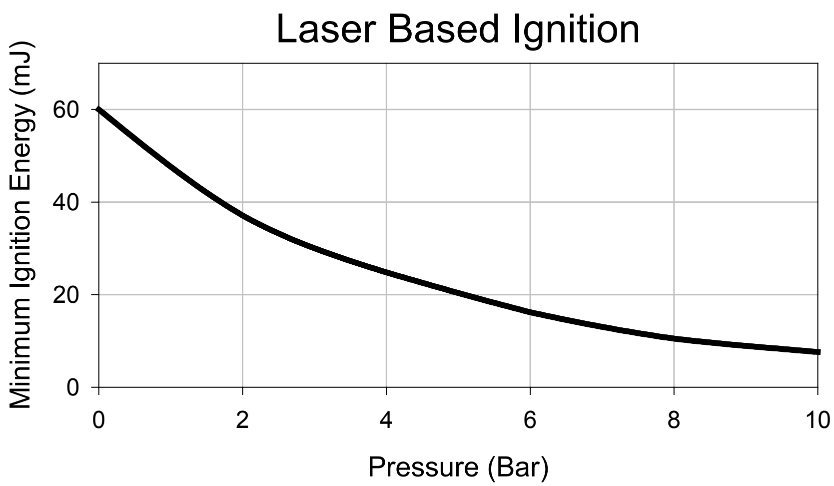
- Though noble metal (Platinum & Iridium) electrodes are used, durability of spark plugs is still a concern

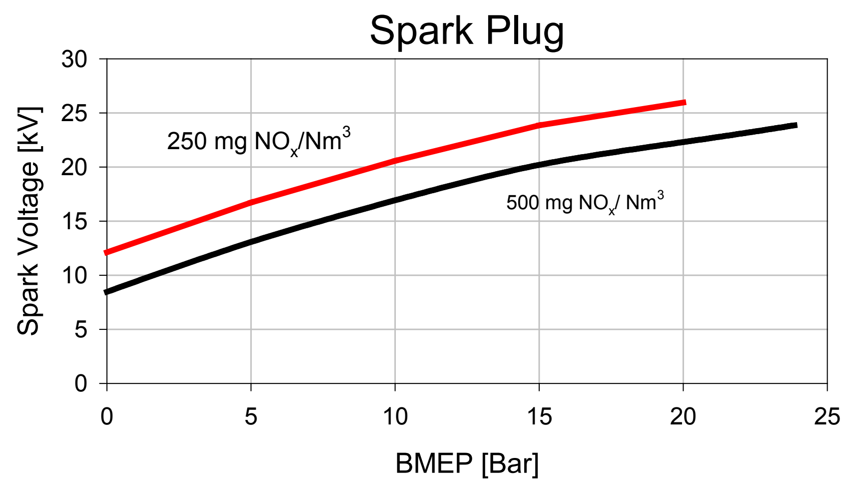
Spark gap adjustment interval

Current: 1000-3000 hrs.

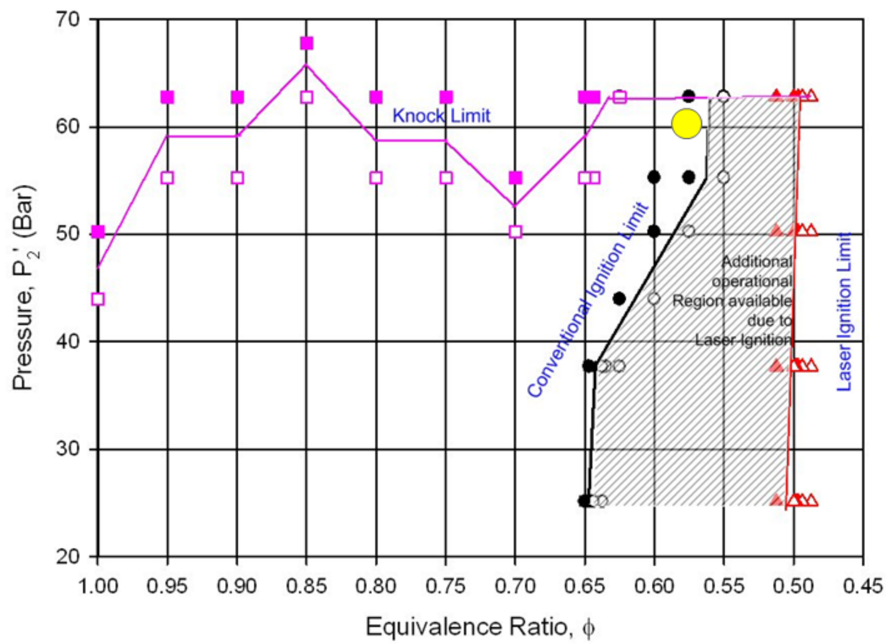
Target: 8000 hrs.

Benefits/ Technical approach



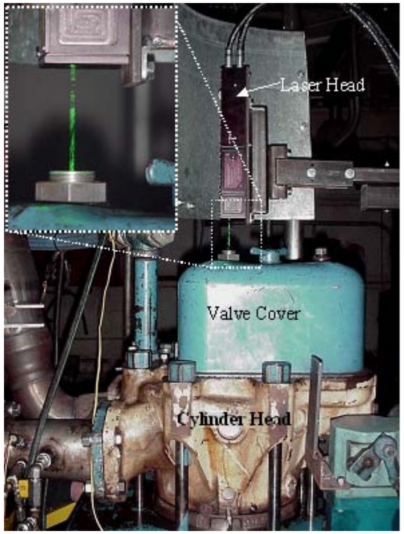


- Ignition of mixtures at higher pressures
  - *- Higher BMEPs → Higher engine efficiencies*
- Ignition of leaner mixtures
  - *- Lower NO_x emissions*
- Ignition kernel away from walls
  - *- Less heat transfer losses*
- Ignition of lower quality fuel-air mixtures
  - *- Syn gas, sewer gas, landfill gas, (CO_2: 20-50%)*
  - *- High levels of EGR*
- Multi-point ignition possible
  - *- higher burn rates*
- No aftertreatment
  - *- could displace expensive SCR systems*

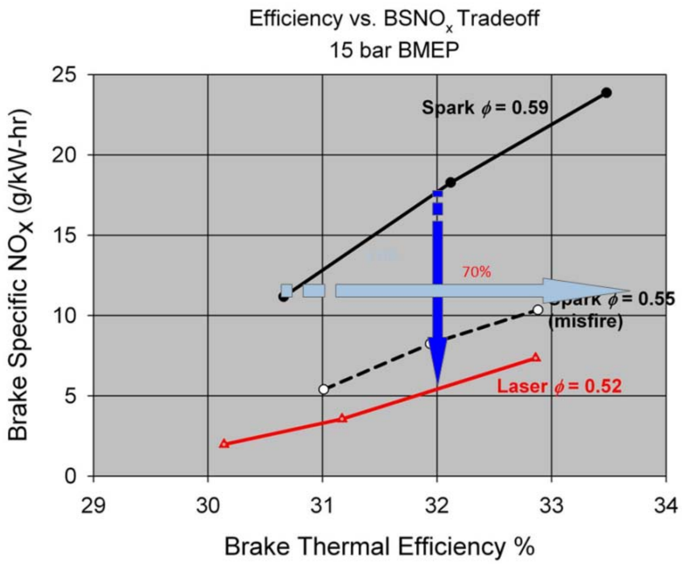


Technical accomplishments

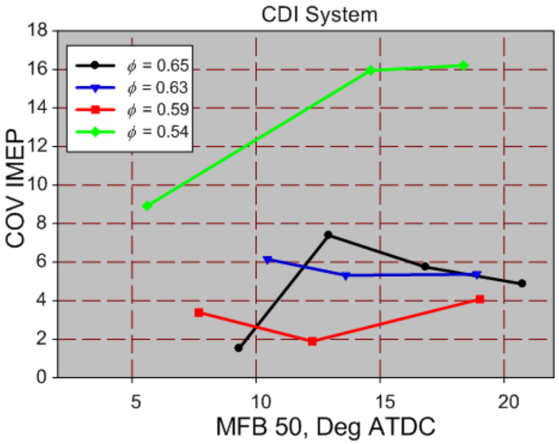
Fiber transmitted

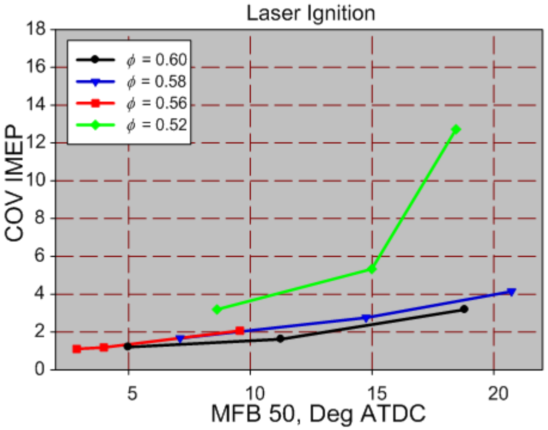


Free-space transmission



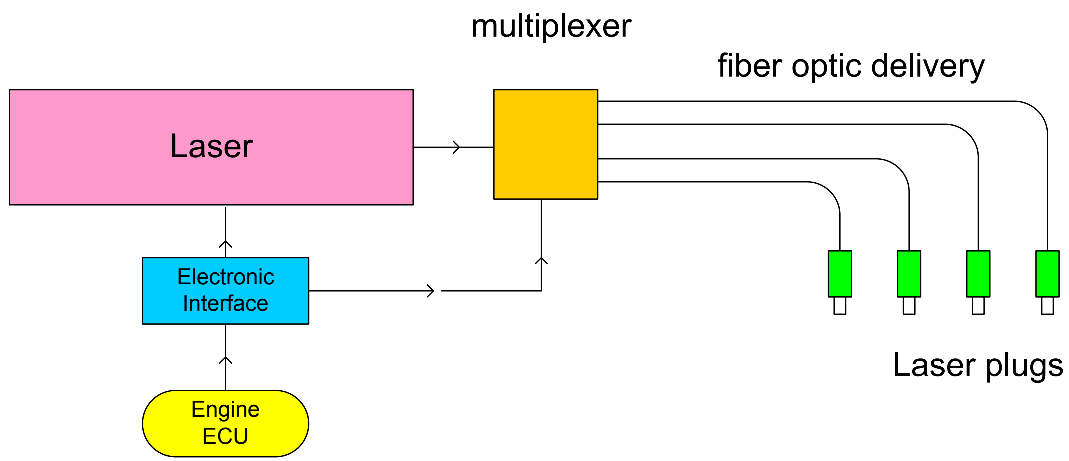
- 70% reduction in NOx emissions , and/or efficiency gains up to 3% points





- significant improvement in combustion stability.

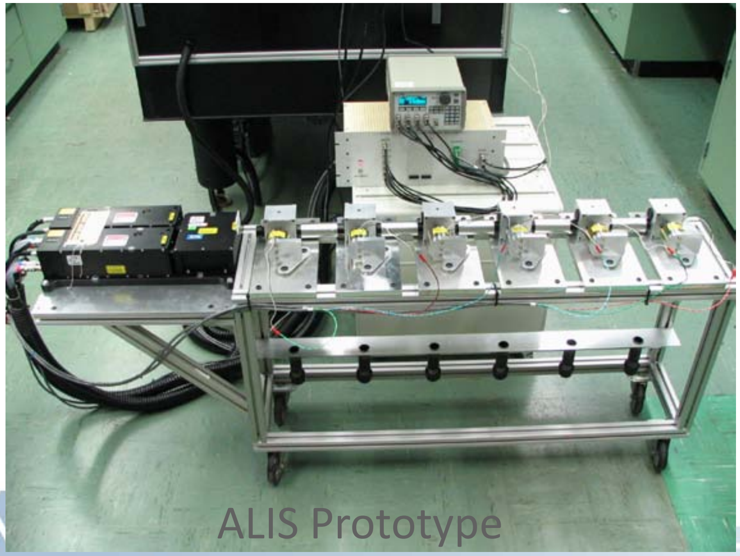
Technical accomplishments



Pulsed output of a single laser multiplexed to different cylinders.

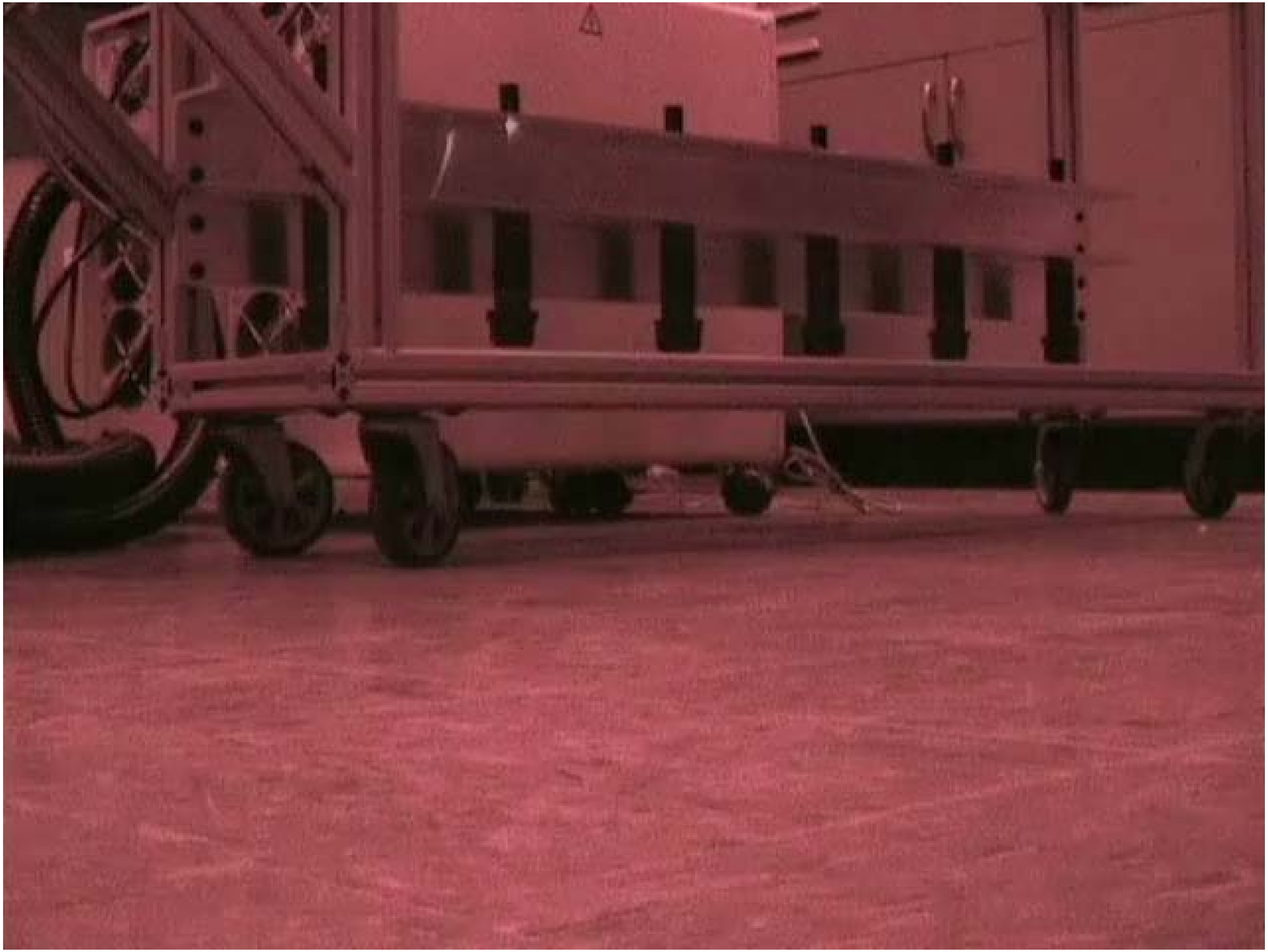
Developed a prototype system

- free space delivery had to be used as fiber transmission proved difficult



ALIS Prototype

- Limited engine tests at Cummins Technical Center
- Improvements made in the system for heat and vibration insensitivity
- Further tests pending completion of DERC test cell#3



Partial view of Argonne's laser ignition system installed on 6-cylinder engine

Laser
Beam

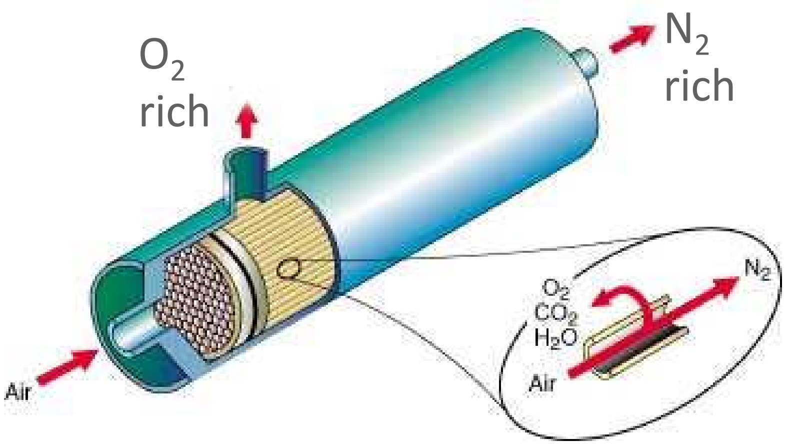
Commercialization approach

- Two patents
- US gas engine manufacturers and ignition system suppliers updated through timely reports/ meetings

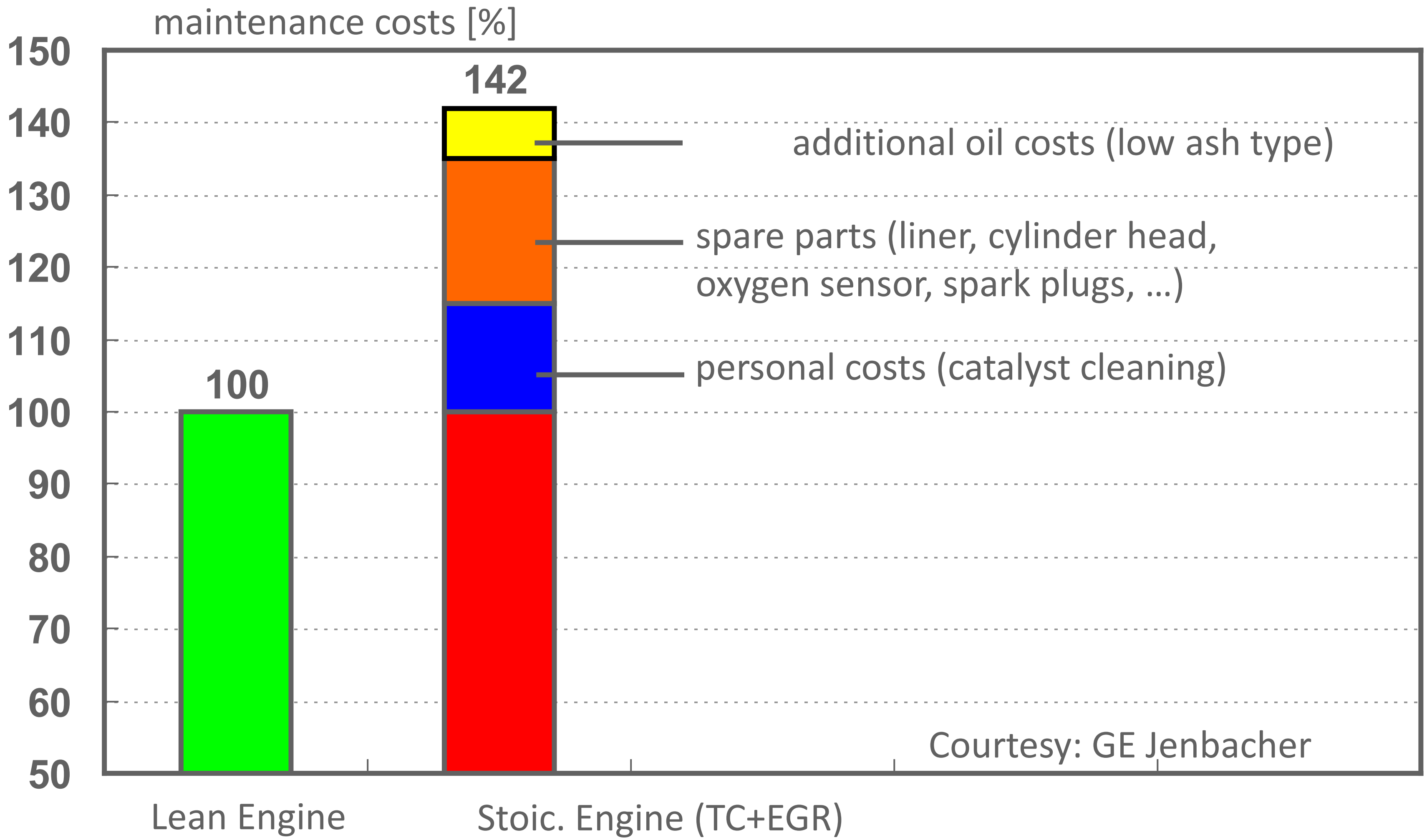
Future Plans

- Demonstrate on Argonne's Cummins 6-cyl engine
- Also, evaluate Takunori Taira's (Japan) micro-laser system

3 Nitrogen Enriched Air (NEA)

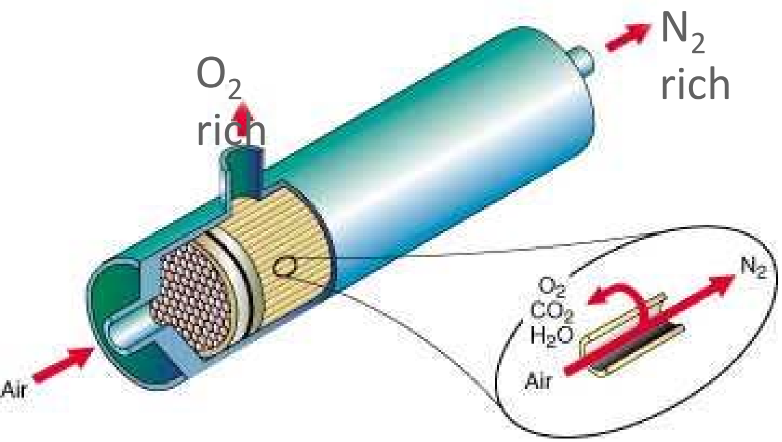


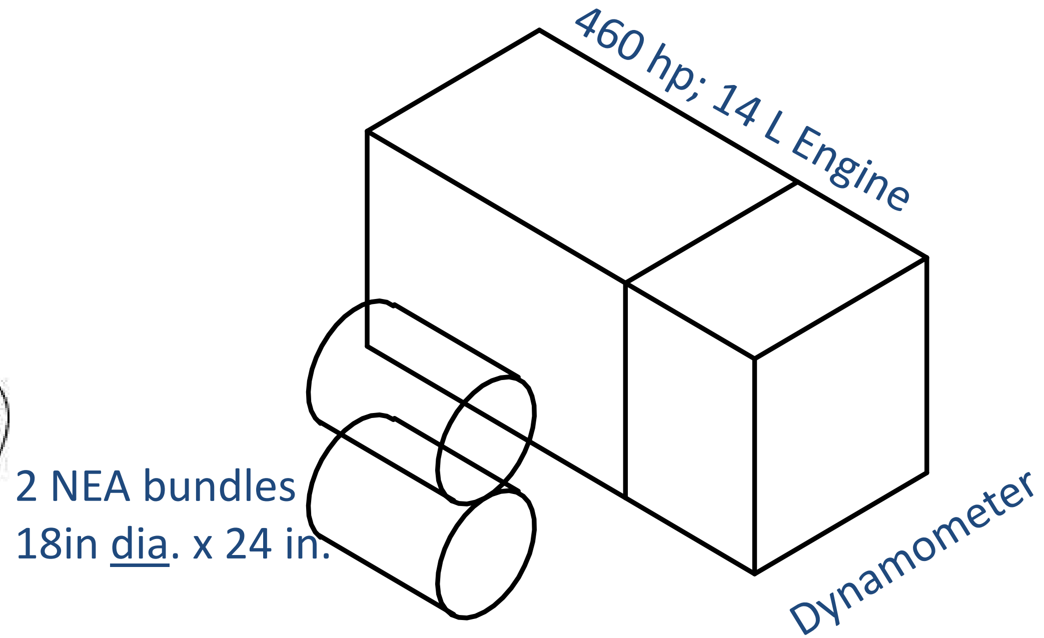
Exhaust gas recirculation leads to increased maintenance costs



Average of all customer engines 1993-2005; sum 1 Mil running hours

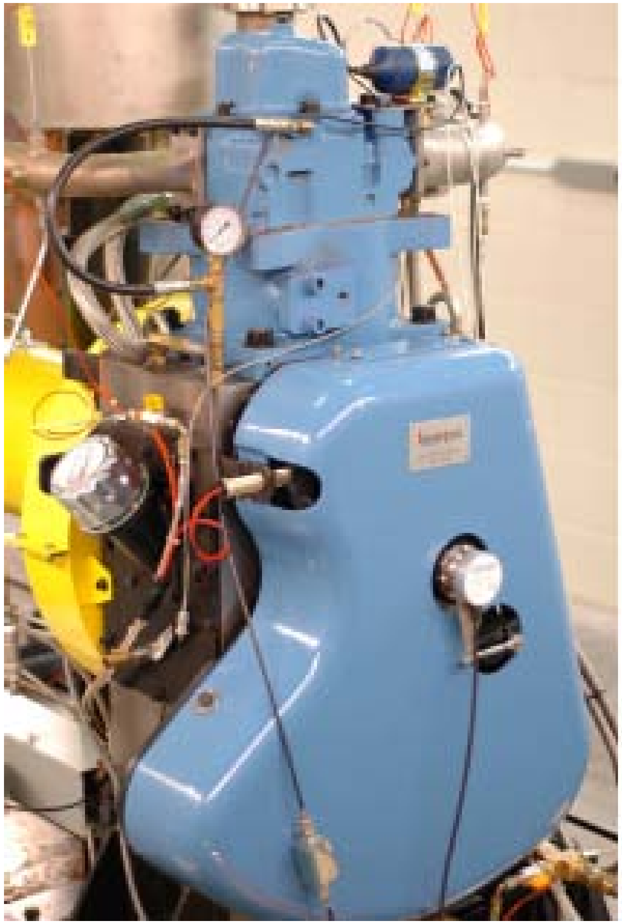
NEA is a clean alternative to EGR





- Ideal for stationary engines
- Unlike EGR, engine reliability is not compromised
- Relatively inexpensive
- 3x-4x longer lifetime compared to aftertreatment devices
- Small foot print

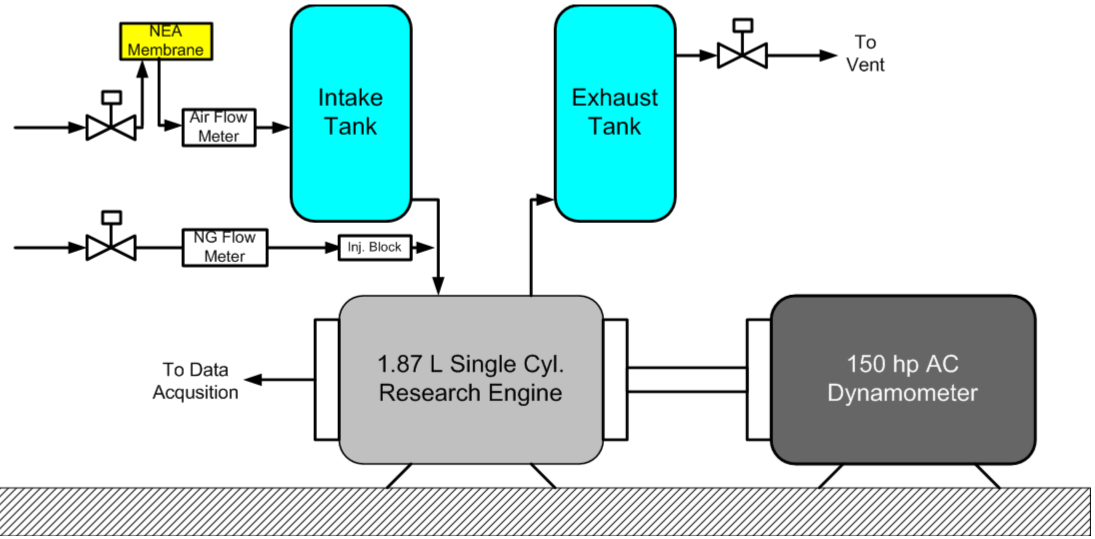
Tests were performed in Argonne's single-cylinder engine



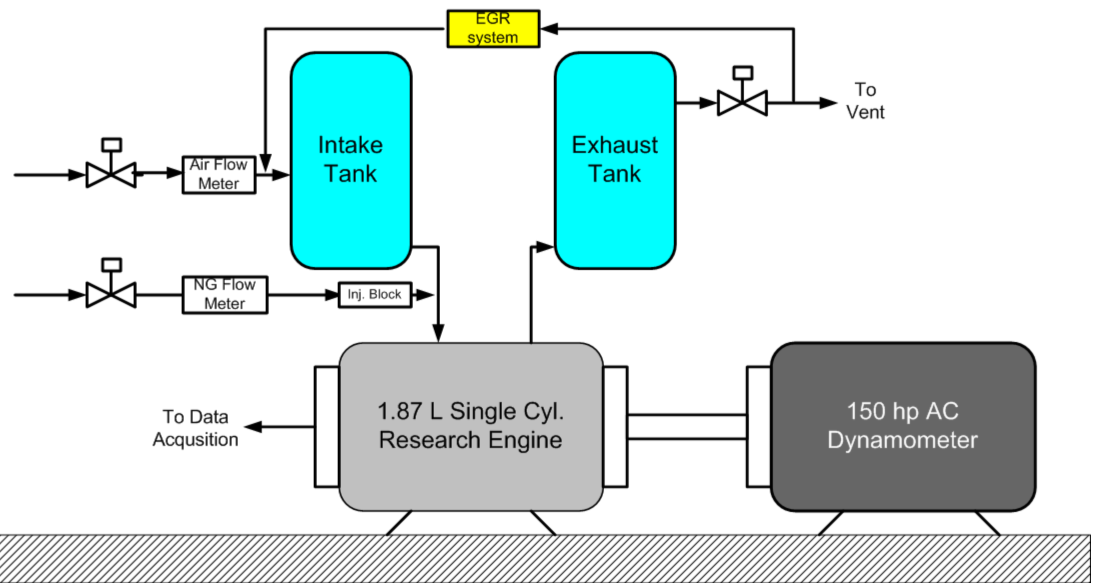
Engine Specifications	Single-Cylinder,4-Stroke, SI
Bore (mm)	130
Stroke (mm)	140
Comp. Ratio	11:1
Displacement (L)	1.857
Power (kW/hp)	33/45
Speed (rpm)	1800
Ignition System	CDI (Altronic, Inc.)

Knobs: Equivalence ratio, ignition timing, % NEA

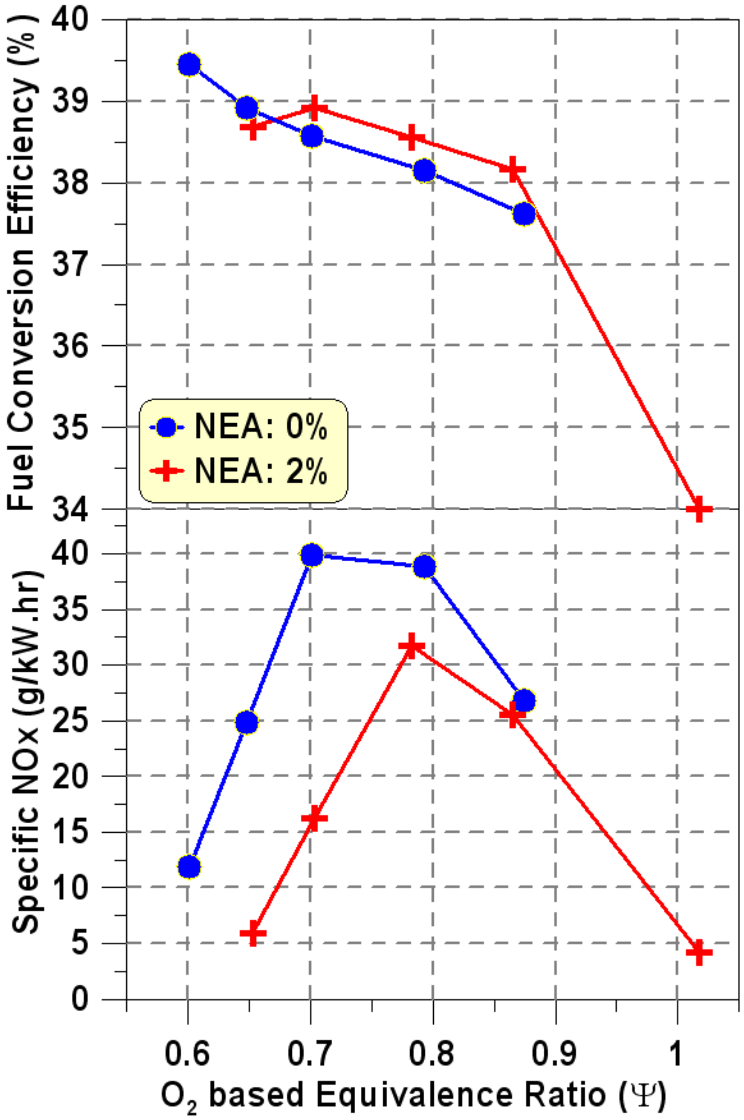
Nitrogen Enriched Air



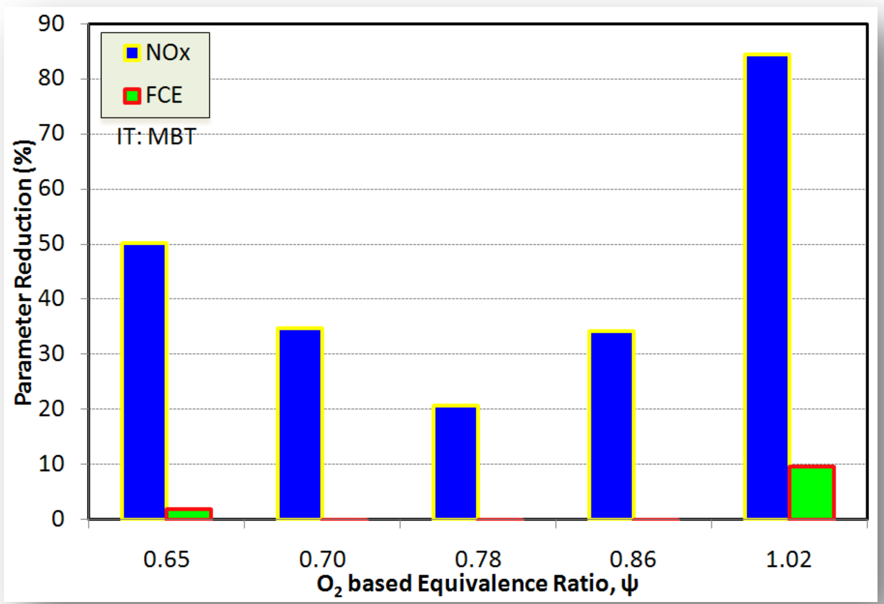
Exhaust Gas Recirculation



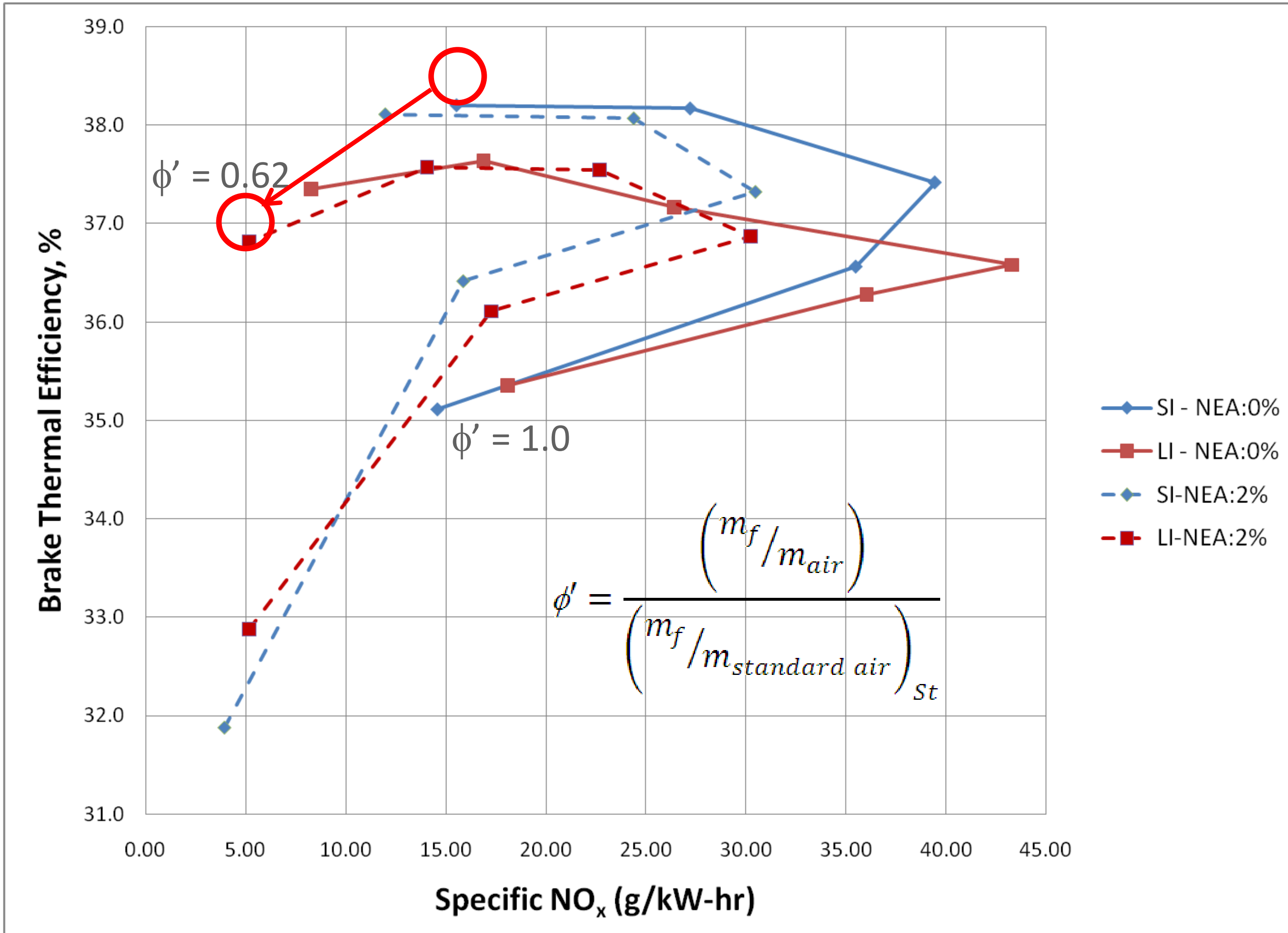
NEA offers promise for NO_x reduction



- 50% NOx reduction with modest efficiency loss under lean conditions
- Further gains possible with improved ignition

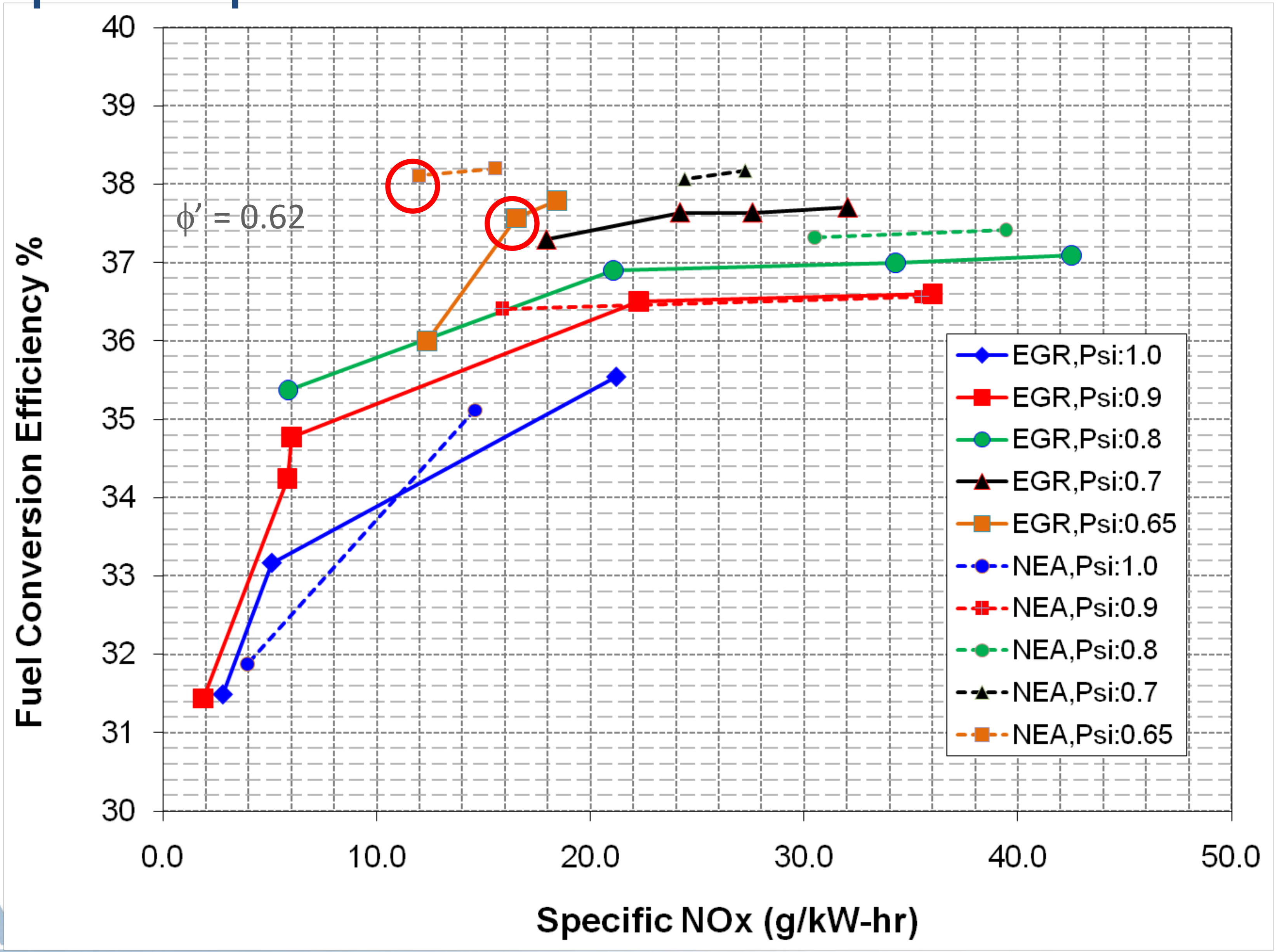


(Laser ignition +NEA) showed 67% NO_x reduction with a modest efficiency penalty



$$\phi' = \frac{\left(m_f/m_{air}\right)}{\left(m_f/m_{standard\ air}\right)_{St}}$$

Within auxiliary power uncertainty, NEA and EGR are of comparable performance



Summary

Commercialization Approach

- One patent
- Work with industries for manufacturing the needed NEA bundles

- Medarray - Compact Membrane Systems - Airproducts

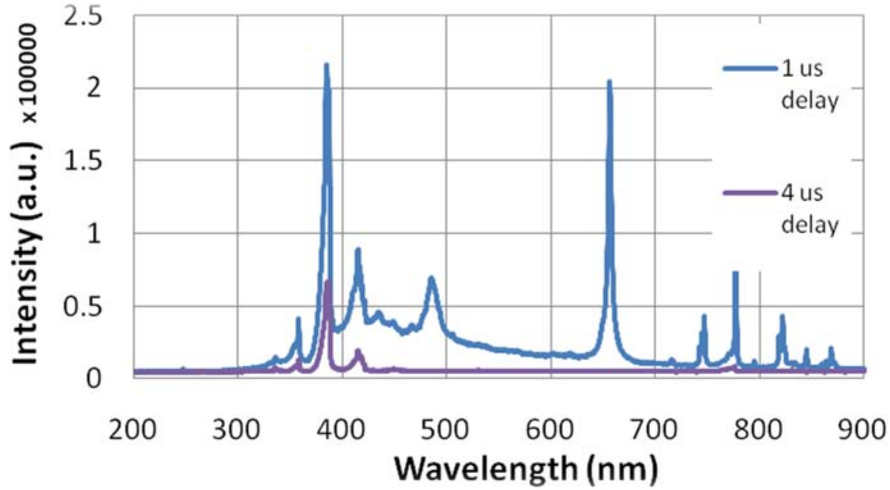
Transition and Deployment

- Retrofit technology for engines existing in the field
- Clean alternative to EGR in future engines

Future Plans

- Demonstrate on Argonne's Cummins 6-cylinder engine

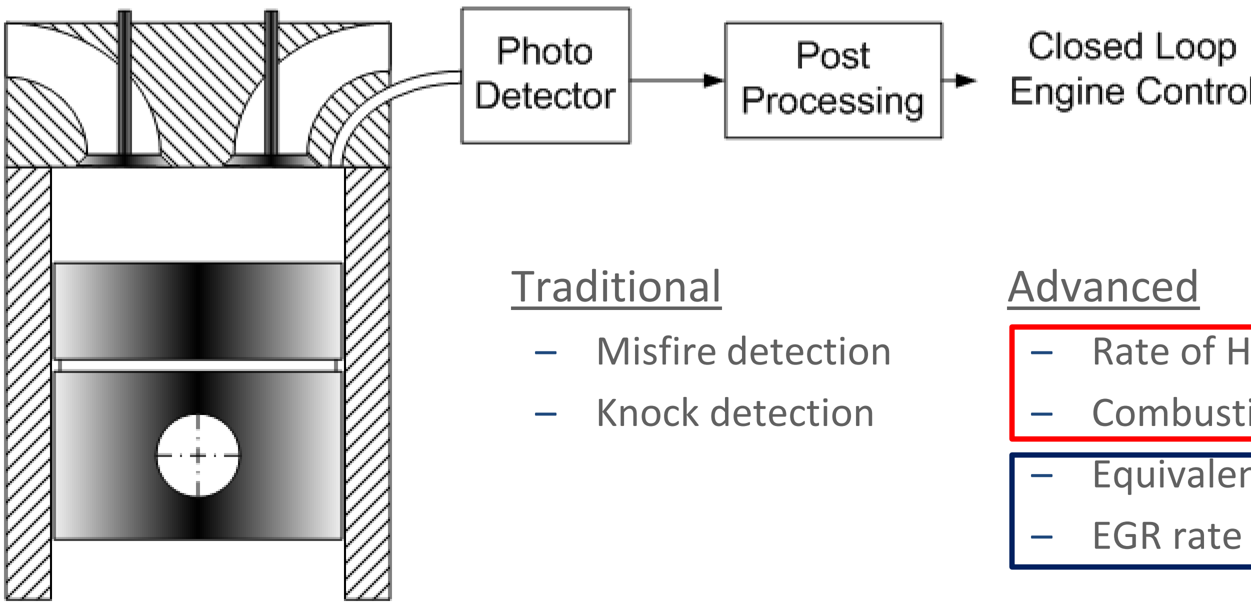
4 Diagnostics for Combustion Metrics



Motivation

- To address the lack of spectral information for natural gas combustion in reciprocating engines (pressures up to 120 bar)
  - A request from Cummins

- To develop advanced diagnostics that are enablers for low-polluting combustion strategies



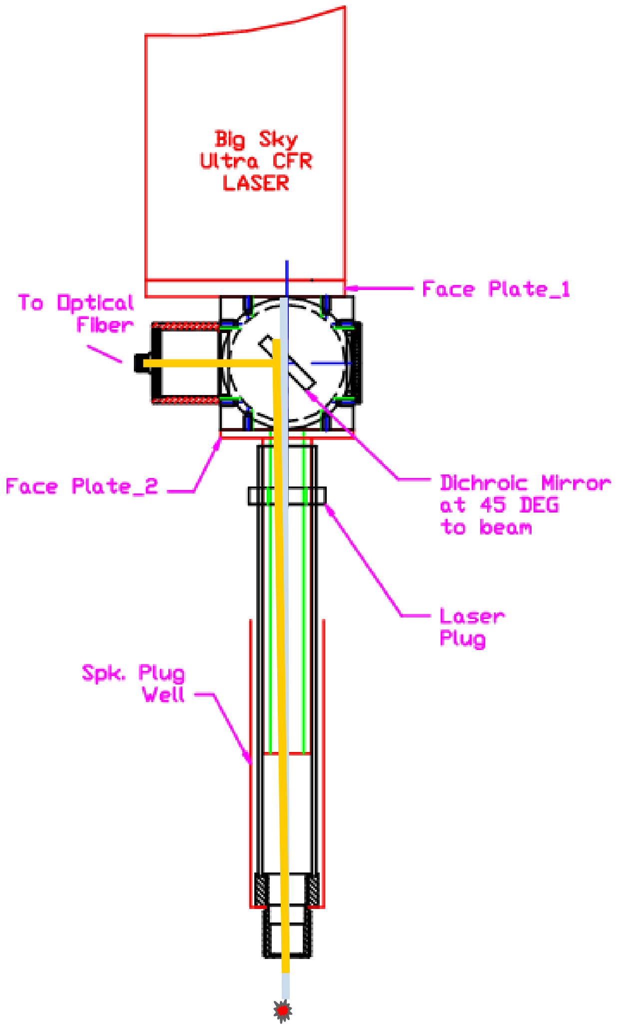
Traditional
- Misfire detection
- Knock detection

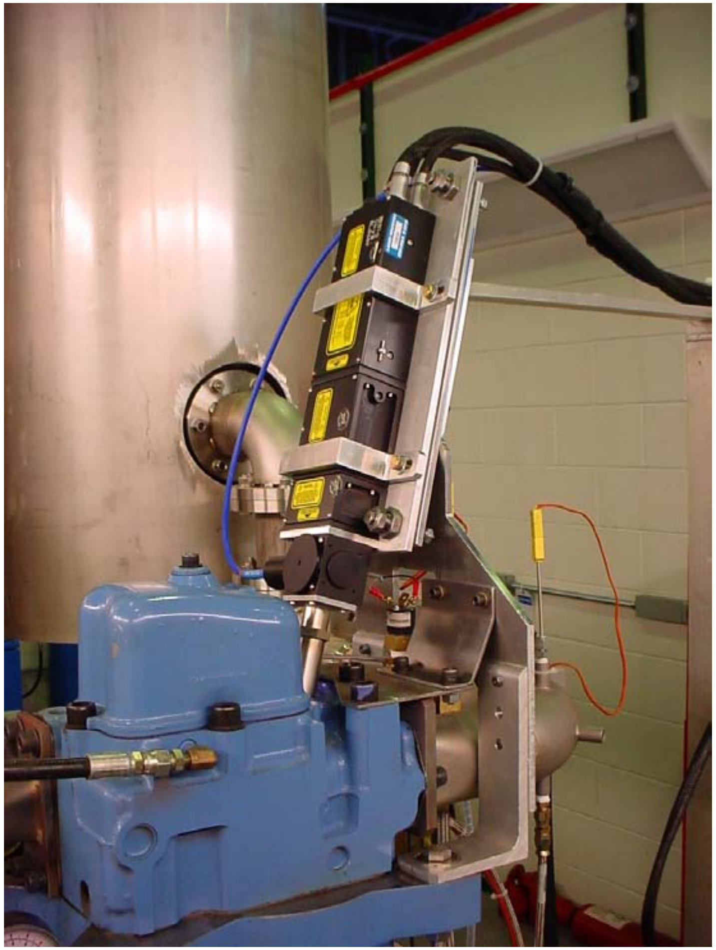
Advanced

Spectroscopy
- Rate of Heat Release
- Combustion Temperature

LIBS
- Equivalence Ratio
- EGR rate

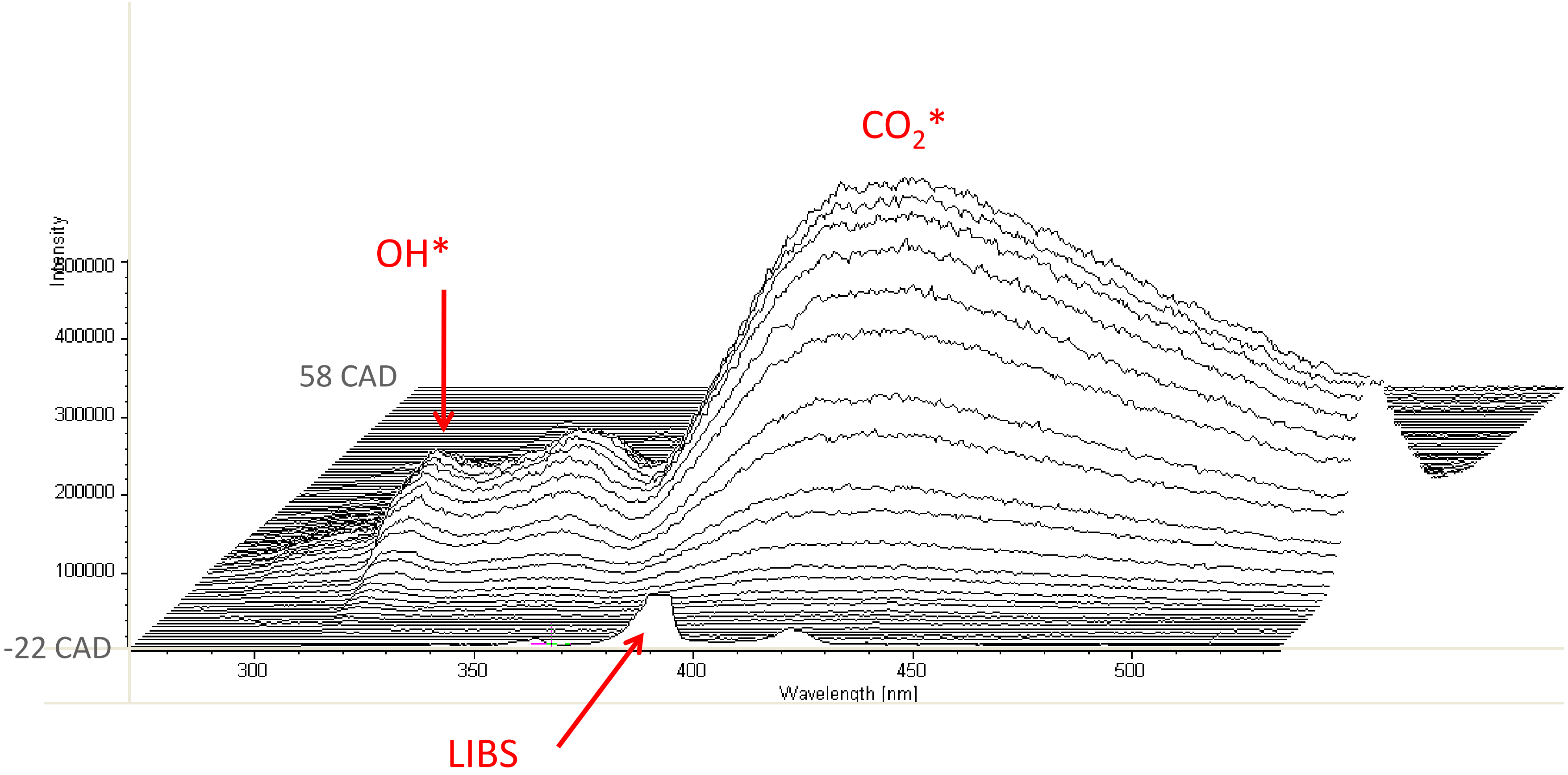
Test setup



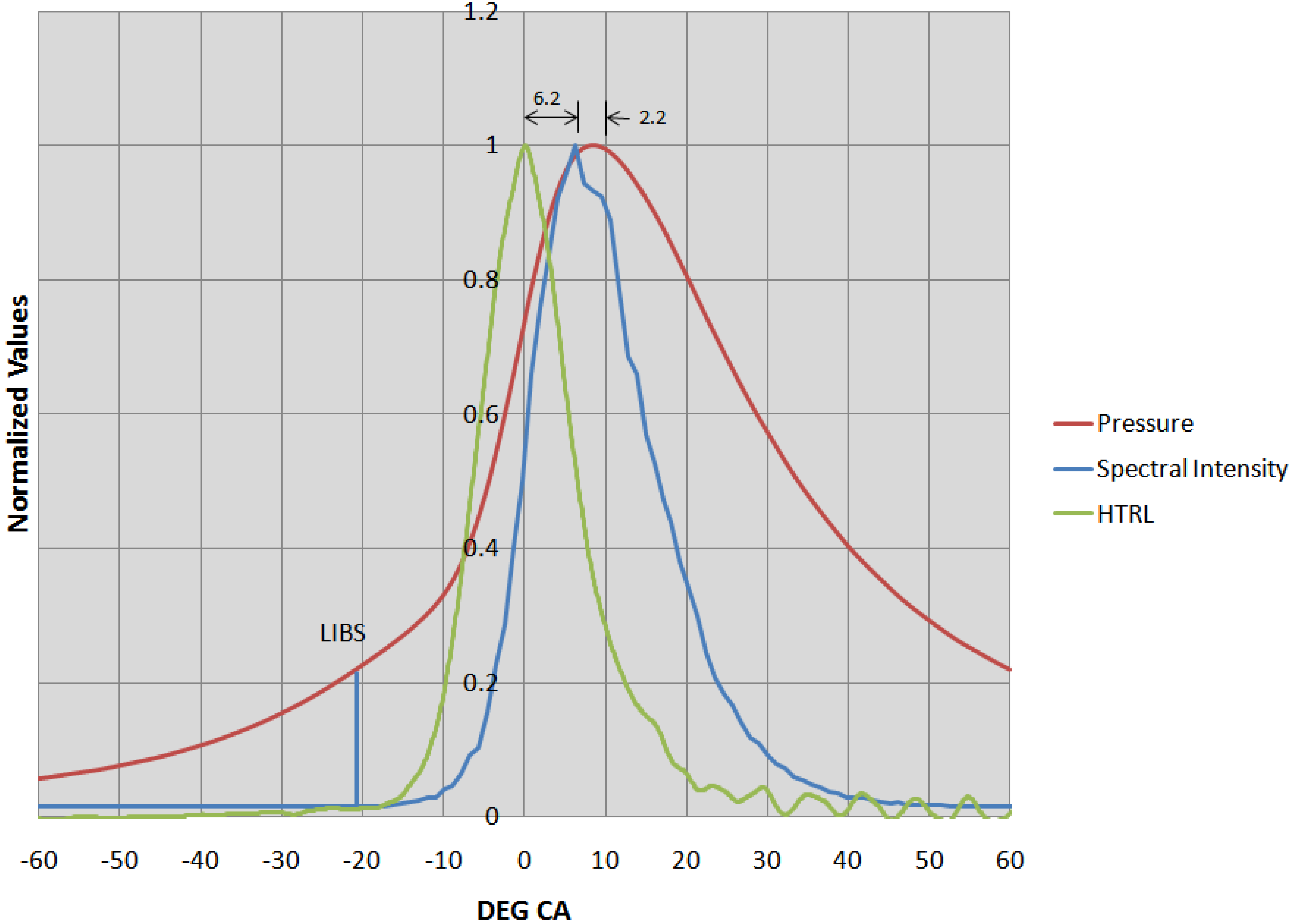


Test Matrix: Equivalence ratio (0.6 to 1.0); EGR (up to 19%)

Time evolution of combustion spectra 272 - 534 nm

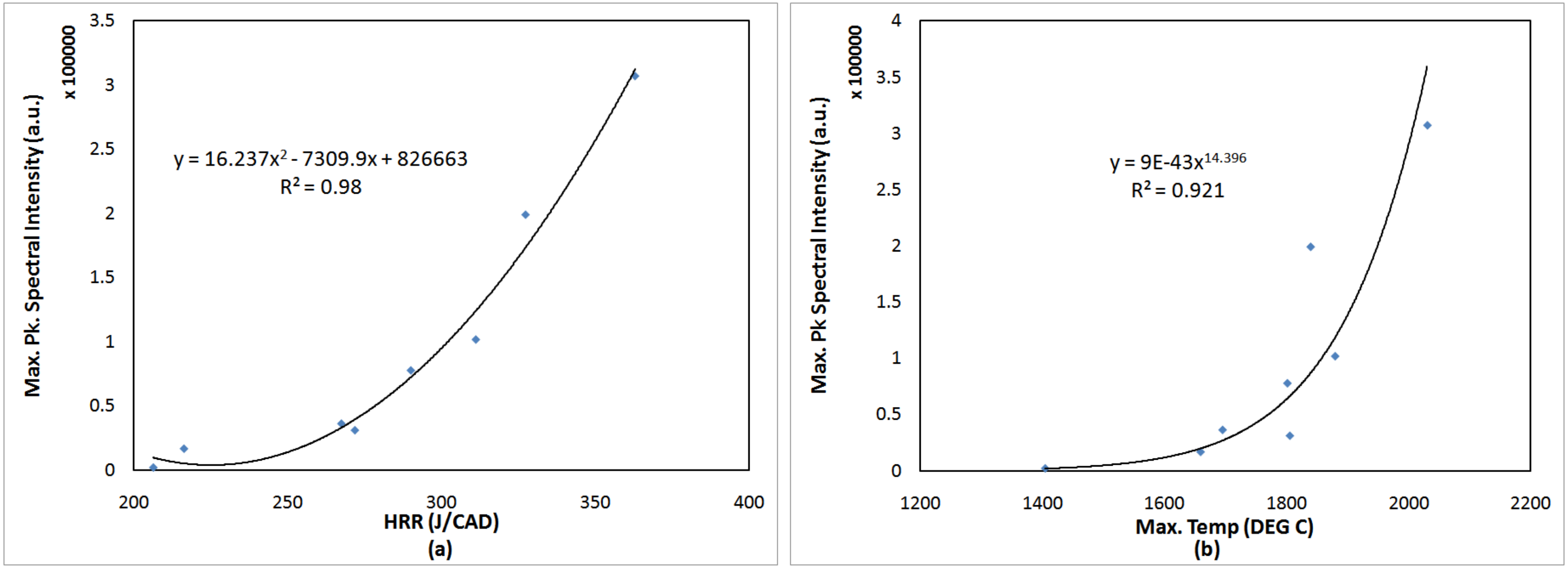


- One spectra obtained per DEG CA from Start of ignition
- Contribution from CH* (431.4 nm) and C2* (473 & 516 nm) species is insignificant



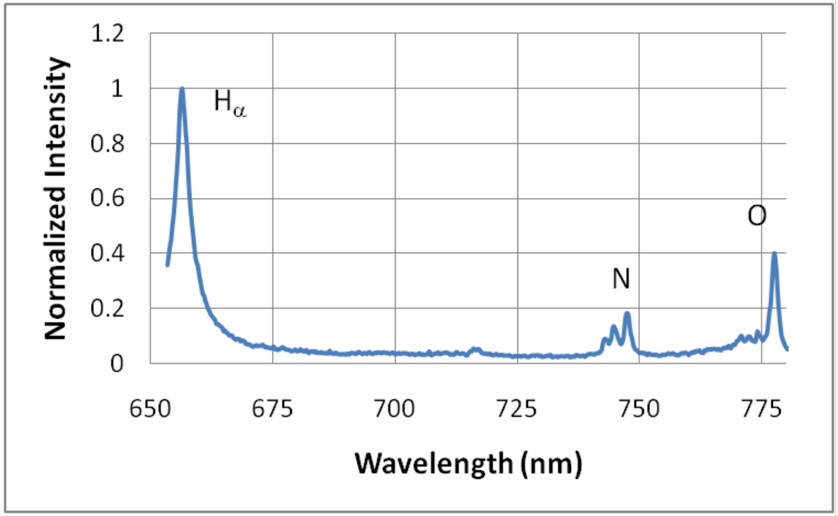
Normalized Values
DEG CA
1.2
1
0.8
0.6
0.4
0.2
0
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60
6.2
2.2
LIBS
Pressure
Spectral Intensity
HTRL

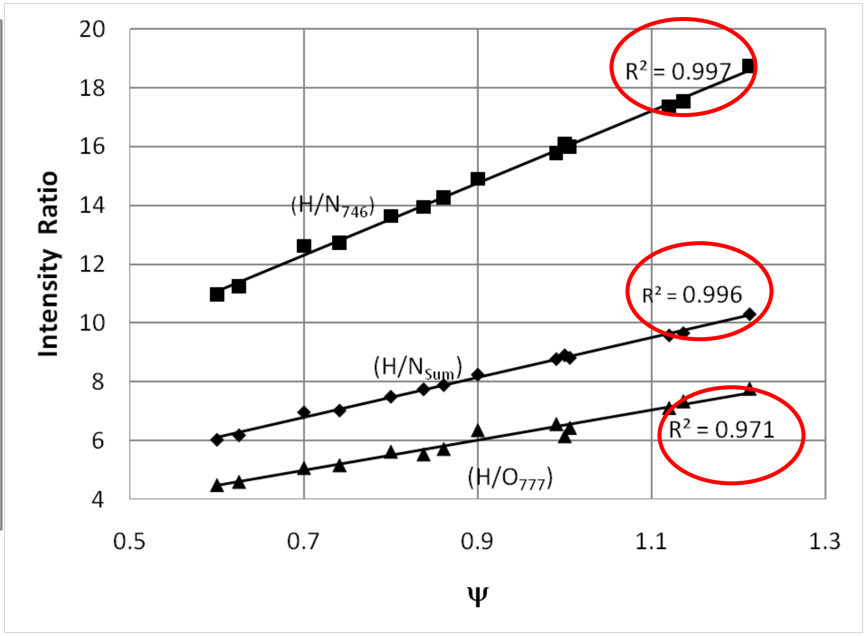
Peak CO_2* signals correlated with peak cycle temperatures and with peak Heat Release Rates



- Potential use of flame emission to monitor Heat Release Rate & Peak cycle temperature in natural gas engines

Laser Induced Breakdown Spectroscopy (LIBS) enables measurement of In-cylinder equivalence ratio





- EGR rate can be calculated with the knowledge of global equivalence ratio

$$\psi = \frac{(m_f/m_{O_2})}{(m_f/m_{O_2})_{st,EGR=0}}$$

Notable milestones in DERC's progress

Patents

- **A Method to Distribute High-Energy Laser Pulses to Multiple Channels**, US patent 7,699,033 B2.
- **Laser Based Ignition System for Natural Gas Reciprocating Engines, Laser Based Ignition System Having Capability to Detect Successful Ignition Event, And Distributor System for use with High-Powered Pulsed Lasers**, *US Patent 7114858*.
- **Nitrogen Enriched Combustion of a Natural gas Internal Combustion Engine to Reduce NOx Emissions**, *US patent 7455046*.

Invention Disclosures

- IN-10-016 and IN-10-045 : **Radiant Emission Based Methods for Measurement of Combustion Metrics in an IC Engine.**

Significant Publications (out of 30+)

- **In-cylinder Equivalence Ratio Measurements in a EGR Equipped Engine**, *JEGTP*, (Vol. 133, Issue. 11), Nov. 2011.
- **On use of CO_2* Chemiluminescence for Combustion Metrics in Natural gas Fired Reciprocating Engines**, *33rd International Symposium on Combustion*, Beijing, China, August 1-6, 2010.
- **Air Separation Membranes: An Alternative to EGR in Large Bore Natural Gas Engines**, *Journal of Engineering for Gas Turbines and Power* (Vol.132, Iss.8), August. 2010.
- **Low Temperature Combustion Using Nitrogen Enrichment to Mitigate NOx From Large Bore Natural Gas Fueled Engines**, *Journal of Engineering for Gas Turbines and Power* (Vol.132, Iss.1), Jan. 2010

Project status

1. Laser Ignition on multi-cyl. engine (In Progress)
2. NEA tests on single-cylinder engine (Completed)
3. Diagnostics development (LIBS, CO2*, OH*) (Completed)
4. DERC Multi-Cylinder Engine Test Cell (TC#3) (In Progress)
5. Opportunity fuels research (Future)

Future plans

Future efforts will address

- Opportunity fuel research
  - Digester gas, landfill gas, syngas, woodgas etc.
  - Infrastructure to be established soon.
- Advanced ignition systems
- Diesel micro-pilot ignition
- Reformer gas enrichment

Questions?