California Advanced Reciprocating Internal Combustion Engine (ARICE) Program and Collaborative – Status and Update

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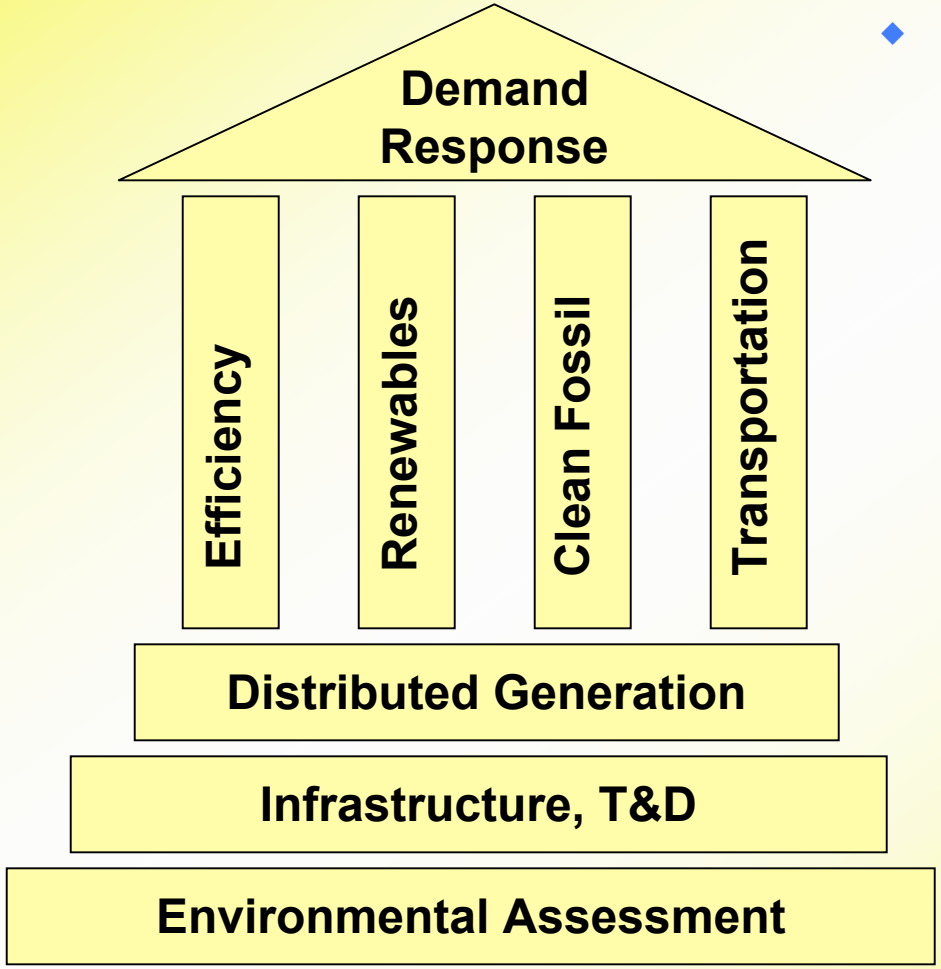
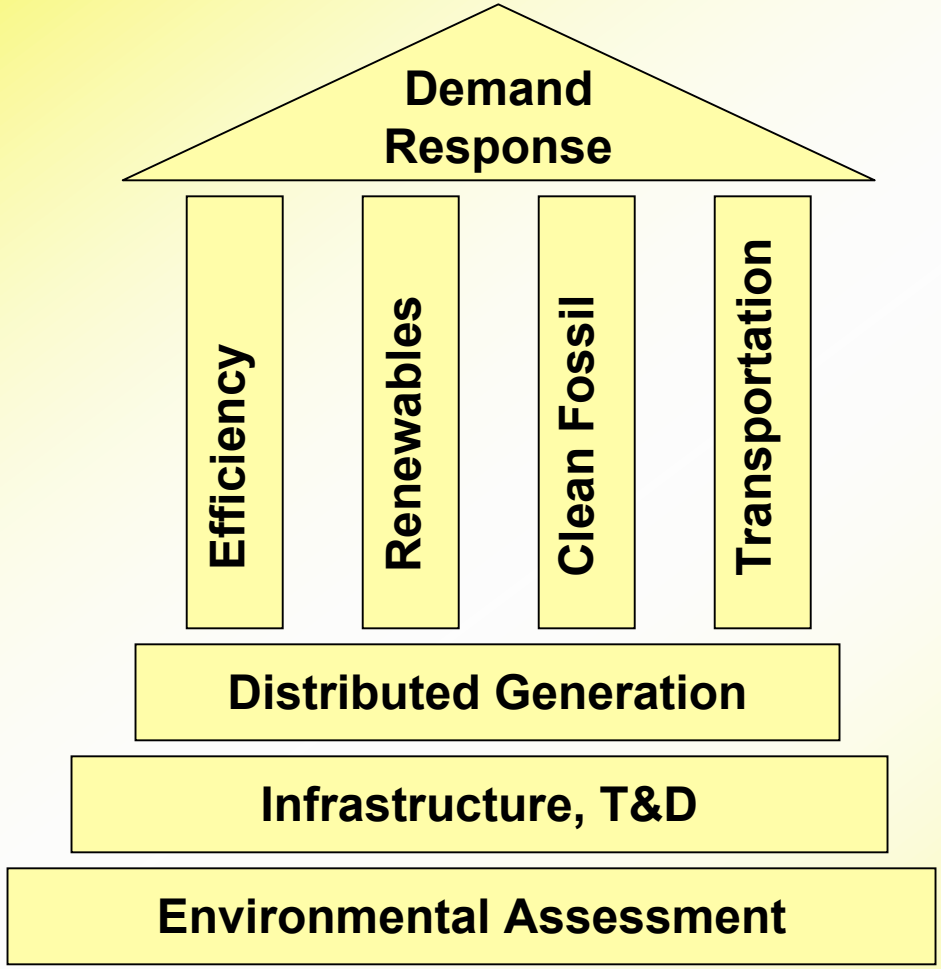
3rd Annual Advanced Stationary Reciprocating Engines Meeting,
Argonne National Laboratory, Argonne, IL
June 28 – 30, 2006

California's Public Interest Energy Research Program is directed by law and CEC policy guidance (Krebs, 2006)



- PIER was established in 1997 as part of Electricity Restructuring
  - $62.5 M annual funding for electricity research
  - Expanded in 2005 by CPUC rule to include natural gas research; will provide $24M by 2009
  - Maintains capacity for applied energy research of benefit to electricity and natural gas ratepayers
  - Leverages public and private investments to advance energy-related S&T to inform California decision makers and provide Californians with clean, affordable energy services

ARICE Technology Connects to Expectations for PIER



- Reliable, Affordable, Clean, Efficient Electricity Generation
  - Central Station
  - Balance for Variable Renewables
  - Distributed Resources (ARICE, MTGs, Fuel Cells)
    - Located close to Loads
    - Mitigates Congestion
    - Combined Heat and Power
    - Sustainable Communities
- Reliable, Affordable, Clean, Efficient Transportation
  - Alternative / Renewable Fuels
- Can reduce Green House Gases in combination with Renewables or Carbon Sequestration

Reciprocating Internal Combustion Engines

- Mature technology used for standby emergency power and back-up generators.
- ~3,000 MW capacity for 300+ kW systems
- Major Problem: Poor atmospheric emissions

ARICE Goal: To develop substantially cleaner ARICE systems to add to our portfolio of modular DG technologies

California ARICE Collaborative Purpose

The purpose of the California Advanced Reciprocating Internal Combustion Engines Collaborative is to take a leadership role in facilitating the research and development (R&D) of advanced reciprocating internal combustion engine (ARICE) systems that are super-efficient and ultra-clean for distributed, mobile, emergency and other power generation and stationary applications throughout California.

California ARICE Collaborative stakeholders ~400

Industry Issues and Concerns

California ARICE Collaborative Workshop July 10, 2001

- emissions/environmental concerns,
- efficiency,
- fuel flexibility,
- operating and maintenance (O&M) cost,
- reliability, availability, maintainability, durability, usability (RAMDU)

Advanced Reciprocating Internal Combustion Engine (ARICE) systems should do one or more of the following:

- meet or exceed current and future California atmospheric emissions requirements and have other desirable environmental attributes;
- improve fuel-to-electricity conversion efficiency;
- increase the overall energy use efficiency through combined heat and power systems;
- lower or maintain current capital cost, installation cost, operation and maintenance cost, and/or life cycle costs;
- enhance reliability, availability, maintainability, durability, and usability;
- promote development of clean (alternative, renewable, and distillate) fuels;
- have multi-fuel use capabilities;
- support integration and aggregation of distributed (both Mobile and Stationary) generation and on-site generation with the power grid;
- in general, lead to the adoption and use of the improved ARICE technologies within California.

USDOE's Advanced Reciprocating Engine Systems (ARES) Program

The USDOE's ARES program, primarily for natural gas fueled engines, is well coordinated with the California's ARICE Program.

The ARES Program goals are:

- increase electric efficiency to >50% and,
- decrease emissions to <0.1 g/bhp-hr (≈0.3 lb/MW-hr) NOx by 2010.

- ARES Program's support to California's ARICE Program – Very critical.
- With ARES Program support, ARICE Program is advancing very quickly to achieve or exceed its performance targets.

Special thanks to Ron Fiskum, Raj Sekar, and Gordon Gerber

- Distributed Generation is a global phenomenon and total capacity is increasing.

Emission Performance Standards for California's DG Program (CARB) were Established in 2002

Two-tiered Emissions Standards for DG Units Exempt from Air Quality (AQ) District Permit, Certified at Manufacturer Level:

- Phase I (Effective Jan. 1, 2003): Emission Requirements based on Best Available Control Technology (BACT)
- Phase II (from Jan. 1, 2007): Central Station Power Plant Level based Emission Requirements (Technology Review by 6/2005)
- BACT Guidance for DG Units Subject to AQ District Permit Requirements
- Check with CARB for the latest information at http://www.arb.ca.gov/energy/dg/dg.htm

Performance Targets for Advanced Reciprocating Internal Combustion Engines (ARICE)

Parameter	2007	2008	2009	2010
Efficiency				
Brake Thermal Efficiency	≥35%	≥38%	≥40%	≥44%
Fuel -to-Electric Efficiency*	≥32%	≥34%	≥38%	≥42%
Overall Energy Efficien cy (CHP)	≥85%	≥85%	≥85%	≥85%
Emissions – *shaft power (g/bhp -hr)*				
Oxides of Nitrogen (NOx)	≤0.015	≤0.015	≤0.015	≤0.01
Carbon Monoxide (CO)	≤0.02	≤.02	≤0.02	≤0.02
Volatile Organic Compounds (VOCs)	≤0.006	≤0.006	≤0.006	≤0.006
Particulate Matter (PM10)	≤0.01	≤0.01	≤0.01	≤0.01
Emissions – *power generation (lb/MW $_e$hr)*				
Oxides of Nitrogen (NOx)	≤0.07	≤0.07	≤0.07	≤0.07
Carbon Monoxide (CO)	≤0.08	≤0.08	≤0.08	≤0.08
Volatile Organic Compounds (VOCs)	≤0.02	≤0.02	≤0.02	≤0.02
Particulate Matter (PM10)	≤0.03	≤0.03	≤0.03	≤0.03
Cost				
Complete Installed Cost ($/kW $_e$)	≤700	≤700	≤700	≤700
O&M Cost ($/kW $_e$h)	≤0.06	≤0.06	≤0.05	≤0.04
Availability & Durability				
Availability	≥88%	≥90%	≥92%	≥95%
B10 Durability (hour s)	≥8,000	≥9,000	≥10,000	≥12,000
Mean Time Between Major Overhaul (hours)	≥35,000	≥40,000	≥45,000	≥50,000

California ARICE Collaborative Activities (since May 2001)

Activity	Completion Date
Prepared Collaborative Plan	May, 2001
Identified and confirmed the Core Group	May 31, 2001
Identified the Advisory Group	May 29 – June 8, 200 1
Organized Workshop with Stakeholders	July 10, 2001
Released RFP/Solicitation (up to $6 million)	December 7, 2001
Received Proposals (9)	February 21, 2002
Selected three (3) Project s	By May 29, 2002
Awarded two (2) Contracts and Started Work (Waukesha - $3.0M and LLNL - $2.0M)	By September, 2002
Advanced Ignition Systems Roundtable	October 8 -9, 2002
Emissions Roundtable	February 10 -11, 2003
ANL Advanced Laser Ignition Contract - $1M	July 10, 2003
Friction -Lubrication -Parasitic Losses Meeting	July 28 -29, 2003
ANL Advanced Laser Ignition Consortium	July 29, 2003
ANL Advanced Laser Ignition Kick -off Mtg.	July 30 , 2003
Catalytic Materials Roundtable	Nov 2003
Ist Annual ARES -ARICE RD&D Conf.	April 14 -15, 2004
ASME ARES -ARICE Symposium	October 2004
2nd Annual ASRE Conference	*March 15 – 16, 2005*
ASME ARES-ARICE Symposium Ottawa	*Oct. 2005*

ARICE RFP Results

- Waukesha Engine Dresser, Inc. (WI) - $3.0 M - Develop and Demonstrate an ARICE Engine with On-board Natural Gas Fuel Reformer.
- Lawrence Livermore National Laboratory (CA) - $2.0 M - Develop and Demonstrate an ARICE Engine with Homogeneous Charge Compression Ignition (HCCI).
- Argonne National Laboratory (IL) - $1.0 Million - Advanced Laser Based Ignition Integrated ARICE System for DG in California. (ALIS Consortium)
- All 3 projects hoped to achieve Phase II CARB DG Emission Standard.

Advanced Ignition Systems Roundtable

Argonne National Laboratory, Argonne (IL), October 8 - 9, 2002

- US DoE initiated roundtable to build consortia for developing advanced ignition systems.
- Organized by ANL; Invited participants only - US DoE, CEC, ANL, LLNL, NETL, ORNL, Sandia NL, Colorado State Uni., Caterpillar, Cummins, Waukesha, SwRI, Altronic..
- Concerted effort by all, under a **single umbrella consortium**, focused on delivering ALIS integrated ARICE system within 2-3 years meeting or exceeding California's DG emission standard and ARICE performance targets.

Result:

- Argonne National Laboratory (IL) - $1.0 Million - Advanced Laser Ignition Integrated ARICE System for DG in California. (ALIS Consortium) - CEC-ANL Contract in progress. ALIS Consortium Monthly conference calls occurred since July 2003 to coordinate.

Ultra-Low Emissions Systems Development Program

Contractor: Waukesha Engine Dresser, Inc. Contract #: 500-02-002

Subcontractors:

Southwest Research Institute
CS Solutions (DVBE)
Manufacturing Resources, Inc.
Miratech
Eta-Tech
SoCalGas as Match Fund Contributing Partner

PIER Funds: $2,995,060
Match Funds: $1,893,139

Contract Start Date: 10/1/2002
Contract End Date: 3/30/2006

Project Start Date: 11/15/2002
Project End Date: 12/21/2005 (3/31/2006)

Project Goal:

Develop a natural gas engine to meet the 2007 EPAG ARICE emissions, efficiency, and installed cost targets

Objectives:

Decrease engine emissions by 90% compared to current baselines

Increase rich burn engine efficiency by 20%

Reduce installed cost of distributed generation systems by 20%

Maintain present engine durability levels

Demonstrate technology with 4000-hr field test at customer site in California

Provide ultra-low emissions, high efficiency, cost-effective, reliable, engine generator sets for distributed generation in California

Ultra-Low Emissions Technology

Technology Developed in 2 Phases

Phase I Technology

- Cooled EGR (Exhaust Gas Recirculation) in a Rich Burn Engine with Three-Way Catalyst aftertreatment
- EGR diluent lowers combustion temperature to reduce NOx out of engine
- EGR increases knock-limited BMEP
- Phase I Development Approach
- Design and install system on Waukesha H24 GSID lab engine
- Develop Cooled EGR and 3-Way Catalyst system and EGR control system on lab engine
- Conduct 500-hr endurance test of engine and controls on lab engine
- Build engine generator set with Phase I engine technology
- Hoped to Conduct 4000-hr field test in a CHP application at a customer site in California in 2005

Phase II Technology

- Enhance combustion by adding hydrogen rich syngas to combustion mixture
- Hydrogen syngas is generated from natural gas fuel by on board reformer
- Hydrogen enhanced combustion allows significant increase in EGR percentage
- Increased EGR further reduces NOx emissions and enhanced combustion improves thermal efficiency.
- Phase II Approach - Not a viable option at this time (Waukesha)

Ultra-Low Emissions Progress

Results So Far

Phase I 500-hr lab endurance test has been completed

- Engine in good condition even after over 600 hours of testing
- Control system performed well and performing well

Phase I emissions are well below the phase II target

Field test engine generator set has been built and test site identified

Fuel reformer testing has demonstrated adequate hydrogen production as expected

Full scale reformer system has been installed on lab engine and testing with hydrogen enhanced combustion has been completed. Limited success. Phase II effort on hold.

Outcomes

Emissions, efficiency, and cost goals not demonstrated for Phase I

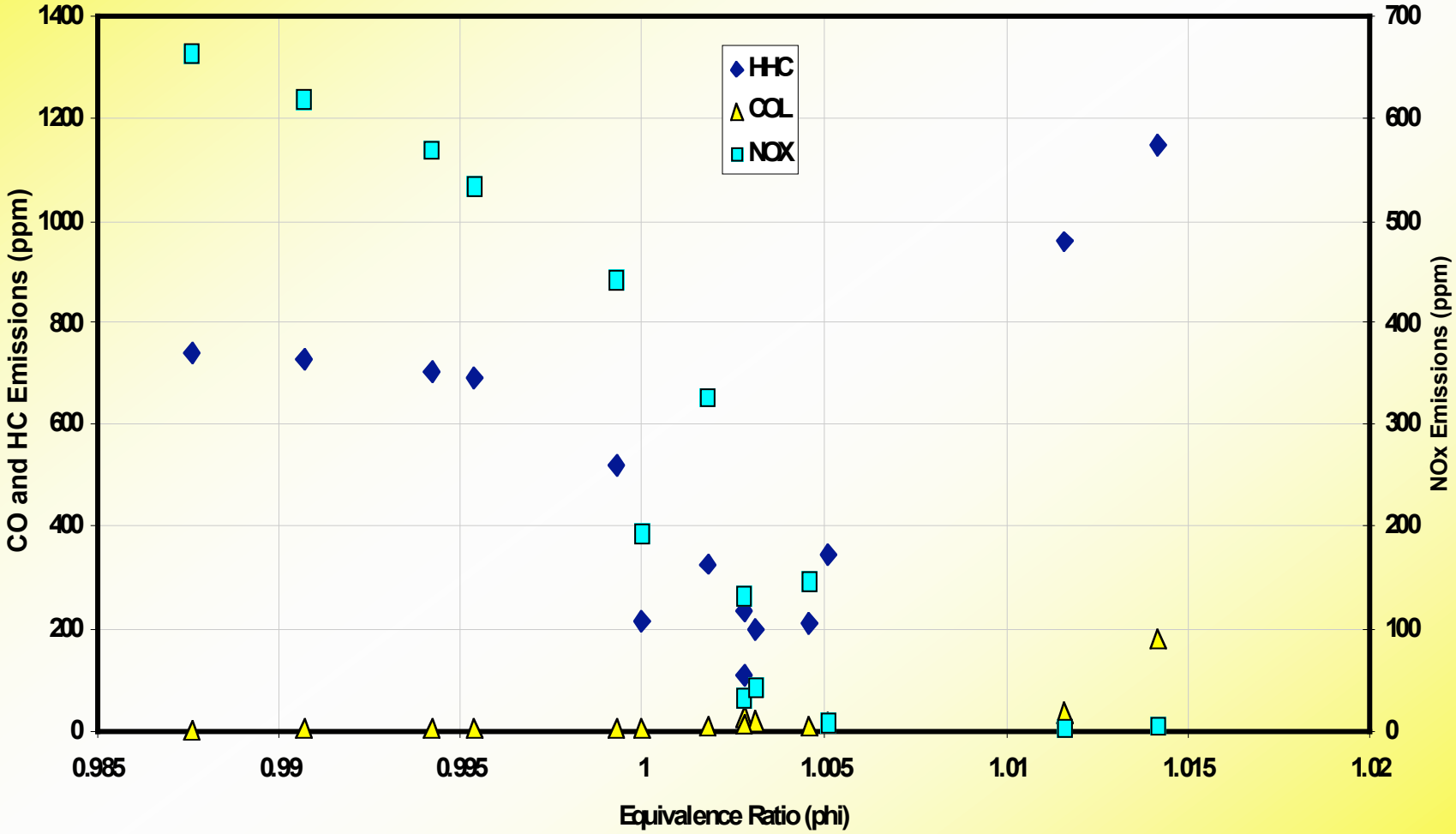
Not Field tested to demonstrate reliability of Cooled EGR technology and 3-Way Catalyst

Overall program emissions and efficiency goals not met yet

Next Steps

None at this time to develop field test and conduct Phase I 4000-hr field test and Make ARICE I commercially available.

Results After 500 Hour Test



Results After 500 Hour Test

- Phase I Targets: NOx = 43 ppmvd, CO = 94 ppmvd
- Phase II Targets: NOx = 4 ppmvd, CO = 9 ppmvd
- Measured: NOx = 2.5 ppmvd, CO = 37 ppmvd
  NOx = 8.4 ppmvd, CO = 2.5 ppmvd
- Achieved Phase I Targets Over a Wide Range
- Can Achieve Phase II Targets Over a Narrower Range
- No takers yet for the Phase I technology to move forward.

LOW COST, HIGH EFFICIENCY, ULTRA-LOW NOx ARICE SOLUTION USING HCCI COMBUSTION

Contractor: Lawrence Livermore National Laboratory **Contract #:** 500-02-003

Subcontractors:

- University of California, Berkeley
- Ricardo Engineering, Inc.
- Hiltner Combustion Systems

Collaborative partner: Caterpillar Engine Company

Start Date: November 1, 2002 **End date:** October 31, 2005 (3/31/2006)

Pier Funds: $2.0 Million

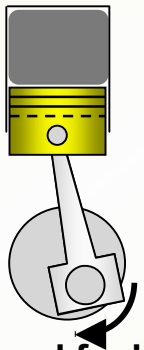
Purpose: To provide the ratepayers of the State of California with a high efficiency, low emissions energy technology that increases reliability of electricity generation while reducing both cost and environmental impacts

Goal: To develop an Advanced Reciprocating Internal Combustion Engine (ARICE) system based on HCCI technology that meets the 2007 ARICE targets

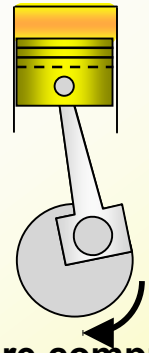
- Backup or base load power applications (100 kW-5 MW)
- >45% Brake Thermal Efficiency
- <0.015 g/bhp-hr NOx
- <700 $/kW cost
- >10,000 hrs B10 Durability (>45,000 hrs between major overhauls)

HCCI combustion process can yield near zero NO_x emissions with engine efficiency comparable or better than Diesel engines

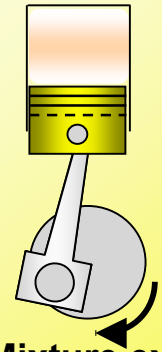
- The Homogeneous Charge Compression Ignition Engine (HCCI) engine concept combines aspects of SI and Diesel engines by compression igniting a pre-mixture of fuel and air
- The key to achieving the potential for high efficiency and low NO_x is combustion control, but combustion control is much more complex than in current engines
- Robust means of HCCI engine control are being developed
- Thermally based control being applied to ARICE HCCI Engine



Premixed fuel and air inducted into cylinder



Mixture compressed until it auto-ignites



Mixture expands

LLNL Multi-cylinder HCCI Engine Facility has been modified to demonstrate ARICE Engine

- Closed loop HCCI engine control successfully demonstrated on single cylinder engine at UC Berkeley
- Single cylinder tests and computational analysis being used to optimize a thermal control system for HCCI mode operation
- Multi-cylinder engine has been redesigned and modifications for HCCI operation are nearly complete
- Limited testing of HCCI engine operation with thermal control concept was conducted through 3/31/2006.
- Project goals not met. No takers yet for the HCCI technology to move forward.

Multi-cylinder engine at LLNL (provided by Caterpillar)

ADVANCED LASER IGNITION (ALIS) INTEGRATED ARICE SYSTEM FOR DISTRIBUTED GENERATION IN CALIFORNIA

Contractor: Argonne National Laboratory **Contract #:** 500-02-022

ALIS Consortium

Caterpillar Colorado State University Cummins

National Energy Technology Laboratory Waukesha Engine, Dresser Inc.

Altronic, Inc. Southwest Research Institute

PIER Funds: $1,000,000 **Match Funds:** $450,000

Contract Term: July 1, 2003 to March 31, 2007

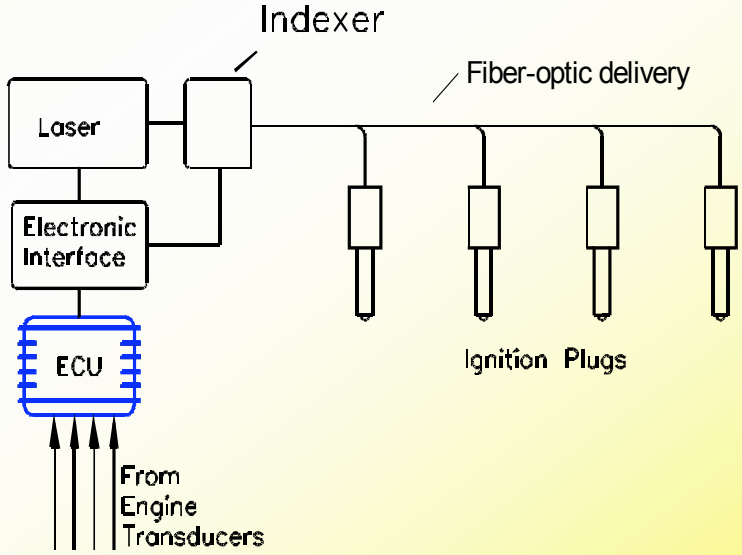
Project Term: July 1, 2003 to July 31, 2006 (Continuing)

Purpose: To improve the energy cost/value of California's electricity and to improve the environmental and public health costs in California

Objective: To develop an advanced laser ignition system for use with natural gas engines used in distributed generation. To gauge the benefits in terms of reduced emissions (NO_X and VOC) and improved efficiencies by the use of such a system against ARICE and ARES goals.

Approach

- Step-I: Determine the laser ignition characteristics through experimental studies
- Step-II: Develop a laser ignition system based on the design parameters so determined
- Step-III: Gauge the benefits of laser ignition against conventional ignition based on tests performed on a natural gas engine.

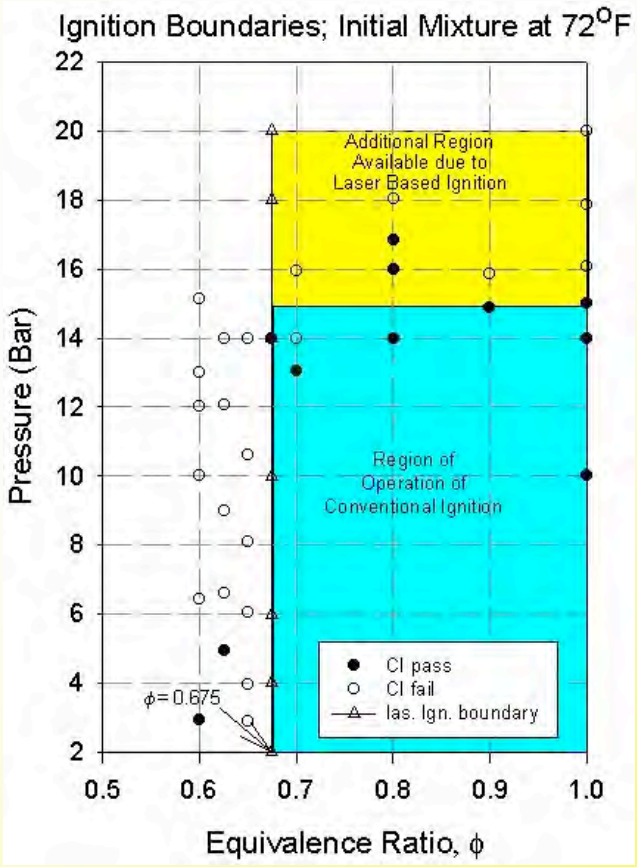


Results so far

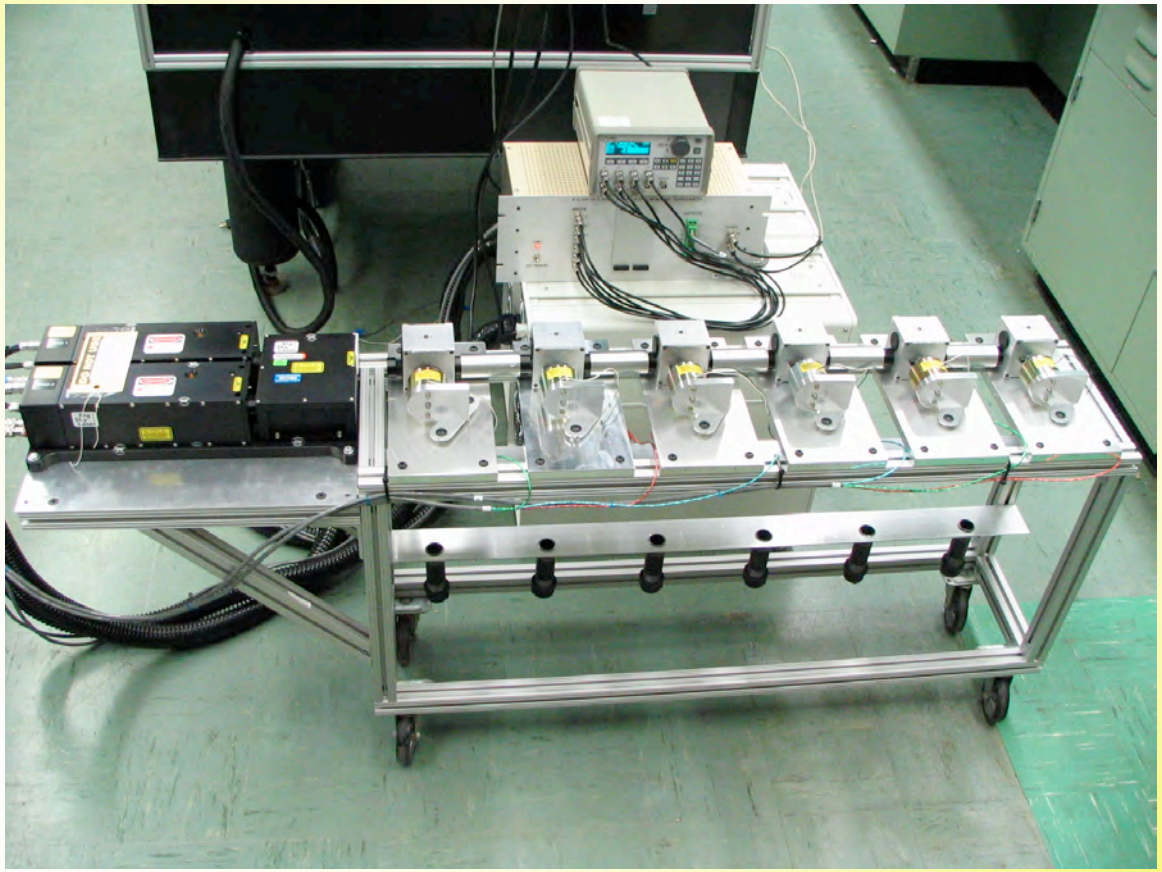
- Tests conducted in a static chamber show that laser ignition enables ignition of mixtures up to 20 bar whereas the conventional ignition fails above 15 bar pressure (See Figure)
- A Rapid Compression Machine (RCM) has been designed to perform ignition tests under in-cylinder like conditions.
- Determined the design requirements of various ALIS components using the RCM.
- Designed and partially developed and tested ALIS

Future Efforts

- **None at this time** to integrate it with a multi-cylinder natural gas engine, and evaluate the engine performance and to demonstrate the ALIS integrated production natural gas engine.



ALIS 6-Channel Assembly on Test Rig



3rd Annual Advanced Stationary Reciprocating Engine Meeting: Moving Forward in Low-emission High-efficiency Technologies

- **Being held now (June 28-30, 2006) at ANL, Argonne, IL.**
- 1st Annual ASRE Conference was held on April 14-15, 2004 at Holiday Inn Capitol Plaza, Sacramento, CA – Opportunities for ARES-ARICE Collaboration
- 2nd Annual ASRE Conference was held on March 15-16, 2005) at SCAQMD, Diamond Bar, CA .
- **Sponsored by** U.S. Department of Energy and California Energy Commission
- **Purpose:** To identify research, development, and deployment activities for advanced stationary reciprocating engine technologies through collaboration between the Advanced Reciprocating Engine Systems (ARES) program and the Advanced Reciprocating Internal Combustion Engine (ARICE) program.
- Complementary work underway and planned in these two programs will be discussed. Future opportunities for collaboration between these programs, the U.S. Department of Energy, complementary California Energy Commission programs, and other private and public stakeholders in the stationary reciprocating engine industry will be explored.
- Conference presentations will include the latest market and regulatory/policy information, both in California and in other states across the country, and will also address potential new applications (e.g., in integrated, packaged systems) for reciprocating engines in distributed environments. To further improve the international market for reciprocating engines and to expand the national market, manufacturers must be prepared to meet stringent environmental standards promulgated in California, as well as emission standards being developed in other states.
- **For more information: http://www.energetics.com/recips06**

Summary

- Developed a California ARICE Collaborative Plan - >400 stakeholders representing USDOE, CEC, CARB, SCAQMD, NRDC, OEMs (EMA), National Labs, Universities, Utilities, Fuel Suppliers, R&D Companies.
- Held first California ARICE Collaborative Workshop on July 10, 2001 in Sacramento, CA. Developed performance targets along with CARB's DG emission standards.
- CARB Phase I Effective since January 1, 2003. Phase II from Jan. 1, 2007 (may be)
- PIER funds ($6 million) awarded for 3 ARICE projects.
- Contracts (Waukesha - $3M & LLNL - $2M) work began Sept., 2002. Projects ended.
- Advanced Ignition Systems (AIS) Roundtable Meeting at ANL (Argonne, IL) during October 8-9, 2002, and built an ALIS consortium. ALIS integrated ARICE system project contract between CEC and ANL ($1M) in progress.
- 3 Roundtables in 2003: NG Reciprocating Engine Emissions- Feb. 10-11; Friction, Lubrication & Parasitic Losses Reduction July 28-29; Catalytic Materials Nov. 2003
- 1st Annual ASRE RD&D Conference April 14-15, 2004, Sacramento); 2nd ASRE Conference (March 15-16, 2005) in Diamond Bar (CA) ARES-ARICE Symposium with ASME in Oct. 2004 Long Beach, ARES-ARICE Symposium with ASME in March 2005 Chicago, and another in Oct. 2005 Ottawa, Canada
- 3nd Annual ASRE Meeting June 28-30, 2006, ANL, Argonne, IL.
- ***What is next?*** ARICE Solicitation (~$6 million) in Summer 2006 and ARES-ARICE Symposium with ASME in Nov. 2006 Sacramento, CA
- **No ARICE Product available yet; Still a CHALLENGE.**

For more information, please visit

California ARICE Collaborative webpage at:

http://www.energy.ca.gov/pier/arice/index.html

or contact:

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Thank You!