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

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Program Manager (ARICE)
California Energy Commission

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
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.
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)
- 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](http://www.arb.ca.gov/energy/dg/dg.htm)
### Performance Targets for Advanced Reciprocating Internal Combustion Engines (ARICE)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
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</thead>
<tbody>
<tr>
<td><strong>Efficiency</strong></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Brake Thermal Efficiency</td>
<td>≥35%</td>
<td>≥38%</td>
<td>≥40%</td>
<td>≥42%</td>
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<tr>
<td>Fuel-to-Electric Efficiency*</td>
<td>≥32%</td>
<td>≥34%</td>
<td>≥38%</td>
<td>≥42%</td>
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<tr>
<td>Overall Energy Efficiency (CHP)</td>
<td>≥85%</td>
<td>≥85%</td>
<td>≥85%</td>
<td>≥85%</td>
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<tr>
<td><strong>Emissions – shaft power (g/kwh -hr)</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Oxides of Nitrogen (NOx)</td>
<td>≤0.015</td>
<td>≤0.015</td>
<td>≤0.015</td>
<td>≤0.01</td>
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<tr>
<td>Carbon Monoxide (CO)</td>
<td>≤0.02</td>
<td>≤0.02</td>
<td>≤0.02</td>
<td>≤0.02</td>
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<tr>
<td>Volatile Organic Compounds (VOCs)</td>
<td>≤0.006</td>
<td>≤0.006</td>
<td>≤0.006</td>
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<tr>
<td>Particulate Matter (PM10)</td>
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<td>≤0.01</td>
<td>≤0.01</td>
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<tr>
<td><strong>Emissions – power generation (lb/MW -hr)</strong></td>
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<td></td>
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<td></td>
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<tr>
<td>Oxides of Nitrogen (NOx)</td>
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<td>≤0.07</td>
<td>≤0.07</td>
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<td>Carbon Monoxide (CO)</td>
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<td>Volatile Organic Compounds (VOCs)</td>
<td>≤0.02</td>
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<td>≤0.02</td>
<td>≤0.02</td>
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<tr>
<td>Particulate Matter (PM10)</td>
<td>≤0.03</td>
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<td>≤0.03</td>
<td>≤0.03</td>
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<tr>
<td><strong>Cost</strong></td>
<td></td>
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<tr>
<td>Complete Installed Cost ($/kW e)</td>
<td>≤700</td>
<td>≤700</td>
<td>≤700</td>
<td>≤700</td>
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<tr>
<td>O&amp;M Cost ($/kW h)</td>
<td>≤0.06</td>
<td>≤0.06</td>
<td>≤0.05</td>
<td>≤0.04</td>
</tr>
<tr>
<td><strong>Availability &amp; Durability</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Availability</td>
<td>≥88%</td>
<td>≥90%</td>
<td>≥92%</td>
<td>≥95%</td>
</tr>
<tr>
<td>B10 Durability (hours)</td>
<td>≥8,000</td>
<td>≥9,000</td>
<td>≥10,000</td>
<td>≥12,000</td>
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<tr>
<td>Mean Time Between Major Overhaul (hours)</td>
<td>≥35,000</td>
<td>≥40,000</td>
<td>≥45,000</td>
<td>≥50,000</td>
</tr>
</tbody>
</table>
California ARICE Collaborative Activities (since May 2001)

<table>
<thead>
<tr>
<th>Activity</th>
<th>Completion Date</th>
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</thead>
<tbody>
<tr>
<td>Prepared Collaborative Plan</td>
<td>May, 2001</td>
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<tr>
<td>Identified and confirmed the Core Group</td>
<td>May 31, 2001</td>
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<tr>
<td>Identified the Advisory Group</td>
<td>May 29 – June 8, 2001</td>
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<tr>
<td>Organized Workshop with Stakeholders</td>
<td>July 10, 2001</td>
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<tr>
<td>Released RFP/Solicitation (up to $6 million)</td>
<td>December 7, 2001</td>
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<tr>
<td>Received Proposals (9)</td>
<td>February 21, 2002</td>
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<tr>
<td>Selected three (3) Projects</td>
<td>By May 29, 2002</td>
</tr>
<tr>
<td>Awarded two (2) Contracts and Started Work</td>
<td>By September, 2002</td>
</tr>
<tr>
<td>(Waukesha - $3.0M and LLNL - $2.0M)</td>
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<tr>
<td>Advanced Ignition Systems Roundtable</td>
<td>October 8 -9, 2002</td>
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<tr>
<td>Emissions Roundtable</td>
<td>February 10 -11, 2003</td>
</tr>
<tr>
<td>Friction - Lubrication - Parasitic Losses Meeting</td>
<td>July 28 -29, 2003</td>
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<tr>
<td>Catalytic Materials Roundtable</td>
<td>Nov 2003</td>
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<tr>
<td>1st Annual ARES - ARICE RD&amp;D Conf.</td>
<td>April 14 -15, 2004</td>
</tr>
<tr>
<td>ASME ARES - ARICE Symposium</td>
<td>October 2004</td>
</tr>
<tr>
<td>2nd Annual ASRE Conference</td>
<td></td>
</tr>
<tr>
<td><strong>ASME ARES - ARICE Symposium Ottawa</strong></td>
<td><strong>March 15 – 16, 2005</strong></td>
</tr>
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</table>
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:
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.  
**PIER Funds:** $2,995,060  
**Contract Start Date:** 10/1/2002  
**Project Start Date:** 11/15/2002  
**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

CO and HC Emissions (ppm)

NOx Emissions (ppm)

Equivalence Ratio (phi)

Before Catalyst Emission Levels
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\textsubscript{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\textsubscript{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

![Diagram](https://example.com/diagram.png)

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

Contractor: Argonne National Laboratory
ALIS Consortium
Caterpillar
Colorado State University
Cummins
National Energy Technology Laboratory
Waukesha Engine, Dresser Inc.
Altronic, Inc.
Southwest Research Institute

Contract #: 500-02-022

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 (NOx 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](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.


- 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.


- 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:

Avtar Bining, Ph.D. (Project Manager – ARICE) at 916-657-2002  abining@energy.state.ca.us

Thank You!