Technical Path Evaluation for High Efficiency, Low Emission Natural Gas Engine

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Southwest Research Institute
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Southwest Research Institute

- Founded as an independent, non-profit, R&D organization in 1947
- Located on 1200 acres in San Antonio, TX, 3000 employees
Presentation Outline

- SwRI ARES Program Description
- SwRI ARES Objective and Scope
- Technical Barriers to High Efficiency
- Pathway to High Efficiency
- Summary
ARES was formed (Nov 1998) as a cooperative research program with funding from industry and government.

**ARES Program Members**
- Department of Energy (OPT and NETL)
- Gas Research Institute
- Caterpillar Inc Engine Division
- Cooper Energy Services
- Cummins Engine Company
- Waukesha Engine Division
- Southern California Gas
- Altronic
- Federal Mogul - Champion
- Woodward Governor

**Program Structure**
SwRI ARES Objective

- Identify enabling technology for development of high efficiency, low emission, stationary natural gas engines
- Efficiency target: 50% Brake Thermal Efficiency
- NO\textsubscript{x} emissions target: 0.1 g/hp-hr NO\textsubscript{x}
Program Scope

■ Modeling and simulation to identify technical paths and barriers

■ Bench scale and single cylinder engine testing to evaluate various technologies
Baseline Engine Energy Balance

Percentages are of the total 12,598 J/cycle cyl from fuel

- Brake Power (39.1%)
- Exhaust Gases (23.4%)
- Cylinder and Exhaust Heat Rejection (20.5%)
- Aftercooler Heat Rejection (7.2%)
- Incomplete Combustion (2%)
- Friction (7.7%)
- Turbocharger Bearing Friction (0.1%) (not shown)
Known Barriers to High Efficiency for Natural Gas Combustion

- Knock (uncontrolled combustion)
- NO\textsubscript{x} emission regulations
- Structural limitations
- Combustion efficiency (unburned fuel)
- Combustion rate (slow reactions at low temperature)
- In-cylinder heat loss
- Frictional losses
- Pumping losses
- Exhaust port and manifold heat loss
- Efficient exhaust energy recovery
ARES Technical Assumptions

- High efficiency will require higher power density (BMEP)
- Knock limitations must be overcome to achieve higher BMEP
- Dilute air-fuel mixtures required for low NO$_x$ - two alternatives
  - Lean air-fuel ratios plus lean NO$_x$ aftertreatment
  - Stoichiometric air-fuel ratios plus high levels of exhaust gas recirculation (EGR) with 3-way catalyst
- Ignition and combustion of dilute mixtures a necessity
- Some type of aftertreatment required
- Exhaust energy retention for turbocharging is a key technology
- Minimized parasitic losses (friction, pumping, etc)

Multiple technologies will be required to achieve both efficiency and emissions goals!
ARES Technologies

- Combustion Chamber Geometry
- Combustion of Dilute Mixtures
- Selective Catalytic Reduction
- Exhaust Aftertreatment LNC, TWC
- Water Injection
- High Power Density
- Multiple Source Ignition
- Friction Reduction
- Turbo-compounding
- Exhaust Energy Retention
Increased Power Density

Higher power density leads to a reduction in frictional losses.
Multiple Site Spark Ignition

- Combustion, initiated at multiple sites, proceeds from outside toward center
- Faster combustion rates and elimination of end gas regions prone to knock
- Improved
  - lean misfire limit
  - shorter combustion duration
  - higher combustion efficiency
  - higher BTE
Pilot Ignition also a Multi-Site Ignition Concept

- Diesel fuel penetrates the combustion chamber prior to ignition
- High pressure enable good penetration
- Injection pressures of diesel injection systems now approaching 30 ksi
Simultaneous Knock and NO\textsubscript{x} Mitigation: Direct In-cylinder Water Injection

Water injection used to lower in-cylinder temperatures reducing potential for knock and NO\textsubscript{x} formation

Spark Plugs
Appropriate design of combustion chamber required for:
- Complete combustion of dilute mixtures
- Knock tolerance
Aftertreatment Options

- Lean NO\textsubscript{x} catalyst (LNC) - currently not a viable technology

- Selective catalytic reduction (SCR)
  - Viable, requires reductant
  - Potential for ammonia slip, control issue
  - 90-95% efficiency

- 3-way catalyst if stoichiometric combustion
  - Proven in light duty, shorter life applications
  - 95-99% efficiency
Engine Development Decisions

- Lean burn vs stoichiometric
  - Dictates exhaust aftertreatment options
    - 3-way catalyst
    - Selective catalytic reduction

- Turbulent combustion chamber vs non-turbulent

- Multiple-site ignition vs single source
**Expected Gains for 50% BTE Come From Application of Multiple Technologies**

<table>
<thead>
<tr>
<th>Description</th>
<th>Contribution (BTE points)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miller Cycle</td>
<td>~1.7 points</td>
</tr>
<tr>
<td>1.5 Expansion Factor</td>
<td></td>
</tr>
<tr>
<td>Turbo-Compounding</td>
<td>~1.5 points</td>
</tr>
<tr>
<td>80% turbine efficiency</td>
<td></td>
</tr>
<tr>
<td>95% gear train efficiency</td>
<td></td>
</tr>
<tr>
<td>Low Heat Rejection Exhaust System</td>
<td>~1.9 points</td>
</tr>
<tr>
<td>60% heat loss reduction</td>
<td></td>
</tr>
<tr>
<td>Low Friction/High BMEP</td>
<td>~2.3 points</td>
</tr>
<tr>
<td>87% to 91% mechanical efficiency</td>
<td></td>
</tr>
<tr>
<td>Burn Rate</td>
<td>~0.7 points</td>
</tr>
<tr>
<td>20 degree to 18 degree</td>
<td></td>
</tr>
<tr>
<td>10 to 90% burn duration</td>
<td></td>
</tr>
<tr>
<td>Flow Improvement</td>
<td>~1.2 points</td>
</tr>
<tr>
<td>20% Improvement</td>
<td></td>
</tr>
<tr>
<td>Two-Stage Compression w/ Intercooling</td>
<td>~0.4 points</td>
</tr>
<tr>
<td>80% compressor efficiency per stage,</td>
<td></td>
</tr>
<tr>
<td>313 K intercooling</td>
<td></td>
</tr>
</tbody>
</table>

Combination of above technologies improves brake thermal efficiency from 40 to 50 percent

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Advanced Reciprocating Engine Systems
Energy Balance for Base Engine, CAT3501 Test Engine, and 50 Percent ARES Engine

<table>
<thead>
<tr>
<th>Percent of Energy Input</th>
<th>Base</th>
<th>CAT3501</th>
<th>50%</th>
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</thead>
<tbody>
<tr>
<td>0%</td>
<td>48.0</td>
<td>42.9</td>
<td>39.1</td>
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<tr>
<td>20%</td>
<td>2.7</td>
<td>4.1</td>
<td>0.0</td>
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<tr>
<td>40%</td>
<td>14.6</td>
<td>25.4</td>
<td>23.4</td>
</tr>
<tr>
<td>60%</td>
<td>4.6</td>
<td>3.0</td>
<td>7.7</td>
</tr>
<tr>
<td>80%</td>
<td>2.0</td>
<td>3.2</td>
<td>7.7</td>
</tr>
<tr>
<td>100%</td>
<td>15.2</td>
<td>13.6</td>
<td>7.3</td>
</tr>
</tbody>
</table>

Legend:
- Brake Power
- TurboCompounding
- Exhaust Gases
- Friction
- Unburned Fuel
- In-cyl Heat Flux&Port
- Aftercooler
# Improvements Required for ARES Engine

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Current Technology</th>
<th>ARES Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power Density (BMEP)</strong></td>
<td>170-200 psi</td>
<td>350 psi</td>
</tr>
<tr>
<td><strong>Peak Cylinder Pressure</strong></td>
<td>1500-1800 psi</td>
<td>3200 psi</td>
</tr>
<tr>
<td><strong>Turbocharger Efficiency</strong></td>
<td>56 %</td>
<td>65+ %</td>
</tr>
<tr>
<td><strong>Mechanical Efficiency</strong></td>
<td>87-89 %</td>
<td>91 %</td>
</tr>
<tr>
<td><strong>Combustion Rate</strong></td>
<td>25-30 Crank Angle Degrees</td>
<td>15-18 Crank Angle Degrees</td>
</tr>
<tr>
<td><strong>Turbocompounding</strong></td>
<td>No</td>
<td>Likely</td>
</tr>
</tbody>
</table>
Accomplishments

- Modeling efforts led to vision of ARES technology
- Bench scale testing and literature review of technology resulted in revision of technical path
- Single cylinder engine testing verified modeling assumptions
- Evaluation of potential combustion systems
  - Miller Cycle, micro-pilot open chamber, direct water injection, multiple-source ignition, lean burn, and stoichiometric with EGR
Conclusions

- Good near term potential to utilize stoichiometric combustion technology with 3-way catalyst for control of NO\textsubscript{x} in advanced reciprocating engine systems for power generation
- Exhaust gas recirculation will be used as diluent for mitigating NO\textsubscript{x} formation and knock
- Lean NO\textsubscript{x} catalyst technology must be developed to enable lean burn combustion systems
- Potential ultra lean burn exception is implementation of homogenous charge compression ignition (HCCI)
Project Benefits and Impacts

- Identified and demonstrated various approaches to achieve the program goals
- Provided the competitive teams with direction for future development
- Provided DOE with direction for evaluation of the various proposals
Next Steps

- Competitive programs in progress
- Precompetitive areas identified for targeted research
- Continue ARES consortium providing guidance for university and commercial programs
  - Keep existing framework of manufactures and suppliers intact as program advisory committee
  - Investigation of combustion concepts with high technical risk not pursued under ARES program
  - Evaluation of stoichiometric-high EGR operation with 3-way catalyst as a promising near term technology
  - Integration of lean-burn combustion engine with various aftertreatment options to achieve ultra-low NOx emissions
A Word About Funding...

- ARES - a multi-year program
- Funded incrementally by government and industry
- Equal cost share
  - Industry / Government
Advanced Reciprocating Engine Systems