Advanced Natural Gas Reciprocating Engines (ARES)

DE-FC26-01CH11078

Cummins Inc./ Wisconsin Engine Research Consultants/ Argonne National Lab/ GTI

Portfolio Review

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Executive Summary

The objective of the Cummins / Department of Energy (DOE) ARES Program, is to develop advanced gaseous fueled engines and technologies for power generation that combine high efficiency, low emissions, fuel flexibility and reduced cost of ownership.

The ultimate goals of the project are to demonstrate engine systems achieving 50% Brake Thermal Efficiency (BTE), <0.1 g/bhp-hr NOx, improved durability and reliability. The program is planned in multiple phases. Key deliverables for each phase include: Phase 1 targets of 44% BTE and 0.5 g/bhp-hr NOx, Phase 2 targets of 47% BTE and <0.1 g/bhp-hr NOx and Phase 3 targets of 50% BTE and <0.1 g/bhp-hr NOx.

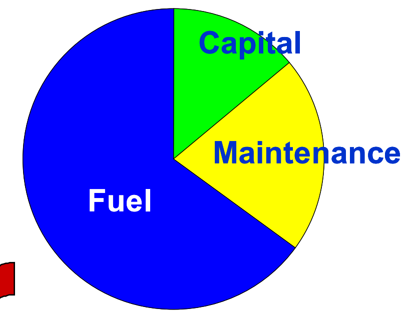
Cummins has successfully completed Phase 1 developing advanced lean burn technology increasing BTE from 36 to 44% with more than 200 MW in commercial applications. For Phase 2 Cummins has demonstrated ultra low emissions of 0.023 g/bhp-hr NOx with Stoichiometric combustion, Exhaust Gas Recirculation, Advanced Three Way Catalyst Technology and is working towards the efficiency demonstration. Also developed advanced technologies, modeling tools, and capability to operate with non-std gases (renewable fuels).

Phase 3 is planned to be completed by Q3 2013.

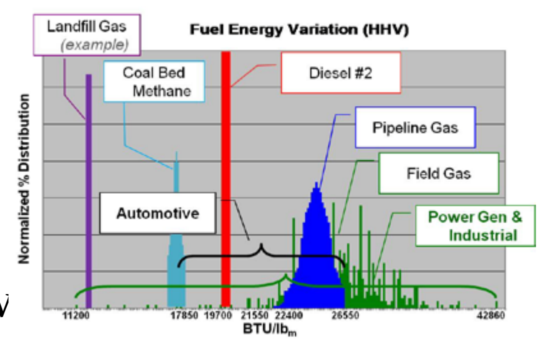
Project Objective

- Increase engine system fuel efficiency at lower emissions levels while attaining lower cost of ownership
- Demonstrate
  - 50% Brake Thermal Efficiency (BTE)
    - Baseline engine efficiency at 36% BTE
  - <0.1 g/bhp-hr NOx System Out Emissions
    - Baseline NOx at 2 to 4 g/bhp-hr NOx
  - 10% Lower Operating Cost
  - No Reliability Penalty
  - Increased Fuel Flexibility (operate with non-std gases: landfill gas and other renewables)
    - Non-std gases characterized by varying BTU, Low Methane Number, Varying Diluents/Composition

Typical Cost Breakdown
8,000 hrs/yr



Efficiency is key



State of the Art

- Pre-ARES Engines Characterized by the following:
  - Limited investment in natural gas engines, based on derivatives of larger volume diesel engines
  - Low combustion systems efficiency, high NOx, high CO_2
  - Limited controls
  - Max power limited by thermal issues, poor performing and unreliable ignition systems
  - Limited operation with non-std fuels
  - Lack of:
    - cost effective aftertreatment technology
    - dedicated modeling tools
    - optimal integration of key sub-systems such as advanced air handling, power cylinder, fuel systems, waste heat recovery

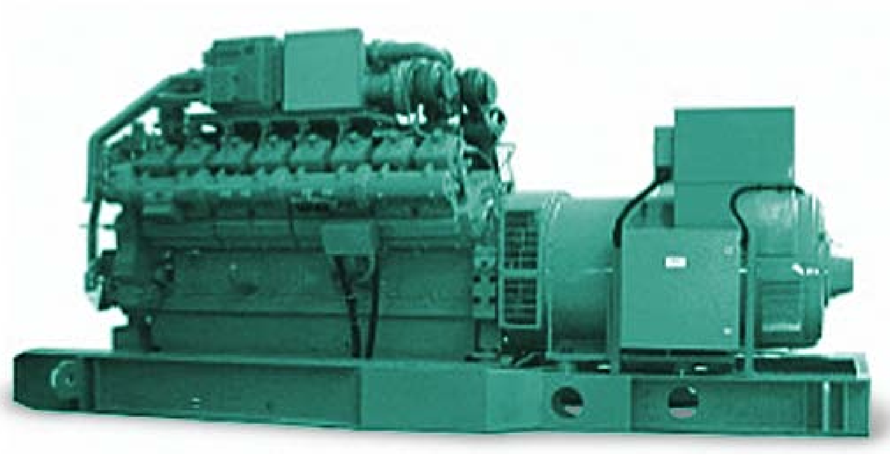
Technical Approach: Architecture

- **Phase 1: Lean Burn Spark Ignited (SI)**
  - This ARES technology is in production with the 60/91L engines
- **Phase 2: Stoichiometric Spark Ignited (SI) w/ Exhaust Gas Recirculation (EGR), Three Way Catalyst (TWC), and Waste Heat Recovery (WHR)**
  - Projected to be the most cost effective engine solution for low emissions markets (<0.1 gNOx)
- **Phase 3: Advanced Stoichiometric SI w/ EGR, TWC and WHR**
  - Further development of Advanced Combustion Systems, Analytic Models, Air Handling, Aftertreatment, Control/Sensor , and Ignition Technologies

Technical Approach: Strategy

- Improve closed cycle efficiency
  - Explore advanced combustion concepts
- Improve open cycle efficiency
  - Improve air handling
- Improve predictive models
- Improve controls/sensing
- Long life ignition system
- Advanced aftertreatment
- Waste heat recovery

Technical Approach – New Technologies



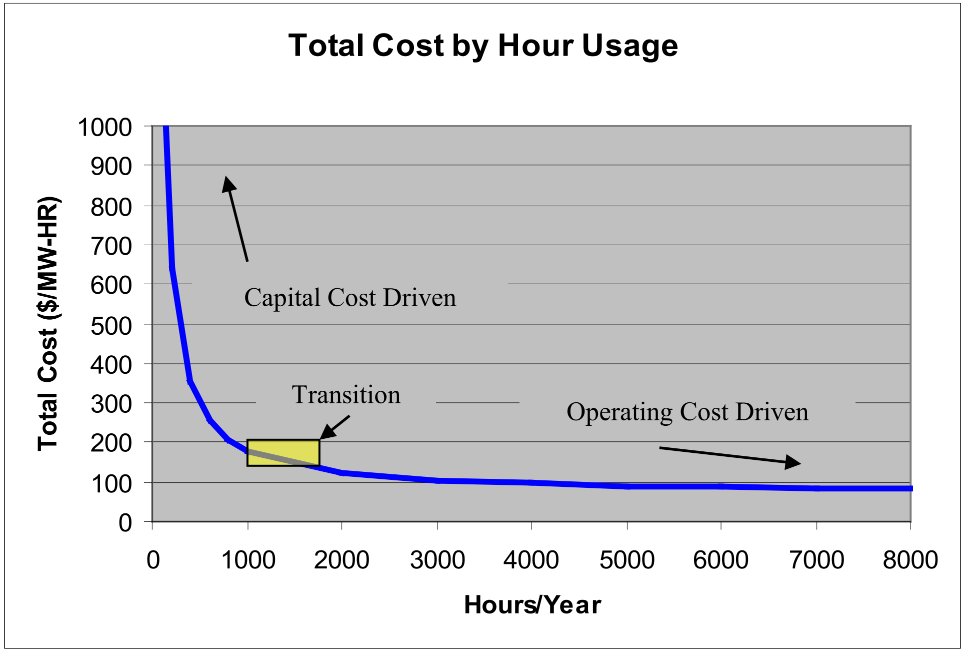
- Base Engine
  - Combustion
  - Air Handling
  - Ignition
  - EGR
- Aftertreatment
  - Air Fuel Ratio Management
  - Advanced Three Way Catalyst
- Waste Heat Recovery
  - Thermo Chemical Recuperation (TCR)
  - Conservation of Exhaust Energy
- Controls / Sensors Development
  - Sensors
  - TCR / Aftertreatment Algorithms
- Analytical Tools Development
  - KIVA-SI
  - GT-Power

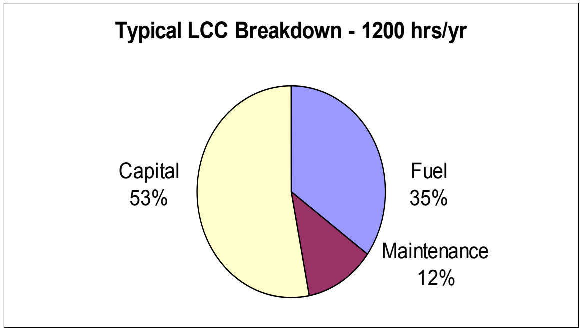
Transition and Deployment

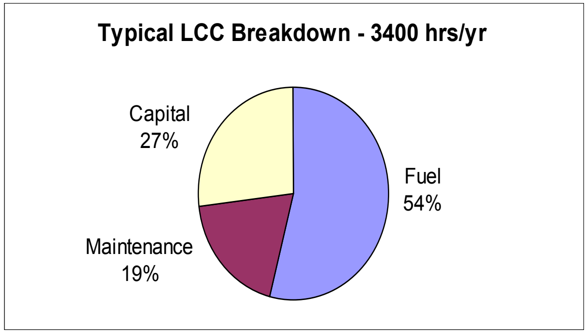
- ARES technology:
  - Improved reliability
  - Improved air quality
  - Reduces customers Life Cycle Cost (LCC)
  - Reduces fuel consumption
- Increased reliability of power grid due to decentralization
- Distributed power creates the opportunity for waste heat utilization through CHP
- Positive impact on Distributed Energy Program

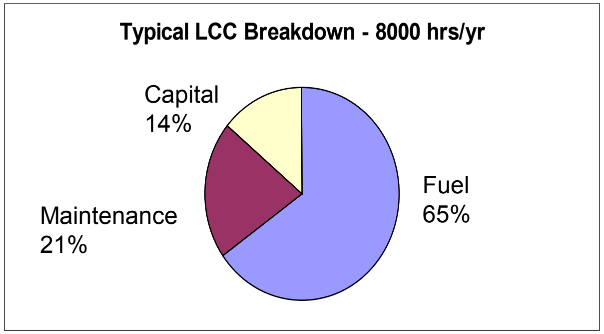
Key Market Driver – Life Cycle Cost

- Total LCC is key
  - Fuel efficiency
  - Maintenance cost
  - Initial capital cost
- Relative importance of each LCC element for a particular customer depends on the duty cycle
- For high hour applications, efficiency is critical









Measure of Success

- The combination of
  - high efficiency
  - low cost of ownership
  - low NO_X emissions

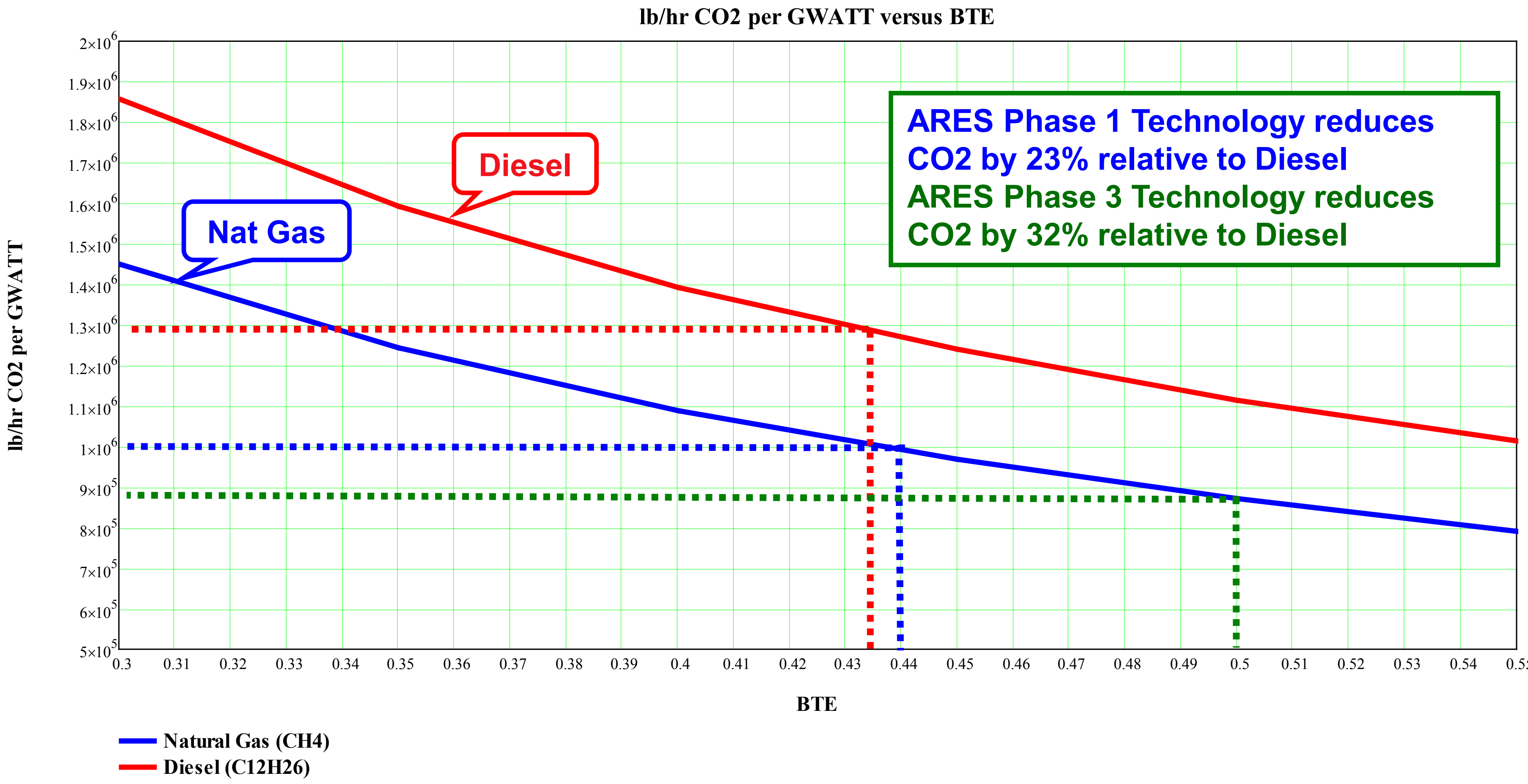
  makes it more attractive for customers to purchase natural gas fueled reciprocating engines. This is expected to have a direct positive impact on distributed power generation.
- Expected >10 % /yr worldwide market growth
- ARES Phase 1 in production with over 200 MW operation
- North America and International expansion expected to be driven by renewable fuels and increase in Natural Gas availability

Benefits

- Increased utilization of natural gas produced in the USA
  - Increases benefits of shale gas production
- Lower cost of ownership shortens payback period and broadens the potential market
- Lower emissions improve air quality
- Decentralization reduces transmission loss
- Can use natural gas in locations where diesel fuel cannot be stored
- Increased reliability of power grid due to decentralization
- Reduced CO_2 emissions vs. diesel or coal
- Distributed power creates the opportunity for waste heat utilization through CHP

Benefits (cont.)

CO2 Production Comparison of Natural Gas and Diesel Power Generation Applications



Benefits: Renewable Fuels

- High BTE using "renewable fuels"
  - Improve BTE by 4 points over engines operating with renewable fuels today
  - Lower net CO_2 and CH_4 emissions
- Maintain lower NOx while varying fuel composition
  - Lower net NOx emissions
- Potential Savings
  - After first 10 years of commercialization
    - Will save 74 MTherms of Natural Gas per year
    - Equivalent to 40,000 rail cars of coal per year
    - Reduce CO_2 emissions by 5M tons per year

Commercialization Approach

Cummins Power Generation Business (CPG)

Energy Solutions Business (ESB)

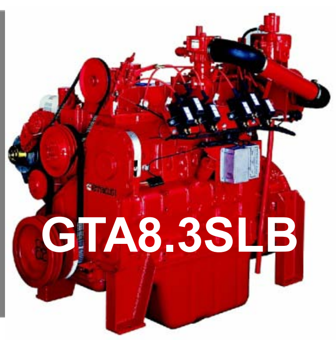
- **Lean-Burn Gas Generator Sets**
  - 300 to 2000 kW – Continuous Power

G-Drive Business (NPower)

- **Stoic/ LB Gas Generator Sets**
  - 200 to 800 kWe – Standby Power

KTA 19GC

- ***Engineering & Manufacturing***
- **CSS : Columbus, IN (Eng'r Only)**
- **CIC : Seymour, IN**
- **DAV : Daventry, England**
- **CNGE : Clovis, New Mexico**
- **CIL : Pune, India**

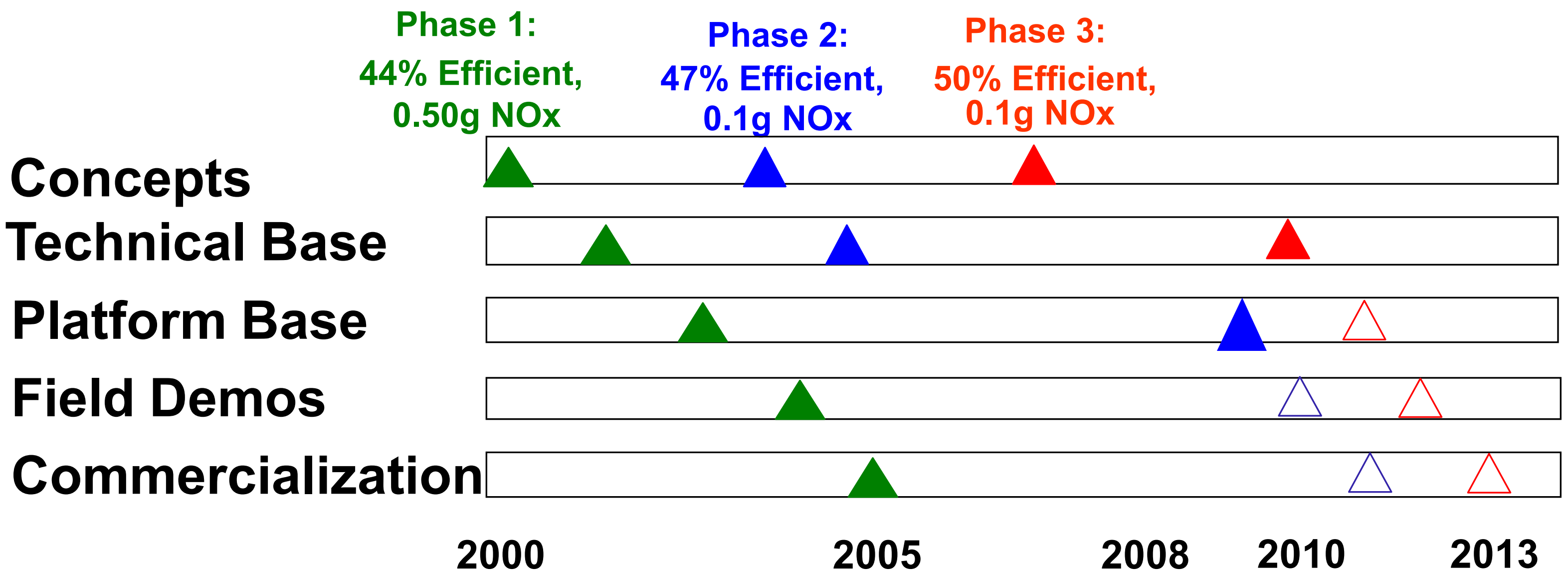


- ***Oil & Gas Business (O&G BU)***
- **Gas Compression**
  - Wellhead (< 500 hp)
  - Gathering (< 1000 hp)
  - Pipeline (> 1000 hp)

Project Management & Budget

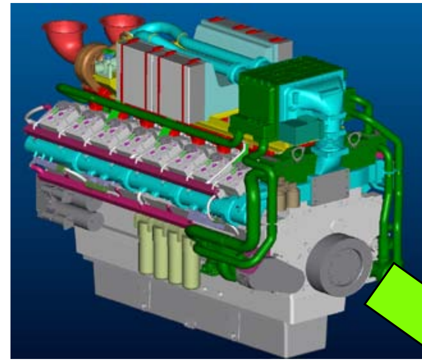
ARES	2011	2012	2013
DOE Investment	$2.7M	TBD	TBD
Cost Share	$2.0M	TBD	TBD
Project Total	$4.7M	$4.6M	$2.9M

Critical Milestones	2011	2012	2013
Phase 2 Design Completed – Target Demons.	Q3	Q2	
Phase 3 Design Completed – Target Demons.		Q3	Q3

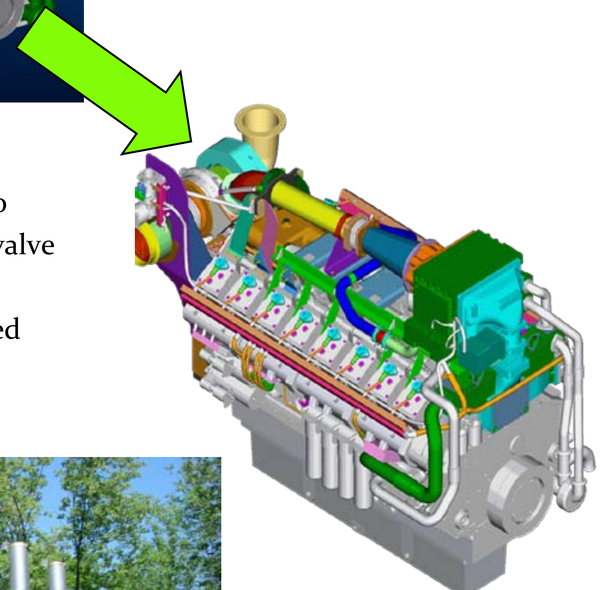


Results and Accomplishments

- Phase 1:
  - Developed new Lean Burn Technology
  - Achieved 44% BTE and 0.1 g/bhp-hr NOx (w/SCR)
  - Applied to 60/91L Platforms
  - Field test completed
  - In Production



- High compression ratio piston
- Miller cycle camshaft
- Long life spark plugs
- Low loss exhaust valves

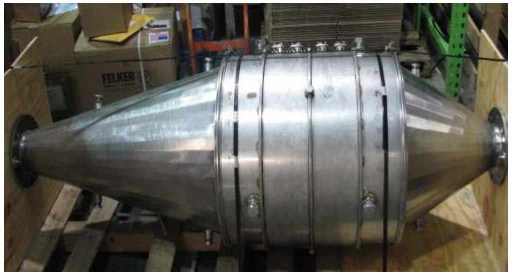


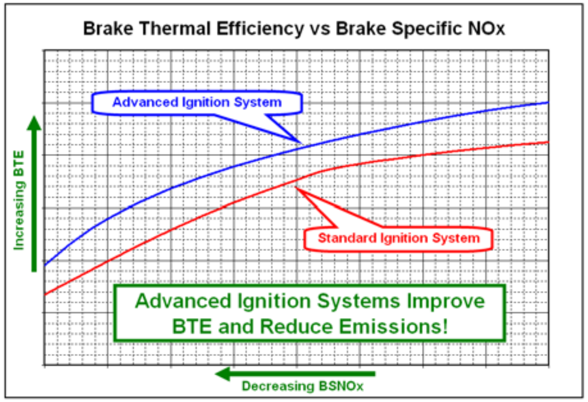
- High efficiency turbo
- Compressor bypass valve
- Advanced controls
- Reduced engine speed
- Increased BMEP

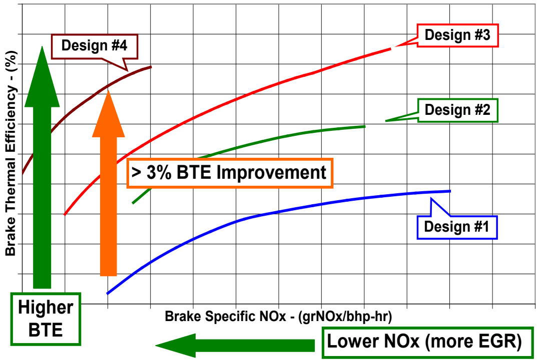
NJ Mountain Creek Resort field test

Results and Accomplishments (cont.)

- Phase 2
  - ✓ Stoichiometric Spark Ignited w/ EGR
    - Demonstrated engine performance targets
  - ✓ Advanced Three Way Catalyst
    - Demonstrated ultra low NOx 0.023 g/hp-hr
  - ✓ Controls / Sensors
    - Demonstrated system for Stoich. w/EGR oper.
  - ✓ Engine Combustion Recipe
    - Modeled and designed unique piston bowl
  - ✓ Ignition System
    - Demonstrated system for Stoich. w/EGR oper.
  - ✓ Renewable Fuels Capability
    - Demonstrated 500 hr cyclic endurance test varying methane number and BTU fuel content while maintaining 0.5 g/hp-hr Nox
    - Demonstrated engine performance targets with Hydrogen rich fuels

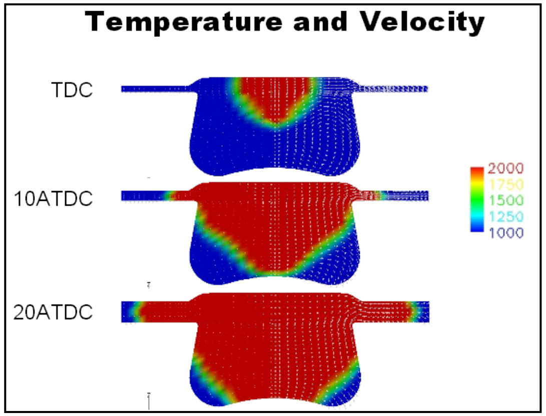


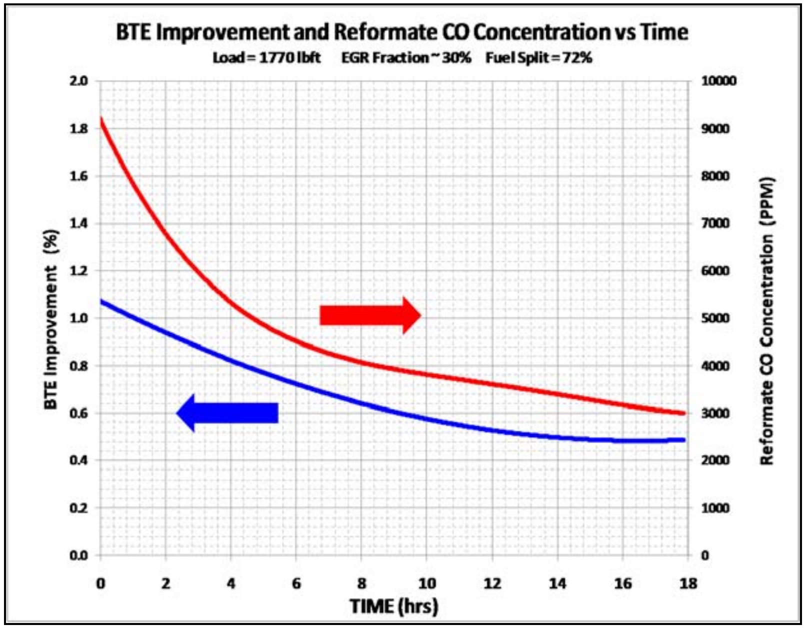




Results and Accomplishments (cont.)

- Phase 2 (cont.)
  - ☑ Analytical Tools Development
    - Developed a combustion predictive tool with the Wisconsin Engine Research Consultants (WERC) for gaseous fuels SI engine modeling
    - Published two papers describing application of advanced modeling techniques @ ASME Congress
  - ☐ Waste Heat Recovery w/Thermo Chemical Recuperation
    - TCR did not perform up to expectations most probably due to carbon poisoning of the catalytic reformer
  - ☐ Advanced Waste Heat Recovery system to replace TCR
    - Integrated on-engine
    - Leveraging on-road engine program





Path Forward

- Maintain the Stoich. w/EGR and TWC engine technology
- Incorporate Advanced Integrated Waste Heat Recovery
  - Demonstrate 47% / 50% efficiency targets
  - Phase 2 completion at end of Q2 2012
  - Phase 3 completion targeted at the current budget and timing Q3 2013
- Confident that this path will achieve program goals

Questions?