Advanced Natural Gas Reciprocating Engines (ARES)

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Cummins Inc.
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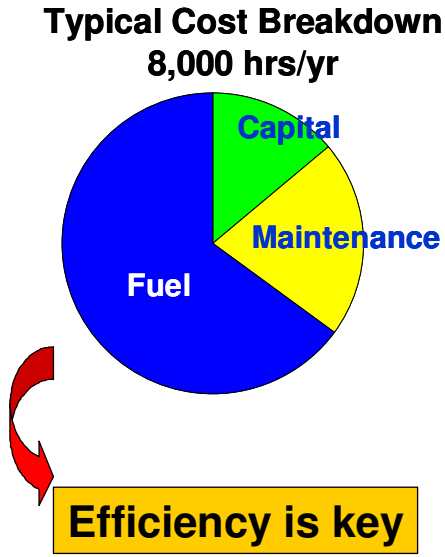
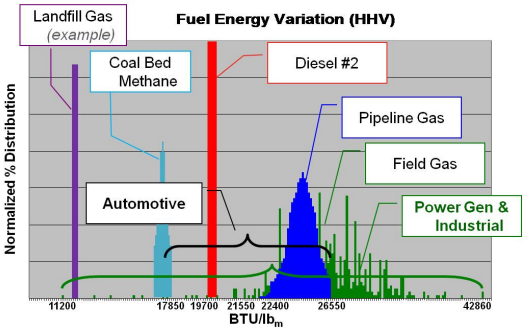
Project Objective

- Increase engine system fuel efficiency at lower emissions levels while attaining lower cost of ownership
- Demonstrate
  - 50% System Brake Thermal Efficiency (BTE) (in three phases: 44%, 47% and 50%)
    - 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
  - 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



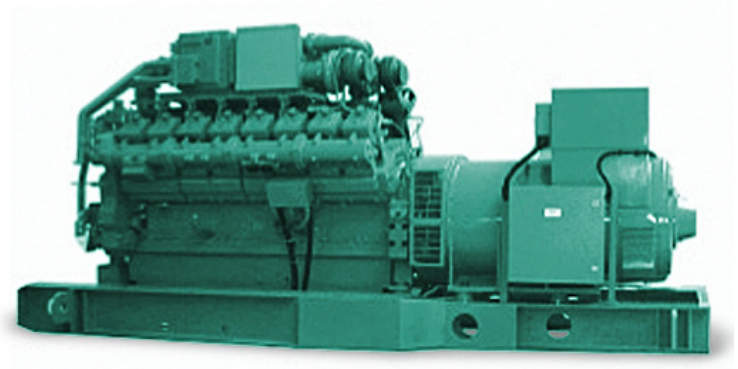


Technical Approach: Architecture

- **Phase 1: Lean Burn Spark Ignited (SI)**
  - Key Technologies: High Efficiency Turbocharging, Miller Cycle, Higher Compression Ratio
    - In production on the 60/91L engines
- **Phase 2: Lean Burn Technology with Exhaust Waste Heat Recovery (WHR) System**
  - Key Technologies: Advanced Ignition System, Combustion Improvement, Integrated Waste Heat Recovery
    - Base engine technologies intended for production within 2 to 3 years
- **Phase 3: Lean Burn Technology with Exhaust and Charge Air Waste Heat Recovery System**
  - Key Technologies: Lower Friction, New Cylinder Head Designs, Improved Integrated Waste Heat Recovery
    - Intended for production within 5 to 6 years

Technical Approach – New Technologies

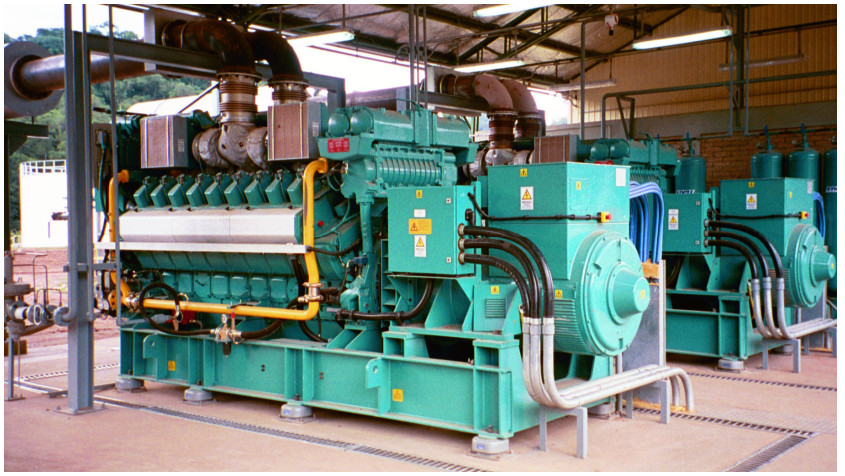
- Base Engine
  - Closed cycle efficiency (Combustion), Open cycle efficiency (Air Handling)
  - Lean Burn, Stoich. w/EGR, Homogenous Charge Compression Ign.
  - Ignition System, Friction Reduction
- Aftertreatment
  - Air Fuel Ratio Management
  - Advanced Three Way Catalyst
- Waste Heat Recovery
  - Conservation of Exhaust Energy
  - Thermo Chemical Recuperation
  - Engine Integrated Waste Heat Recovery System
- Controls / Sensors Development
  - Engine and Aftertreatment Algorithms
- Analytical Tools Development
  - In Cylinder Computational Fluid Dynamics
  - Advanced Cycle Simulation

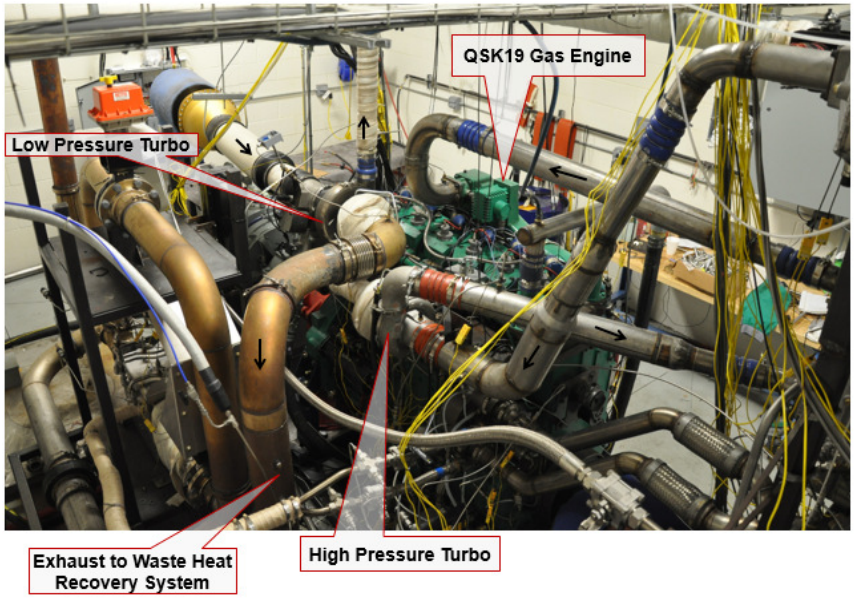


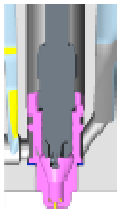
MIT
ARGONNE NATIONAL LABORATORY
Colorado State University Knowledge to Go Places
PURDUE
WERC

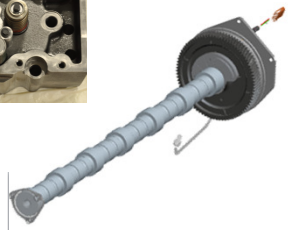
Transition and Deployment

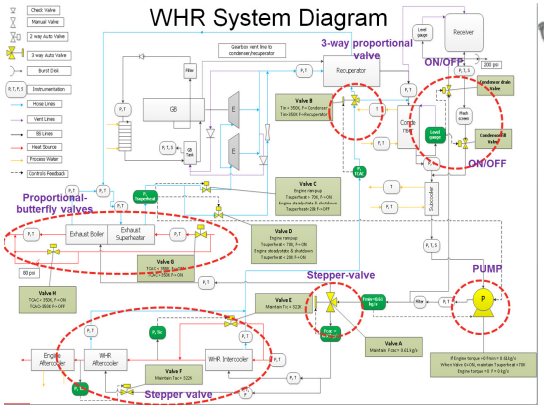
- ARES technology for Power Gen:
  - Reduced Fuel Consumption
  - Improved Reliability
  - Reduced Life Cycle Cost
- Present and Future Cummins products with firm introductory dates are in development using ARES technologies











Commercialization Approach

- Cummins is committed to the launch of next generation of large advanced NG engines based on ARES technology to be commercialized worldwide

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

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

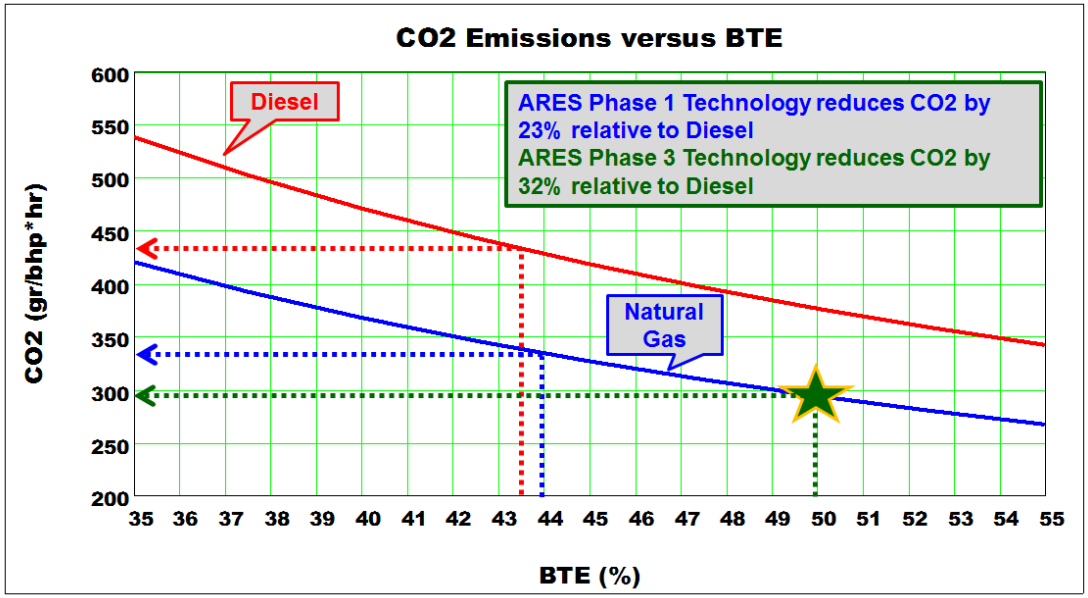
- ***Oil & Gas Business (O&G BU)***
- **Gas Compression**
  - Wellhead (< 500 hp)
  - Gathering (< 1000 hp)
  - Pipeline (> 1000 hp)

Measure of Success

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

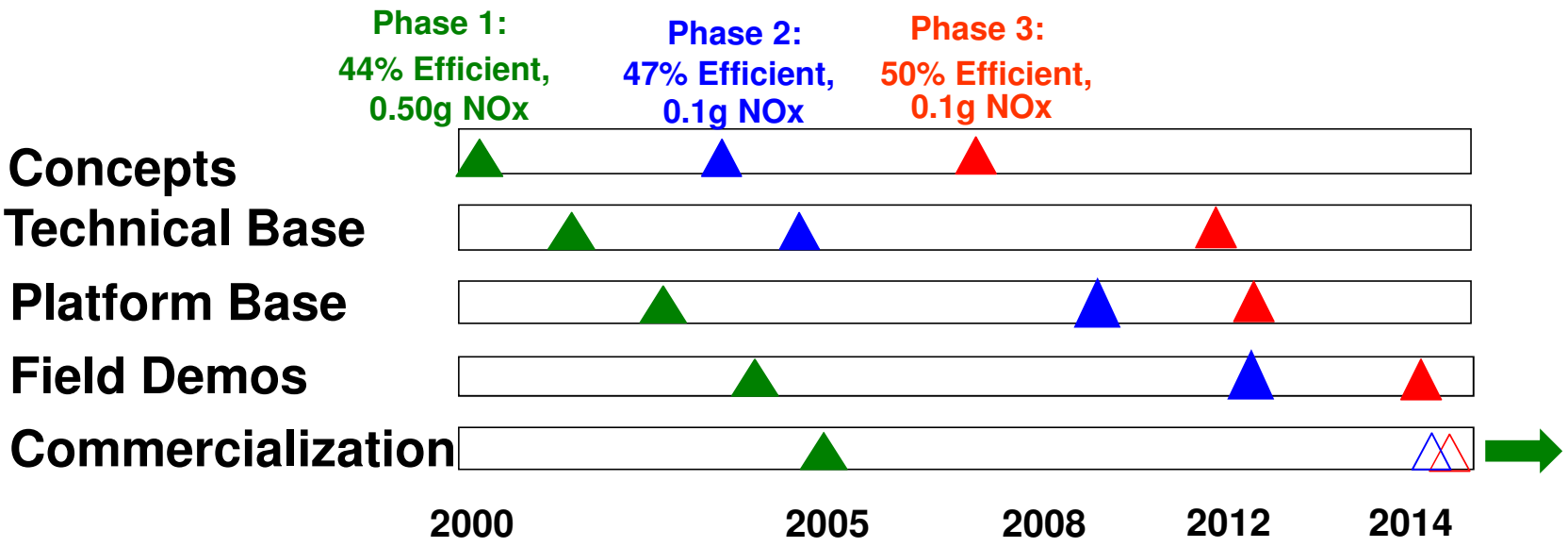
  makes it more attractive for customers to purchase natural gas fueled reciprocating engines. Over 500MW of ARES Phase 1 Technology sold.

CO2 Production and Comparison of Natural Gas and Diesel Power Generation Applications



- Increased utilization of natural gas produced in the USA
- Potential Energy Impact
  - After first 10 years of commercialization
    - Will save 74 MTherms of Natural Gas per year
    - Reduce CO_2 emissions by 4.2M tons per year

Project Management & Budget



ARES Budget	Total
DOE Investment	$18.5 M
Cost Share	$14.2 M
Project Total	$32.7 M

Results and Accomplishments

- Phase 1:
  - Achieved Phase 1 targets
  - Applied to 60/91L Platforms
- Phase 2:
  - Achieved Phase 2 targets and demonstrated Engine Integrated Waste Heat Recovery (WHR) Syst.
- Phase 3:
  - Achieved Phase 3 targets and demonstrated 'Integrated Waste Heat Recovery from Charge Air'
  - Developed a pool of technologies that will be used in future Cummins Natural Gas engines