Advanced Natural Gas Reciprocating Engines (ARES)

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Caterpillar, Inc.
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Executive Summary

The Caterpillar ARES program has developed improvements in power density and fuel consumption that have delivered substantial improvement in owning and operating costs thereby improving the economics of distributed power generation using reciprocating gas engines.

Milestones delivered:

- Phase I: 44% efficiency and 0.50 g/hp-hr NOx demonstrated (2004)
- Phase II: 47% efficiency and 0.10 g/hp-hr NOx demonstrated (2008)
- Phase III: 50% efficiency and 0.10 g/hp-hr NOx technologies under development (demo targeted for 2013)

Market impact:

- Phase I technologies commercialized in the G3500C/E engines
- As of 2009 more than 3.84 gigawatts of ARES technology deployed worldwide
- Strong market pull continues

Projects and Objectives

System level…

- Organic Rankine Cycle for heat recovery to power
  - Problem – efficiency for high hour applications
  - Difficulty – 50% of energy rejected as lower grade heat
- Use of alternative fuels – producer gas
  - Problem – need to reduce environmental impact
  - Difficulty – process and feedstock variations
- Turbocompound
  - Problem – high value efficiency measure for applications still requiring waste heat
  - Difficulty – design and integration of turbomachinery and the effect on the combustion system

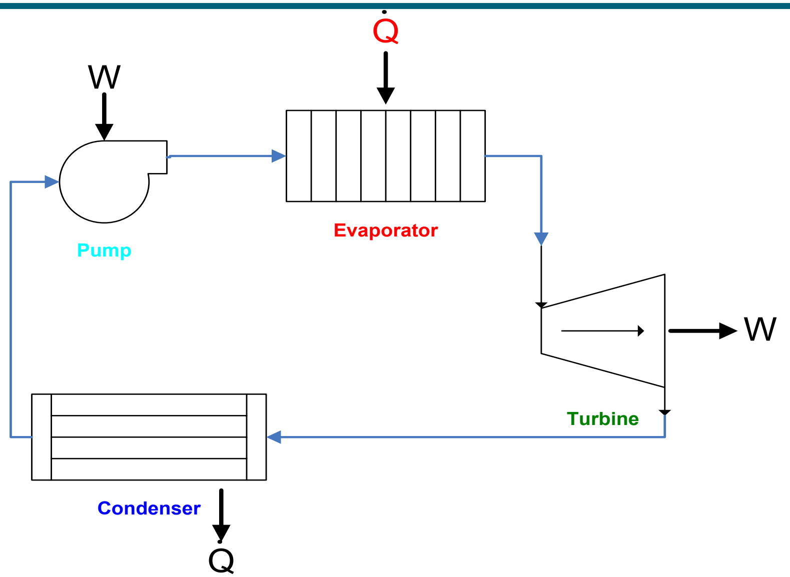
Projects and Objectives (cont'd)

Component level…

- Variable Inlet Valve Actuation
  - Problem – need to control combustion cylinder to cylinder and cycle to cycle – improve efficiency and response
  - Difficulty – dynamics of valve train – integration with combustion system
- Cylinder Pressure Monitoring
  - Problem – need detailed combustion feedback for control
  - Difficulty – durability at acceptable cost
- Laser Ignition
  - Problem – provide energetic, robust, long-life ignition
  - Difficulty – packaging and durability at acceptable cost

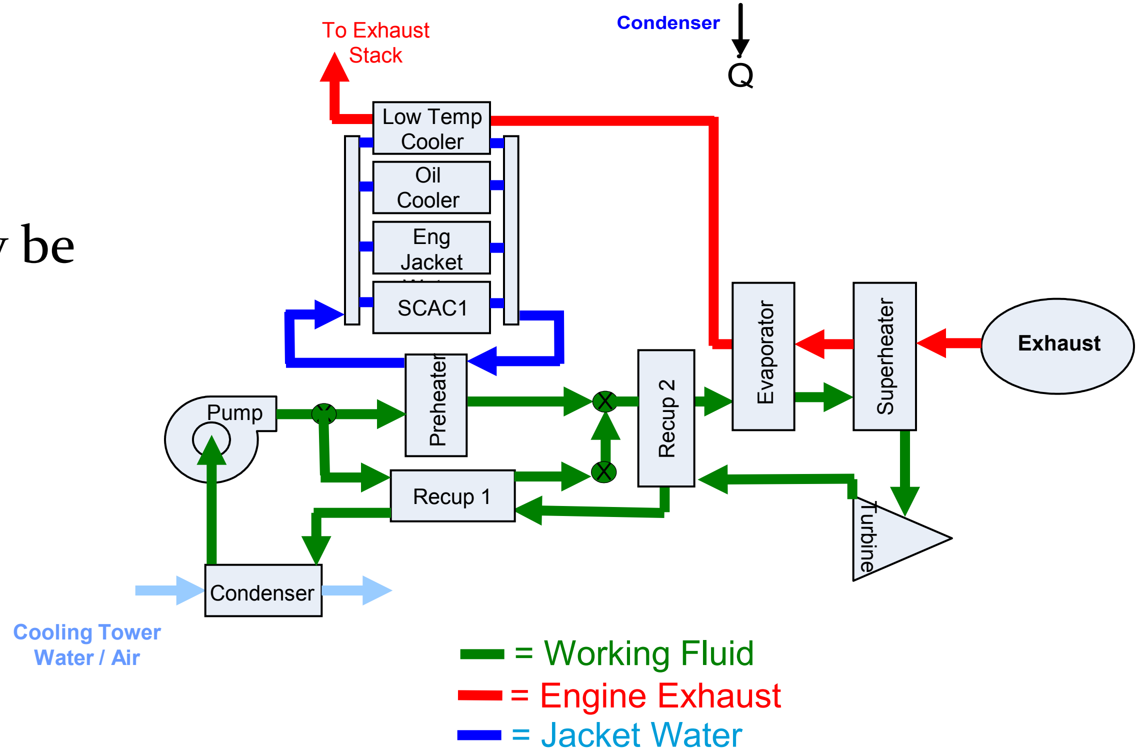
Organic Rankine Cycle

Today, offered via a third party, unique, not optimized or available within a reciprocating engine system solution



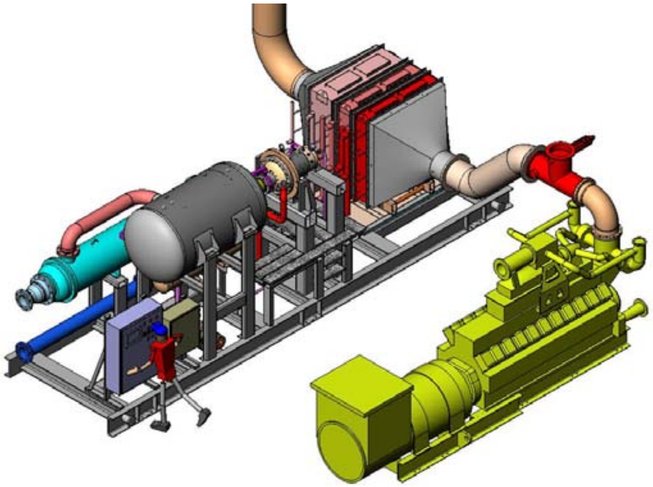
Cycle concept is simple in principle

In practice, configurations may be significantly more complicated

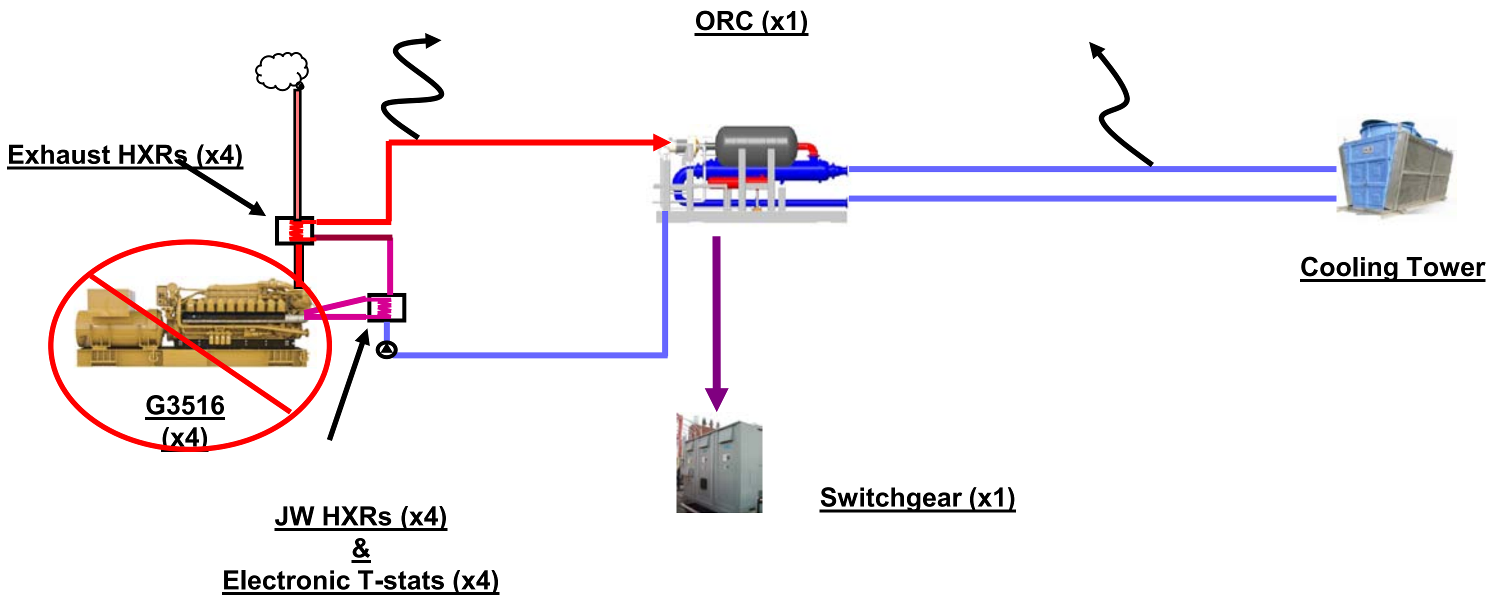


Organic Rankine Cycle

Approach – purpose-built single engine system built for Phase II demonstration – technical capability understood



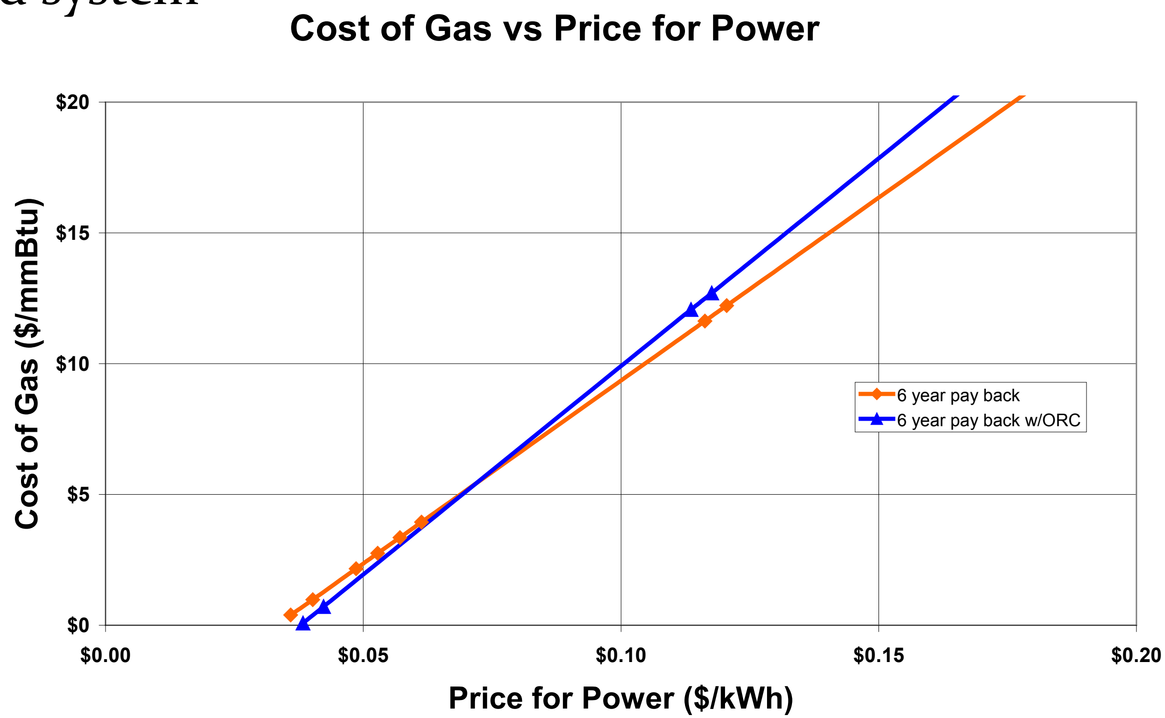
Next step – understand real-world applications and system operational characteristics



Organic Rankine Cycle

Benefit – power generation from waste heat – no additional criteria pollutants or GHG emissions

Challenges – today's business environment of low gas cost, low electricity prices, lack of a packaged system



Path forward –

- Deploy commercial components as a system to gain operational experience
- When environment supports, offer a system solution

Alternative Fuels – Producer Gas

Concept

- Provide a system to convert renewable energy feedstocks to low greenhouse gas (GHG) electric power in an ARES-class genset
- Define an engine configuration that is flexible over the range of fuels likely to be encountered

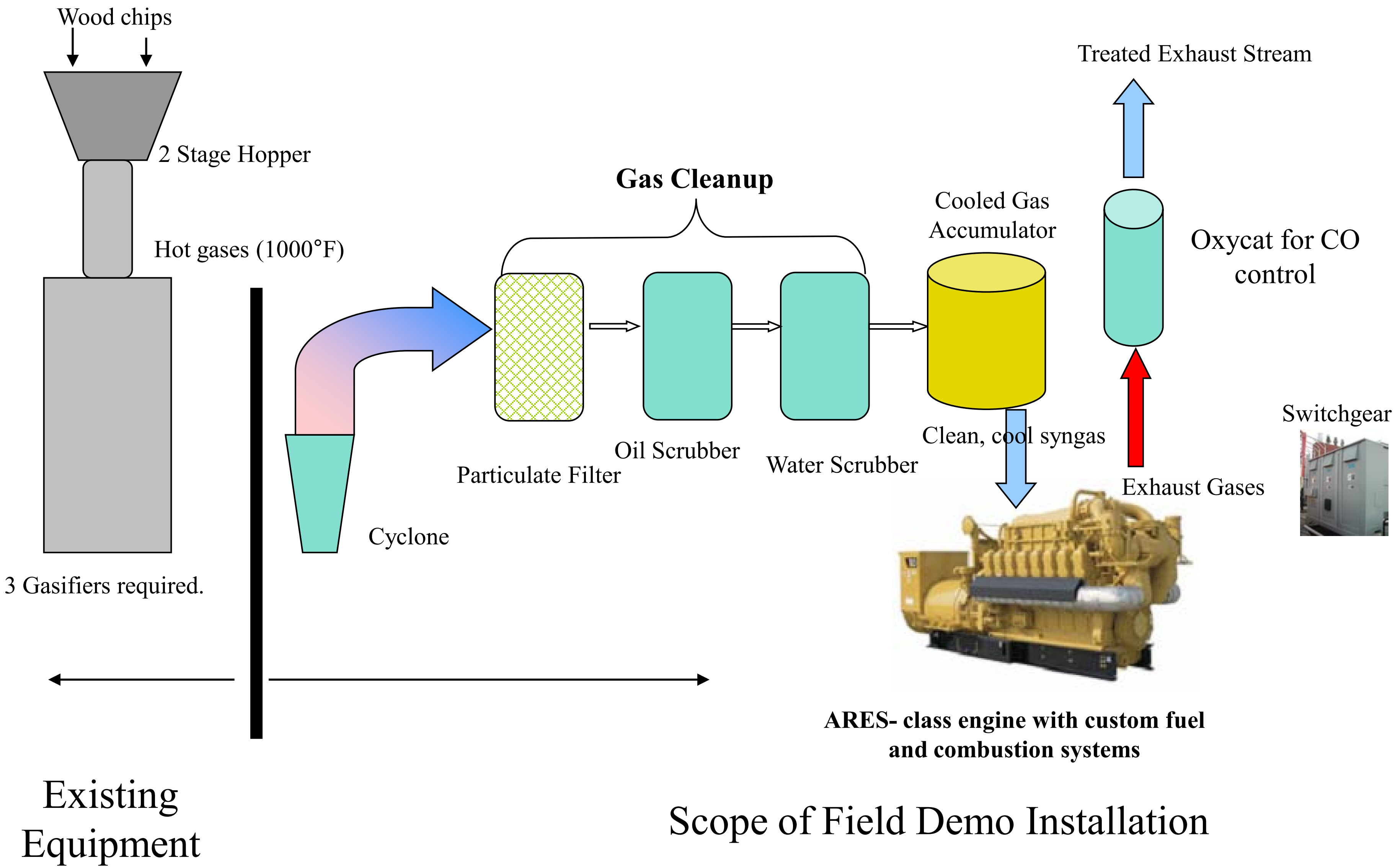
Today

- Offered with a unique combination of components for each application
  - Costly to engineer and deploy

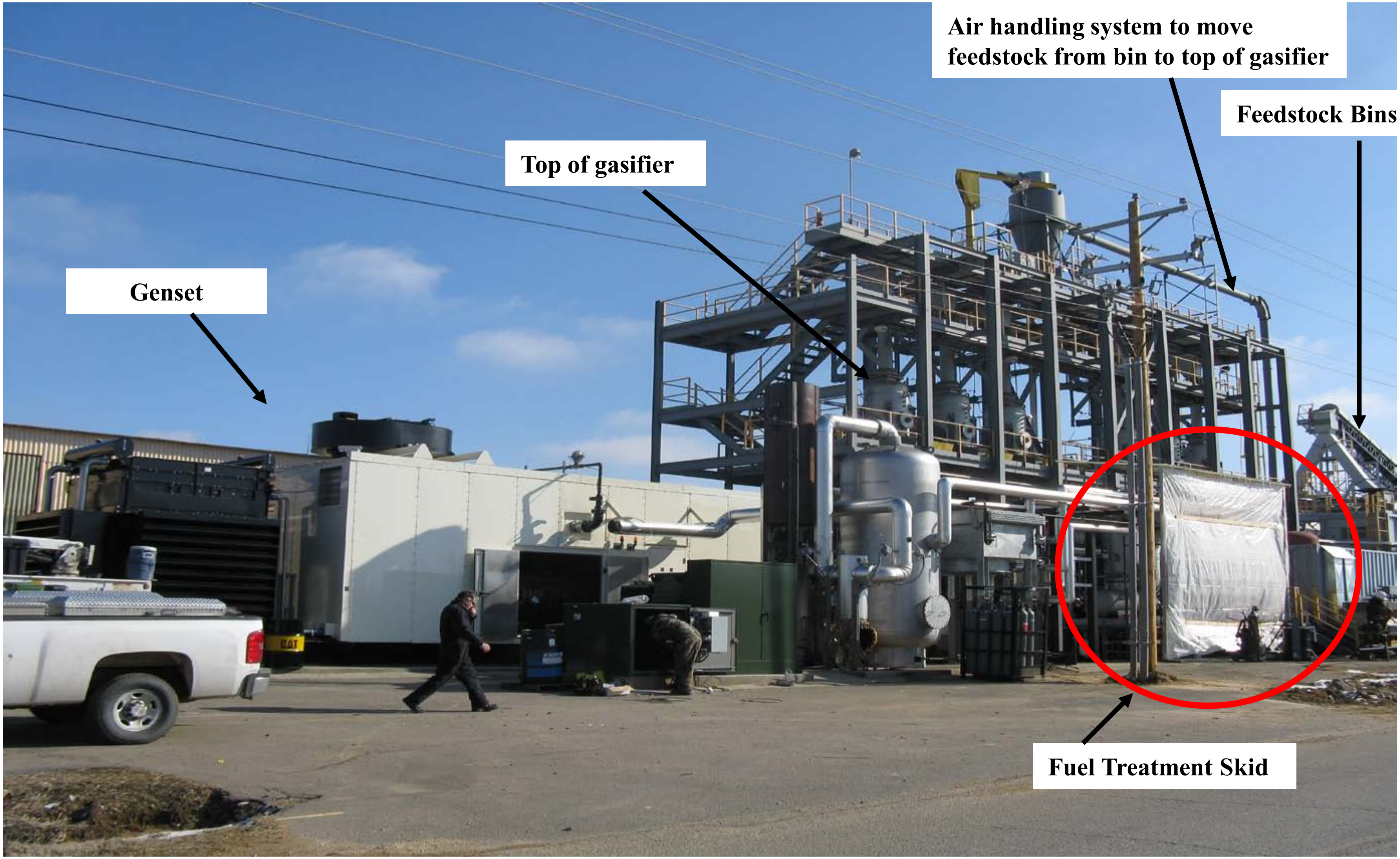
Approach

- Engineer a combination of system components that work well together for a variety of feedstocks
- Purpose-built engine, generator set combination with appropriate fuel and combustion systems
- Deploy first unit and learn what's required to offer as a "standard" product
- Develop fuel characterization tool via work with Colorado State University

Alternative Fuels – Producer Gas Demo



Alternative Fuels – Producer Gas Demo



Alternative Fuels – Producer Gas

Current status

- Engine and gasifier system on-site and under test
- Have operated on producer gas for 40 minutes at 50% of targeted load
- Next testing will be with genset paralleled to grid
- Expect full power demonstration within next two months

Future plans

- Operate power system for one year and then transfer ownership to customer
- Offer the complete system, gasifier, cleanup, genset, control system as a one stop solution for biomass gasification to electric power

Turbocompound

Concept

- Use an additional turbine downstream of the turbocharger turbine to convert exhaust energy to power

Today

- Not offered for reciprocating gas engine power generation applications
- Used in a few mobile diesel products

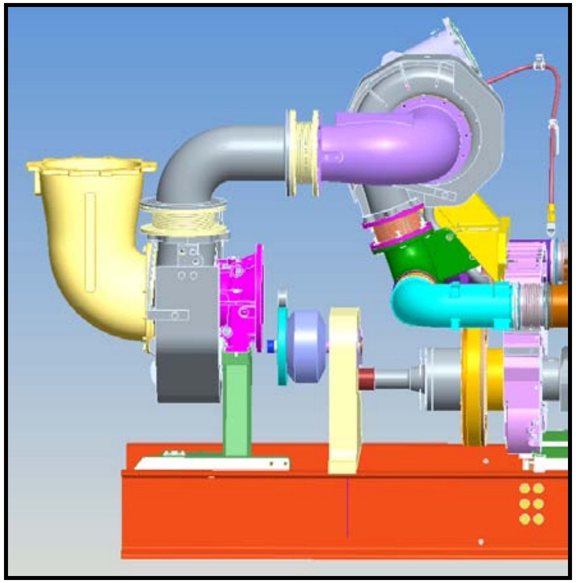
Approach

- Evaluate impact via single cylinder engine evaluation
- Target new high efficiency platform
- Concept design to evaluate value proposition
- If favorable cost/value, design and procure proof of concept iron – potential Phase III building block

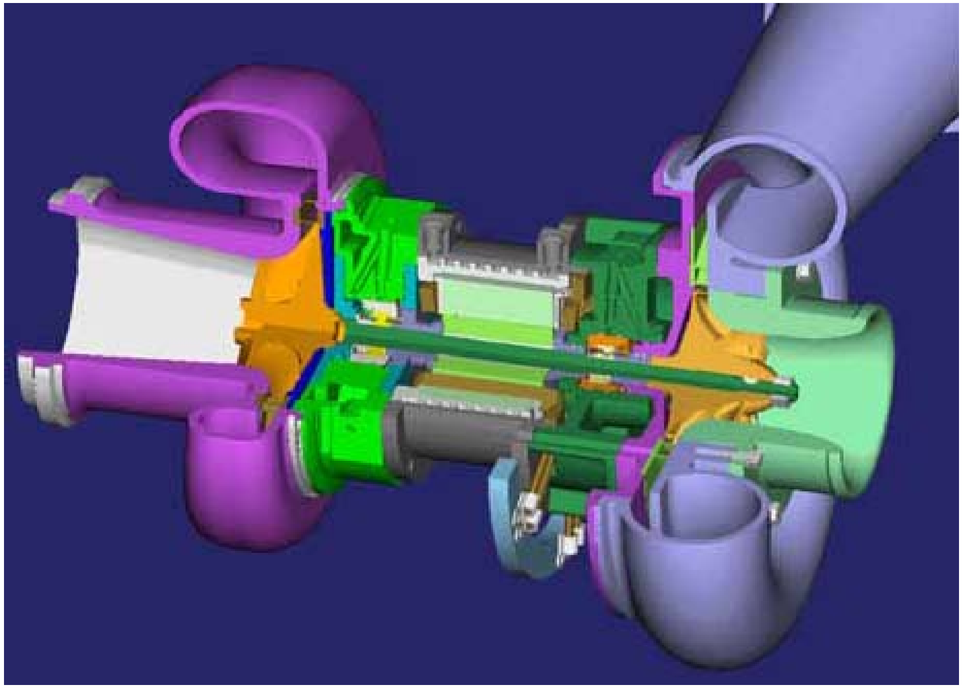
Turbocompound

Candidate arrangements include

- Generator on turbo shaft either between components or in front of compressor
- Power turbine downstream of the turbocharger – mechanical drive to crankshaft

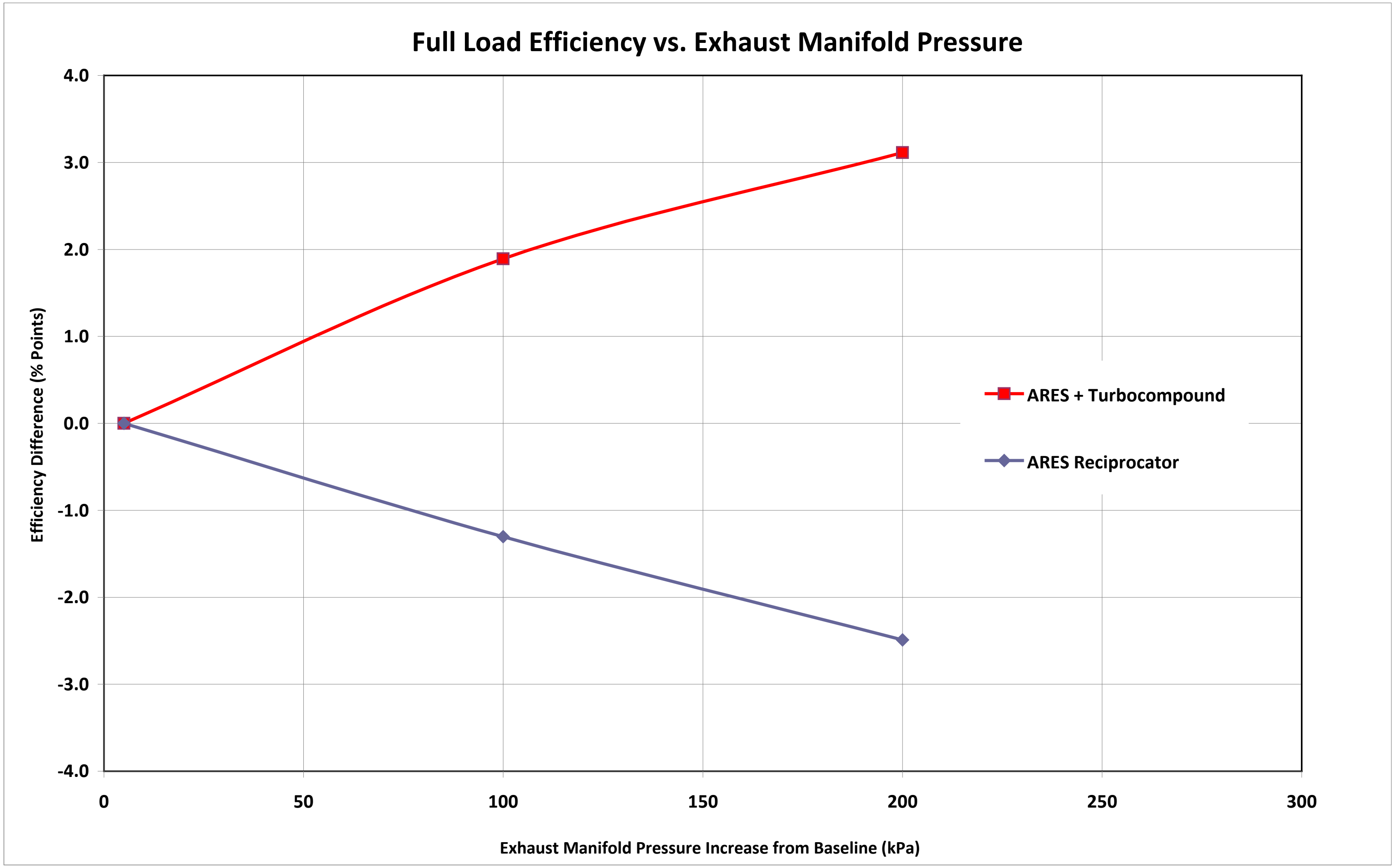


Power turbine downstream of turbocharger



High speed generator between compressor and turbine

Turbocompound



Challenges

- Increasing cylinder pressure
- Decreasing detonation margin

Turbocompound

Current Status

- Testing on single cylinder test engine indicates potential benefits
- Work underway to test concept on new high efficiency ARES platform

Future Plans

- Complete concept design based on results from high efficiency ARES platform tests
- Evaluate cost/value relationship relative to to other Phase III technologies
- If attractive proceed to detailed design and procurement for multicylinder demonstration

Variable Inlet Valve Actuation

Concept

- Use of variable inlet valve timing on a Miller cycle engine allows manipulation of fuel/air charge on a per cycle basis

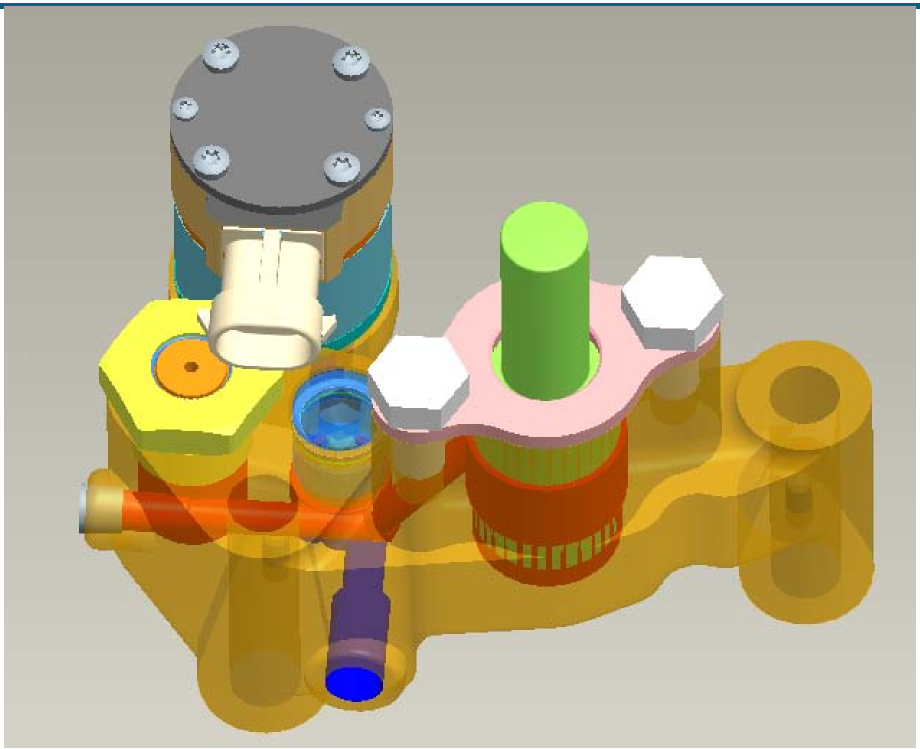
Today

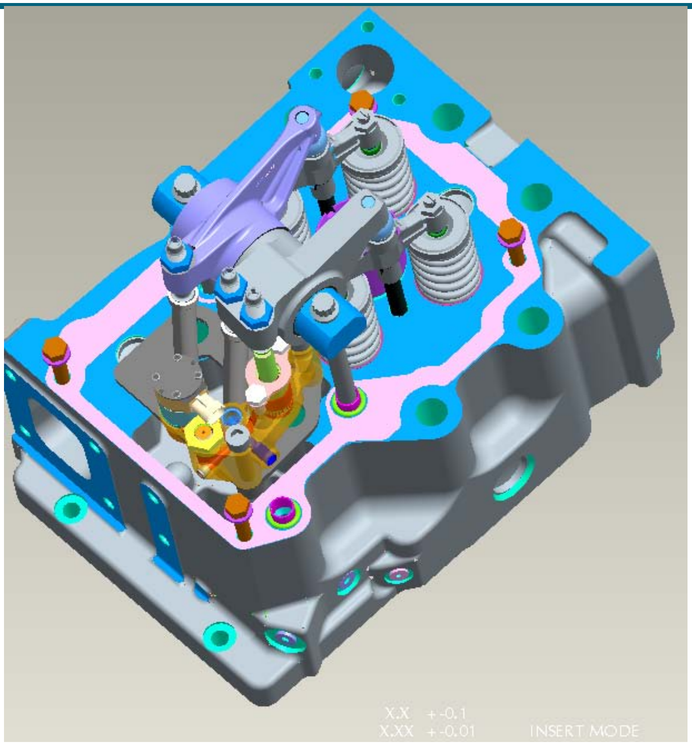
- Offered in some diesel applications for variable compression ratio and compression braking (when applied to exhaust)
- Not currently applied to ARES-class reciprocating gas engines

Approach

- Design and procure system for single cylinder engine evaluation
- Performance test on G3500C/E
- Evaluate value proposition relative to other control solutions
- If most favorable cost/value, procure proof of concept system for multicylinder engine – potential Phase III building block

Variable Inlet Valve Actuation





- Flexible method of varying the effective compression ratio
- Closed loop control to trim the charge pressure
    - Closed loop requires cylinder pressure monitoring
- Improved transient response

Variable Inlet Valve Actuation

Current Status

- Testing on single cylinder test engine verifies performance is as predicted
- Work underway on alternative method of cylinder balancing

Future Plans

- Results of VIVA learning captured, multicylinder work on hold pending results of alternative method
- VIVA work will be taken to multicylinder engine if cost/value analysis supports, relative to other solution

Cylinder Pressure Monitoring

Concept

- Cylinder pressure monitoring provides more combustion information than provided today by detonation detection system
- Useful for feedback control for per cylinder actuators during "normal" combustion

Today

- Complete system is not commercially available for heavy duty engine operation at an attractive cost.
- Used in engines much larger than ARES-class engines

Approach

- Evaluate sensors from three suppliers
- Endurance test the two most attractive options

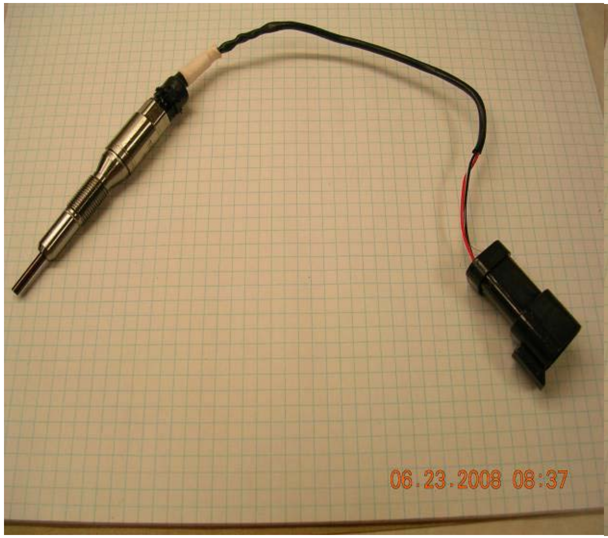
Cylinder Pressure Monitoring - Sorting

Three manufacturer technologies

- Micro Strain Gage
- Piezo-electric
- Optical

Detonation Testing

Endurance Testing



Cylinder Pressure Monitoring

Status - G3520C landfill engine in Massachusetts

- 20 sensors from two different suppliers
- Over 9000 hrs per sensor
- Failure modes identified
  - Mfr "A" has a manufacturing (batch) issue
  - Mfr "B" has an insulation issue (fix identified)
- Heads will be changed in June and sensors collected for retesting against baseline performance

Future plans

- Summarize post test results
- Complete the cost/value analysis

Laser Ignition

Concept

- Laser ignition holds promise as a robust, long life ignition source option
- Enabler for lean mixture ignition at very high cylinder pressures/loads
- Low NOx enabler
- Long life and low maintenance attractive as means to extend engine service interval

Today

- Not commercially available as a reciprocating engine ignition system

Approach

- Team with experts at Colorado State University to identify and remove technology obstacles
- Target demonstration on Phase III platform

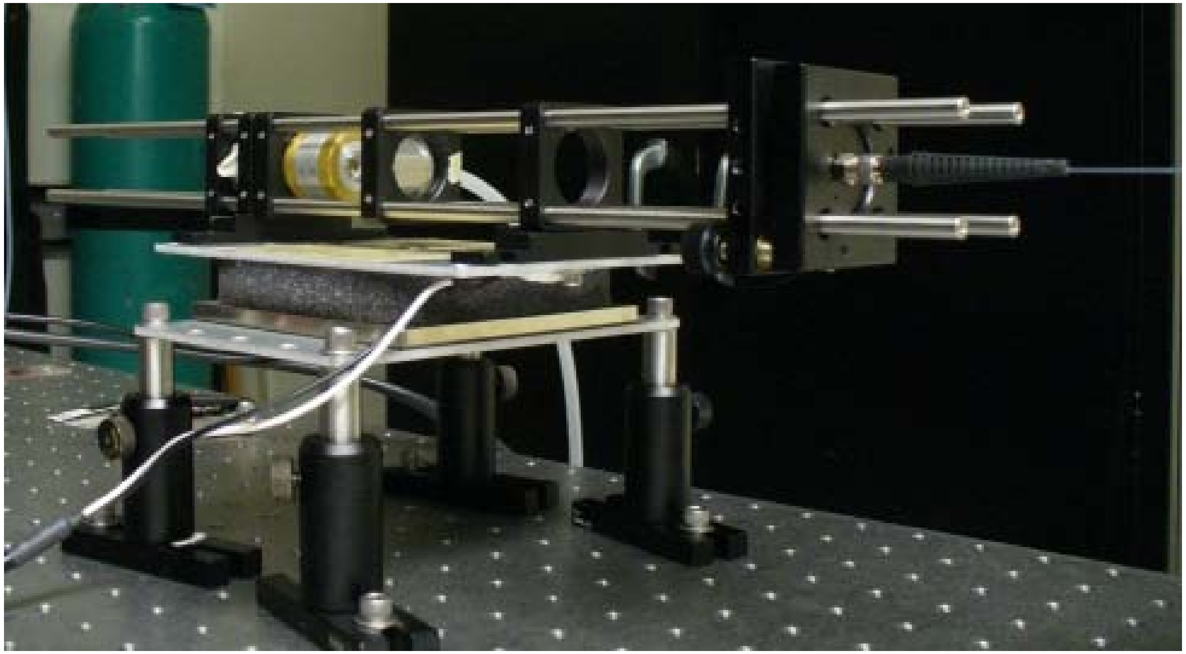
Laser Ignition

Current Status

- Spark delivery demonstrated with commercial silica fibers
- Engine demonstration of two cylinders with one laser

Future plans

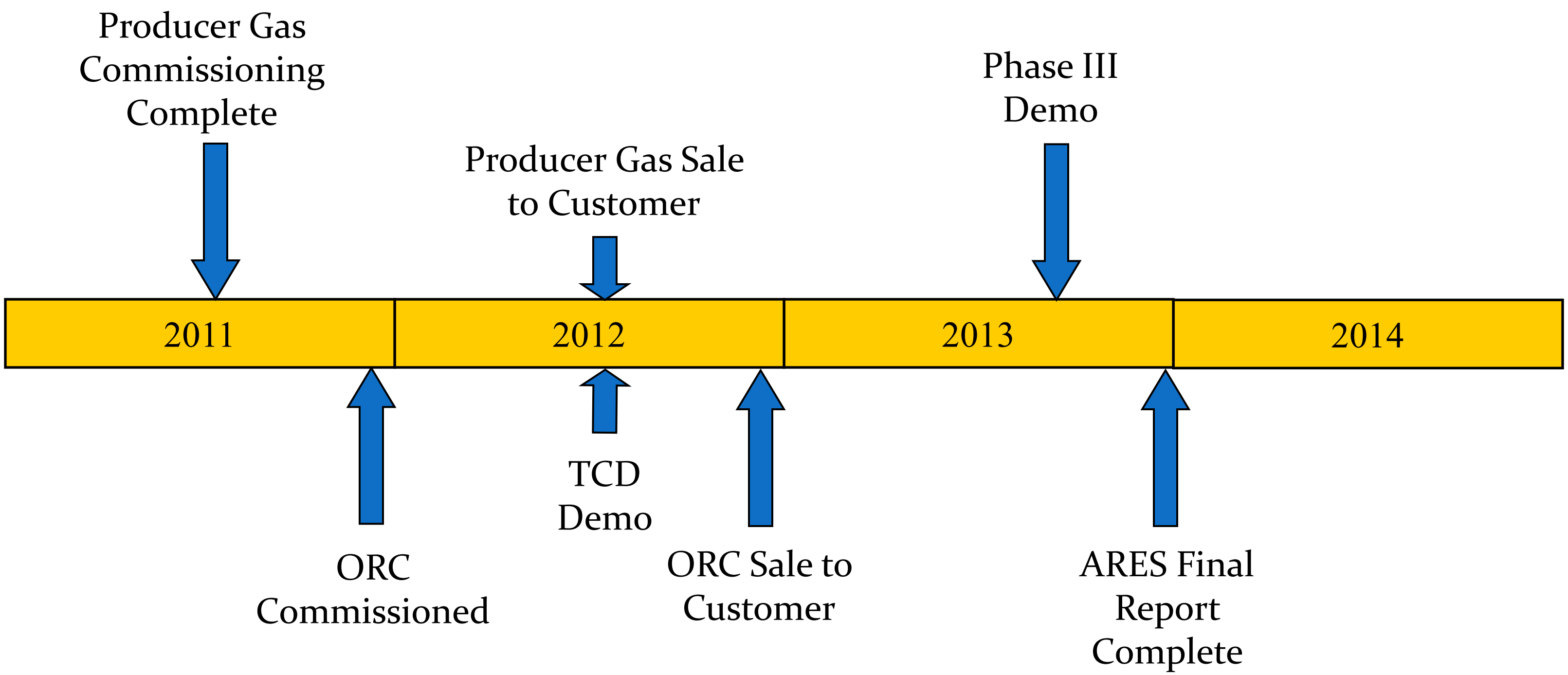
- Emphasis is on fiber reliability at needed energy and engine vibration conditions



Summary

- Phase I technologies successfully deployed beginning in 2004 – demand has validated value
- Phase II technologies are on a commercial development path
- System and component technology development projects are underway to address efficiency, fuel flexibility, and owning and operating cost
- Fuel and electricity pricing will determine the path to lowest owning and operating cost

Project Management & Budget



Program Budget				
	FY11	**FY12**	**FY13**	**FY14**
DOE Investment	$3,080,000	$728,454	$2,934,855	-
Cost Share	$1,913,863	$4,850,166	$1,905,041	-
Project Total	$4,993,863	$5,578,620	$4,839,896	-

Questions?