An Engine System Approach to Exhaust Waste Heat Recovery

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Note: This presentation does not contain any proprietary, confidential, or otherwise restricted information.
Overview

Timeline
- Start: Oct 2005
- Finish: Jun 2011
- 52% Complete

Budget
- Total Project Funding
  - DOE - $3,938K
  - Contractor - $3,938K
- Funding received FY08 & FY09
  - DOE - $1,176K
  - Contractor - $1,176K

Barriers Addressed
- Efficiency typically reduced by measures to reduce NOx
- Poor cost effectiveness of exhaust heat utilization systems
- Limitations of air handling components and systems

Partners
- Honeywell Turbo Technologies
- Barber-Nichols Inc.
- Concepts NREC
- Turbo Solutions Engineering
Objectives

Project Objective: Develop components, technologies, and methods to recover energy normally *exhausted as waste heat* from the engine to demonstrate a 10% improvement in overall thermal efficiency.

FY08 – FY09 Objective: Demonstration of significant progress (+ 6 to 10%) in system thermal efficiency improvement via:

- Detailed design / analysis / procurement of prototype components
- Bench testing of prototype components
- On-engine demonstration of prototype hardware
Milestones

- Analysis Focus – Aerodynamic, structural, rotordynamic
- Test Focus – Aerodynamic, rotordynamic performance

- Analysis / Detailed Design
- Component Procurement
- Bench Testing
- On-Engine Testing
- System Analysis
- Refine / Refocus Program

Go / No-Go: Demonstration of system level thermal efficiency improvement of 6-10% via test / analysis of prototype components

Current status
**Approach**

An integrated system solution to waste heat recovery

Numbers in ( ) indicate % increase in thermal efficiency from this component

Baseline C15
LPL (low pressure loop) configuration

• Turbocompound or bottoming cycle: supplements engine power via electrical or mechanical connection to flywheel

Strategy Optimization

- Stack Recovery* (4.0%)
- Piping (0.5%)
- Port Insul. (0.5%)
- Intercooling (1.3%)
- Compressors (0.7%)
- HP Turbine (2.0%)
- LP Turbine (1.0%)

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Technical Progress – HP Turbine

Target: + 2% Engine Thermal Efficiency:
• + 8% Turbine Stage Efficiency
• Improved Exhaust Pulse Utilization

Technology 1 – Radial, Nozzled, Divided (RND) Turbine
• High efficiency turbine wheel + nozzled and divided turbine housing

Prior Accomplishments
• Gen1 “research” design demo’d + 5% turbine efficiency

2008-9 Accomplishments To Date
• Detailed design / analysis complete – Gen2 “production-able” design
  • Single-piece cast nozzle ring
• Procurement / assembly complete
• Predict + 6-7% turbine efficiency
  • Improved low-loss nozzle design
• Gas stand testing March – April
• Engine testing – June - July
Technical Progress – HP Turbine

Target: + 2% Engine Thermal Efficiency:
• + 8% Turbine Stage Efficiency
• Improved Exhaust Pulse Utilization

Technology 2 – Mixed Flow Turbine
• Nozzle-less, divided volute designed for exhaust pulse utilization

Prior Accomplishments
• Gen1 mixed flow design demo’d ability to improve pulse utilization
• Gen1 peak efficiency –1%; code calibration required

2008-9 Accomplishments To Date
• Detailed design / analysis complete - Gen2 wheel & housing
• Predict +2-3% peak turbine efficiency; +3-5% on-engine efficiency
• Procurement underway
• Gas stand testing May-June
• Engine testing – July-Aug
• Gen3 – mixed flow nozzled divided (MND) to hit target
Technical Progress – LP Turbine

Target: + 1% Engine Thermal Efficiency:
  • + 6% Turbine Stage Efficiency

Technology – High Efficiency Nozzled Turbine

Prior Accomplishments
  • Design / Analysis verifies + 6% efficiency w/ Caterpillar axial turbine
    • Packaging concerns w/ series turbos and turbocompound

2008-9 Accomplishments To Date
  • Detailed design complete - new radial wheel & nozzle
  • Predict + 4% turbine efficiency
    • Concept evaluation ongoing to achieve additional +2%

  • Procurement underway
  • Gas stand testing May-June
  • Engine testing – June - July
Technical Progress – Compressors

Target: + 0.7% Engine Thermal Efficiency:
• +2.5% Compressor Stage Efficiencies

Technology – Highly backswept compressor stage + vaned diffusers

Prior Accomplishments
• Gen1 design demo’d + 2.5% compressor efficiency

2008-9 Accomplishments To Date
• Detailed design / analysis complete – Gen2 highly backswept wheel
• Predict +4% compressor efficiency
• Hardware procured
• Assembly / balancing underway
• Gas stand testing April – May
• Engine testing – June - July
Technical Progress – Stack Recovery

Target: +4% Engine Thermal Efficiency
• Stack recovery on baseline LPL engine

Technology – Mechanical Turbocompound

Prior Accomplishments
• Engine simulation verifies + 4% efficiency w/ turbo technologies developed here

2008-9 Accomplishments To Date
• Detailed design complete – improved high efficiency power turbine bearing system (Gen2)

• Procurement underway
• Gas stand testing April – May
• Engine testing – June - July
Technical Progress – Stack Recovery

Target: + 4% Engine Thermal Efficiency
• Stack recovery on baseline LPL engine

Technology – Electrical Turbocompound

Prior Accomplishments
• Prior DOE-Caterpillar research program
  • Design / procure / test integrated Gen1 turbo-generator
  • Thermal management challenge – unit overheats above 15kw

2008-9 Accomplishments To Date
• Concept design complete – Gen2 permanent magnet turbo-generator
  • Turbo-generator on LP stage of series turbocharged base engine
  • Analysis – meets performance, structural, thermal requirements
Technical Progress – Stack Recovery

Target: +4% Engine Thermal Efficiency
- Recovery on High Pressure Loop (HPL) Engine Configuration

Technology – Brayton Bottoming Cycle

Prior Accomplishments
- Previously analyzed on LPL base engine
  - Heat exchanger packaging challenge

2008-9 Accomplishments To Date
- Completed capability analysis on Brayton Cycle operating on HPL
- Benefit increases as recirculation rates increase
Technical Progress – Stack Recovery

**Target:** + 4% Engine Thermal Efficiency
- Recovery on High Pressure Loop (HPL) Engine Configuration

**Technology** – Turbocompound

**Prior Accomplishments**
- Power turbine technology under development

**2008-9 Accomplishments To Date**
- Engine simulation confirming effectiveness of turbocompound for driving HPL recirculation
  - Up to 5-6% efficiency benefit at high load versus use of VNT to drive recirculation
  - Benefit will increase if combined with low backpressure DPF’s
  - Benefit will be strongest with high recirculation rates
Future Work – Current BP

Gas Stand Testing (complete Jun - Jul 09):
- RND (radial, nozzled, divided) turbine – GEN2
- Mixed flow turbine – GEN2
- High backsweep compressor stage – GEN2
- Mechanical turbocompound – GEN2 bearing system

Engine Testing (complete Jun - Aug 09):
- All of the above

Analysis (complete Aug - Sep 09):
- Turbocompound
  - Map fuel economy benefits vs engine speed/load, gas recirculation rates, aftertreatment backpressure, and component efficiencies
  - Calculate cycle fuel economy benefits
  - Transient simulation to establish response benefit
Future Work – Beyond Current BP

- Validation of Gen2 ‘production-able’ RND housing design
  - Technology works – focus to get it production-ready

- Ongoing development of radial turbines to higher efficiency
  - Need additional +2% turbine efficiency to meet component goal

- Evaluation of mixed flow – nozzled – divided turbine (MND)
  - Can it meet HP target? Is it production-viable?

- Detailed design, procurement, test of Gen2 turbo-generator
  - Ongoing development of electric turbocompound
Future Work – Beyond Current BP

Current demo: C15 MY07 on-hw (LPL engine configuration)

Future application - determined by emissions requirements

Technology applicability:
- LPL engine configuration
- HPL engine configuration
- Series turbocharged
- Single-stage turbocharged

If series turbocharged: apply 3-wheel single shaft turbo to improve packaging and cost
Summary

RND, Mixed Flow Technologies
- Prior: +1.0% demo’d
- Now: +1.2-1.4% predicted
  - more “production-able”

Nozzled Turbine Technology
- Prior: +1.0% predicted
- Now: +0.6% predicted
  - Better package

Stack Recovery
- Prior: +4.0% predicted
- Now: +4.0% predicted
  - Replaced Brayton with Turbocompound
  - Better cost, package

High Backsweep Compressor
- Prior: +0.7% demo’d
- Now: +1.0% predicted

- Demo of +8 - 8.5% for LPL engine planned
  - Path to 10% established
  - Solution path promising for HPL engine