An Engine System Approach to Exhaust Waste Heat Recovery

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Caterpillar Inc.

DOE Merit Review
Washington, D.C.
June 10, 2010

DOE Contract: DE-FC26-05NT42423
DOE Technology Manager: John Fairbanks
NETL Project Manager: Carl Maronde
Project ID: ACE039

Overview

Timeline

- Start: Oct 2005
- Finish: Jun 2010
- Percent complete: ~95%

Budget

- Total Project Funding
  - DOE ⇨ $2,188K
  - Contractor ⇨ $2,188K
- 2009 Funding:
  - DOE ⇨ $659K
  - Contractor ⇨ $659K
- 2010 Funding:
  - DOE ⇨ $207K
  - Contractor ⇨ $207K

Barriers Addressed

Barriers to achieving VT Program goals of 50% and 55% heavy truck efficiency:

- Poor cost effectiveness of exhaust heat utilization systems
- Efficiencies of current air handling components and systems

Partners

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

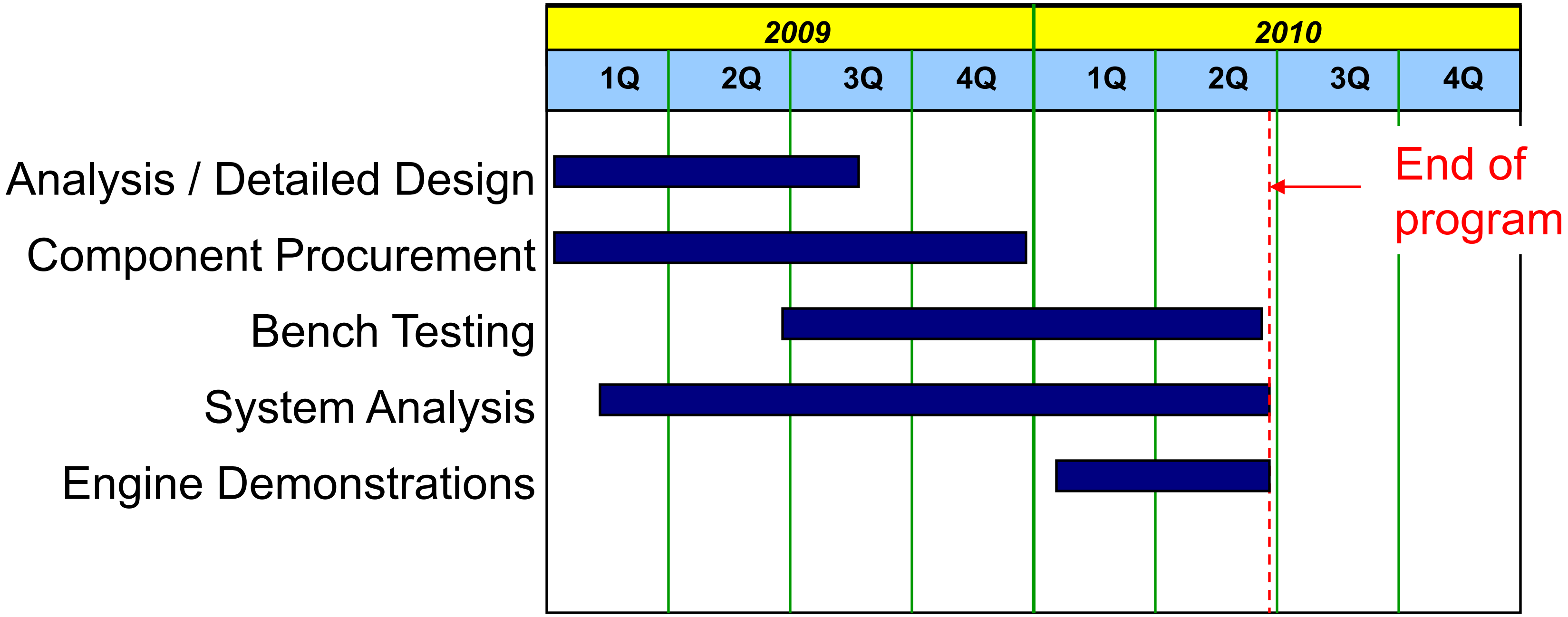
Project Objectives - Relevance

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 (for example, from 42% to 46.2% thermal efficiency)

FY09 – FY10 Objective: Demonstration of significant progress (+ 6 to 10%) in system thermal efficiency improvement via:

- Design / analysis / procurement / test of high efficiency turbomachinery stages
- Procurement / test of high efficiency turbocompound power turbine stage
- Engine demonstrations of component hardware

Milestones

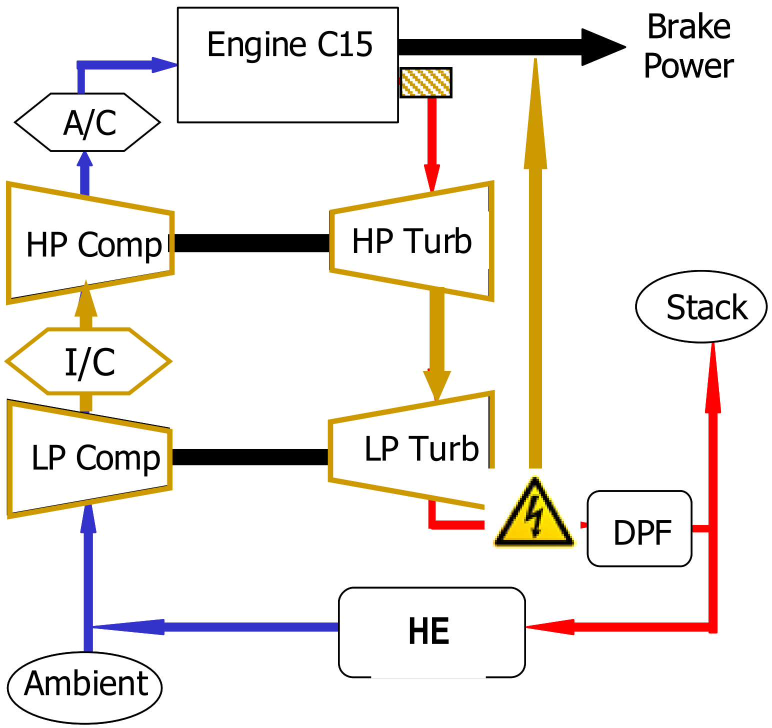


- Analysis Focus – Aerodynamic, structural, rotordynamic
- Test Focus – Aerodynamic, rotordynamic performance

Goal: Demonstration of system level thermal efficiency improvement of 6-10% via test / analysis of prototype components

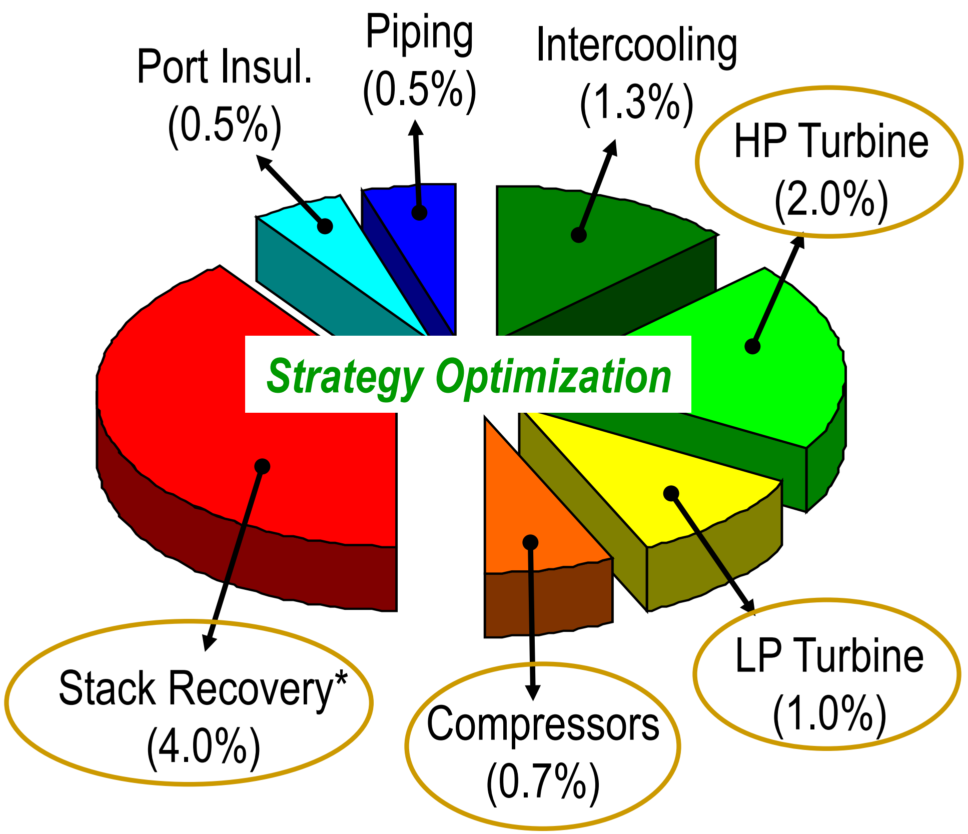
Approach / Strategy

An integrated system solution to waste heat recovery



Baseline C15
LPL (low pressure loop) configuration

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

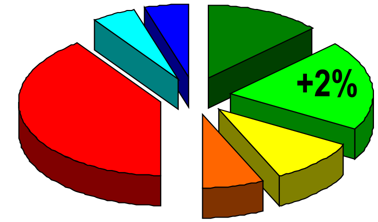


•Turbocompound or bottoming cycle: supplements engine power via electrical or mechanical connection to flywheel

Approach / Strategy

- **"System" Solution**
  - Modular; "Best" elements can be carried to production
- **Production-Viable Technologies**
  - Cost, Packaging, Manufacturing
- **Broad Emissions Architecture Applicability**
  - Viable for LPL, HPL, or non-EGR solutions
    - Simulations have generally shown greater benefits of the technologies under development on HPL configurations
  - Compatible w/ Aftertreatment

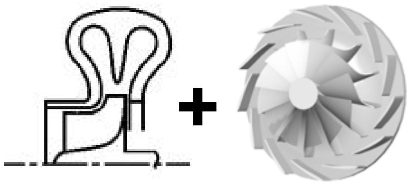
Technical Progress – HP Turbine



Target: + 2% Engine Thermal Efficiency:

- + 8% Turbine Stage Efficiency ⟸
- Improved Exhaust Pulse Utilization

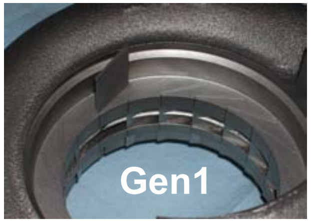
Technology 1 – Radial, Nozzled, Divided (RND) Turbine



- High efficiency turbine wheel + nozzled and divided turbine housing

Prior Accomplishments

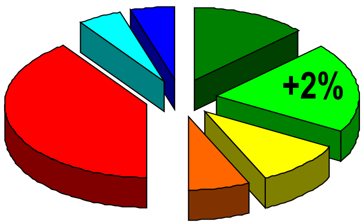
- **Gen1** "research" design demo'd + 5% turbine efficiency



2009-10 Accomplishments To Date

- Procurement / test complete ⇨ **Gen2** "production-able" design
  - Single-piece cast nozzle ring
- Demonstrated +6% peak turbine efficiency on gas stand
  - Worth +1.5% thermal efficiency on series turbo LPL engine
- On-engine demonstration ⇨ C15 single-stage turbo HPL EGR
  - + 2-3% thermal efficiency at 1200rpm and 1500rpm lug
  - Demonstrated 30% response improvement on-engine

Technical Progress – HP Turbine



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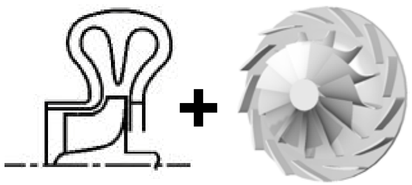
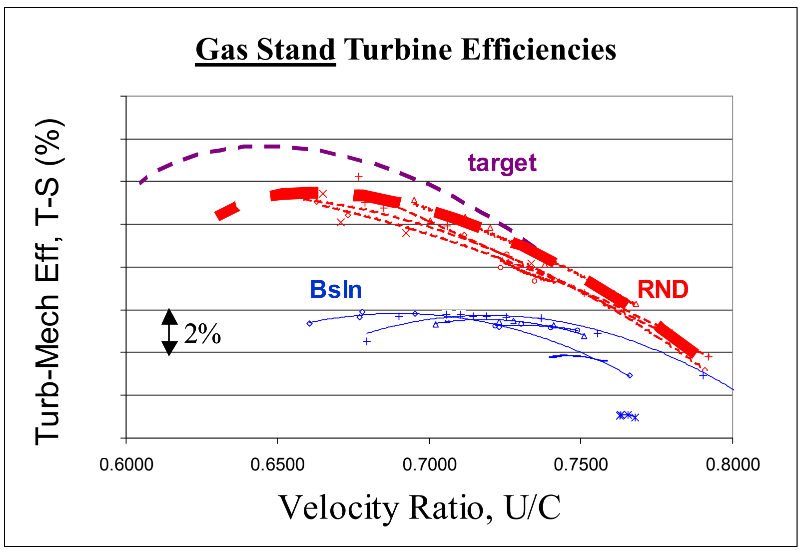
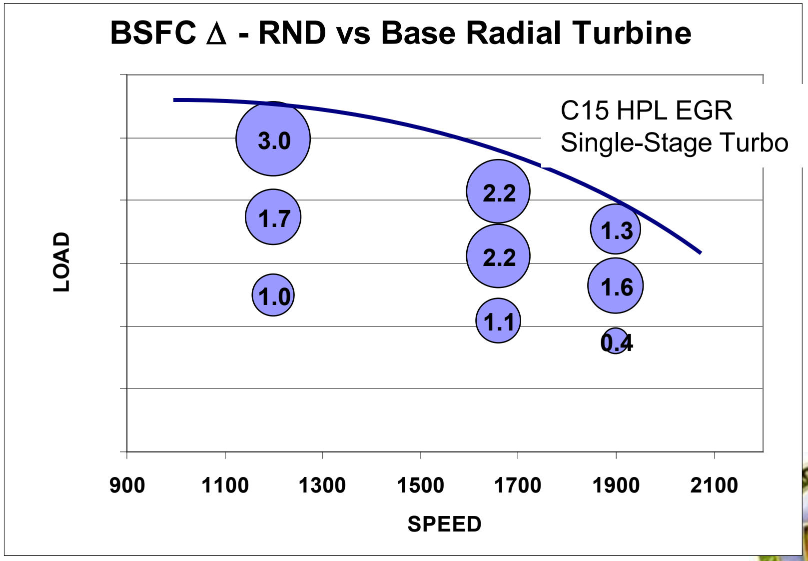


Technology 1 – Radial, Nozzled, Divided (RND) Turbine

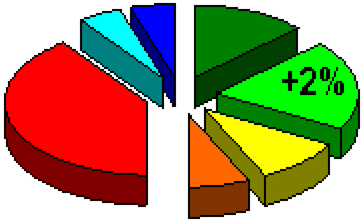
- High efficiency turbine wheel + nozzled and divided turbine housing

2009-10 Accomplishments To Date





Technical Progress – HP Turbine



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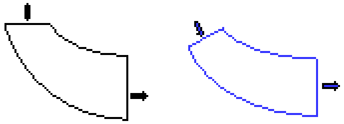


Technology 2 – Mixed Flow Turbine

- Nozzle-less, divided volute designed for exhaust pulse utilization

Prior Accomplishments

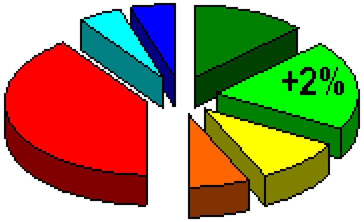
- **Gen1** mixed flow design demo'd ability to improve pulse utilization
- **Gen1** peak efficiency –1-2%; code calibration required

2009-10 Accomplishments To Date

- Procurement / test complete ⇨ **Gen2** mixed flow wheel & housing
- Demonstrated +2-3% peak turbine efficiency on gas stand
- Demonstrated peak efficiency shift for improved pulse utilization
- On-engine demonstration ⇨ C15 LPL EGR series turbo
  - + 1.3% thermal efficiency at 1200rpm and 1500rpm lug


Gen2 Wheel

Technical Progress – HP Turbine



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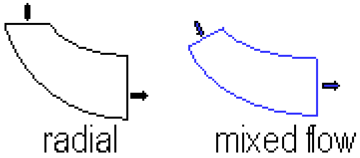

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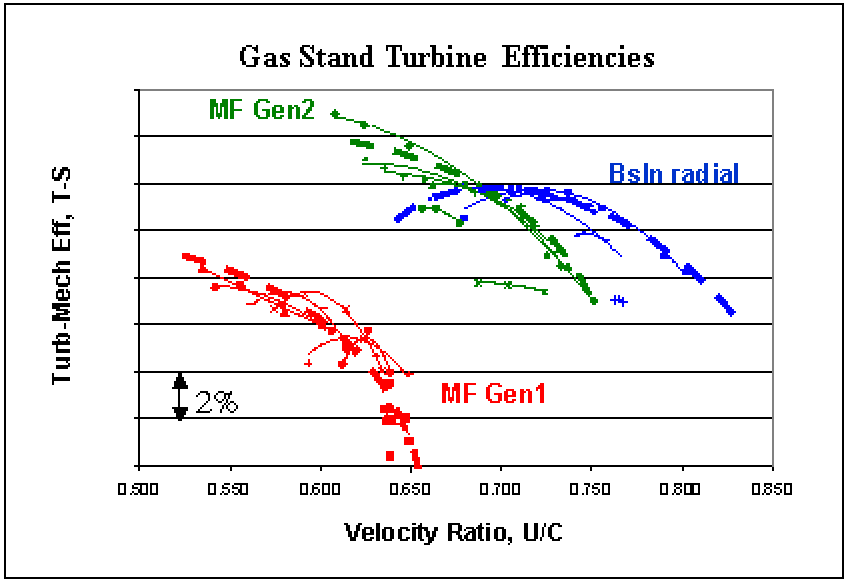
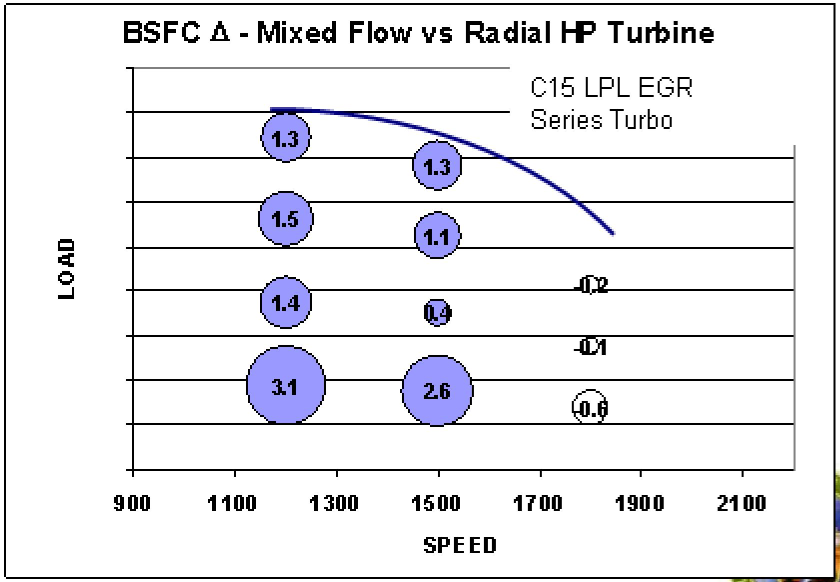
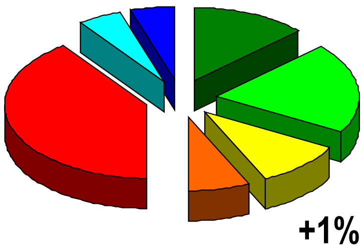
2009-10 Accomplishments To Date



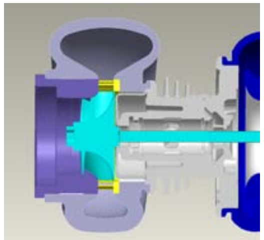


Technical Progress – LP Turbine

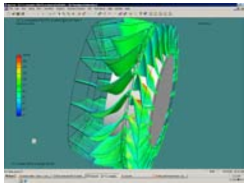


Target: + 1% Engine Thermal Efficiency:

- + 6% Turbine Stage Efficiency



Technology – High Efficiency Nozzled Turbine



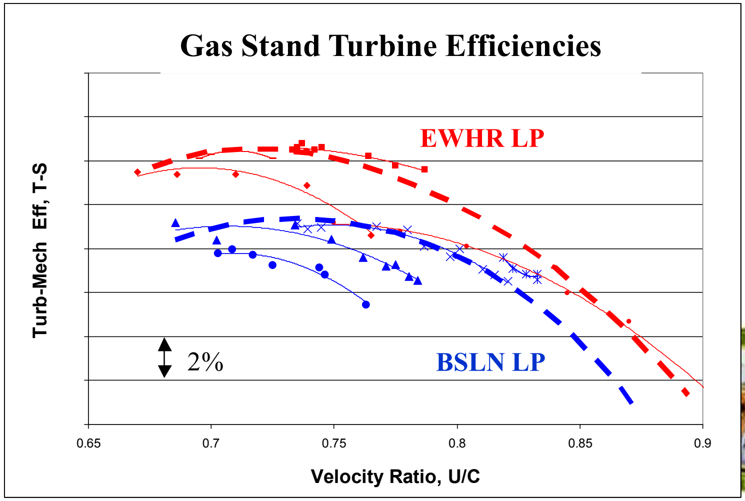
Prior Accomplishments

- Design / Analysis verifies + 6% efficiency w/ Cat **axial** turbine
  - Packaging concerns w/ series turbos and turbocompound

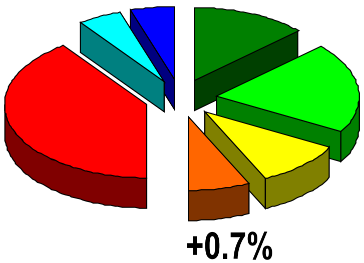
2009-10 Accomplishments To Date

- Procurement / test complete ⇨ high efficiency nozzled radial stage
- Demonstrated +4% peak turbine efficiency on gas stand

Nozzled LP Turbine



Technical Progress – Compressors



Target: + 0.7% Engine Thermal Efficiency:

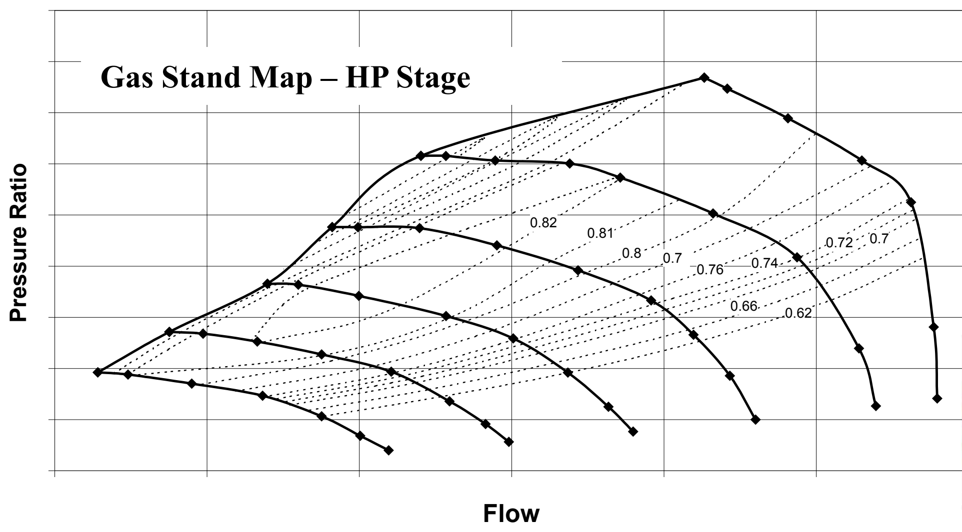
- +2.5% Compressor Stage Efficiencies

Technology – Highly backswept compressor stage + vaned diffusers

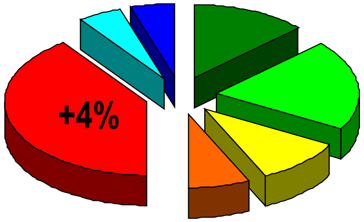
2009-10 Accomplishments To Date

- Procurement / test complete ➪ HP compressor stage
  - Demonstrated +1.5% peak compressor efficiency on gas stand
- Hardware procured ➪ LP compressor stage
  - Gas stand tests ➪ May - June

High backsweep HP compressor



Technical Progress – Stack Recovery



Target: + 4% Engine Thermal Efficiency

- Stack recovery on baseline LPL engine

Technology – Mechanical Turbocompound

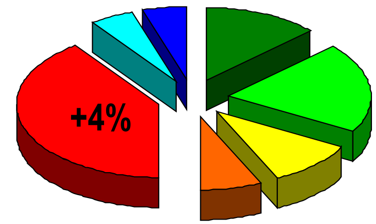
Prior Accomplishments

- Simulation ⇨ + 4% efficiency for LPL EGR, series turbo engine
- Simulation ⇨ + 5-6% efficiency for HPL EGR, single turbo engine
- Simulation ⇨ 0.5-1.0% thermal efficiency penalty w/ journal bearings
- Concept design / analysis complete ⇨ Gen2 electric turbocompound

2009-10 Accomplishments To Date

- Developed method to test power turbine on gas stand
  - Use engine as compressor to load power turbine
  - Shaft motion instrumentation to measure rotordynamic behavior
- Assembly / test complete ⇨ ball-bearing power turbine
  - Excellent shaft motion characteristics at all speeds

Technical Progress – Stack Recovery



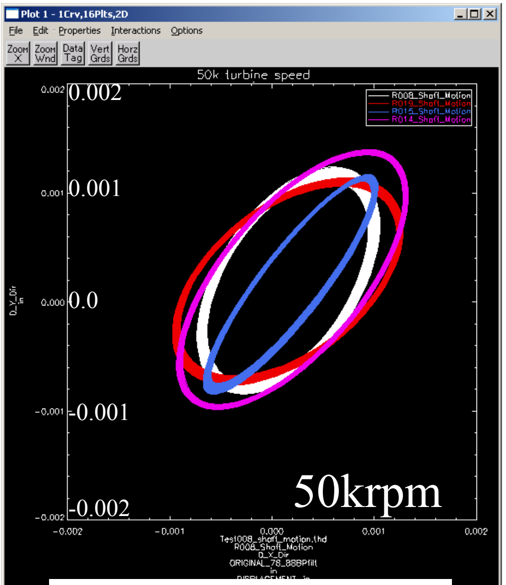
Target: + 4% Engine Thermal Efficiency

- Stack recovery on baseline LPL engine

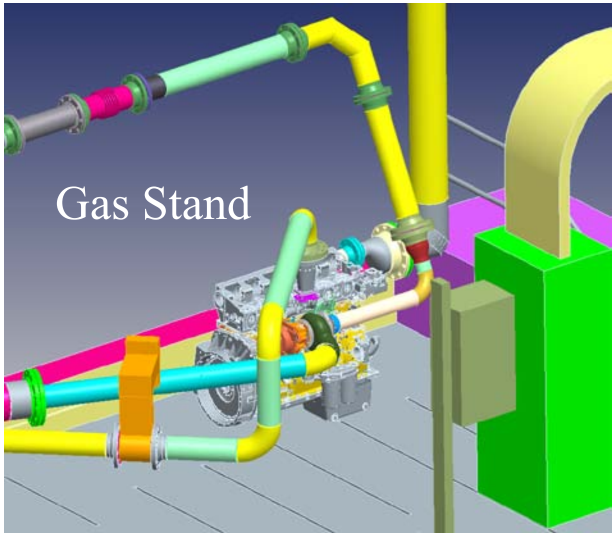
Technology – Mechanical Turbocompound

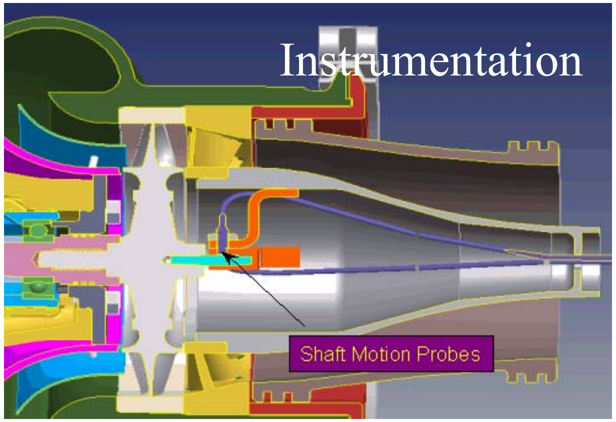
2009-10 Accomplishments To Date

- Gas Stand Test Conditions
  - 5 bearing systems
  - Speeds from 25k-60krpm
- Gas Stand Test Results
  - Excellent shaft motion: < 0.002" at all speeds
  - Aero performance as predicted: 80-84% efficiency



Shaft Motion Results





Collaborations

Barber-Nichols Inc. – Subcontractor

- Concept design / analysis of Gen2 Turbocompound Turbogenerator

Concepts NREC – Subcontractor

- Assist in design / analysis of high efficiency turbo wheels / volutes

Turbo Solutions Engineering – Subcontractor

- Assist in design / analysis of high efficiency turbo wheels / volutes

Honeywell Turbo Technologies – Project Support

- Manufacturing / balancing of high efficiency turbine wheels & shafts

Imperial College – Project Support

- Full-width maps of RND and mixed flow turbines on dyno gas stand

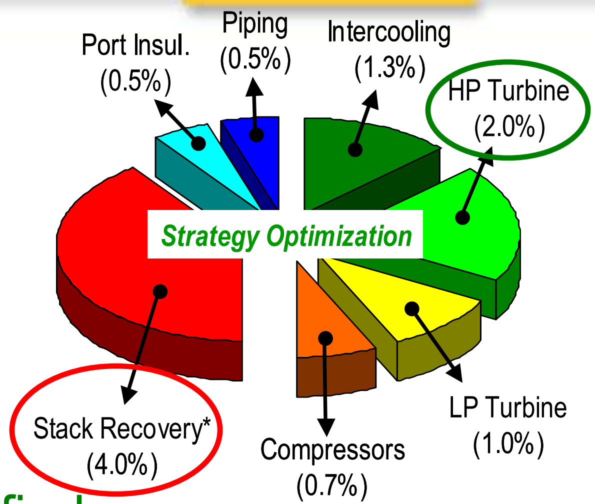
Oak Ridge National Lab – Project Support

- On-engine testing of high efficiency turbine stages

Future Work

- Validation of Gen2 ‘production-able’ RND turbine design
  - Technology works – move it toward production-readiness
- Evaluation of mixed flow – nozzled – divided turbine (MND)
  - Can it exceed RND performance?
- Detailed design, procurement, test of Gen2 turbo-generator
  - Ongoing development of electric turbocompound
- Evaluation of alternate mechanical turbocompound arrangements
  - Improve cost, packaging for mobile engine applications

Summary



Turbine Technologies

- RND Turbine
  - Production-viable design developed
  - + 6% turbine efficiency
  - + 2-3% thermal efficiency ⇨ HPL engine
- Mixed Flow Turbine
  - Capability for improved pulse-utilization verified
  - + 1-1.5% thermal efficiency ⇨ LPL engine

Stack Energy Recovery

- Electric Turbocompound
  - Gen2 turbo-generator designed / analyzed
    - Analysis ⇨ corrects thermal management / efficiency issues of Gen1
- Mechanical Turbocompound
  - High-efficiency ball-bearing power turbine developed / validated

Engine simulations based on demonstrated component performances

- + 7 - 8% capability for series turbo, LPL engine predicted
- + 8 – 10% capability for single-stage turbo, HPL engine predicted