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An Engine System Approach to Exhaust Waste Heat Recovery

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Caterpillar Inc.

DOE Merit Review
Washington, D.C.
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DOE Contract: DE-FC26-05NT42423
DOE Technology Manager: John Fairbanks
NETL Project Manager: Carl Maronde
Project ID: ace_39_kruiswyk

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

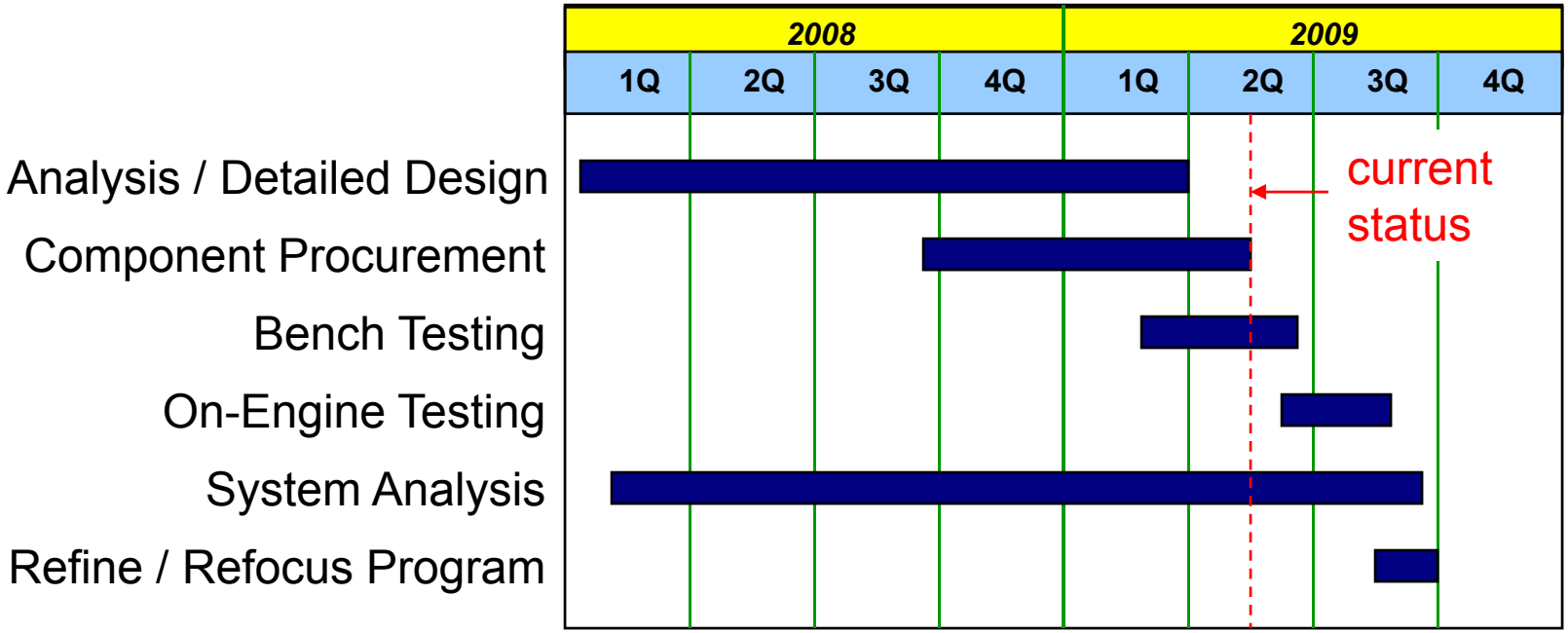
Objectives

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

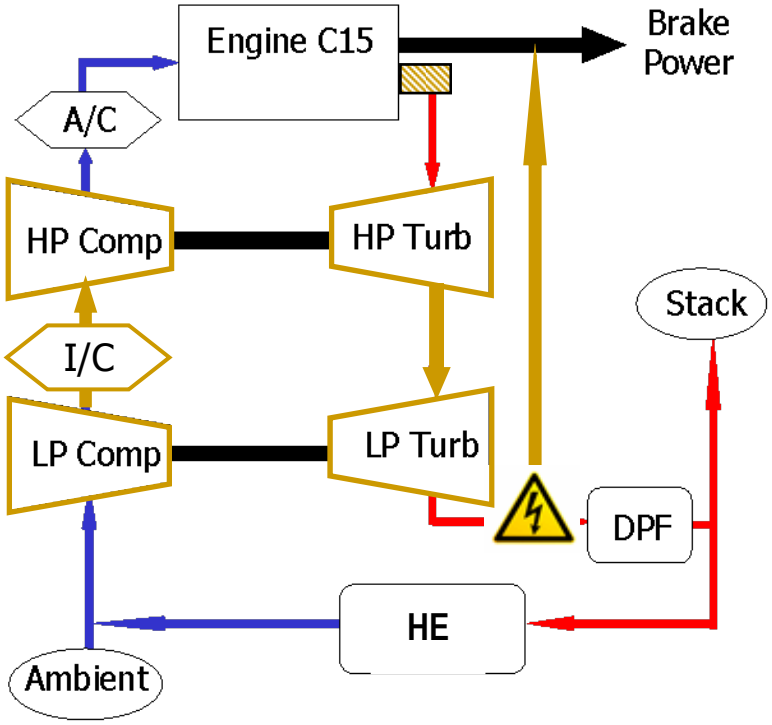


- Analysis Focus – Aerodynamic, structural, rotordynamic
- Test Focus – Aerodynamic, rotordynamic performance

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

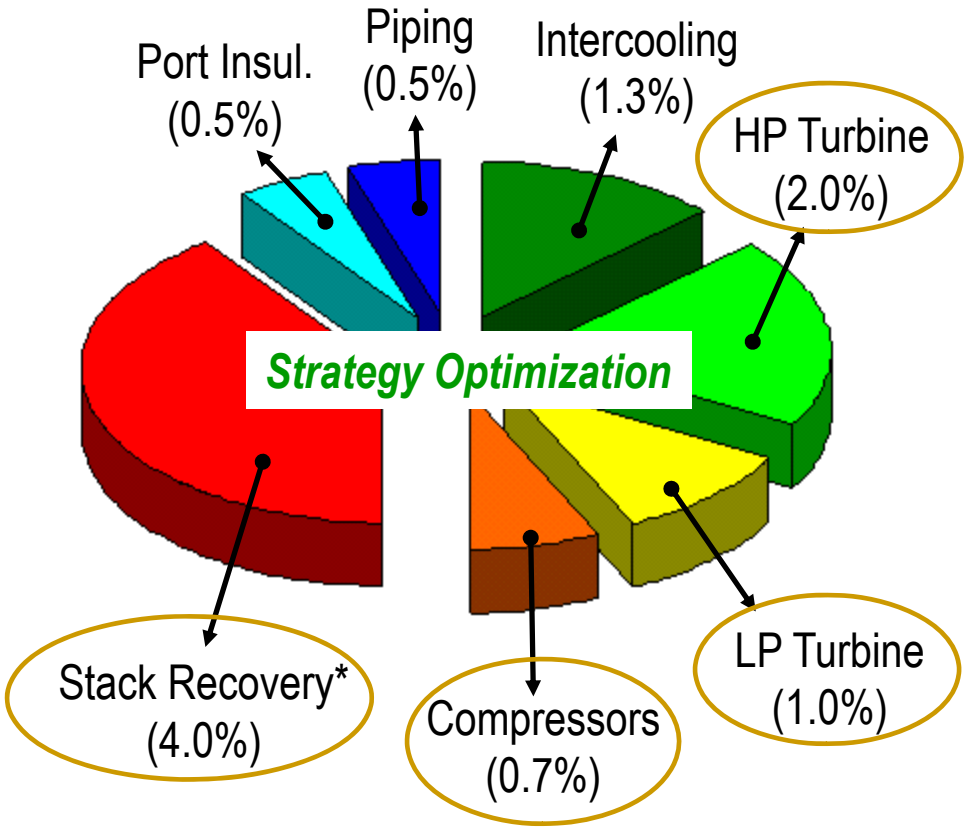
Approach

An integrated system solution to waste heat recovery



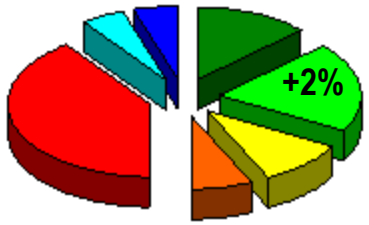
Baseline C15
LPL (low pressure loop) configuration

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



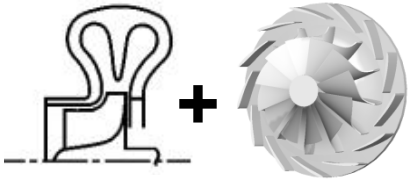
•Turbocompound or bottoming cycle: supplements engine power via electrical or mechanical connection to flywheel

Technical Progress – HP Turbine



Target: + 2% Engine Thermal Efficiency:

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

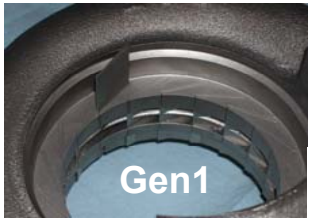


Technology 1 – Radial, Nozzled, Divided (RND) Turbine

- High efficiency turbine wheel + nozzled and divided turbine housing

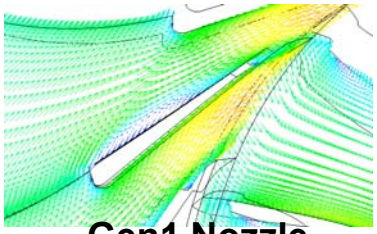
Prior Accomplishments

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

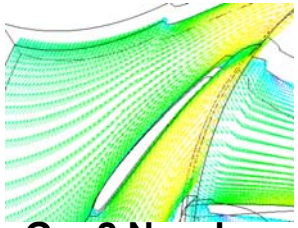


2008-9 Accomplishments To Date

- 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

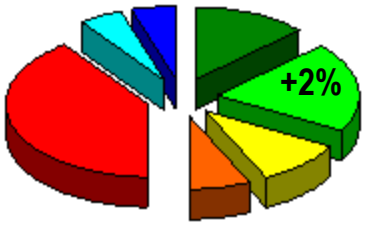


Gen1 Nozzle



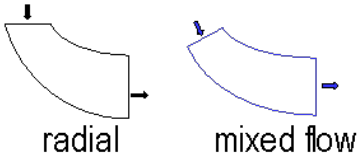
Gen2 Nozzle

Technical Progress – HP Turbine



Target: + 2% Engine Thermal Efficiency:

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

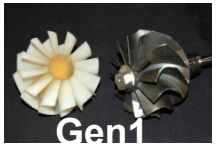


Technology 2 – Mixed Flow Turbine

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

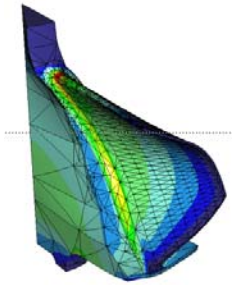
Prior Accomplishments

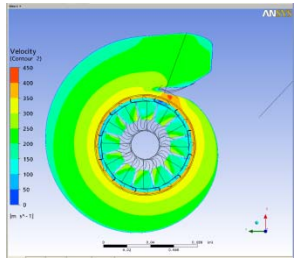
- **Gen1** mixed flow design demo'd ability to improve pulse utilization
- **Gen1** peak efficiency –1%; code calibration required

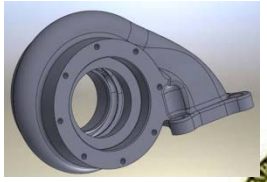


2008-9 Accomplishments To Date

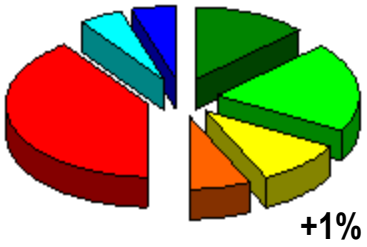
- Detailed design / analysis complete - **Gen2** wheel & housing
- Predict +2-3% peak turbine efficiency; +3-5% on-engine efficiency
- Procurement underway
- Gas stand testing May-June
- Engine testing – July-Aug
- Gen3 – mixed flow nozzled divided (MND) to hit target





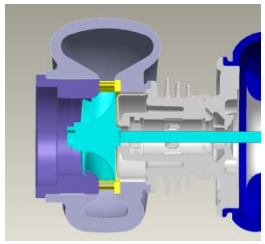


Technical Progress – LP Turbine

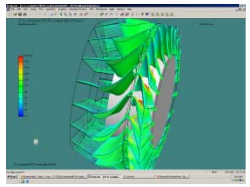


Target: + 1% Engine Thermal Efficiency:

- + 6% Turbine Stage Efficiency



Technology – High Efficiency Nozzled Turbine



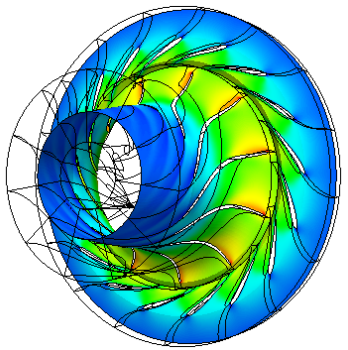
Prior Accomplishments

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

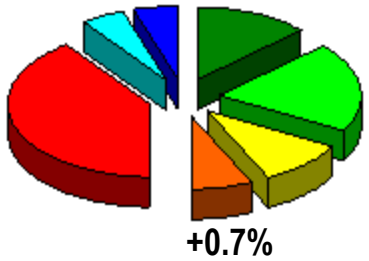
2008-9 Accomplishments To Date

- 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:

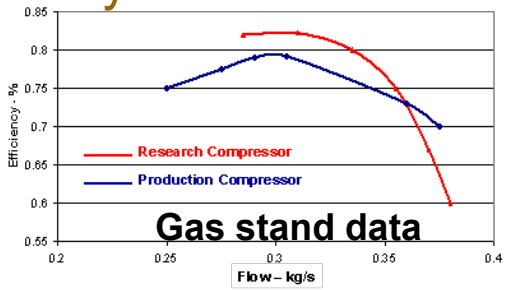
- +2.5% Compressor Stage Efficiencies

Technology – Highly backswept compressor stage + vaned diffusers

Prior Accomplishments

- **Gen1** design demo'd + 2.5% compressor efficiency

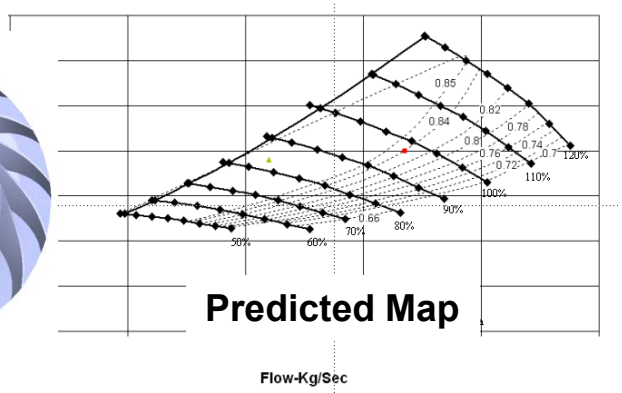
Gen1



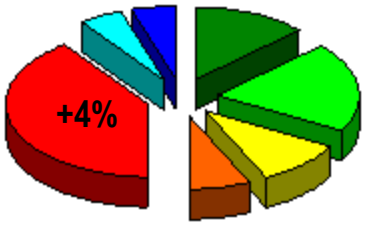
2008-9 Accomplishments To Date

- 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

Gen2



Technical Progress – Stack Recovery



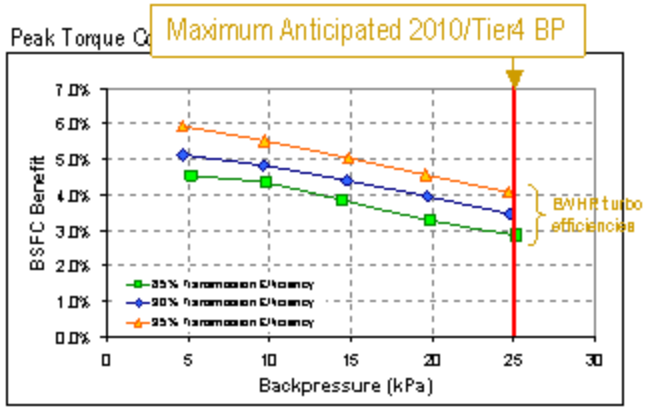
Target: + 4% Engine Thermal Efficiency

- Stack recovery on baseline LPL engine

Technology – Mechanical Turbocompound

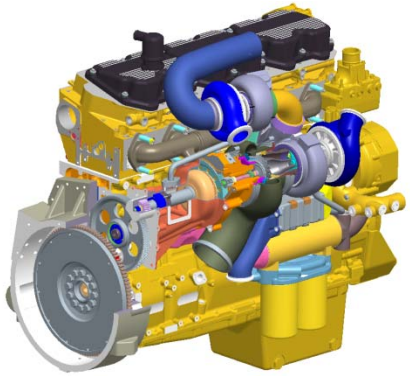
Prior Accomplishments

- Engine simulation verifies + 4% efficiency w/ turbo technologies developed here



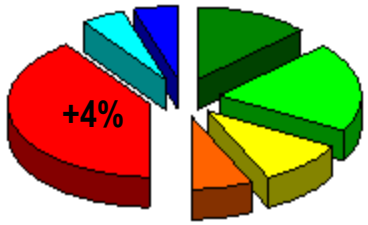
2008-9 Accomplishments To Date

- Detailed design complete – improved high efficiency power turbine bearing system (**Gen2**)



- Procurement underway
- Gas stand testing April – May
- Engine testing – June - July

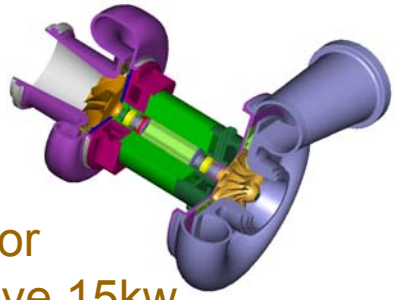
Technical Progress – Stack Recovery



Target: + 4% Engine Thermal Efficiency

- Stack recovery on baseline LPL engine

Technology – Electrical Turbocompound

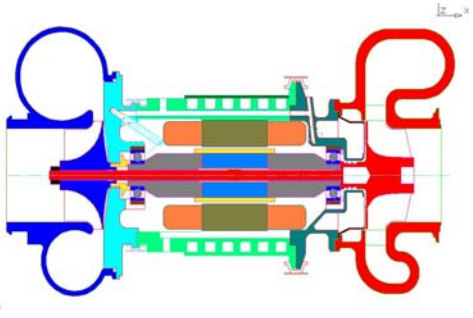


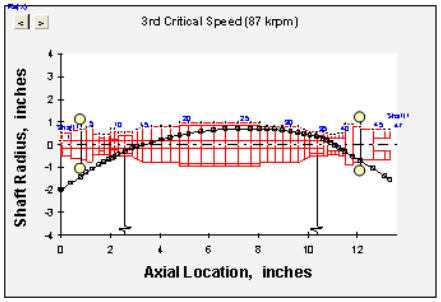
Prior Accomplishments

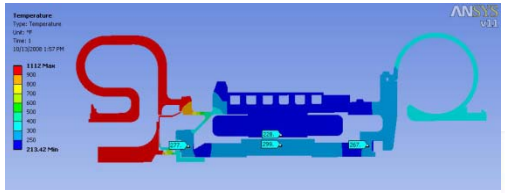
- Prior DOE-Caterpillar research program
  - Design / procure / test integrated **Gen1** turbo-generator
  - Thermal management challenge – unit overheats above 15kw

2008-9 Accomplishments To Date

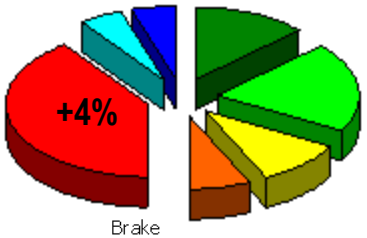
- Concept design complete – **Gen2** permanent magnet turbo-generator
  - Turbo-generator on LP stage of series turbocharged base engine
  - Analysis – meets performance, structural, thermal requirements







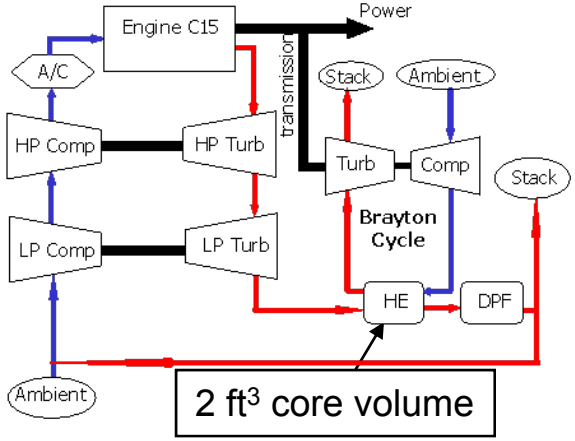
Technical Progress – Stack Recovery



Target: + 4% Engine Thermal Efficiency

- Recovery on High Pressure Loop (HPL) Engine Configuration

Technology – Brayton Bottoming Cycle

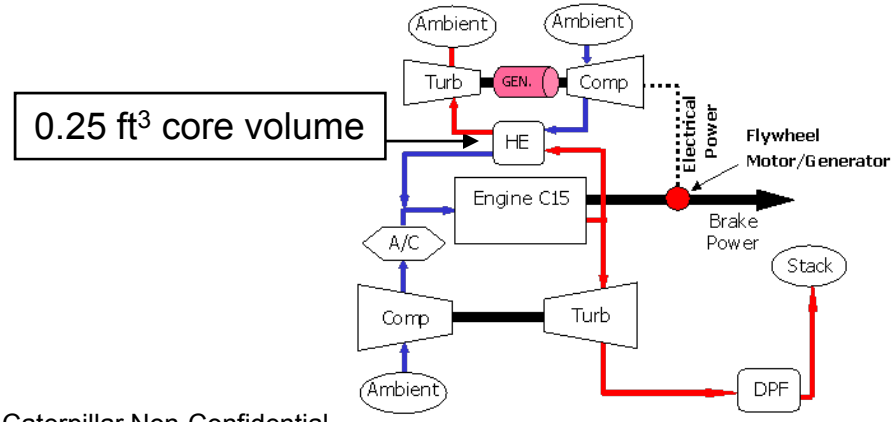


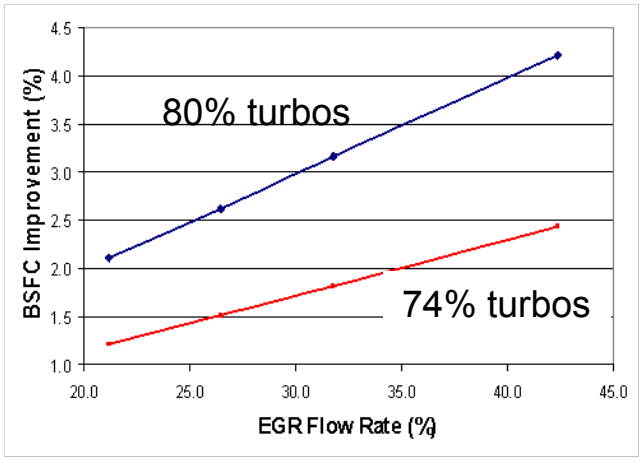
Prior Accomplishments

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

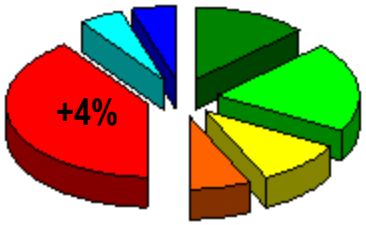
2008-9 Accomplishments To Date

- 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

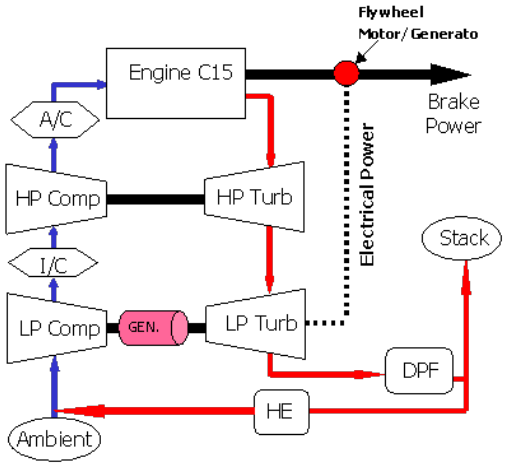
Technology – Turbocompound

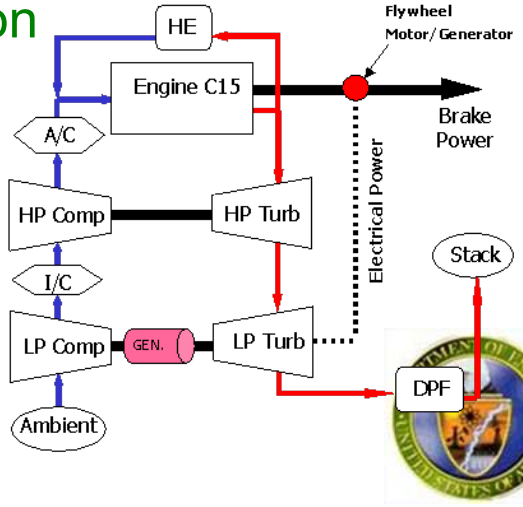
Prior Accomplishments

- 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

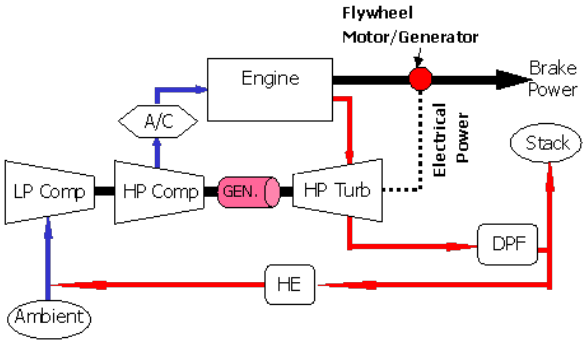
Analysis (complete Aug - Sep 09):

- 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

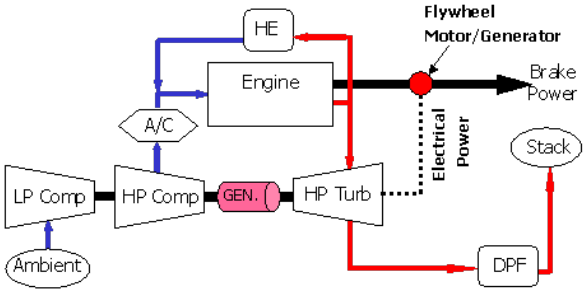
Future Work – Beyond Current BP

- 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

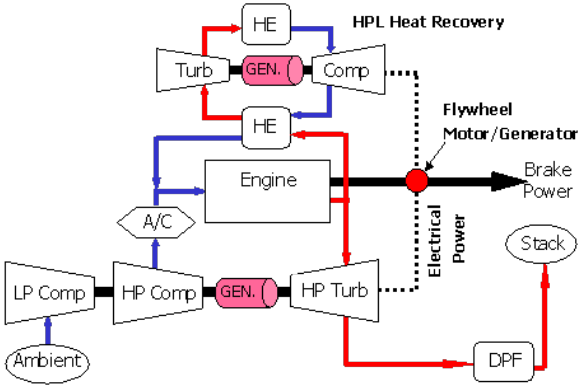
Future Work – Beyond Current BP



LPL Configuration
- Stack Recovery



HPL Configuration
- Stack Recovery



HPL Configuration
- Stack Recovery
- HPL Recovery

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

Future application - determined by emissions requirements

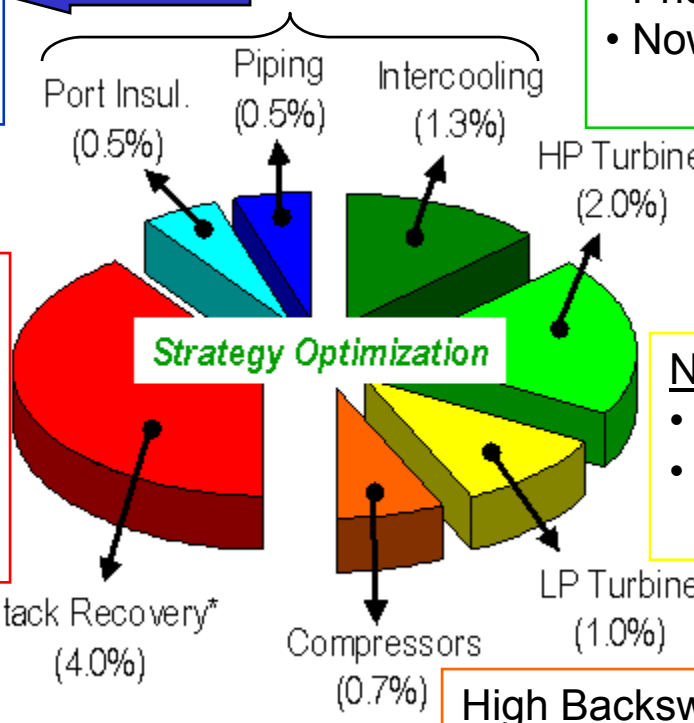
Technology applicability:
- LPL engine configuration
- HPL engine configuration
- Series turbocharged
- Single-stage turbocharged

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

Summary

Insul., piping, intercooling
- Prior: + 1.8% predicted
- Now: + 1.8% predicted

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



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

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