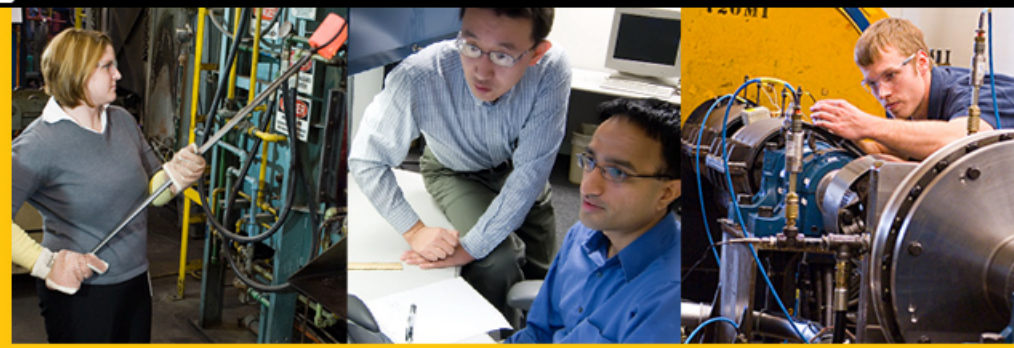
T&SD Technology & Solutions Division

Caterpillar Engine Technologies



An Engine System Approach to Exhaust Waste Heat Recovery

Principal Investigator: Richard W. Kruiswyk

Caterpillar Inc.

DOE Contract: DE-FC26-05NT42423

DOE Technology Manager: John Fairbanks

NETL Project Manager: Ralph Nine

DOE Merit Review

Washington, D.C.

February 27, 2008

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Note: This presentation does not contain any proprietary or confidential information.

Purpose of Work

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

2007 Objective: Validate approach to achieve 10% improvement via:

- Detailed analysis and/or tests to verify target performance of key components
- Engine simulation analysis to verify system capability with updated component performance parameters
- Development of design concepts to verify production viability of components

Previous Review Comments

- "did not think that air bottoming cycle was clearly justified as the best path"
- "packaging issues with the proposed system"
- "Cost-benefit analysis should be conducted on bottoming cycle"
  - Technology downselect for stack recovery was re-visited after expanded investigation into heat exchanger technologies and aftertreatment characteristics
- "some collaborations, but mostly in-house work being done"
  - Turbomachinery aerodynamic developments done in consultation with world-recognized leaders in industry
  - Collaboration with turbo suppliers will be key to developing production ready versions of advanced turbomachinery

Barriers

The technical barriers to delivering a 10% improvement in engine thermal efficiency via waste heat recovery *that are being addressed by this project* are:

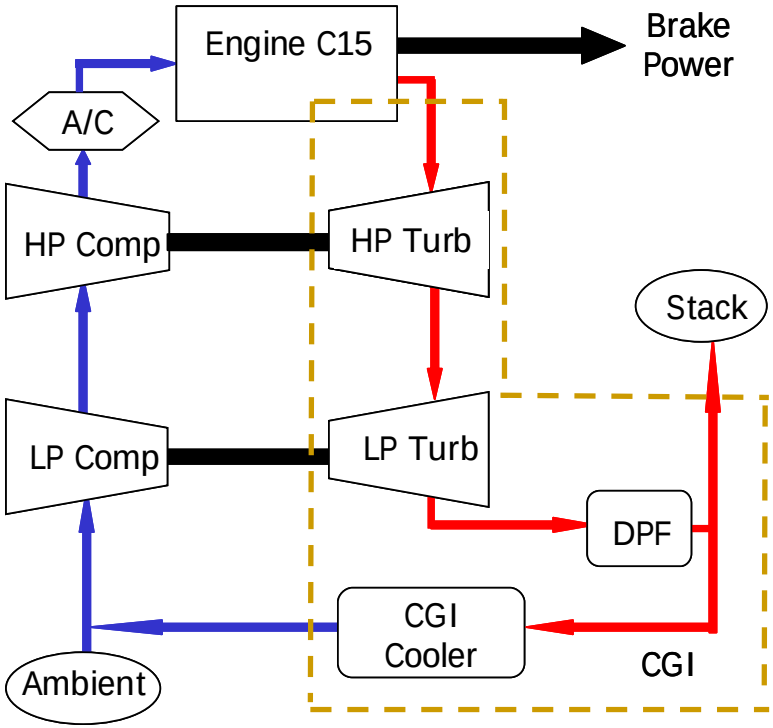
- Aerodynamic efficiencies of production turbine and compressor wheels
  - 2-fold impact

Engine Turbocharger Aero Efficiencies	Direct impact on engine SFC via pumping work	Determines energy 'left over' after boost requirement is met
Aero Efficiencies of Waste Heat Recovery Turbomachinery		Impacts recovery of 'left over' energy

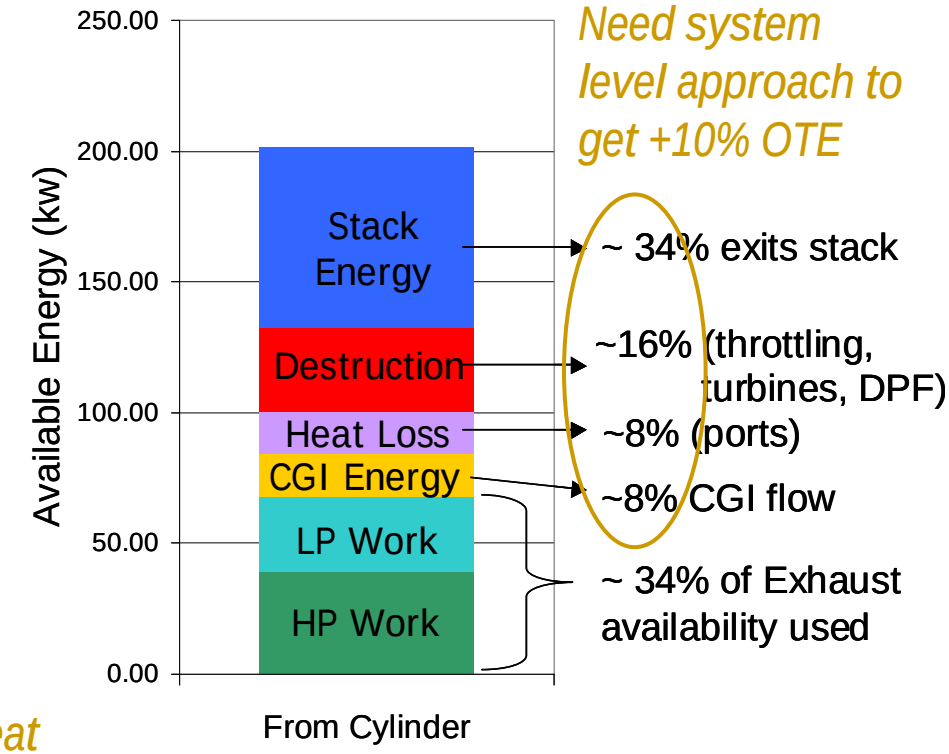
- Achieving a solution package / cost acceptable for mobile applications
  - Solution must fit in a 2010 Class 8 On-Highway Truck

Approach

Baseline Engine
Caterpillar 2007 C15 OHT



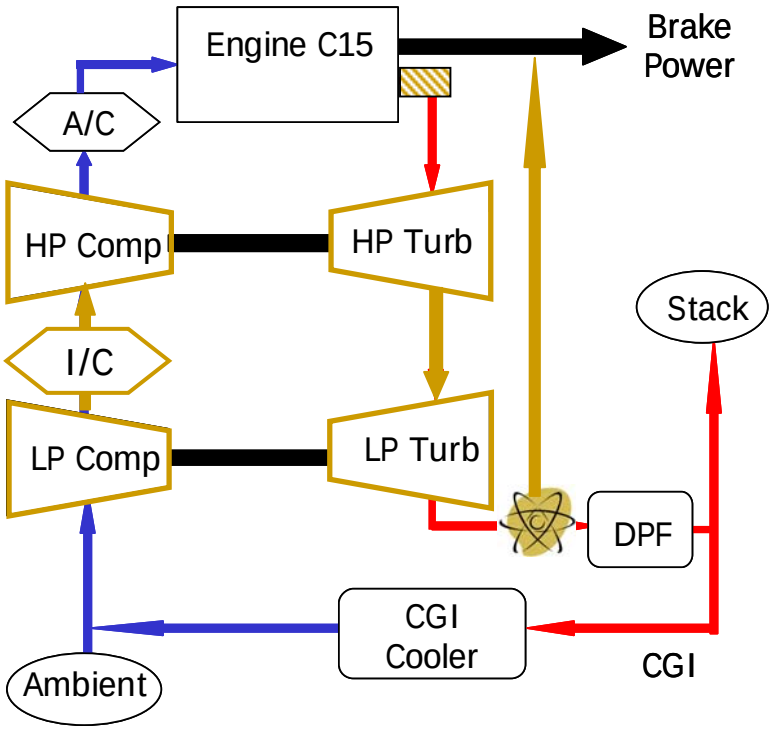
Available Energy Analysis
Peak Torque Conditions

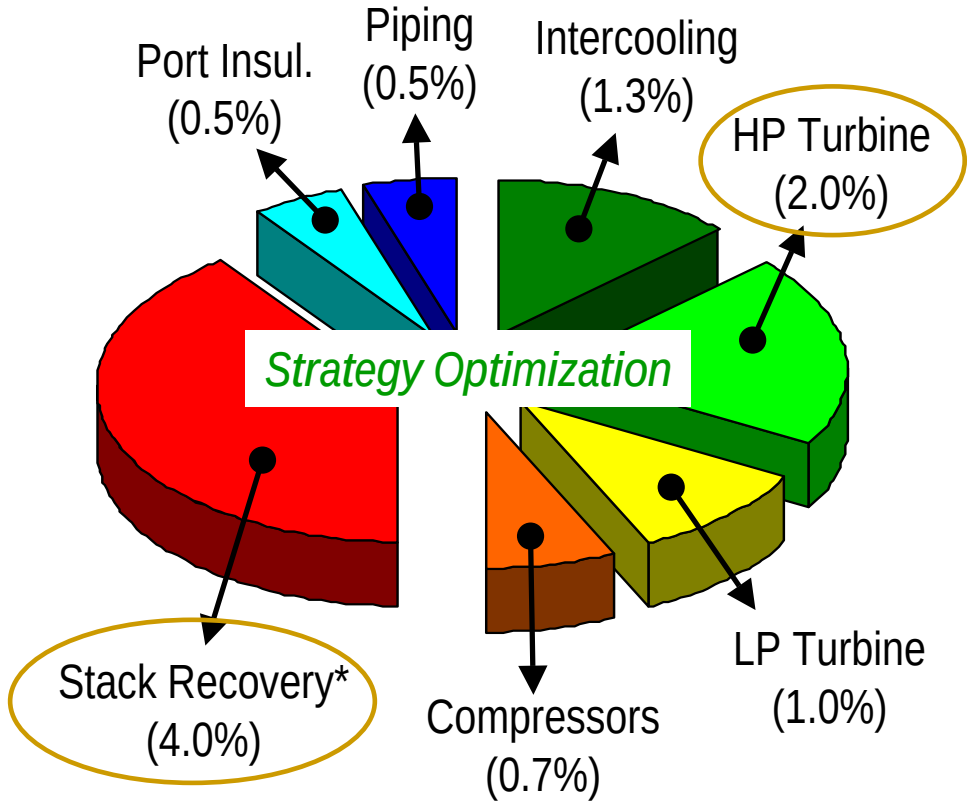


- *No high temperature source of waste heat*
- *Series turbocharged*

Approach

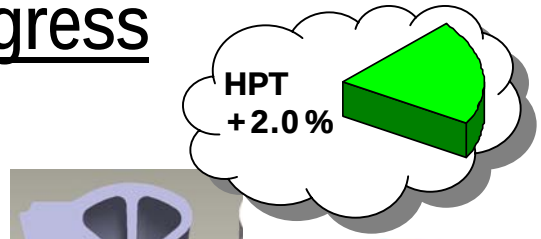
An integrated system solution to waste heat recovery





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

HP (High Pressure) Turbine Stage - Progress

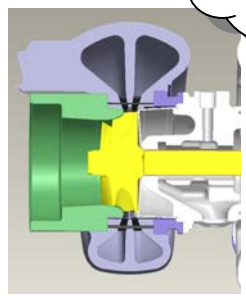


Target: +2.0% overall thermal efficiency

- Translates to ~ +10% turbine stage efficiency

Technology: Radial / Nozzled / Divided (RND) Turbine

- ➢ High efficiency wheel + divided / nozzled housing

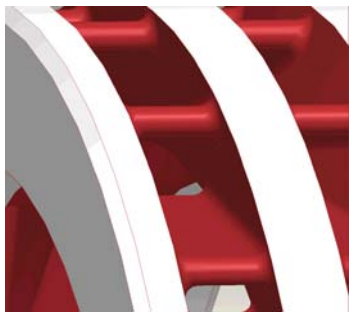


Accomplishments

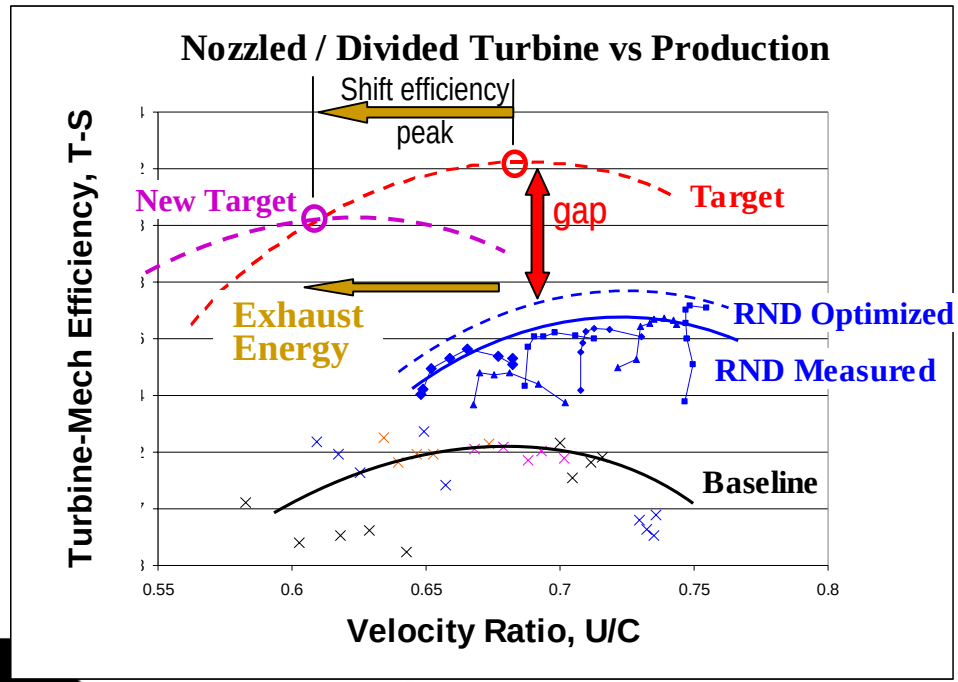
✓ Nozzle/divider aero design refined

✓ Pro-E & structural analysis initiated for production-viable design concepts

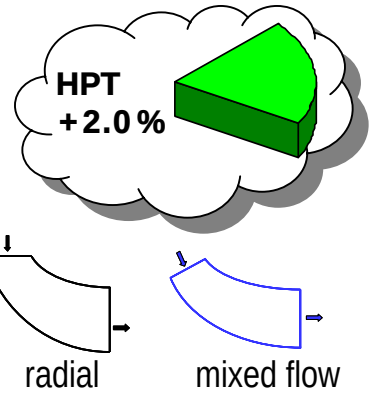
Performance-Demo Iron



Production Concepts under development



HP (High Pressure) Turbine Stage - Progress



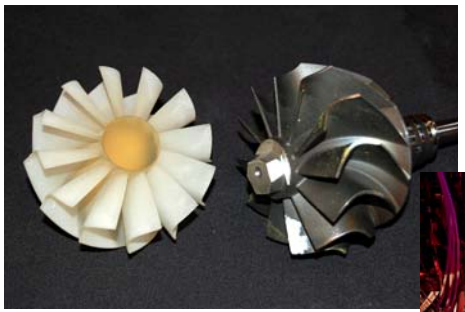
Target: +2.0% overall thermal efficiency

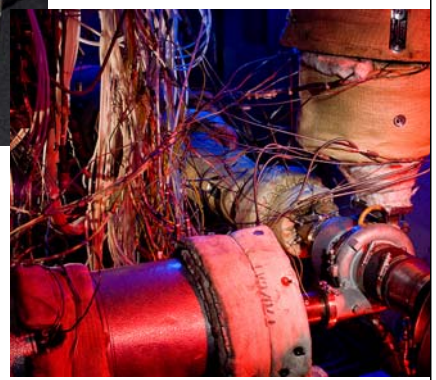
- Translates to ~ +10% turbine stage efficiency

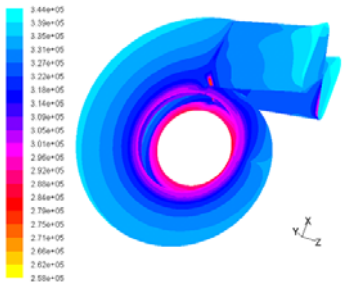
Technology: Mixed Flow Turbine – improve 'on-engine' efficiency

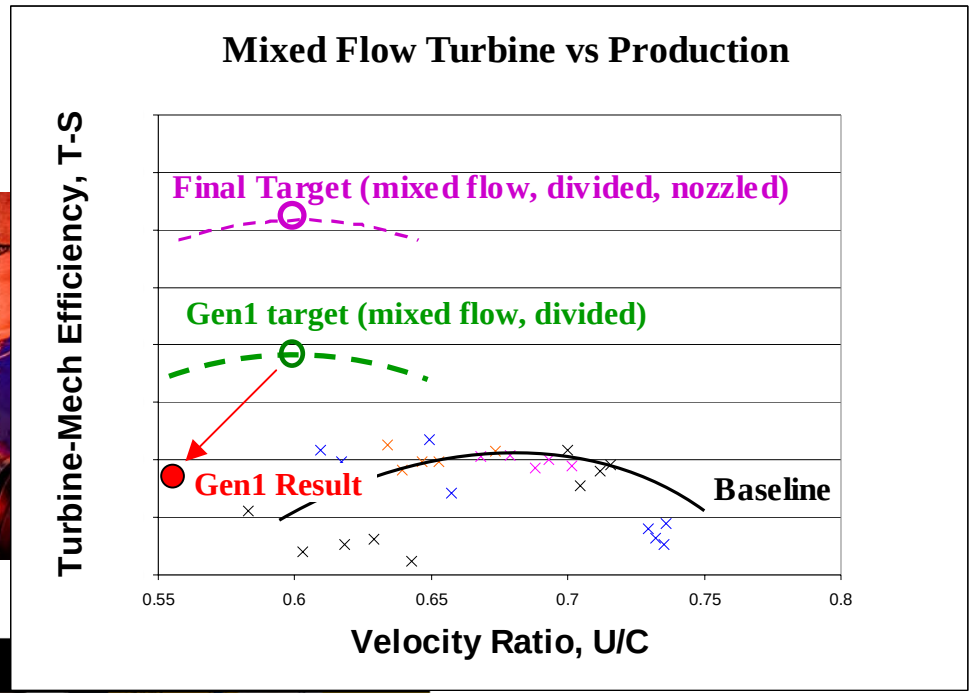
Accomplishments

✓ Gen1 nozzle-less mixed flow turbine procured, assembled, tested

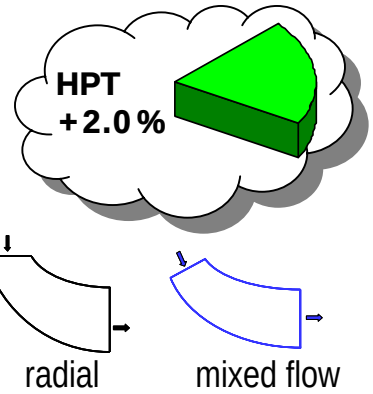








HP (High Pressure) Turbine Stage - Progress



Target: +2.0% overall thermal efficiency

- Translates to ~ +10% turbine stage efficiency

Technology: Mixed Flow Turbine – improve 'on-engine' efficiency

Accomplishments

✓ Gen1 nozzle-less mixed flow turbine procured, assembled, tested

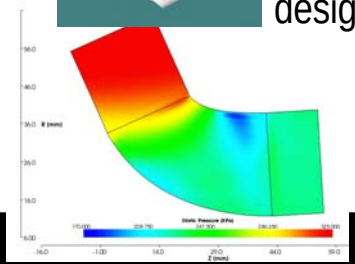
✓ Gen2 aero design complete

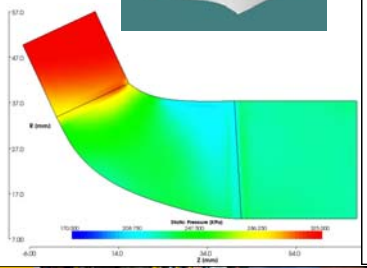
Gen1

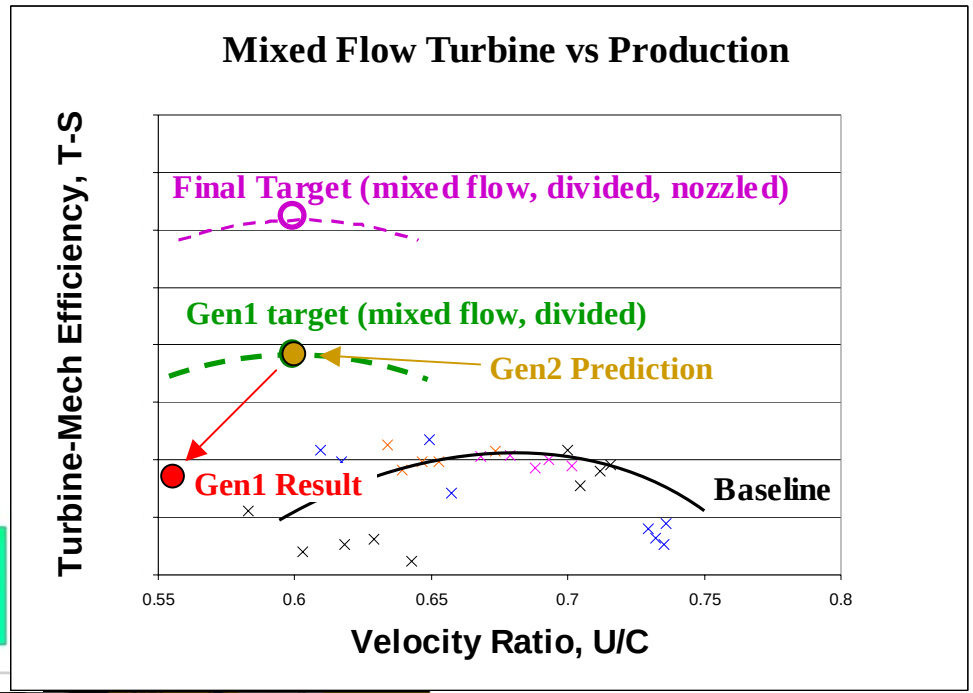
Gen1: emphasis on demo'ing shift in peak efficiency

Gen2: used Gen1 lessons to optimize design

Gen2







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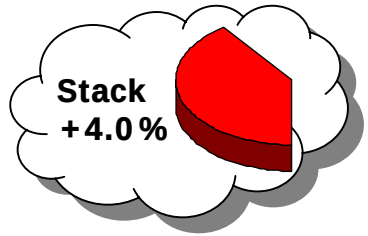
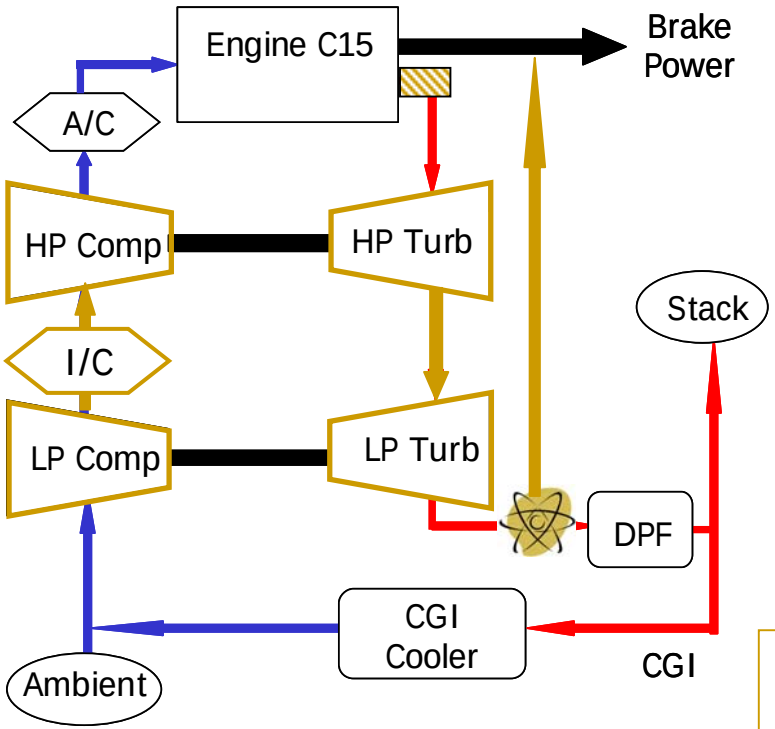
Stack Recovery - Progress

Target: +4.0% overall thermal efficiency

Technology: Brayton Cycle & Turbocompound Evaluated





	Turbocompound	Brayton Cycle
+' s	▪ Known technology ▪ 'Easy' to package ▪ Cost	▪ Insensitive to backpresssure
-' s	▪ Sensitive to backpressure* (?)	▪ Sensitive to component efficiencies (✓) ▪ Packaging (?) ▪ Cost

*Concern for 2010/Tier4 w/ DPF and NOx aftertreatment

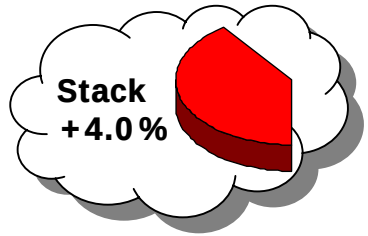
Preliminary Engine Simulations:

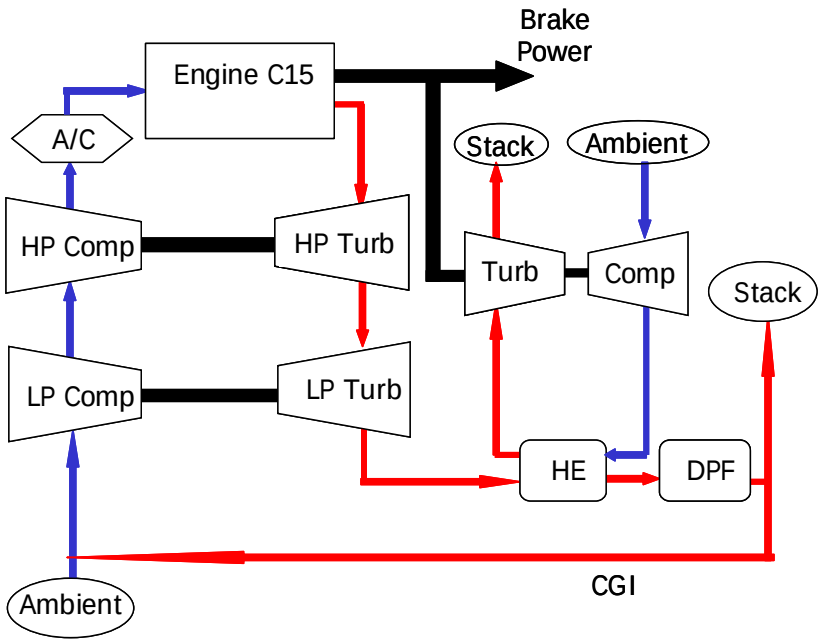
- Turbocompound can deliver +4% OTE if backpressure is 'low enough'
- Brayton can deliver +4% OTE if component efficiencies are 'high enough'

Stack Recovery - Progress

Target: +4.0% overall thermal efficiency

Technology: Brayton Cycle & Turbocompound Evaluated



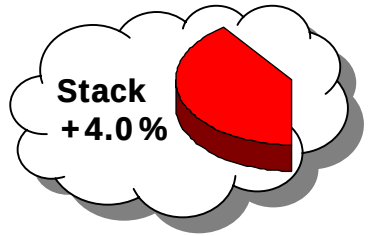


Open-Loop Air Brayton Cycle

	Turbocompound	Brayton Cycle
+' s	▪ Known technology ▪ 'Easy' to package ▪ Cost	▪ Insensitive to backpresssure
-' s	▪ Sensitive to backpressure* (?)	▪ Sensitive to component efficiencies (✓) ▪ Packaging (?) ▪ Cost

*Concern for 2010/Tier4 w/ DPF and NOx aftertreatment

Stack Recovery - Progress



Target: +4.0% overall thermal efficiency

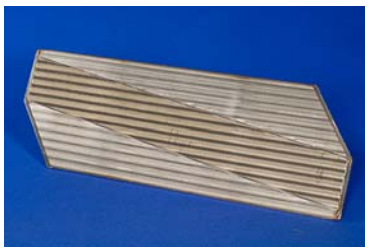
Technology: Brayton Cycle & Turbocompound Evaluated

Accomplishments

✓ Heat Exchanger sizing, concept designs

✓ Brayton packaging investigation completed

- Primary Surface technology

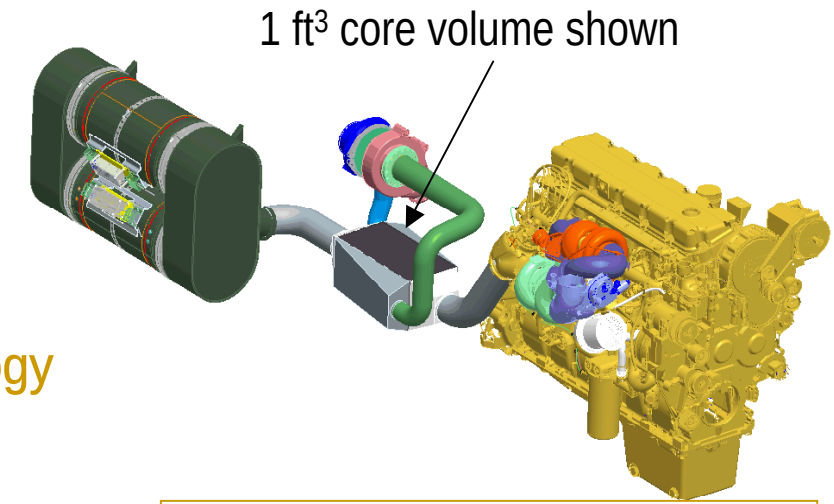


Caterpillar technology
2 ft^3 core vol.

- Microchannel manufacturing technology

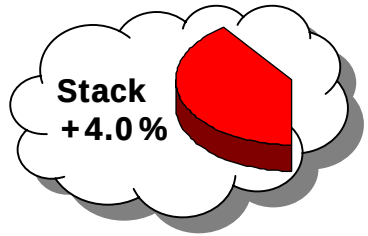
Preliminary estimate: ~ 0.5 - 1 ft^3 core

Concept design: 1.5 ft^3 core vol.



Even at 1 ft^3 core volume, system packaging is challenge

Stack Recovery - Progress



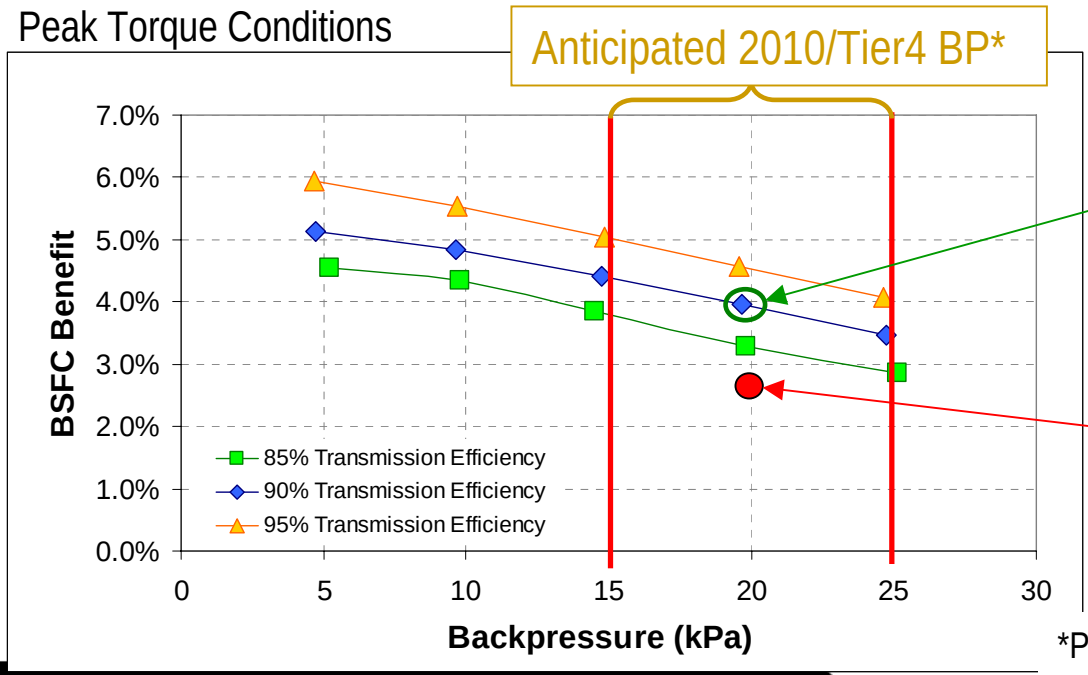
Target: +4.0% overall thermal efficiency

Technology: Brayton Cycle & Turbocompound Evaluated

Accomplishments

✓ Turbocompound Engine Simulation Analysis Re-visited

Peak Torque Conditions

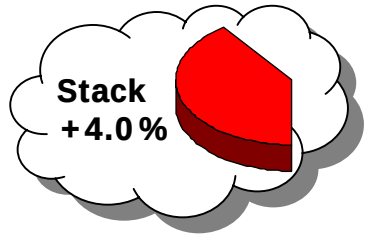


+4% target can be achieved w/ 90% transmission and EWHR turbo efficiencies

+4% target cannot be achieved w/ 90% transmission and production turbo efficiencies

*Partially loaded DPF

Stack Recovery - Progress



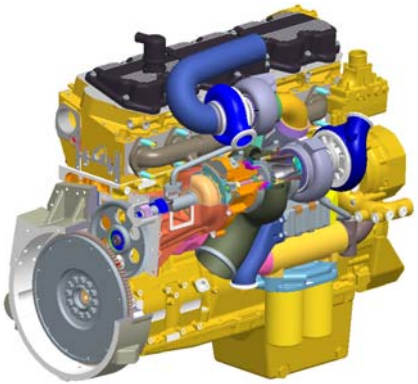
Target: +4.0% overall thermal efficiency

Technology: Brayton Cycle & Turbocompound Evaluated

Accomplishments

✓ Turbocompound System Downselect Initiated

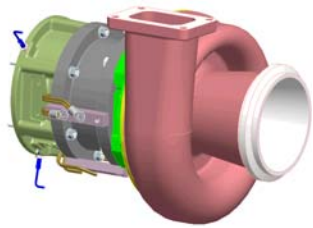
Mechanical Turbocompound



- Package demonstrated
- Limited off-design control
- No integration with hybrid engines

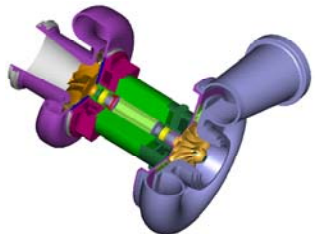
Electrical Turbocompound

Separate Power Turbine



- Off-design control, optimization
- Integration with hybrid engines

Integrated Turbo-Generator



- Optimal package for TC
- Control of engine turbo, multiple benefits
- Experience, DOE ETC program 2001-2004

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Future Work

- Phase III Mid-Program System Demonstration
  - Demonstrate + 3.5% to 4% on-engine with port insulation, intercooling, and improved turbochargers
  - Develop turbocompound generator and measure performance on bench test. Use analysis to predict engine benefit (+ 2.5 to 4% predicted)
  - Combine results for mid-program demonstration of + 6 to + 8% improvement

Summary

Port Insulation
- ✓ +0.5% predicted (engine simulation)
- ✓ sleeves designed

Piping
- ✓ No Progress

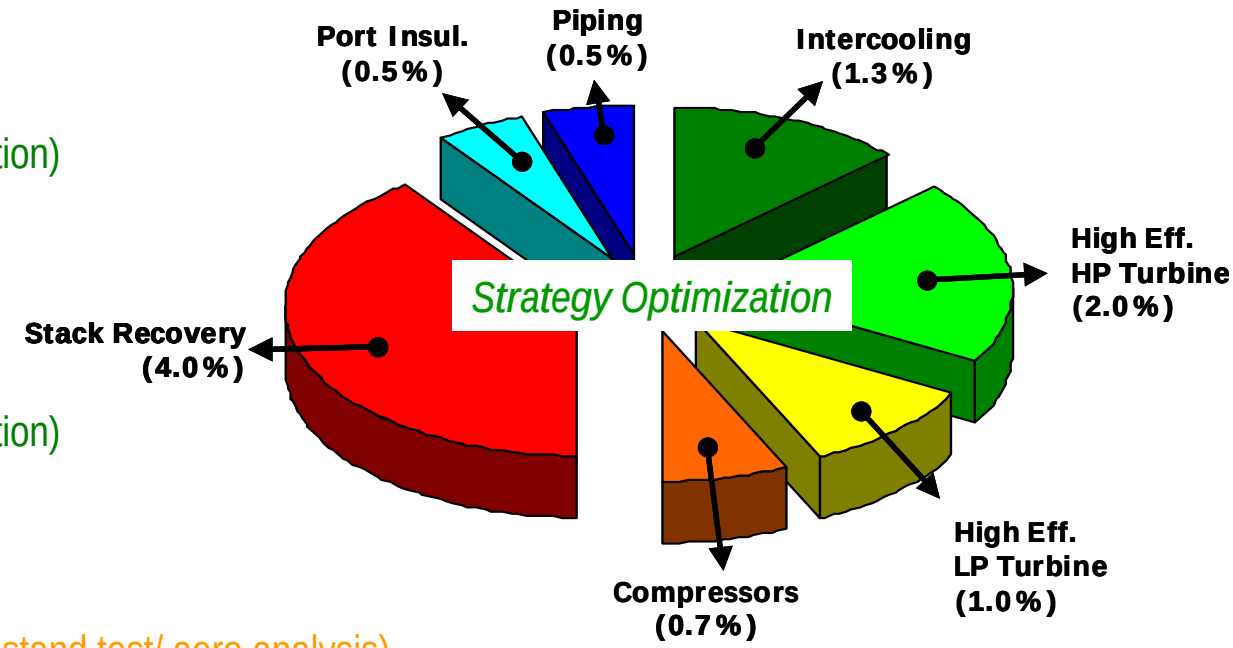
Intercooling
- ✓ +1.3% predicted (engine simulation)
- ✓ intercooler designed

HP Turbine
- ✓ +0.8% verified (gas stand test)
- ✓ +1.2% additional predicted (gas stand test/ aero analysis)

LP Turbine
- ✓ +0.7 verified (gas stand test)
- ✓ +0.3 additional predicted (aero analysis)

Compressors
- ✓ +0.7% verified (gas stand test)

Stack Recovery
- ✓ +3.5% predicted (w/ verified aero efficiencies)
- ✓ +0.5% additional predicted (w/ predicted aero efficiencies)



Thermal Eff. Improvement

Verified w/ high confidence: +7.5%

Line-of-sight via analysis: +2.0%

Pending Development: +0.5%

Goal of +10% OTE can be achieved w/ this recipe

Publications / Presentations / Patents

Presentations: 2007 DEER Conference, Detroit MI, 15Aug07

Patent Applications:

Title:	Turbocharger Having Divided Housing with Nozzle Vanes
Pub. No.:	2007/0175214
Status:	Patent Application Filed

Title:	Turbocharger Having Inclined Volutes
Pub. No.:	NA
Status:	Patent Application Filed