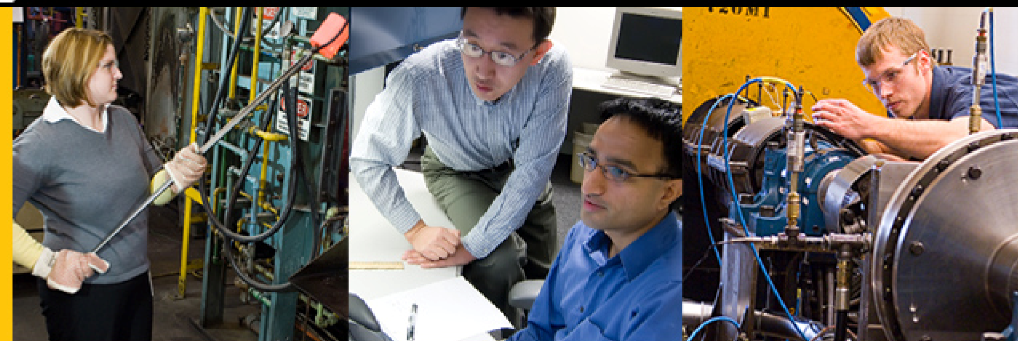
T&SD Technology & Solutions Division

Caterpillar Engine Research



An Engine System Approach to Exhaust Waste Heat Recovery

Principal Investigator: David J. Patterson

Presenter: Richard W. Kruiswyk

Caterpillar Inc.

15 August 2007

DEER Conference

DOE Contract: DE-PS26-04NT42099-02

DOE Technology Manager: John Fairbanks

NETL Program Manager: Ralph Nine

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

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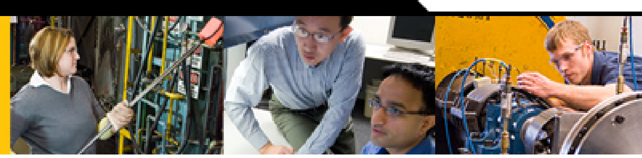
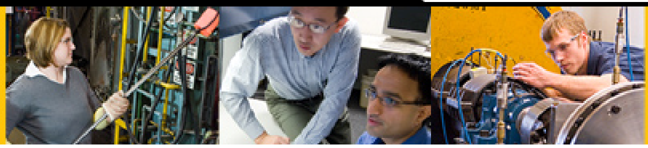
- Program Objectives
- Technical Approach
- Accomplishments
- Packaging Concepts
- Summary and Conclusions



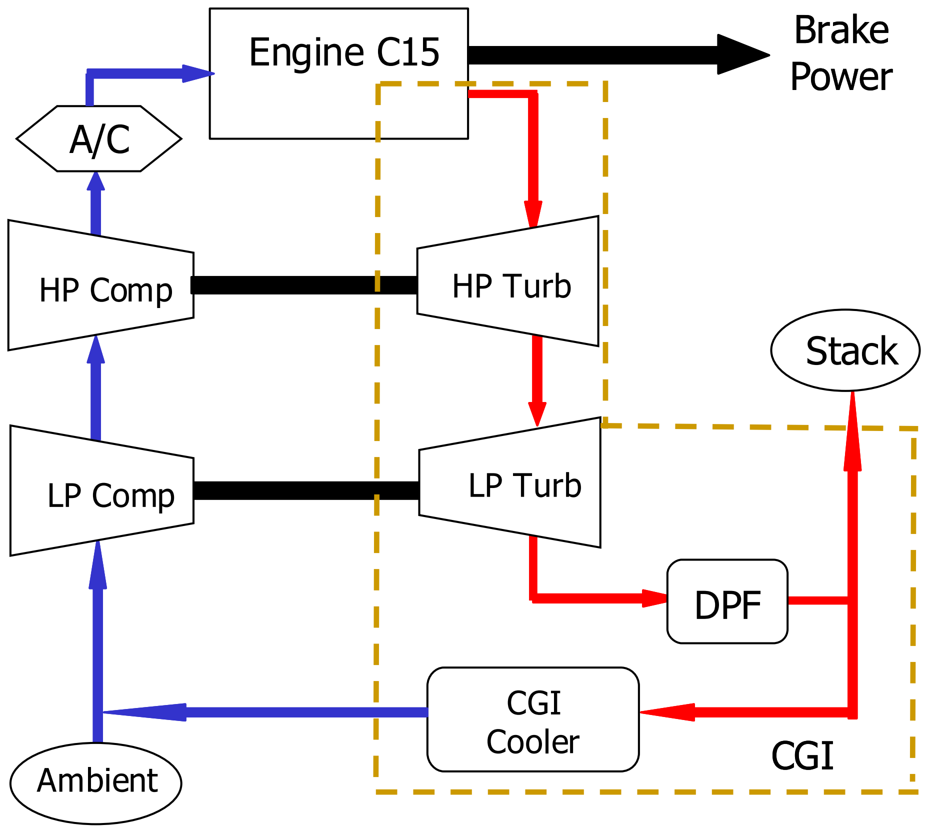
Program Objectives

- Recover energy lost in the *exhaust processes* of an internal combustion engine and utilize that energy to improve engine thermal efficiency
- Improve engine efficiency with:
  - No increase in emissions
  - No reduction in power density
  - Compatibility with anticipated aftertreatment
- TARGET – Demonstrate 10% improvement in overall thermal efficiency (OTE)



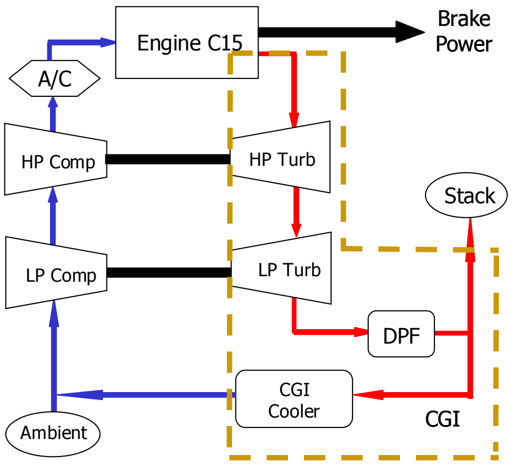
Technical Approach

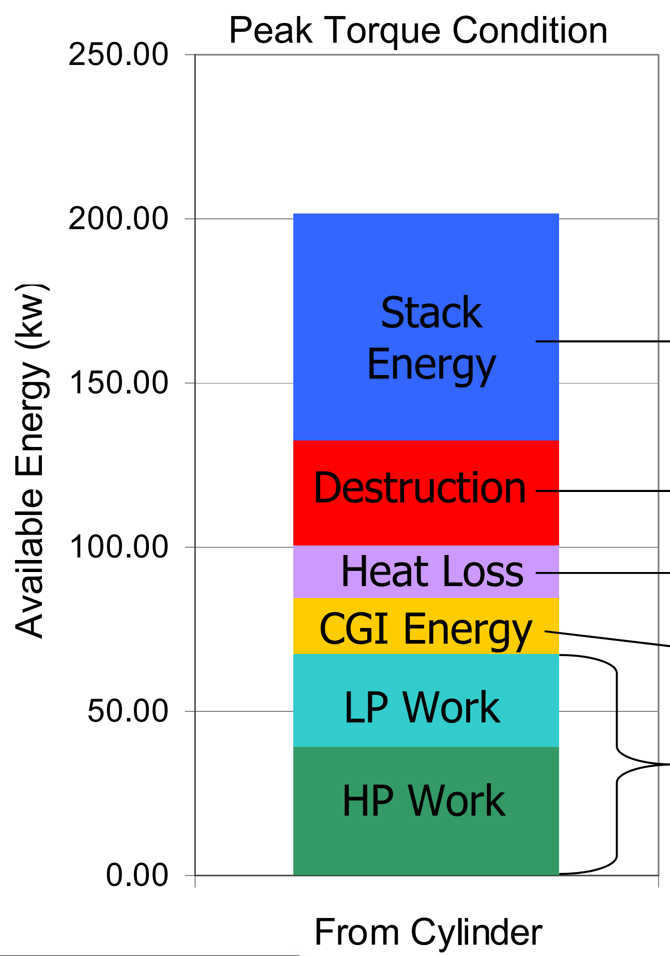
Recover energy lost in the *exhaust processes*



Baseline Engine

Technical Approach





Need System Level Approach to Maximize Exhaust Recovery

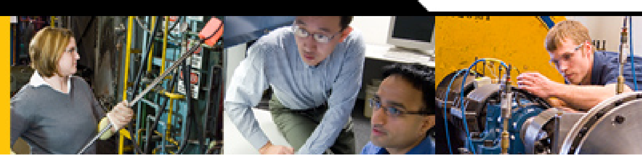
~ 34% exits stack

~16% (throttling, turbines, DPF)

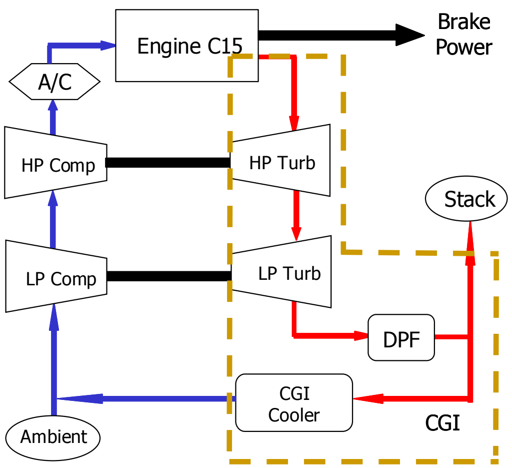
~8% (primarily ports)

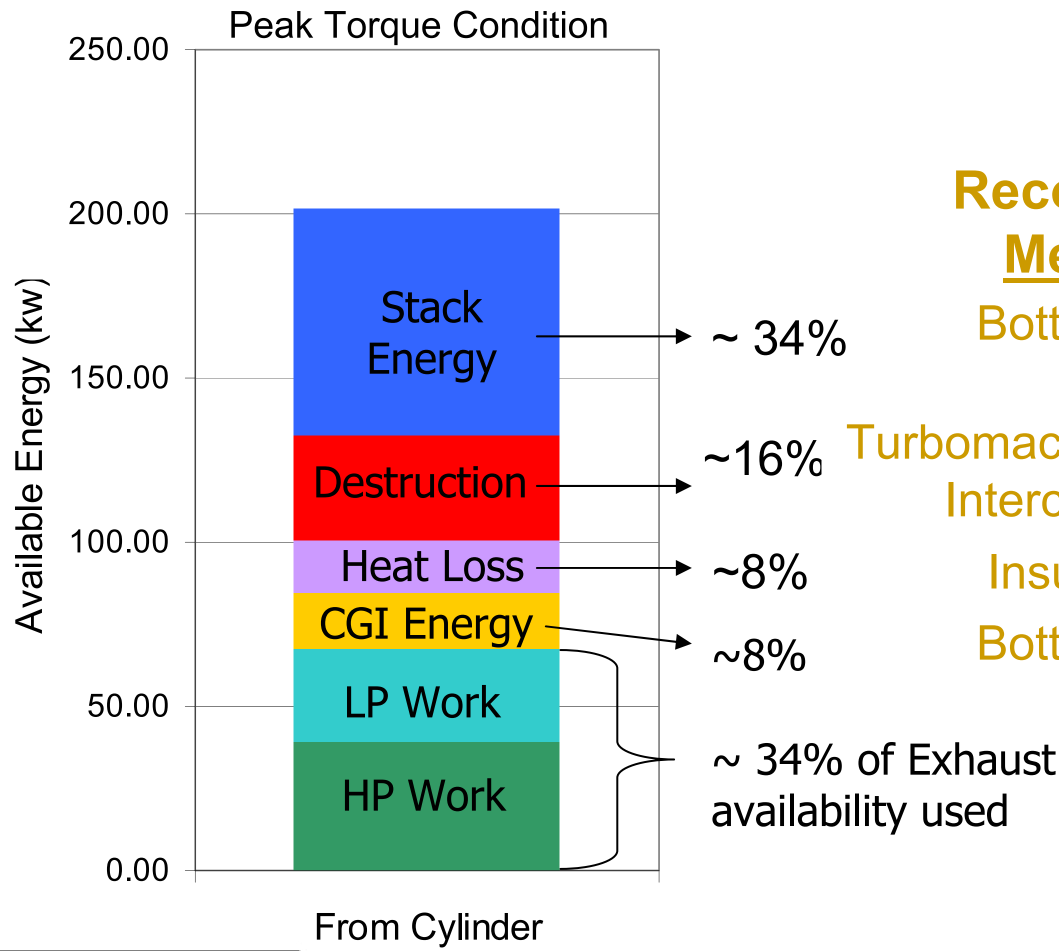
~8% CGI flow (dumped)

~ 34% of Exhaust availability used



Technical Approach





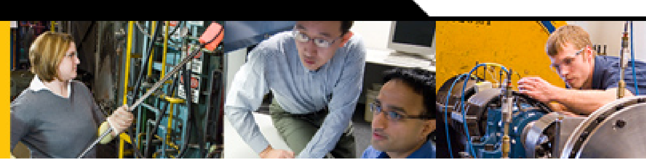
Recovery Method

Bottoming Cycle

Turbomachinery Intercooling

Insulation

Bottoming Cycle



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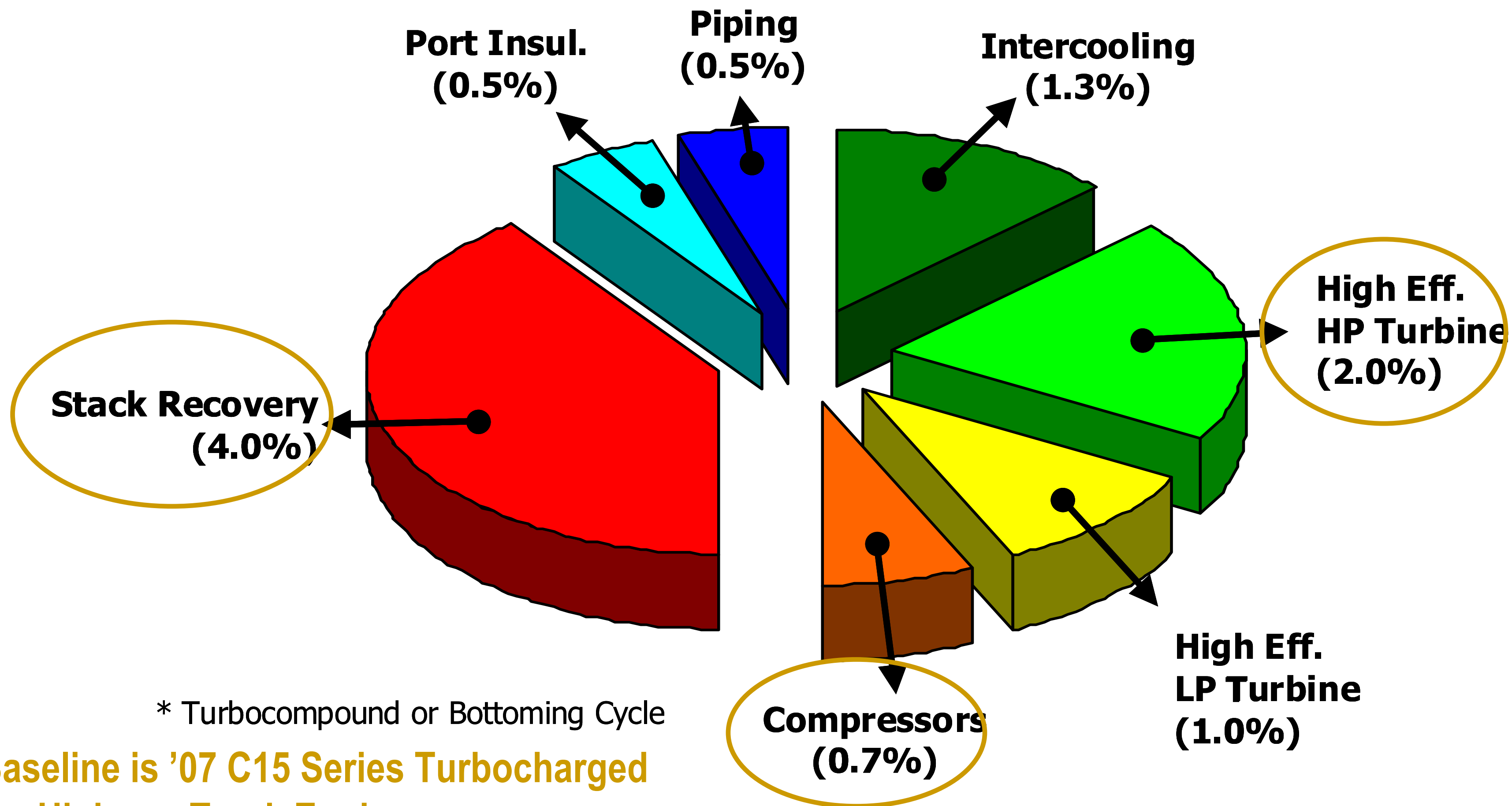
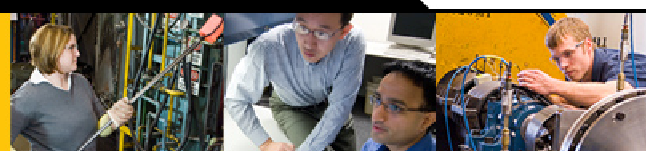
Technical Approach

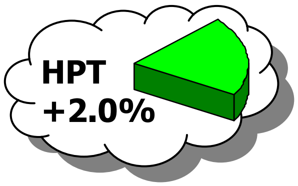


* Turbocompound or Bottoming Cycle

Baseline is ’07 C15 Series Turbocharged On-Highway Truck Engine



Accomplishments

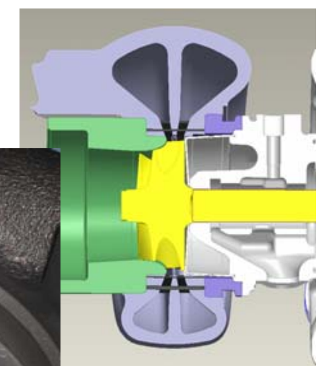


Target: + 2.0% overall thermal efficiency

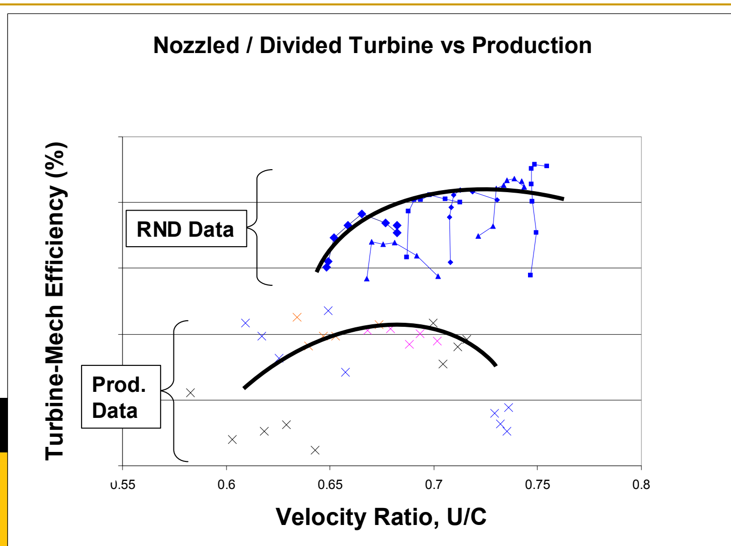
- Translates to ~ +10% turbine stage efficiency

Radial / Nozzled / Divided (RND) Turbine

- High efficiency radial turbine wheel
- Divided housing for engine breathing / pumping
- Nozzled inlet for incidence control, turbine efficiency



+5% Turbine Efficiency Demonstrated



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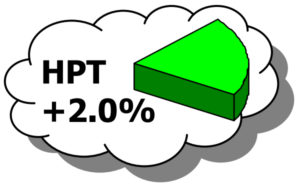
Accomplishments

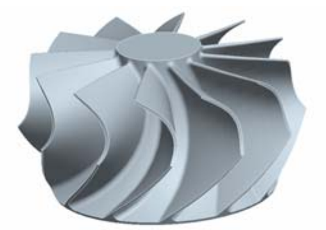


Target: + 2.0% overall thermal efficiency

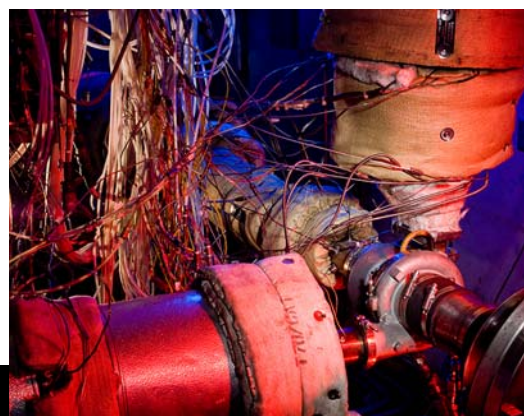
- Translates to ~ +10% turbine stage efficiency

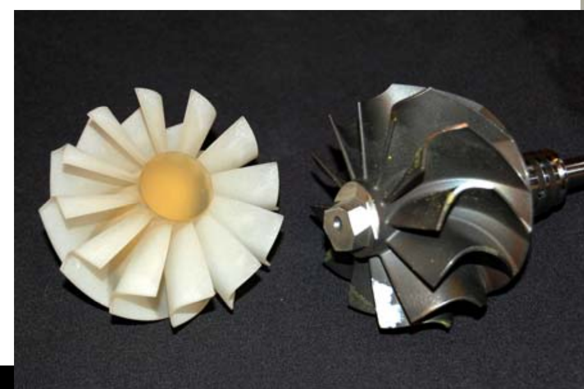
Mixed Flow Turbine

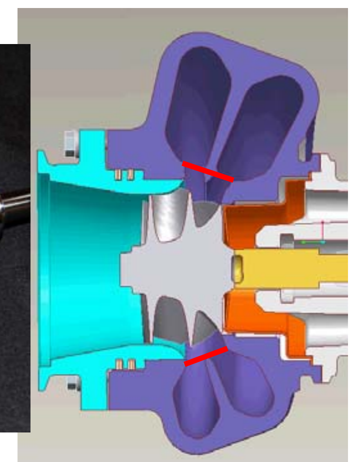
- High efficiency wheel designed for improved pulse utilization
- Inclined volute for maximum stage efficiency
- Ball Bearings for low mechanical losses



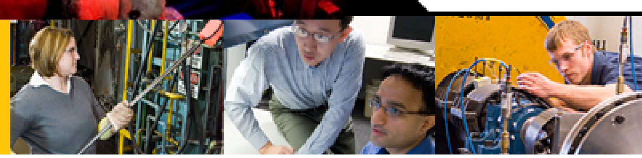
Hardware Procured, Testing Underway







Engine Research



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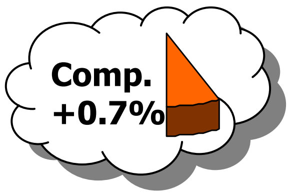
Accomplishments



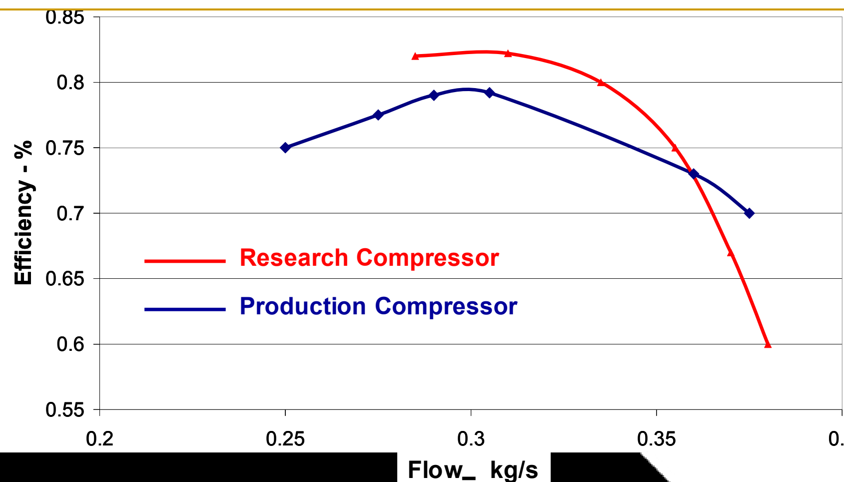
Target: + 0.7% overall thermal efficiency

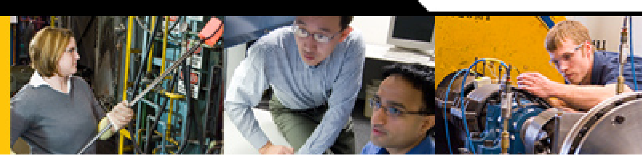
- ➢ Translates to ~ +2.5% compressor stage efficiency

High Efficiency Radial Compressor

- Highly backswept wheel
- Low solidity vaned diffuser

+2.5-3% Compressor Efficiency Demonstrated



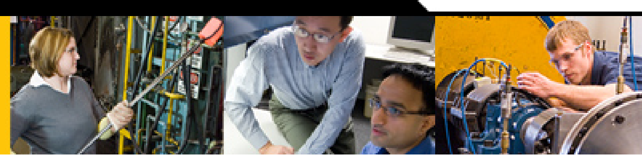


Accomplishments

Target: + 4.0% overall thermal efficiency

Stack Recovery Methods

	Advantages	Disadvantages
Turbocompound	▪ Known Technology ▪ 'Easy' to package	▪ Sensitive to BP
Rankine Cycle	▪ Cycle Efficiency ▪ Insensitive to BP	▪ Packaging / cost ▪ ORC - additional fluid
Brayton Cycle	▪ No additional fluid ▪ Insensitive to BP ▪ Lower cost (compared to Rankine)	▪ Cycle Efficiency ▪ Packaging



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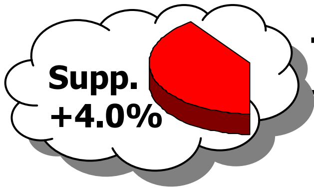
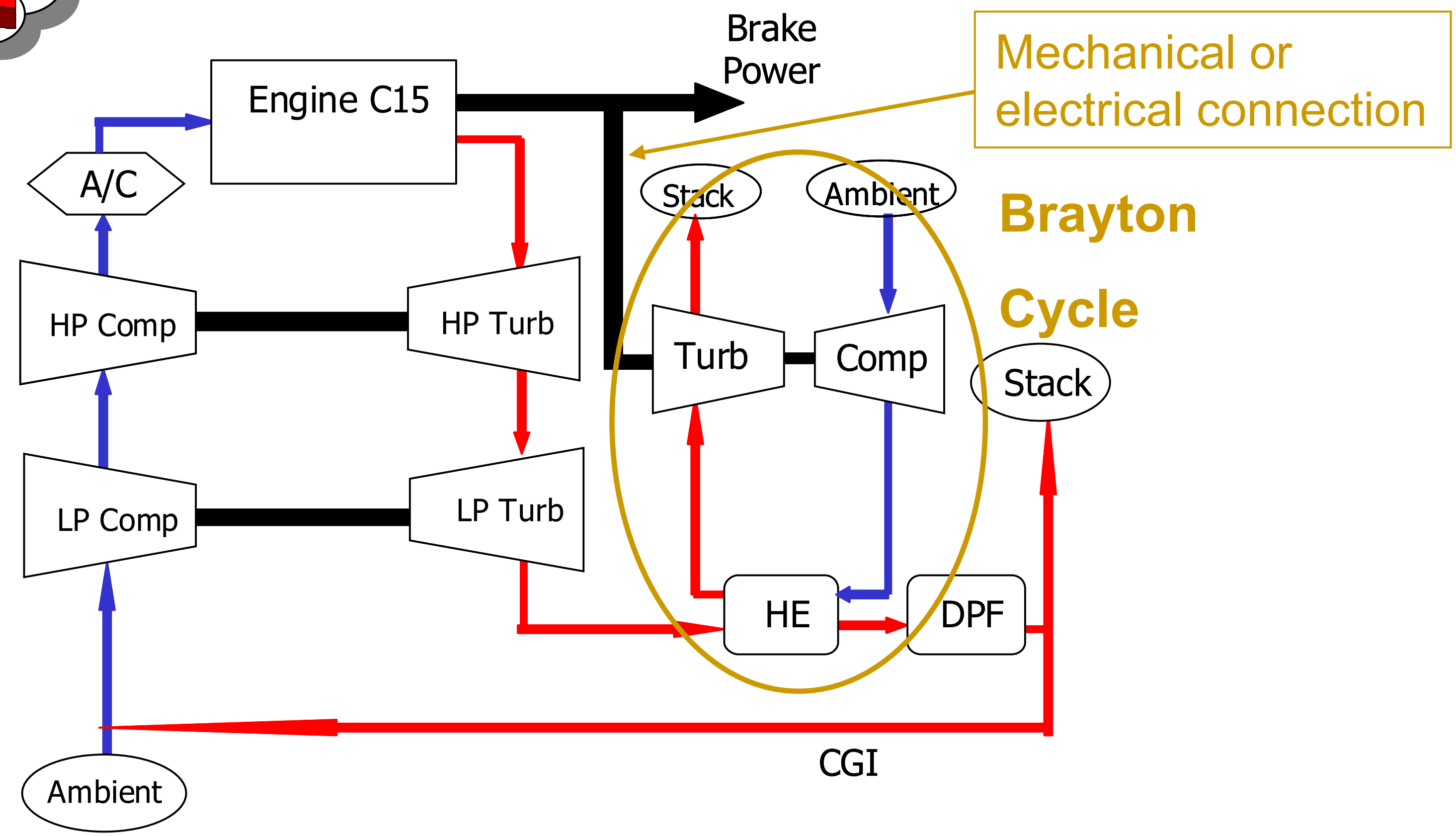
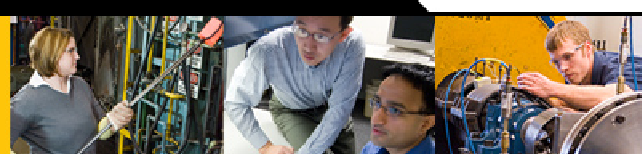
Accomplishments



Target: + 4.0% overall thermal efficiency





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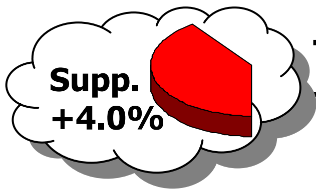
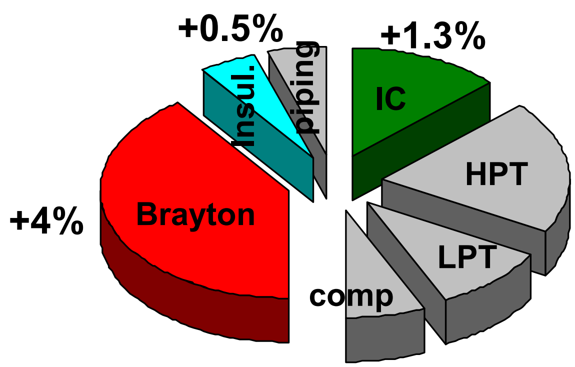
Accomplishments



<u>Target</u>: + 4.0% overall thermal efficiency

<u>Brayton Cycle – Engine Simulation Results</u>

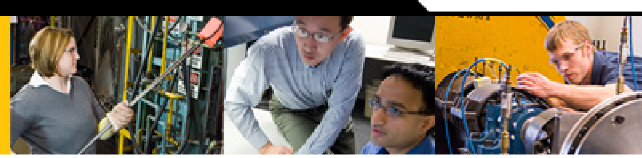
- Simulated over speed load range w/ Brayton + port insul + IC



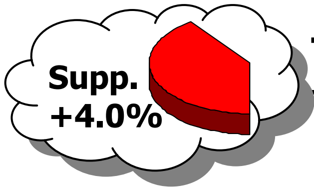
+5.8% Target at Design Pt.

- Assumptions: 85% Brayton compressor
  85% Brayton Turbine
  90% Heat Exch. Effectiveness
  3% Heat Exch. $\Delta P/P$
  93% transmission efficiency

Backpressure representative of NOx A/T plus partially loaded DPF



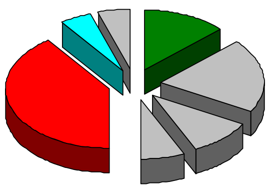
Accomplishments



__Target__: + 4.0% overall thermal efficiency

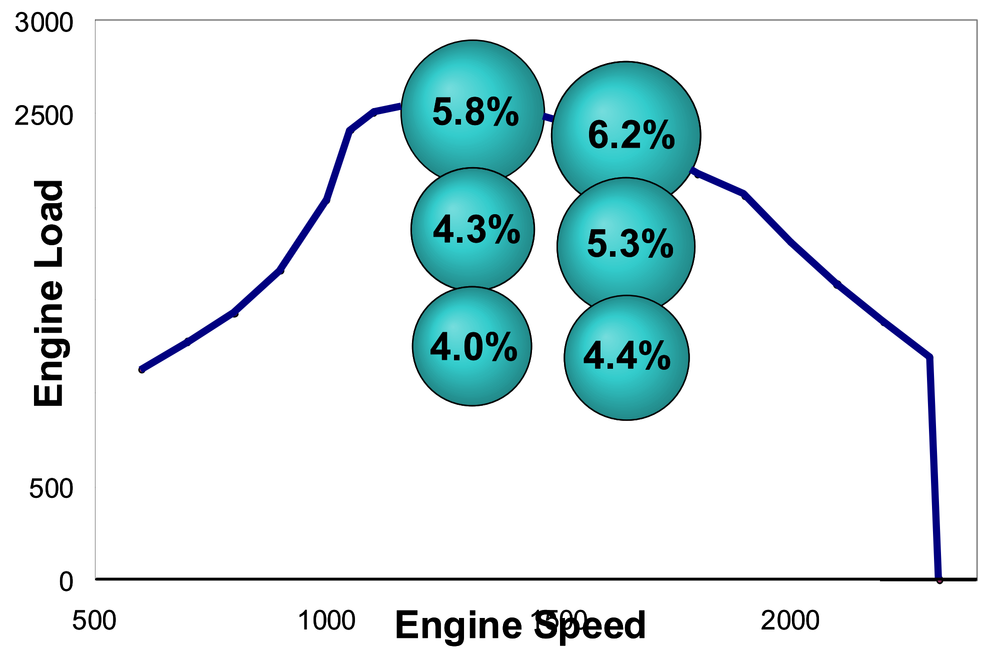
__Brayton Cycle – Engine Simulation Results__

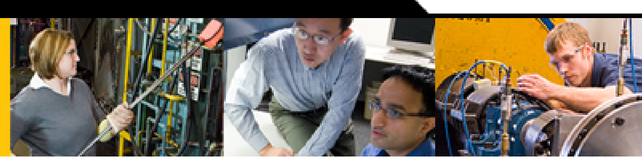
- Simulated over speed load range w/ Brayton + port insul + IC



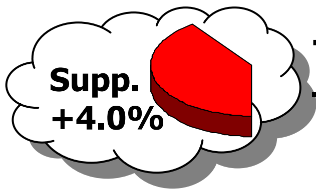
Simulated Thermal Efficiency Δ

Design Point:	***+ ~6%***
Drive Cycle:	***+ 4-5%***





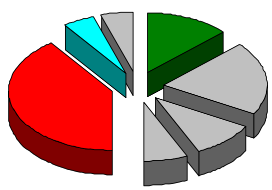
Accomplishments



Target: + 4.0% overall thermal efficiency

Brayton Cycle – Engine Simulation Results

- Simulated over speed load range w/ Brayton + port insul + IC

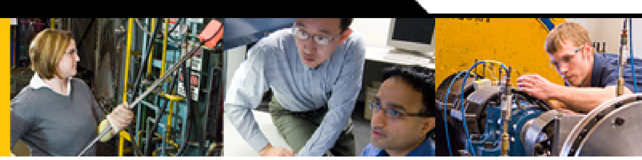


- Assumptions: 85% Brayton compressor
  85% Brayton turbine
  90% Heat Exch. effectiveness
  3% Heat Exch. $\Delta P/P$
  93% transmission efficiency

Simulated Thermal Efficiency Δ

Design Point: + ~6%
Drive Cycle: + 4-5%

System will work if component performance targets are met



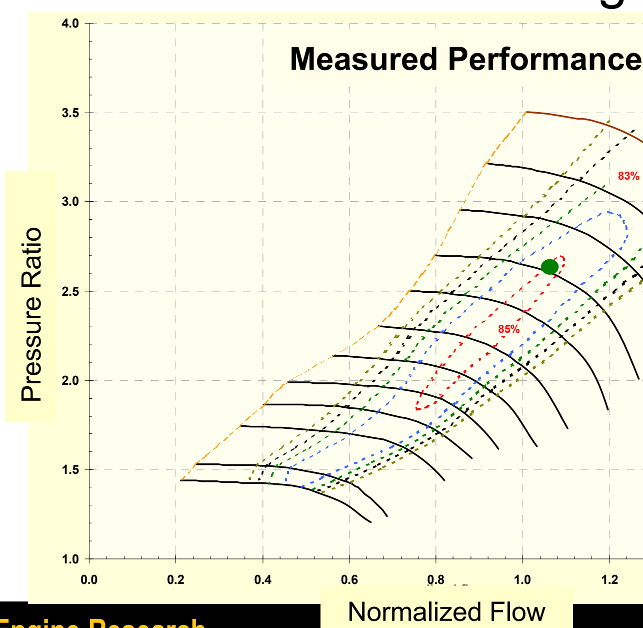
Accomplishments

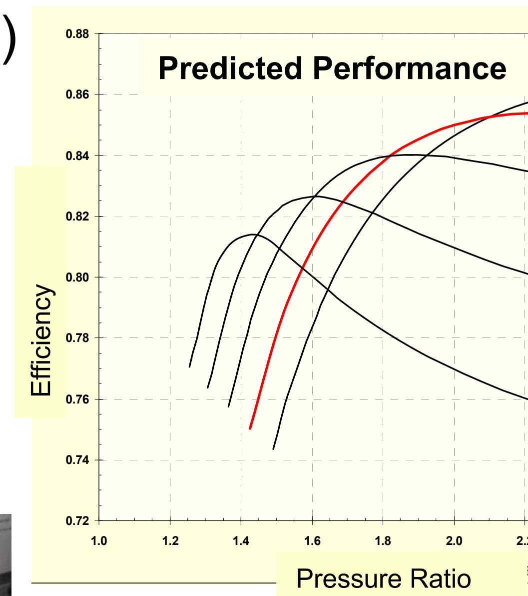
Supp. +4.0%

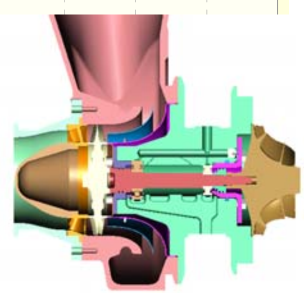
Target: + 4.0% overall thermal efficiency

Brayton Cycle Component Development

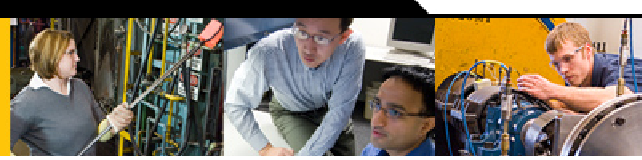
- Compressor Wheel (85% target)
  - Aero Design Complete







- Turbine Wheel (85% target)
  - Aero Design Complete



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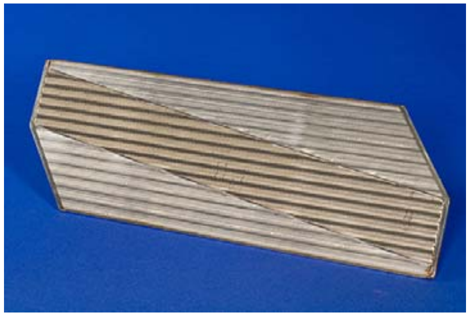
Accomplishments

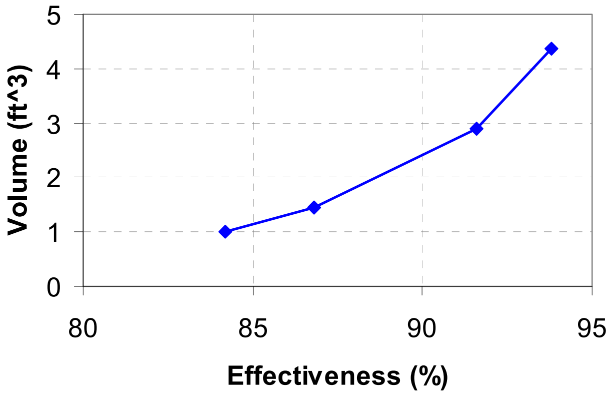
Supp. +4.0%

Target: + 4.0% overall thermal efficiency

Brayton Cycle Component Development

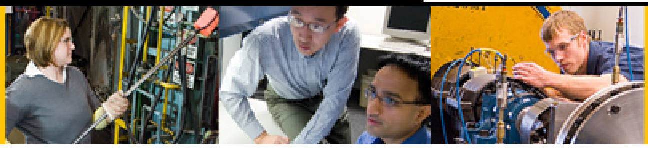
- Heat Exchanger (targets: 90% effective, 3% ΔP/P)
  - Current ACPS technology: ~2ft^3





  - Unique microchannel manufacturing technology: ~1ft^3

Ongoing research to achieve further reductions



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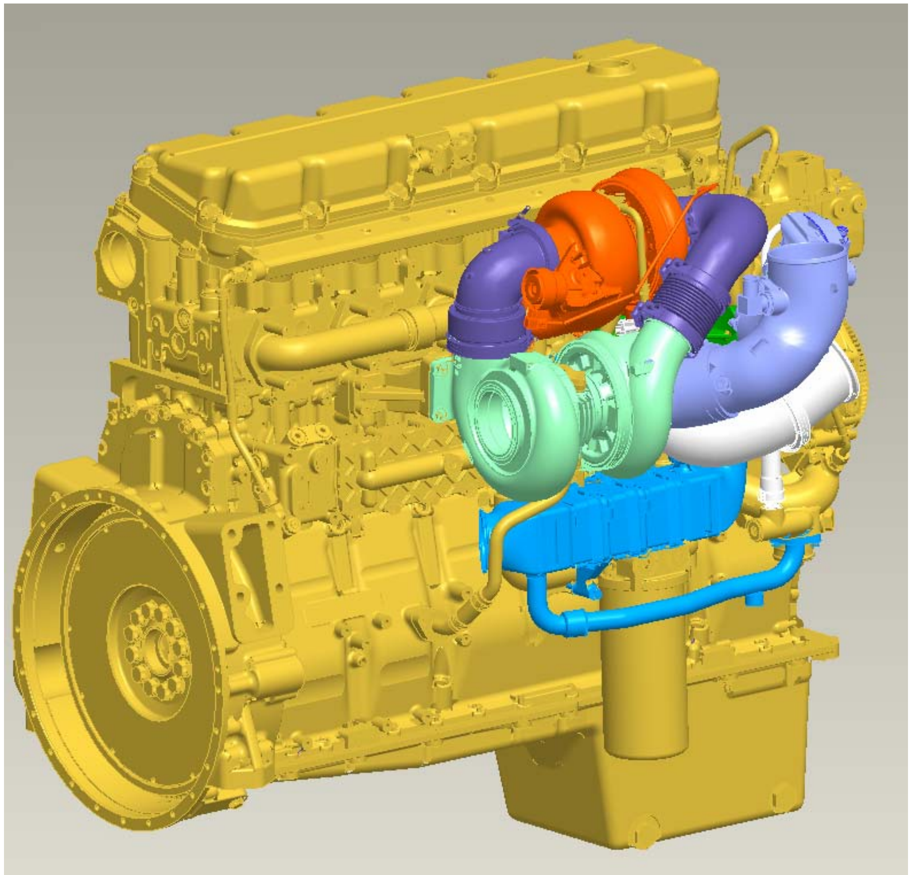
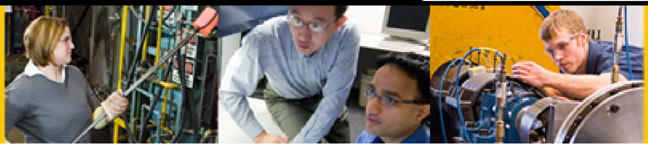
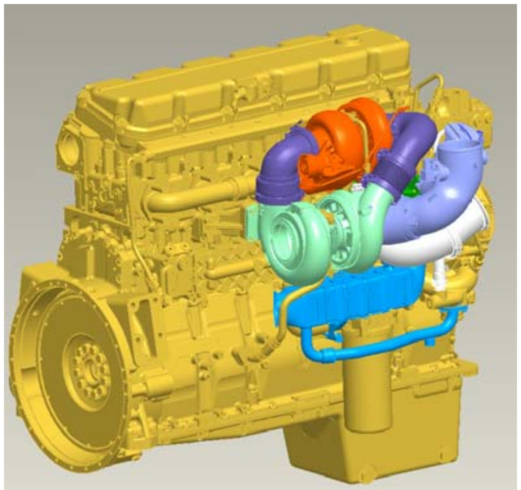
Packaging



Base Engine



Packaging



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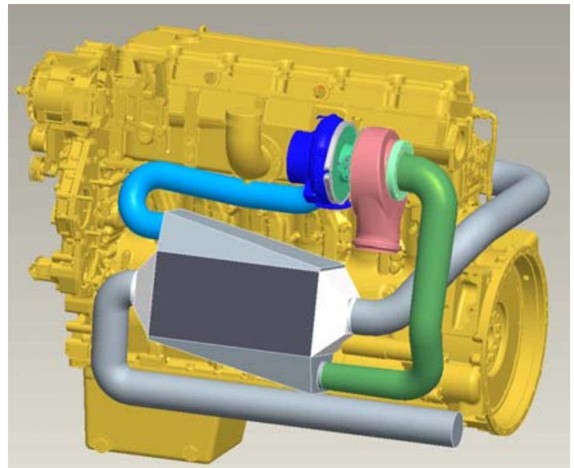
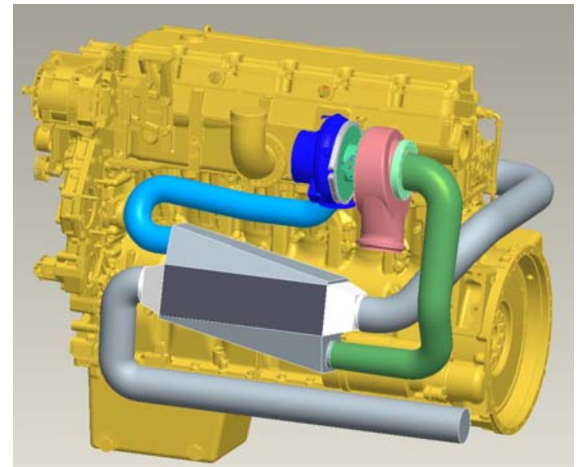
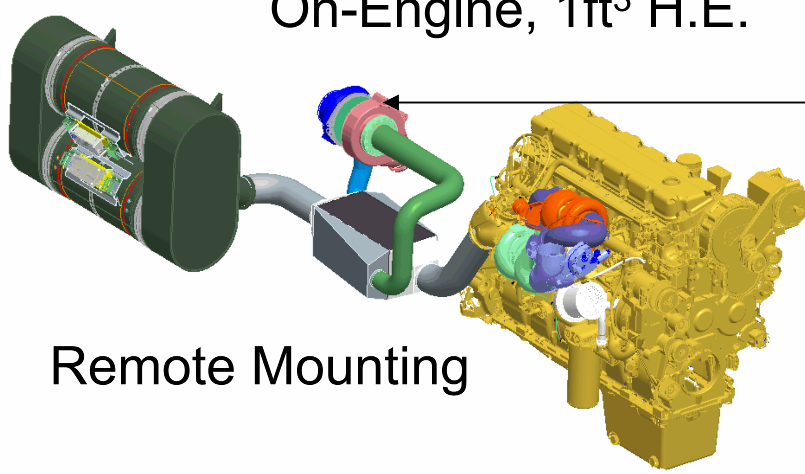


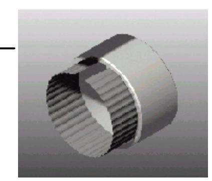
On-Engine, 1ft^3 H.E.



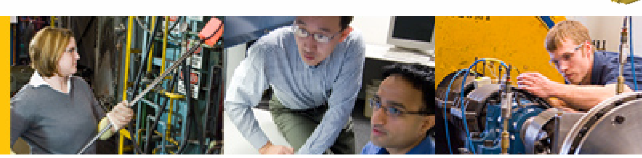
On-Engine, 0.5ft^3 H.E.



Remote Mounting

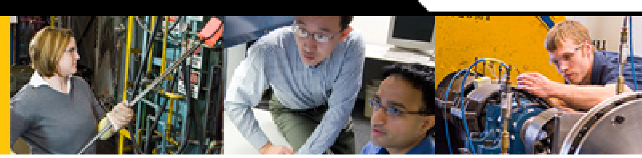


Foil Bearings



Summary

- Program goals can be achieved
  - Path defined to achieve engine thermal efficiency of +10% at design point, + ~7% over drive cycle. Capability confirmed via engine simulation.
- Key components have been designed, analyzed, procured, and tested; component efficiencies at or close to target levels demonstrated
- Heat exchanger technology development key to packaging of system in mobile applications
- Next Steps: On-engine demonstration of advanced turbocharger technologies and design / procurement / bench-testing of Brayton cycle components



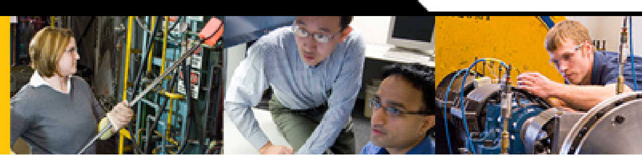
Acknowledgements

Caterpillar Thanks:

Honeywell — Turbomachinery design consulting, component procurement and integration.

Concepts NREC — Turbomachinery design consulting and optimization.

Turbo Solutions Engineering LLC — Turbomachinery design consulting and optimization.



Acknowledgements

Caterpillar Thanks:

- Department of Energy
  - **Gurpreet Singh**
  - **John Fairbanks**

- DOE National Energy Technology Laboratory
  - **Ralph Nine**