T&SD Technology & Solutions Division

Caterpillar Engine Technologies

An Engine System Approach to Exhaust Waste Heat Recovery

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DEER Conference

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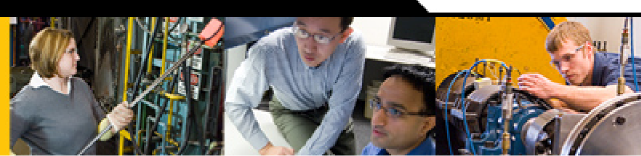
Note: This presentation does not contain any proprietary or confidential information.

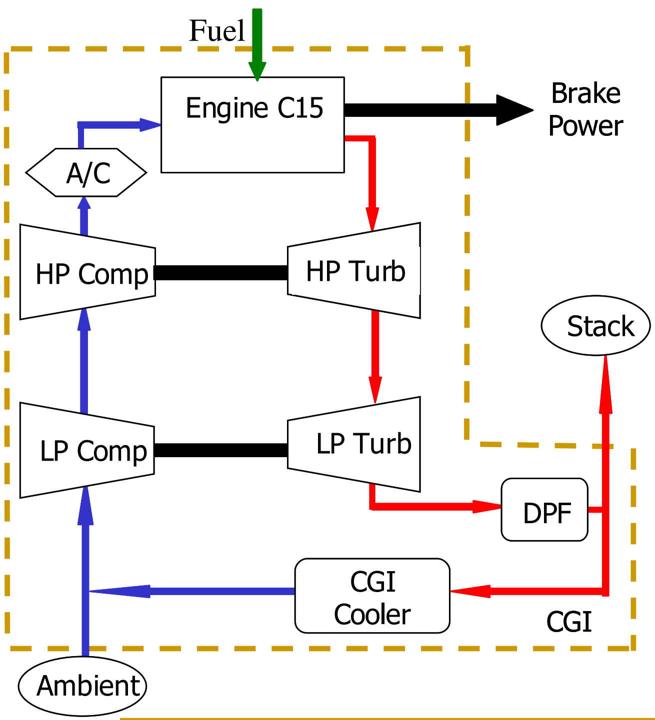
AGENDA

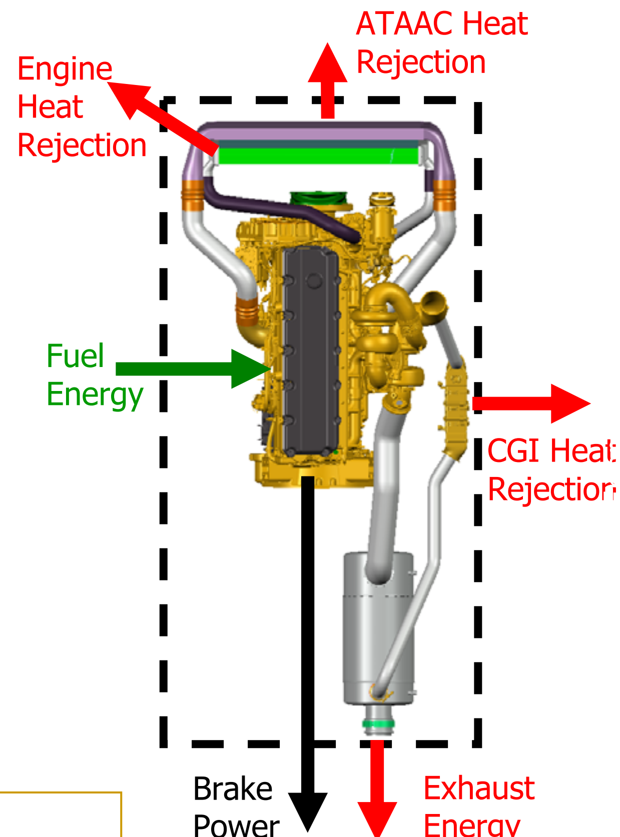
- Overview - Engine Thermal Efficiency and Waste Heat Recovery
- EWHR Program Objectives, Timeline, Scope
- Technical Developments
- Summary and Conclusions

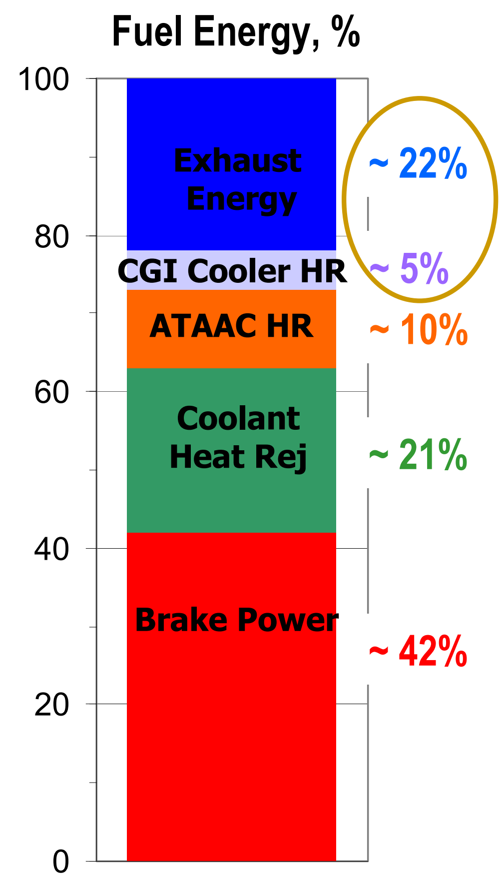


Diesel Engine Thermal Efficiency

2007 C15 On-Highway Truck







- Series Turbocharged
- LPL CGI (clean gas induction)

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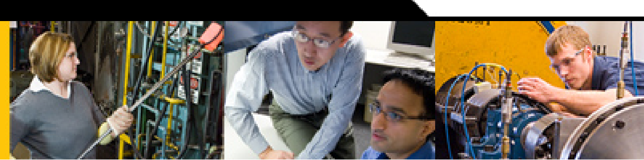
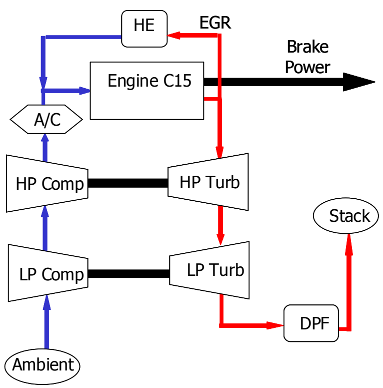
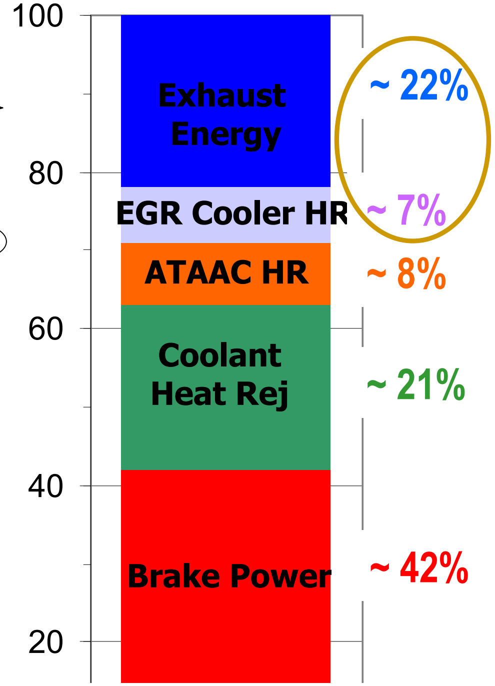


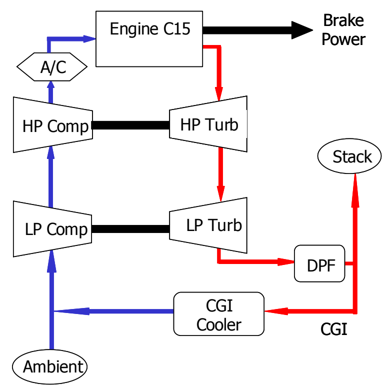
Diesel Engine Thermal Efficiency & Exhaust Waste Heat

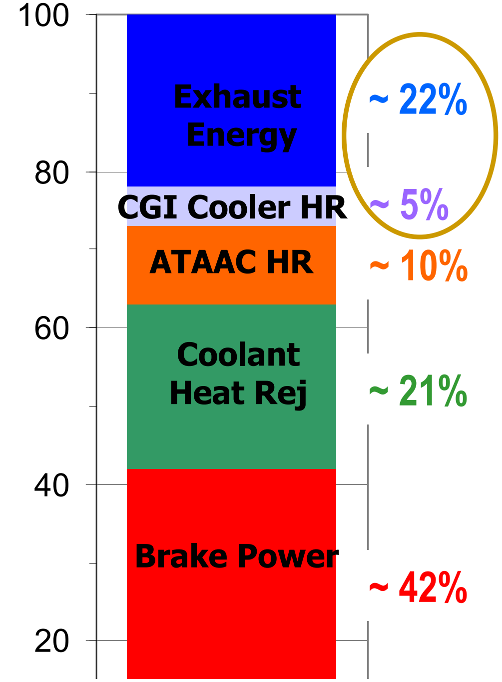
HPL Engine





LPL Engine





Roughly half of the lost fuel energy is carried in the exhaust streams

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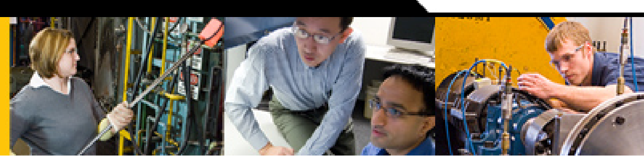
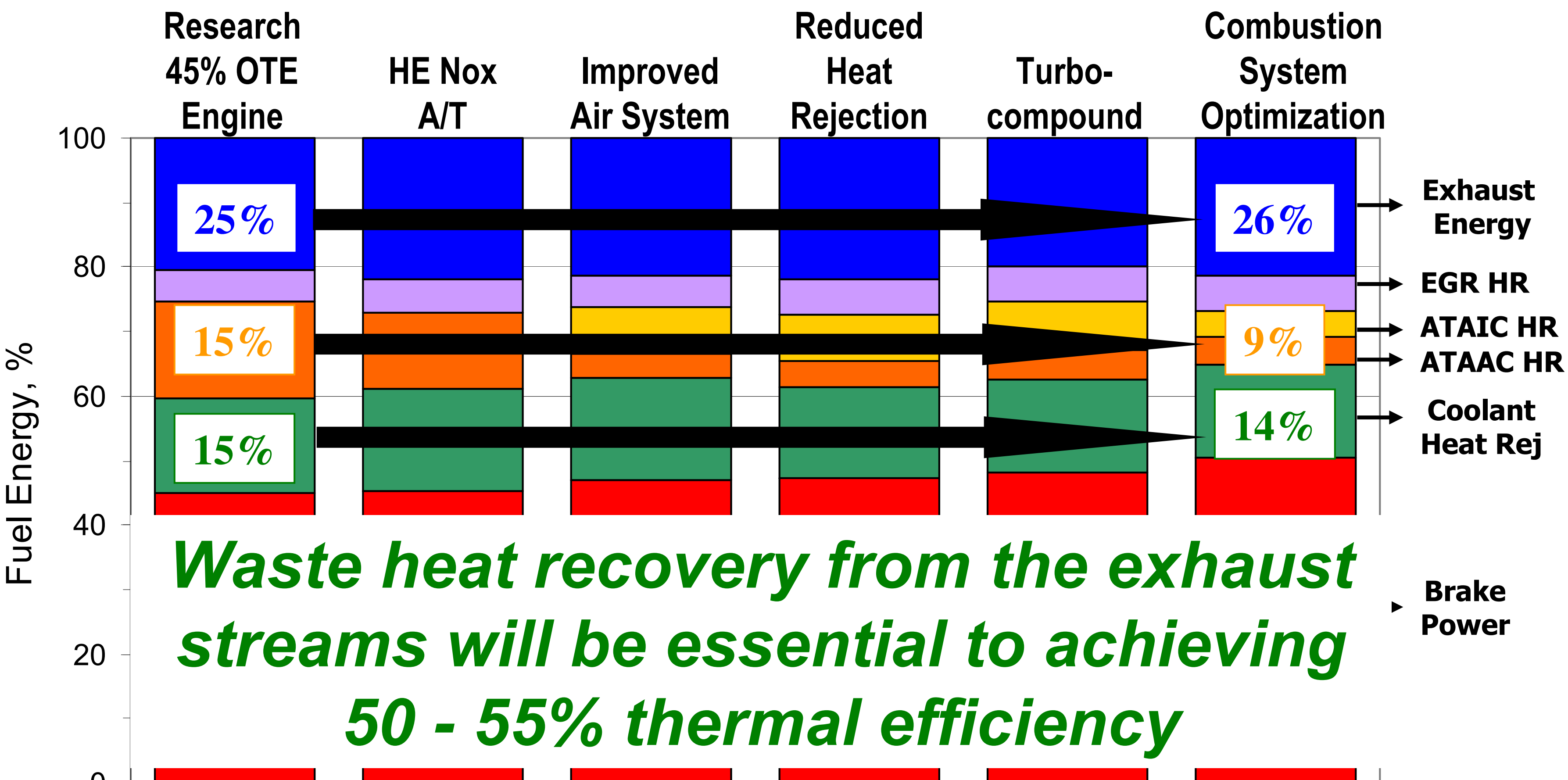
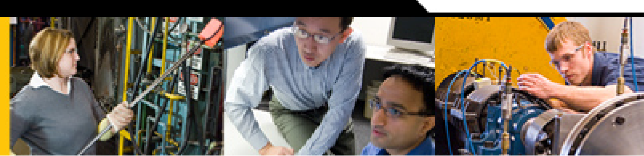


Diesel Engine Thermal Efficiency & Exhaust Waste Heat

HTCD 50% OTE Program – Analysis Results



Waste heat recovery from the exhaust streams will be essential to achieving 50 - 55% thermal efficiency

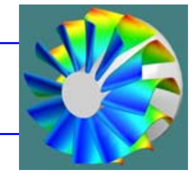


Challenges to Efficient Exhaust Waste Heat Recovery

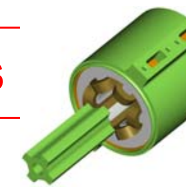
Technology	Challenges for 2010 & Beyond	Development Needs
Turbocompound	▪ Turbo Efficiencies ▪ Transmission ▪ *Aftertreatment BP*	
Bottoming Cycles	▪ Cycle Efficiencies ▪ Packaging ▪ Transmission ▪ *Aftertreatment inlet temperatures*	

Development Needs

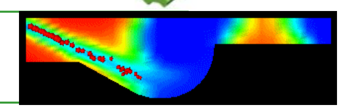
- Turbo Efficiencies



- Electrical Machines

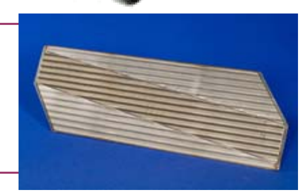


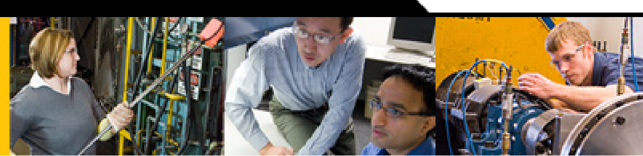
- Combustion



- Aftertreatment

- Compact Heat Exchangers





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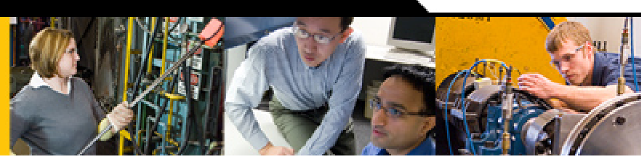
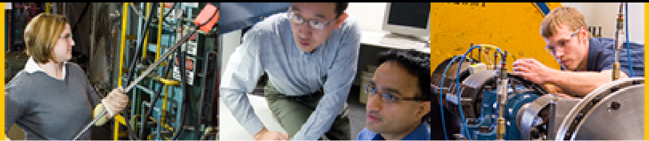


Program Objective

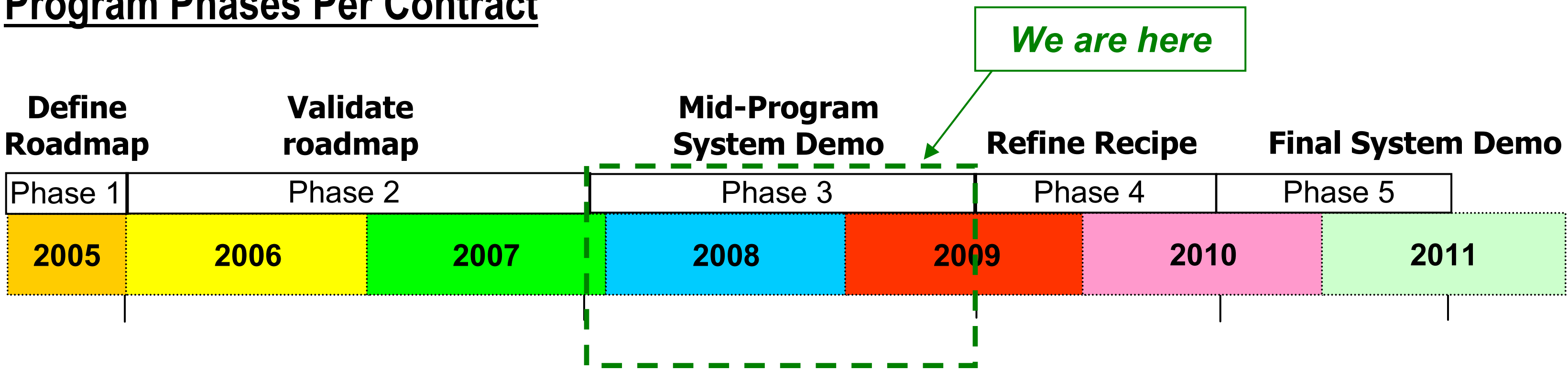
Develop components, technologies, and methods to recover energy lost in the *exhaust processes* of an internal combustion engine and utilize that energy to improve engine thermal efficiency by 10% (i.e. from ~ 42% to ~46% thermal efficiency)

- No increase in emissions
- No reduction in power density
- Compatible with anticipated aftertreatment



Program Timeline

Program Phases Per Contract



Phase 3 Objective: Demonstration of significant progress (+ 5-10%) in system thermal efficiency improvement via testing/analysis of prototype components. This will include an on-engine system demonstration of prototype hardware.

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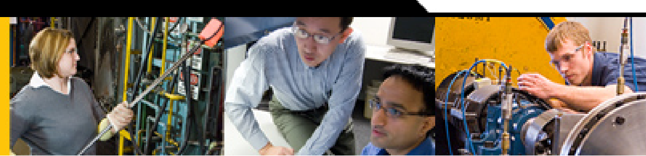
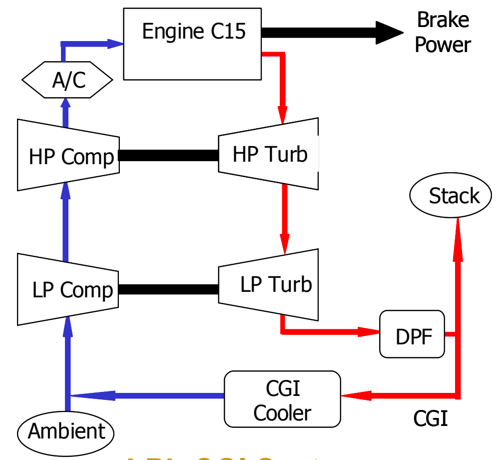


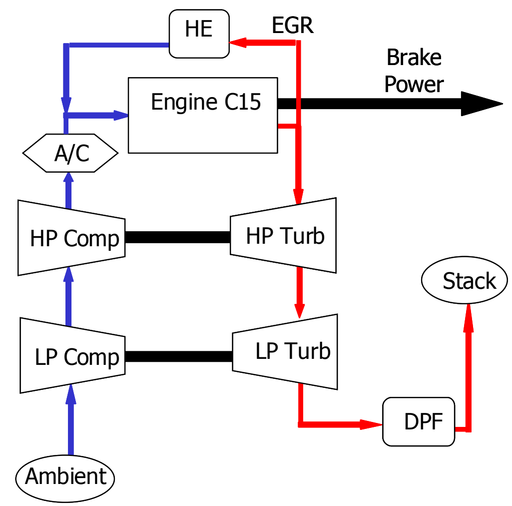
Program Scope

- Solutions compatible w/ production engines – transferable technologies
  - Baseline - 2007 C15 on-highway engine with LPL CGI system



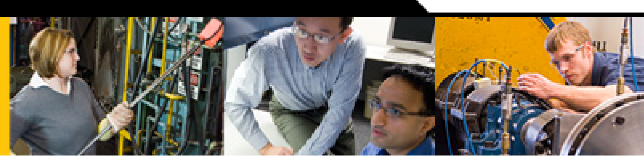
LPL CGI System

- Solutions compatible with future engines – technologies for HECC solutions
  - HPL or HPL-LPL advantageous in some scenarios



HECC HPL EGR System

Program scope revised to include investigation of LPL & HPL solutions



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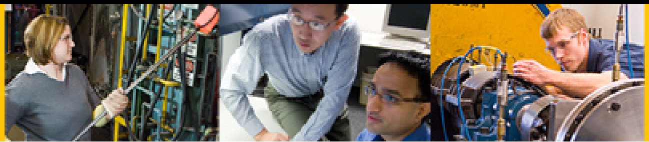
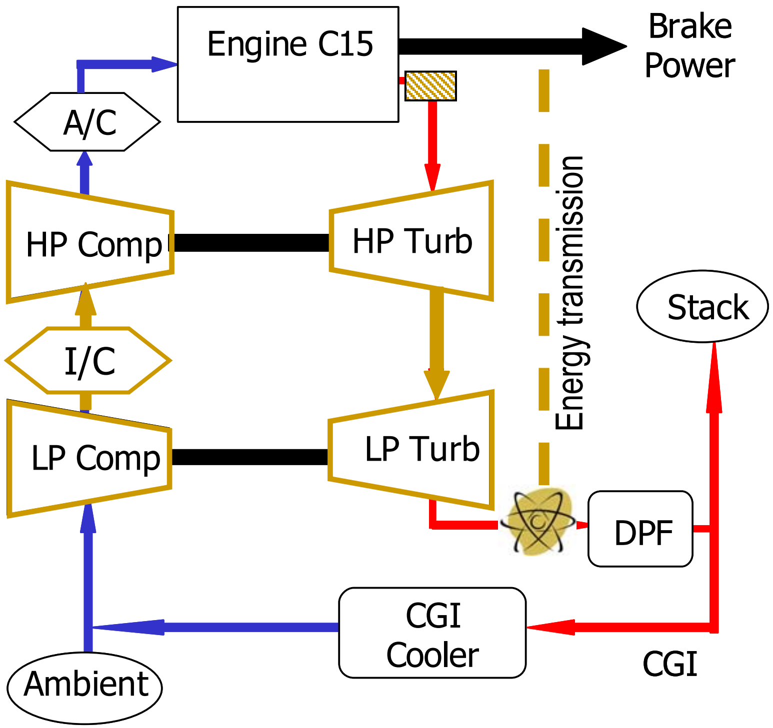
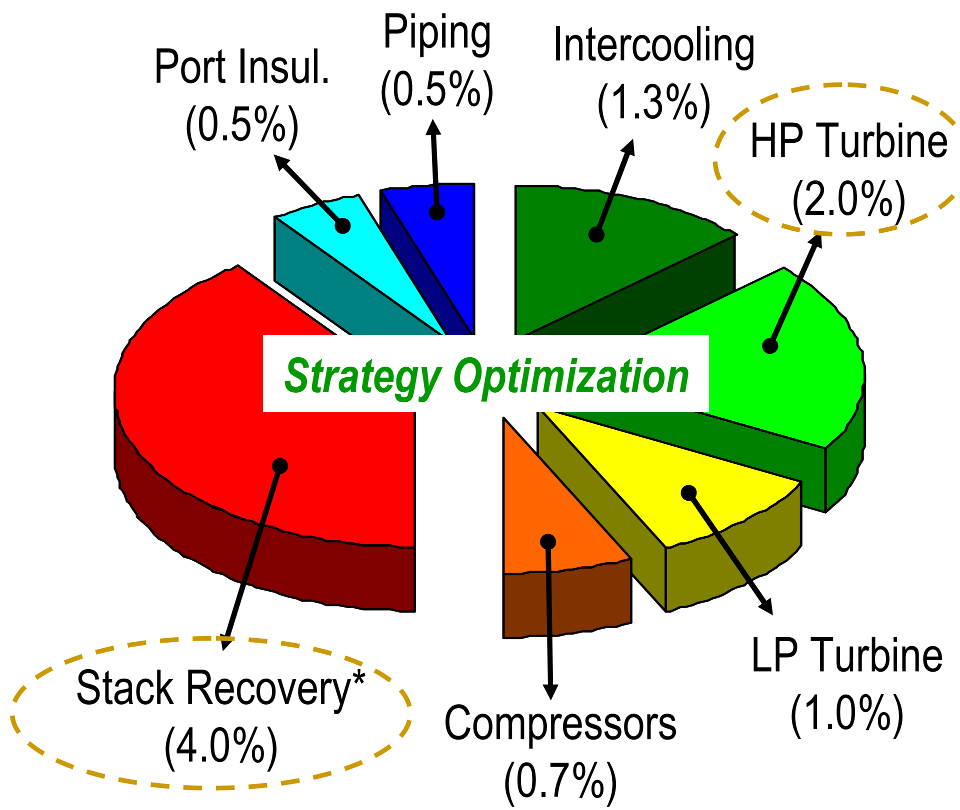


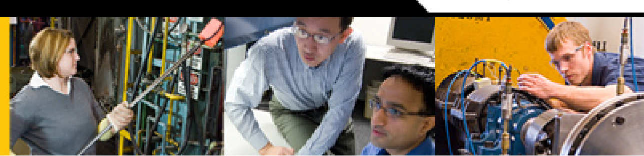
Technical Developments – Proposed System

An integrated system solution to waste heat recovery

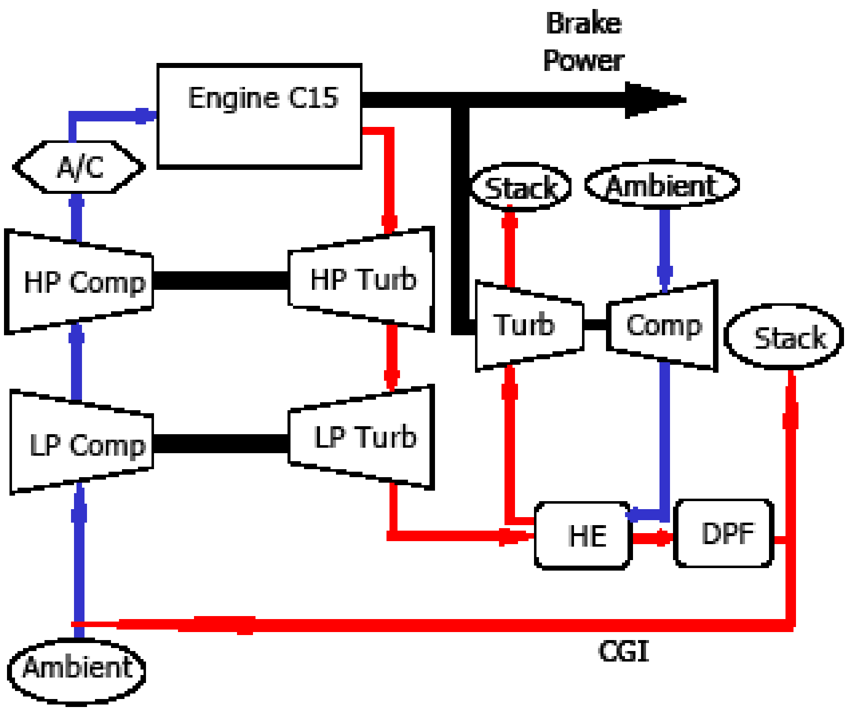




* Turbocompound or bottoming cycle: supplements engine power via electrical or mechanical connection to flywheel



Technical Developments – Stack Energy Recovery



Early in program:

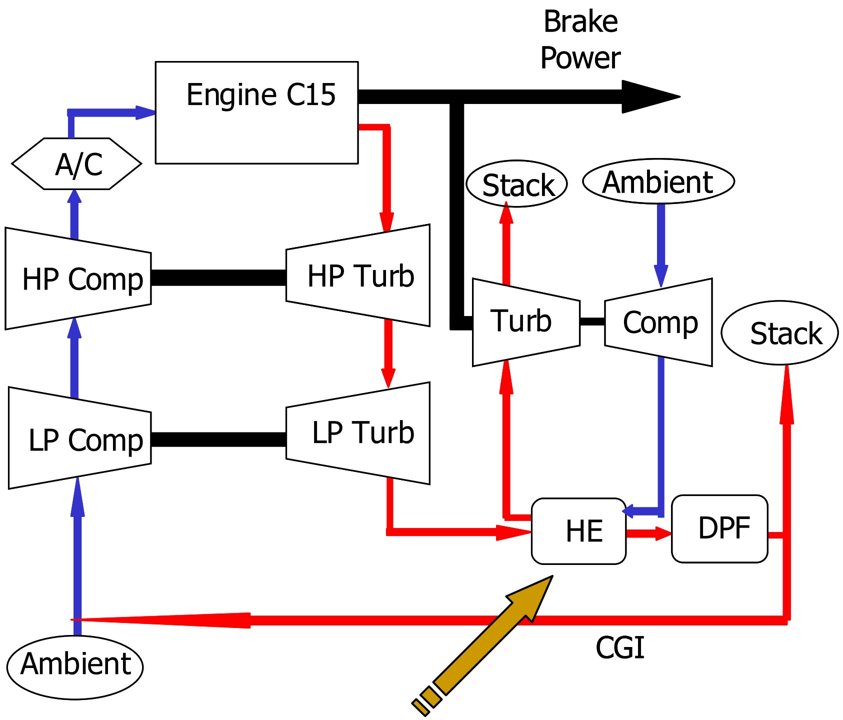
- 2010 A/T backpressure levels not known with certainty
- Turbocompound known to be negatively affected by backpressure

Forced consideration of "backpressure insensitive" solutions

Technical Developments – Stack Energy Recovery

Phase 1 Proposed Solution

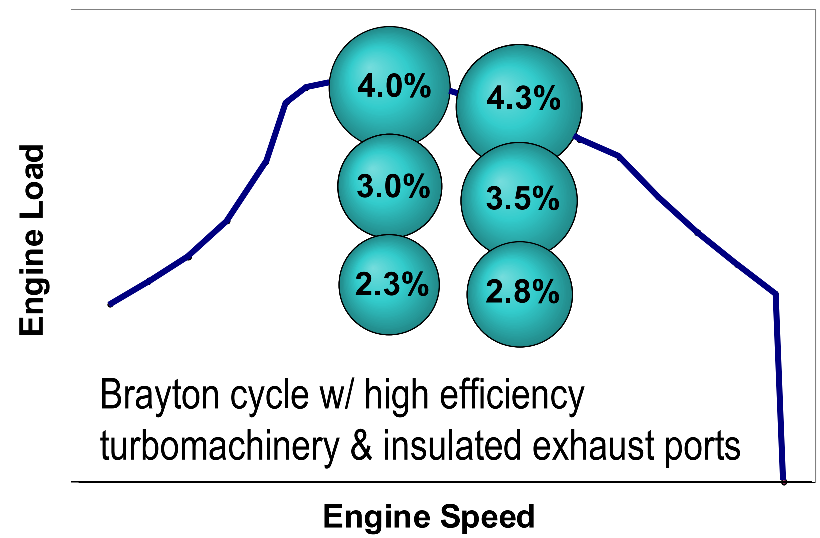
Open Air Brayton Cycle



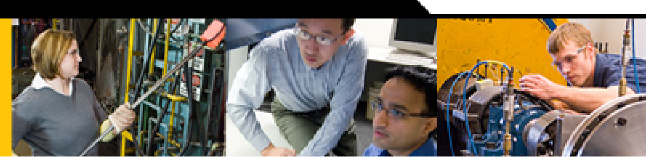
Packaging???

Phase 2 Engine Simulations

BSFC Benefit of Brayton on C15



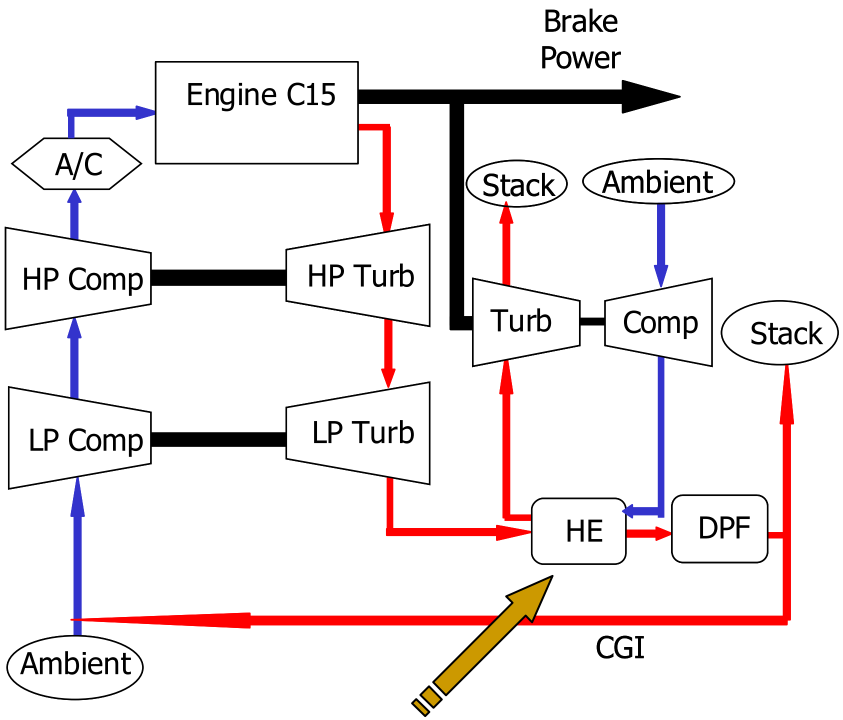
Performance Objective CAN be met with Brayton Cycle Solution and supporting technologies



Technical Developments – Stack Energy Recovery

Phase 1 Proposed Solution

Open Air Brayton Cycle

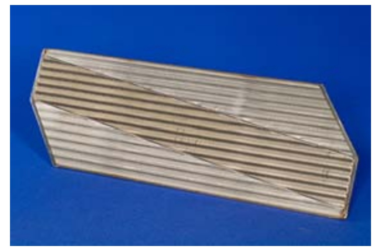


Packaging???

Phase 2

Heat Exchanger Technology Evaluations

- **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.

At end of Phase 2, no line of sight to a HE core smaller than 1.5 – 2.0 ft^3

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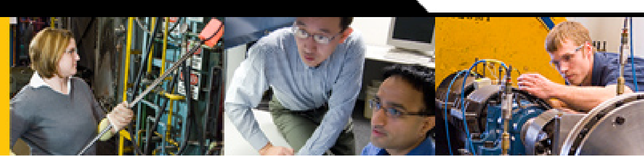

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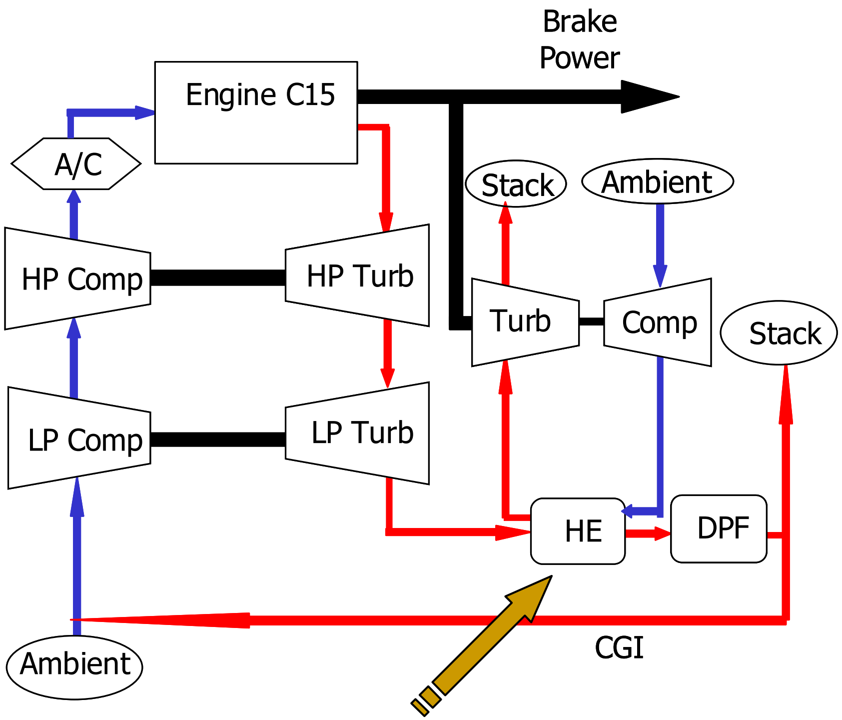
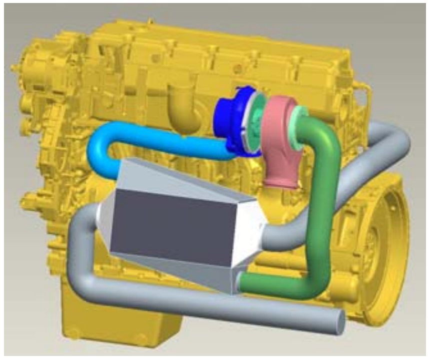
Technical Developments – Stack Energy Recovery

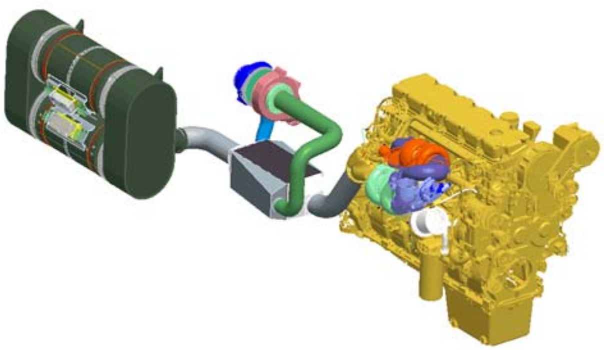
Phase 1 Proposed Solution
Open Air Brayton Cycle



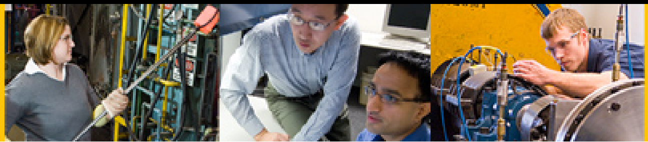
Packaging???

Phase 2 Packaging Studies with
1 ft^3 heat exchanger core





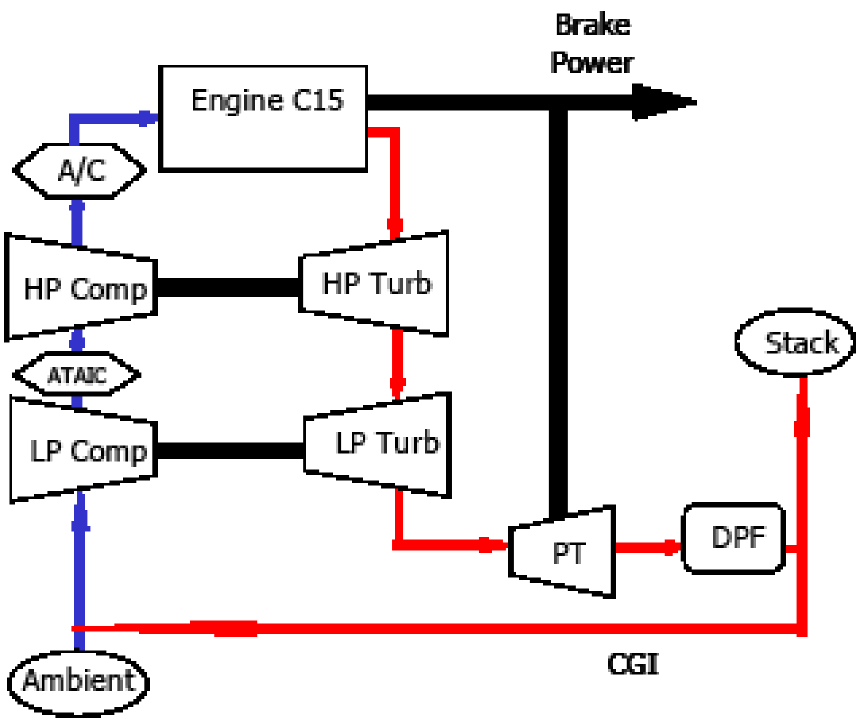
Even at 1 ft^3 core volume, system packaging is challenge



Technical Developments – Stack Energy Recovery

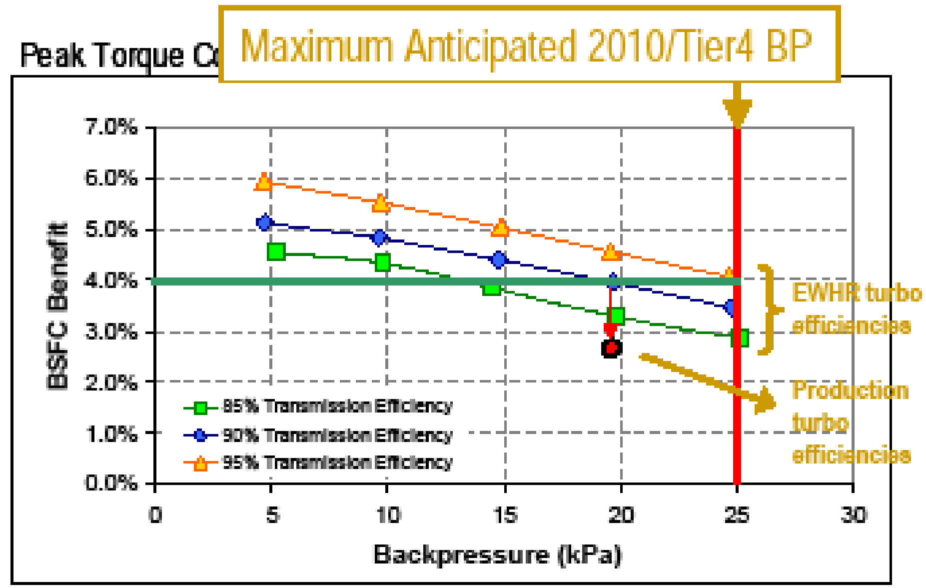
Phase 3 Proposed Solution

Turbocompound - *Revisited*



Phase 3 Engine Simulation Results

BSFC Benefit of Turbocompound on C15

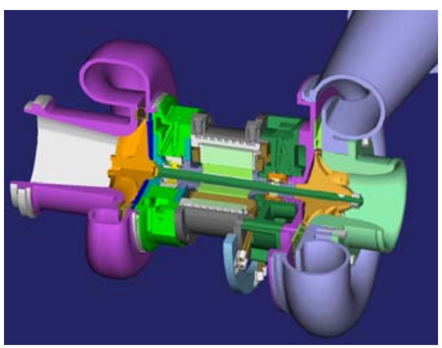


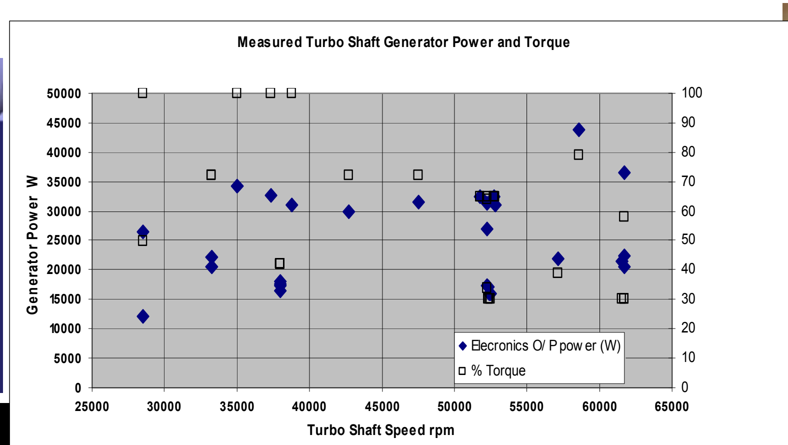
Performance Objective CAN be met with turbocompound utilizing <u>high</u> <u>efficiency</u> turbomachinery

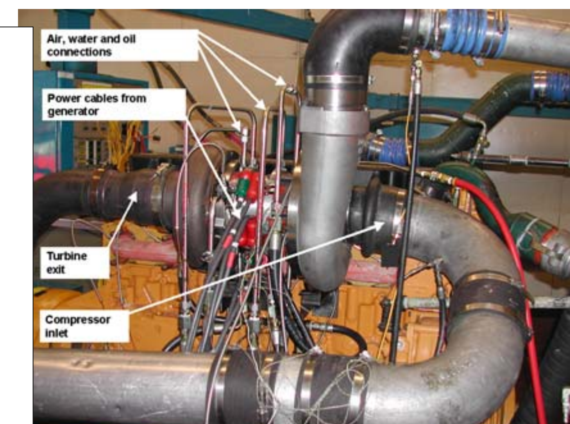
Technical Developments – Stack Energy Recovery

Electric Turbocompound

- Gen1 – Caterpillar / DOE 2001-2004 Development Program
  - Approach – Turbocompound function integrated into engine turbo
  - Specification – 40kw @ 60krpm in generating mode
  - Results
    - Excellent stability of rotor / shaft system
    - Generated 44kw at 59krpm
      - Turbo generator short of efficiency target
      - Heating problems – powers above 15kw limited to 30-60sec runtime







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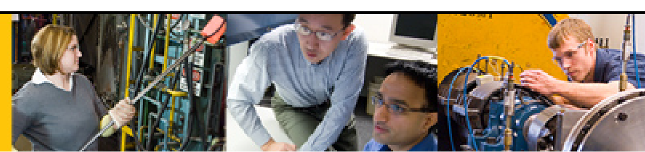

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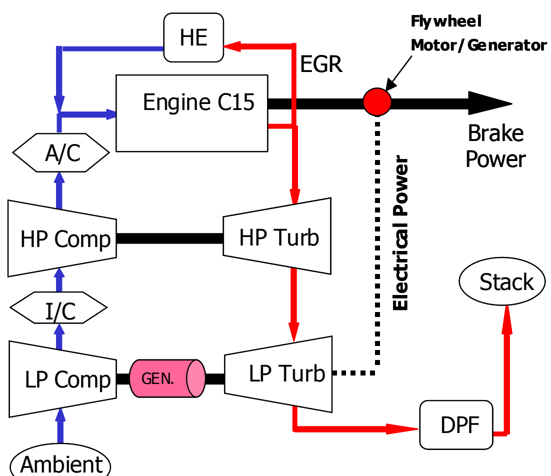
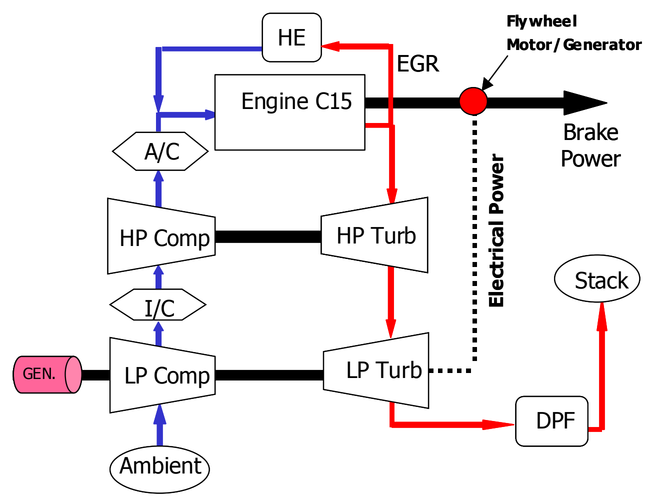
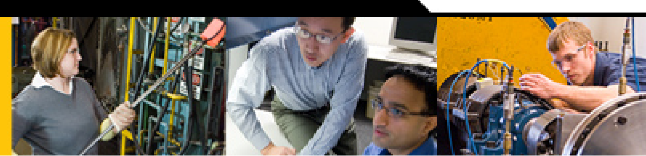
Technical Developments – Stack Energy Recovery

Electric Turbocompound

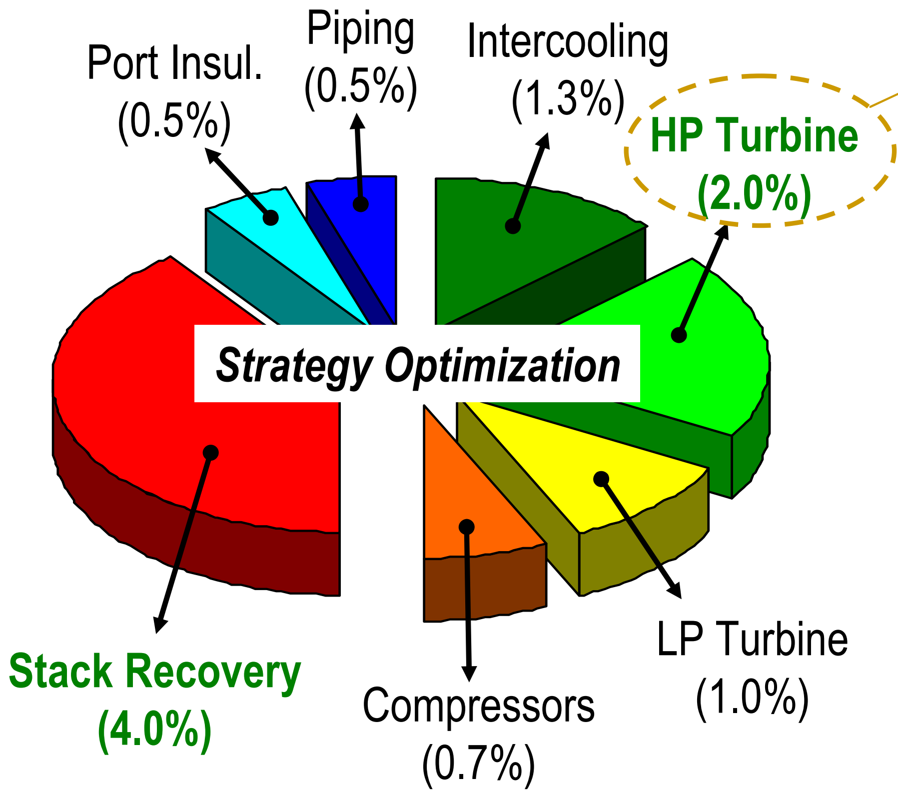
- Gen2 – Concept design collaboration with consultant
  - Specification: 20-25kw power generation
  - Two design options to be evaluated
    - 'Between-the-wheels' option
    - 'In-front-of-compressor' option
  - Thermal, stress, rotordynamic analysis to evaluate options
  - Scheduled completion: 30Oct08



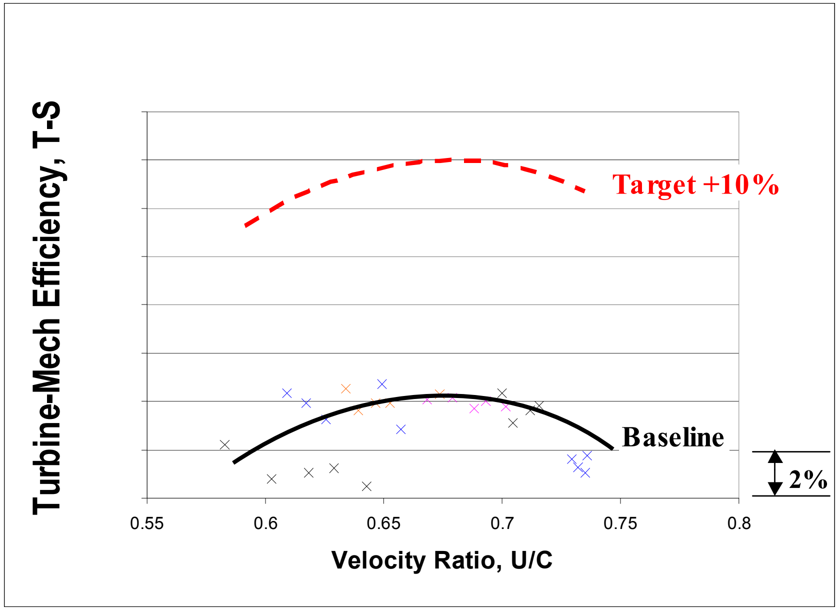




Technical Developments – HP Turbine



+2% Thermal Efficiency Requires +10% Turbine Stage Efficiency



Technologies

- RND – radial, nozzled, divided turbine
- Mixed Flow Turbine

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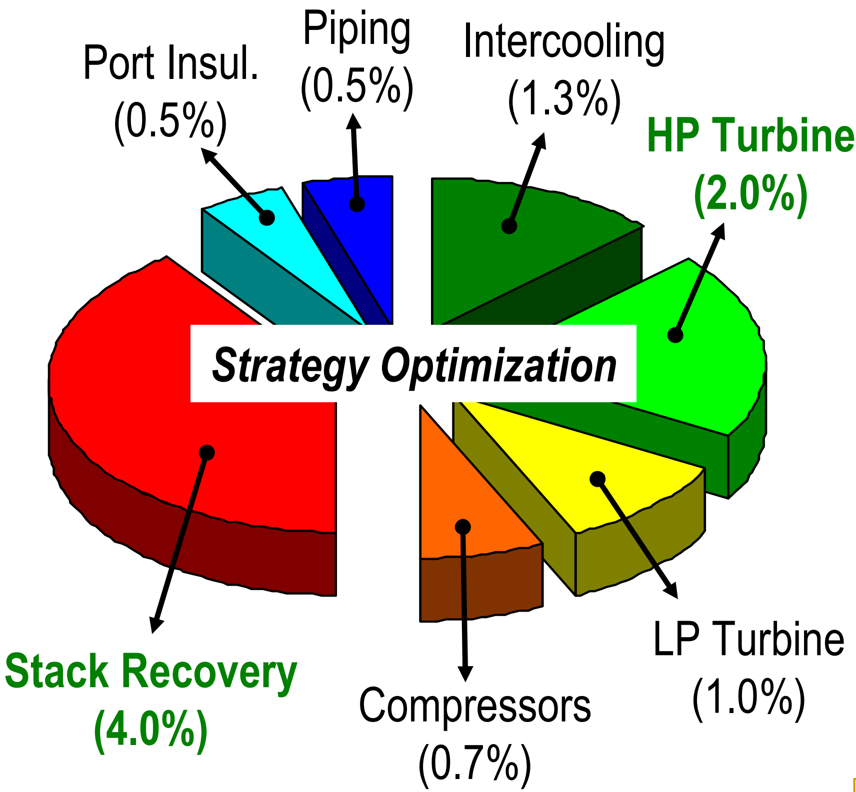
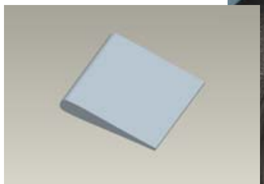
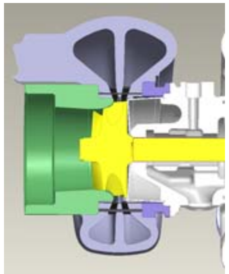
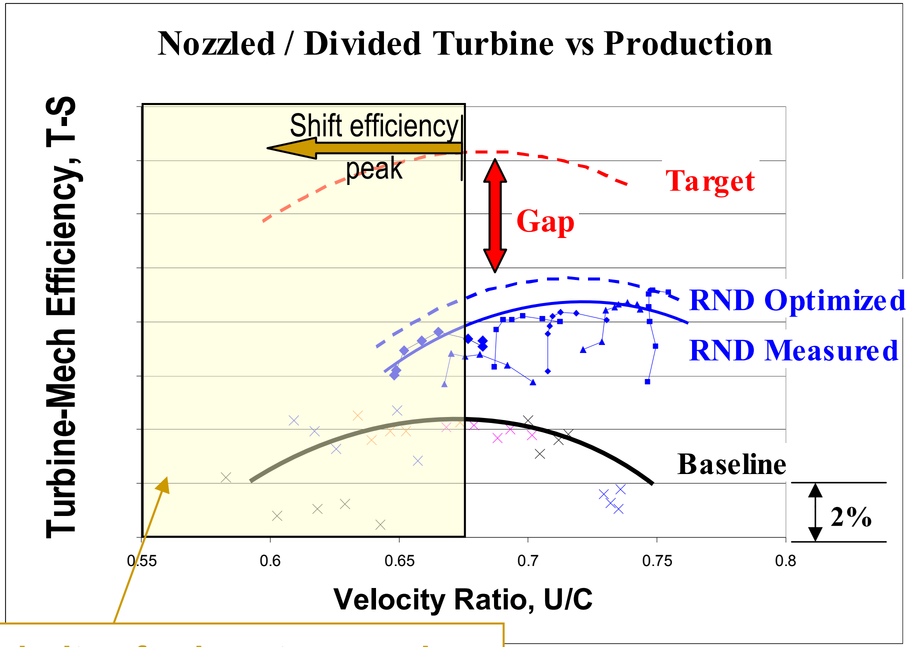
Technical Developments – HP Turbine

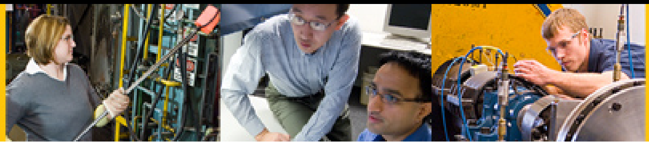








Majority of exhaust energy is entering turbine in this region



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Technical Developments – HP Turbine

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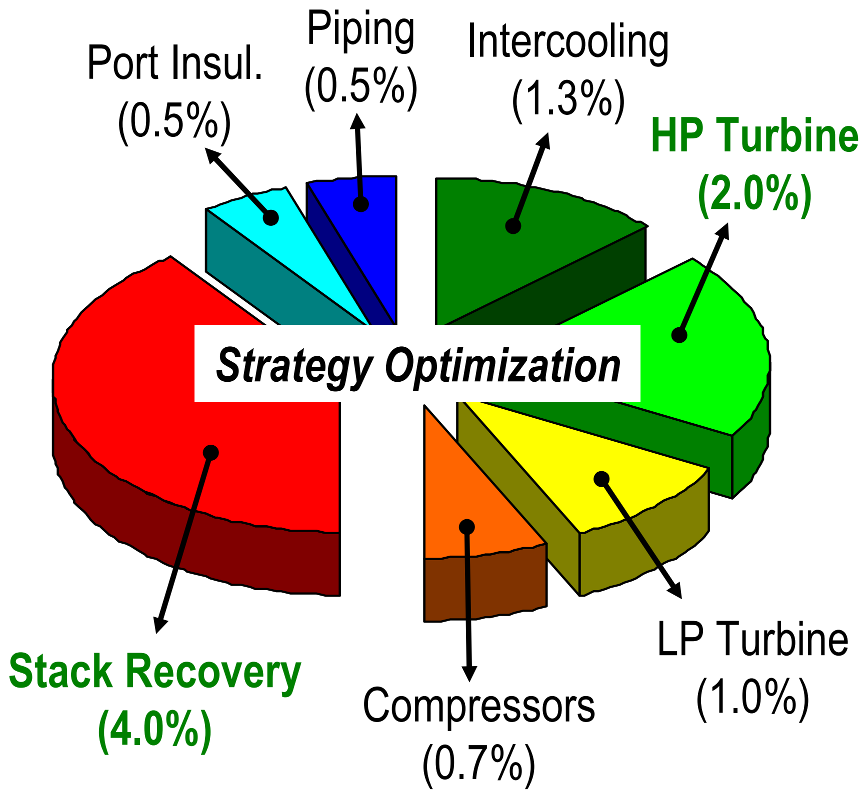

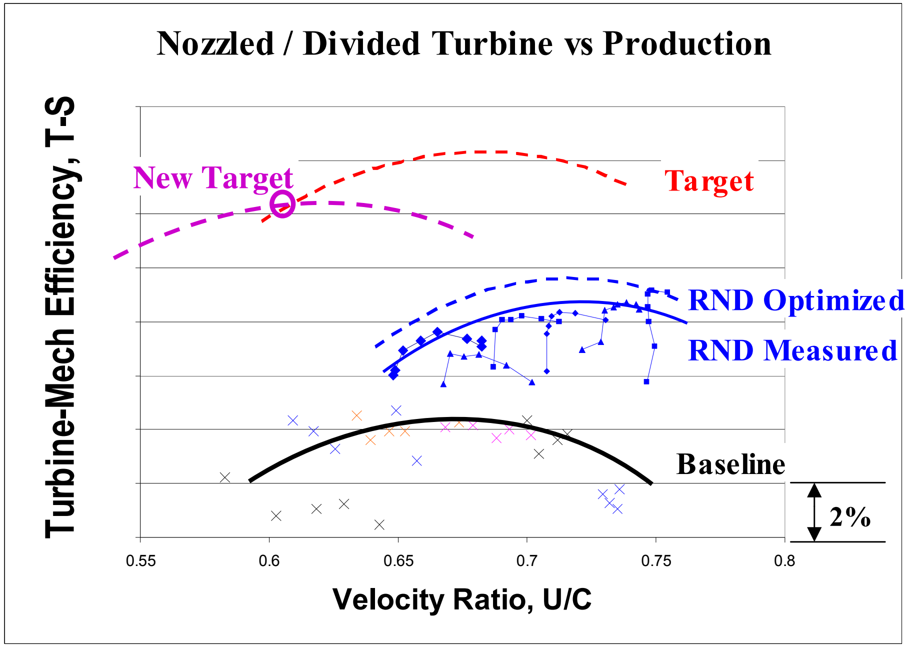

Shifting peak efficiency – mixed flow turbine

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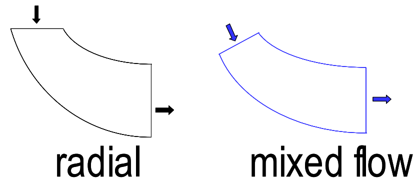
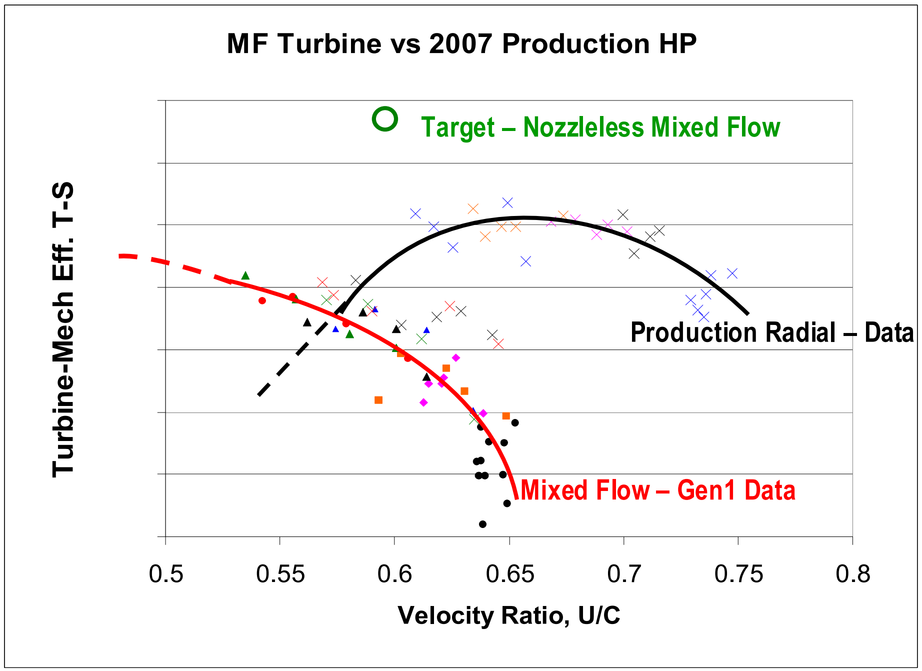
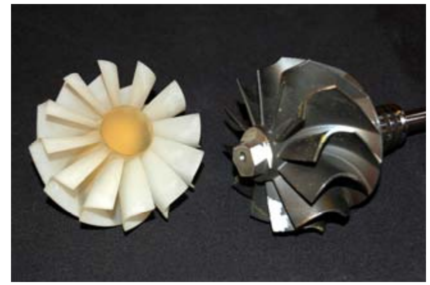
Technical Developments – HP Turbine

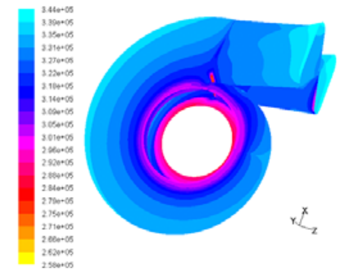
Mixed Flow Turbine



- Gen1 wheel designed / procured / tested

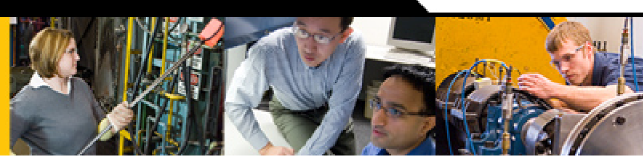






Gen1 missed target performance:

- Over-aggressive design
  - Desire to clearly demo efficiency shift
- First use of codes for mixed flow
  - Calibration required



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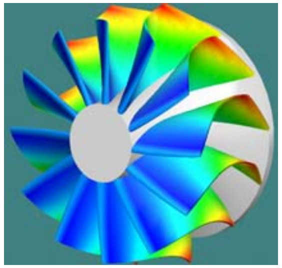
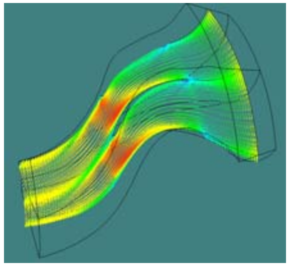
Technical Developments – HP Turbine

Mixed Flow Turbine

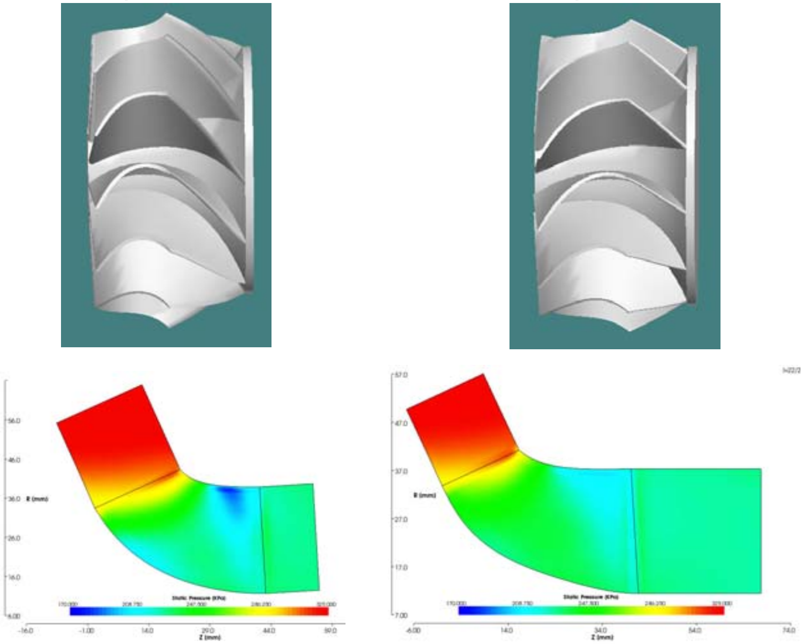
- Gen2 wheel designed / analyzed
  - Gen1 lessons used to optimize design
  - 6-8% improvement in efficiency predicted vs Gen1 over range of interest

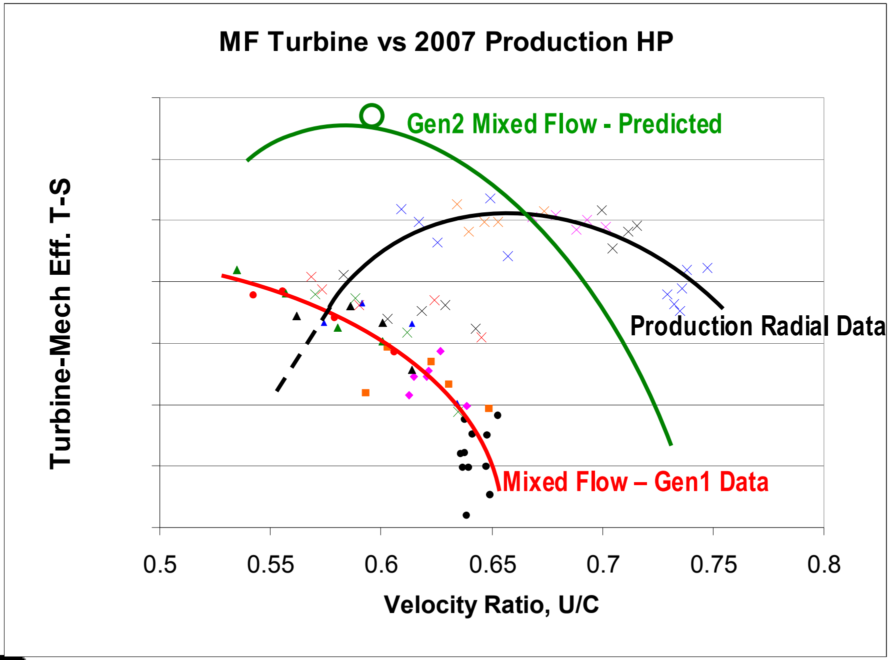


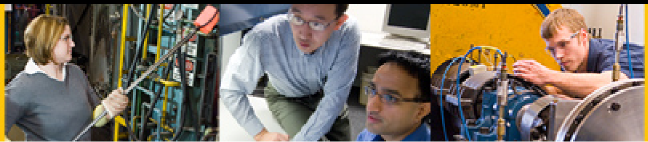


Gen1

Gen2







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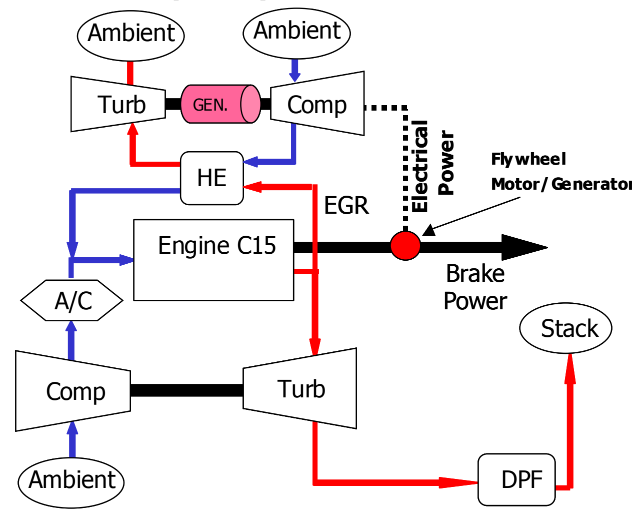
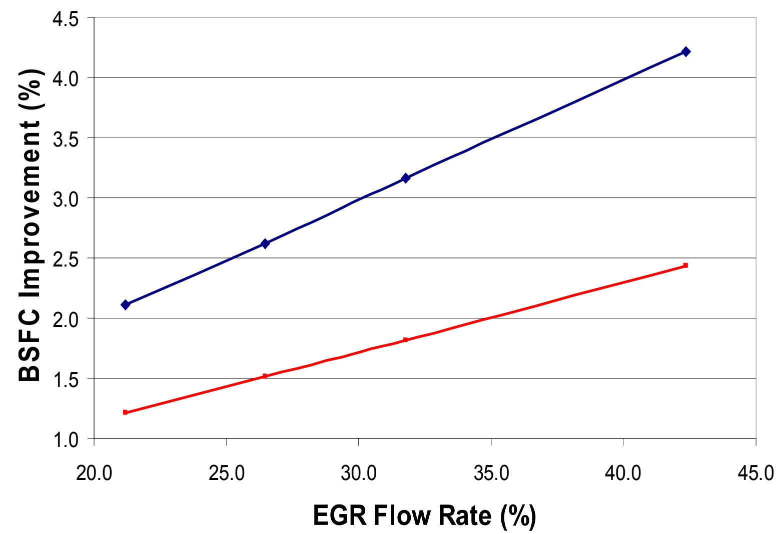
Technical Developments – HECC HPL EGR Waste Heat Recovery

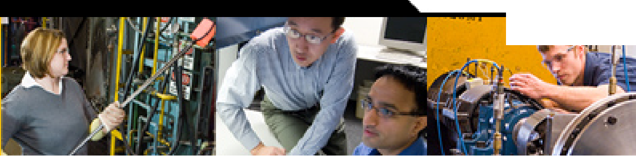
Brayton Cycle

- System Capability Evaluation
- Assumptions:
  - Brayton turbo efficiencies 80%
  - Single stage for packaging
  - Heat exchanger: 90% effectiveness
  - Transmission Efficiency: 90%
- Packaging: Excellent
  - Heat Exchanger: 0.25 ft^3 core
  - Turbo: ~ 2" compressor
- Performance: Low-Moderate
  - At 20 - 40% EGR:
    - + ~2 - 4% w/ 80% turbomachinery
    - + ~1.5 - 2.5% w/ 74% turbomachinery

Brayton Cycle



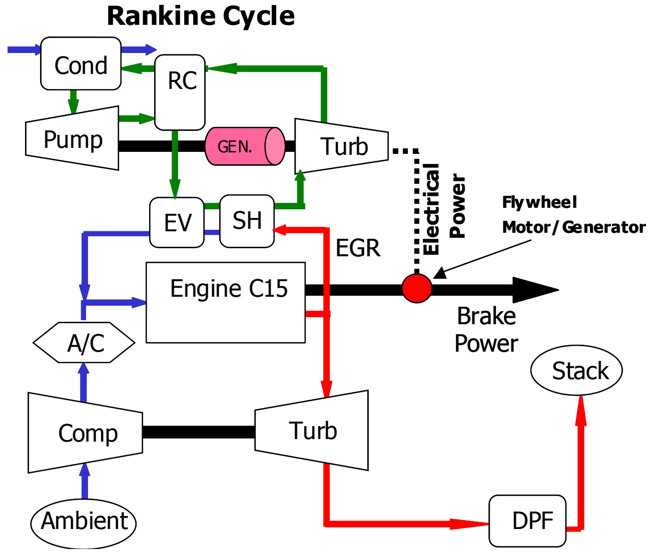


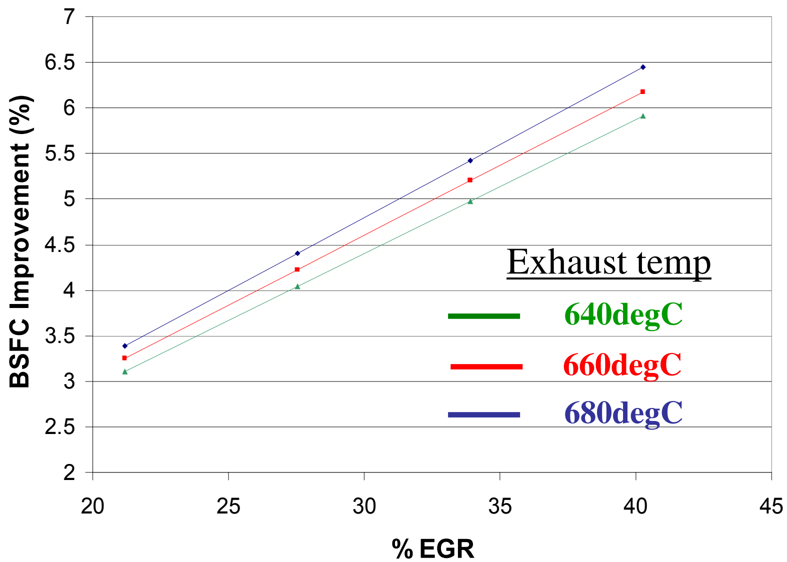


Technical Developments – HECC HPL EGR Waste Heat Recovery

Rankine Cycle

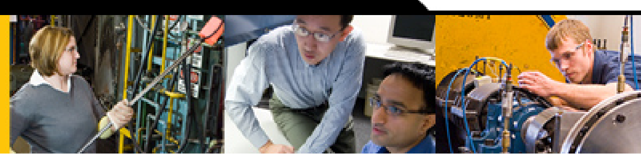
- System Capability Evaluation
- Assumptions:
  - Turbine efficiency 80%
  - Pump efficiency 65%
  - R245fa working fluid
  - Transmission Efficiency: 90%
- Packaging: Challenge
  - Multiple heat exchangers
- Performance: Moderate-Good
  - + 3-6% depending on EGR rates





AGENDA

- Overview - Engine Thermal Efficiency and Waste Heat Recovery
- EWHR Program Objectives, Timeline, Scope
- Technical Developments
- Summary and Conclusions



Summary

- Significant progress made toward program objectives:
  - With LPL CGI, turbocompound + high efficiency turbos provides +4% BSFC w/ 20kPa aftertreatment backpressure.
  - Progress on supporting technologies, especially turbine technologies, suggests performance target can be met
- Waste heat recovery for future HECC engine solutions prompts consideration of HPL and HPL-LPL EGR configurations
  - Turbocompound still effective for stack recovery. Benefit dependent on aftertreatment backpressure, required EGR rates
  - Brayton cycle offers moderate benefit for HPL loop heat recovery
  - Rankine cycle offers significant benefit for HPL loop heat recovery

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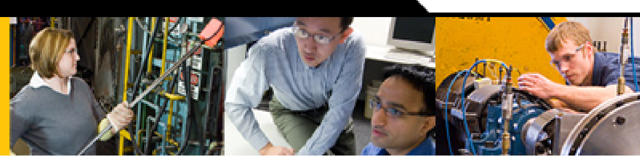

Acknowledgements

Caterpillar Thanks:

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ConceptsNREC	Turbomachinery design consulting and optimization.
Turbo Solutions	Turbomachinery design consulting and optimization.
Barber-Nichols Inc.	Electric turbocompound design consulting

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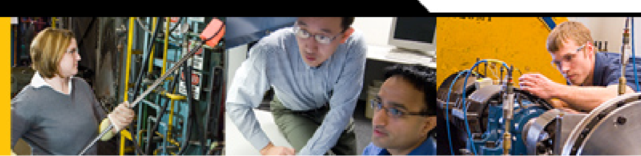

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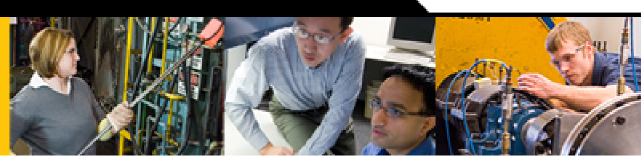

Disclaimer

The work described in this presentation, conducted under the Caterpillar / DOE cooperative research agreement, was conducted by the Technology and Solutions Division (T&SD) of Caterpillar Inc. The cooperative research described in the presentation was done to evaluate proof-of-concept for technologies that meet EPA 2010 on-highway emissions with the potential to improve peak brake thermal efficiency by 10%. Cursory consideration was given to which technologies may have some ability to be commercialized by the engine divisions of Caterpillar which have commercialization responsibility. The process to validate technologies as commercially viable was not in the scope of the program, nor was it undertaken. Commercialization aspects such as cost/benefit analysis, reliability, durability, serviceability and packaging across multiple applications were only considered at a cursory level. Until such analysis is completed,any attempt to imply commercial viability as a result of the material in this presentation is not justified.