Engine System Approach to Exhaust Energy Recovery

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DEER Conference

Outline

- Program Objectives
- Establishing the Baseline
- Technical ‘Recipe’ for Improved WHR
- Summary and Conclusions

Program Objective

- Develop components, technologies, and methods to recover energy normally *exhausted as waste heat* from the engine.
- Improve engine efficiency with:
  - No increase in emissions
  - No reduction in power density
  - Compatible with anticipated aftertreatment
- TARGET – Demonstrate 10% improvement in overall thermal efficiency (OTE).

Focus on technologies that have a strong chance of being brought to production for 2010 and/or TierIV

Caterpillar/DOE EWHR Program Timeline

Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Year 1	Year 2	Year 3	Year 4	Year 5
Applied Research	Exploratory Development	Advanced Development		Engineering Development

Define Roadmap to achieve 10% improvement

Validate roadmap via preliminary component testing

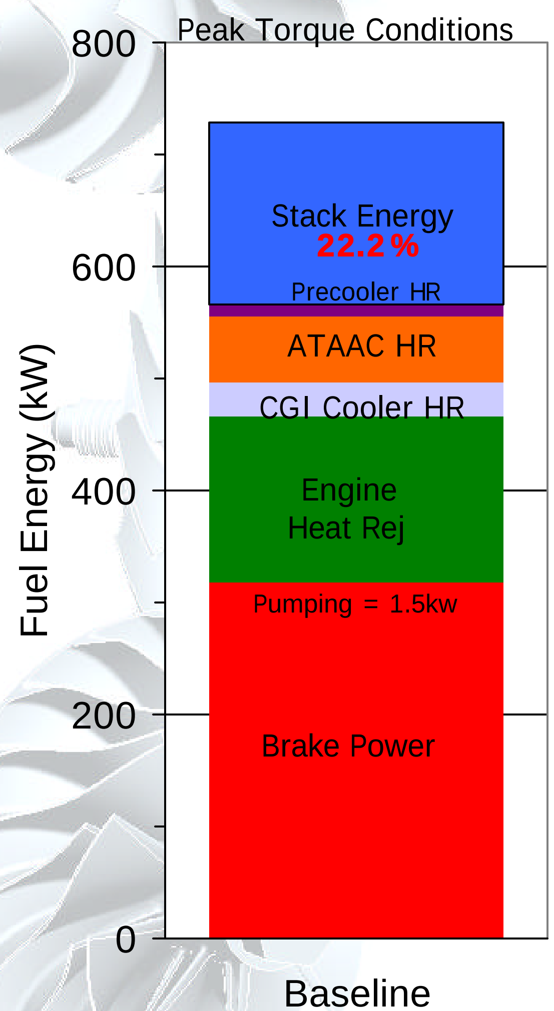
Demonstrate system improvements of 6-10% w/ prototype components

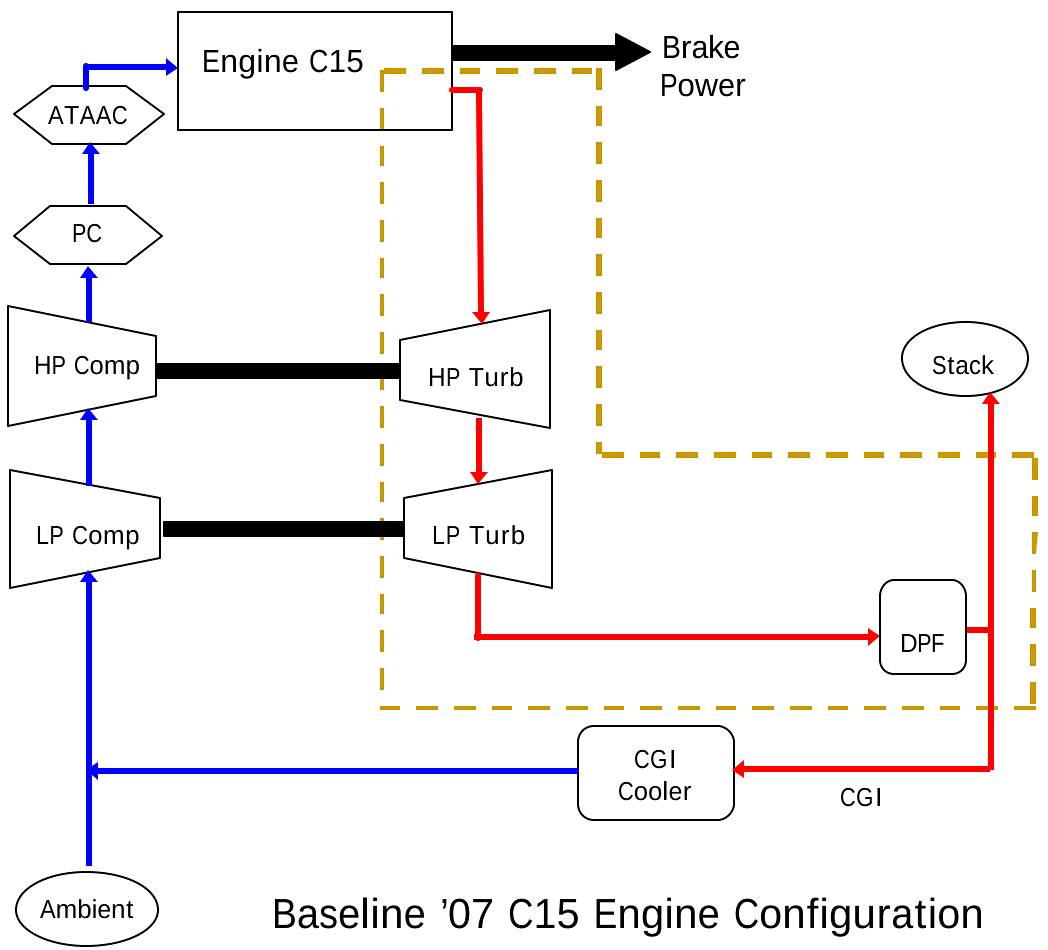
Refine recipe, final component and system design. Analytical demo of 10% improvement

Final component and Engine system Demo

We are here

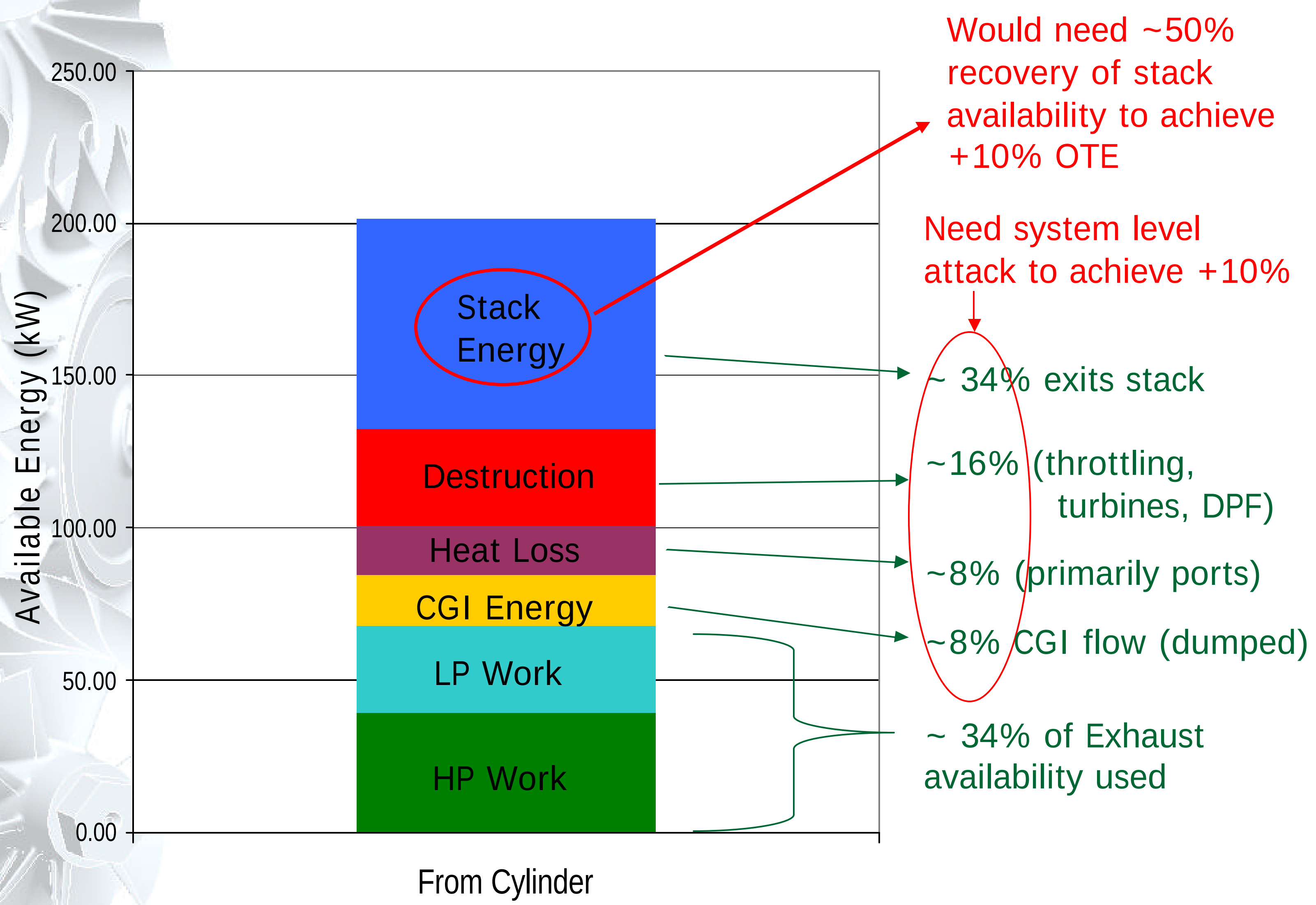
Base Engine Energy Balance



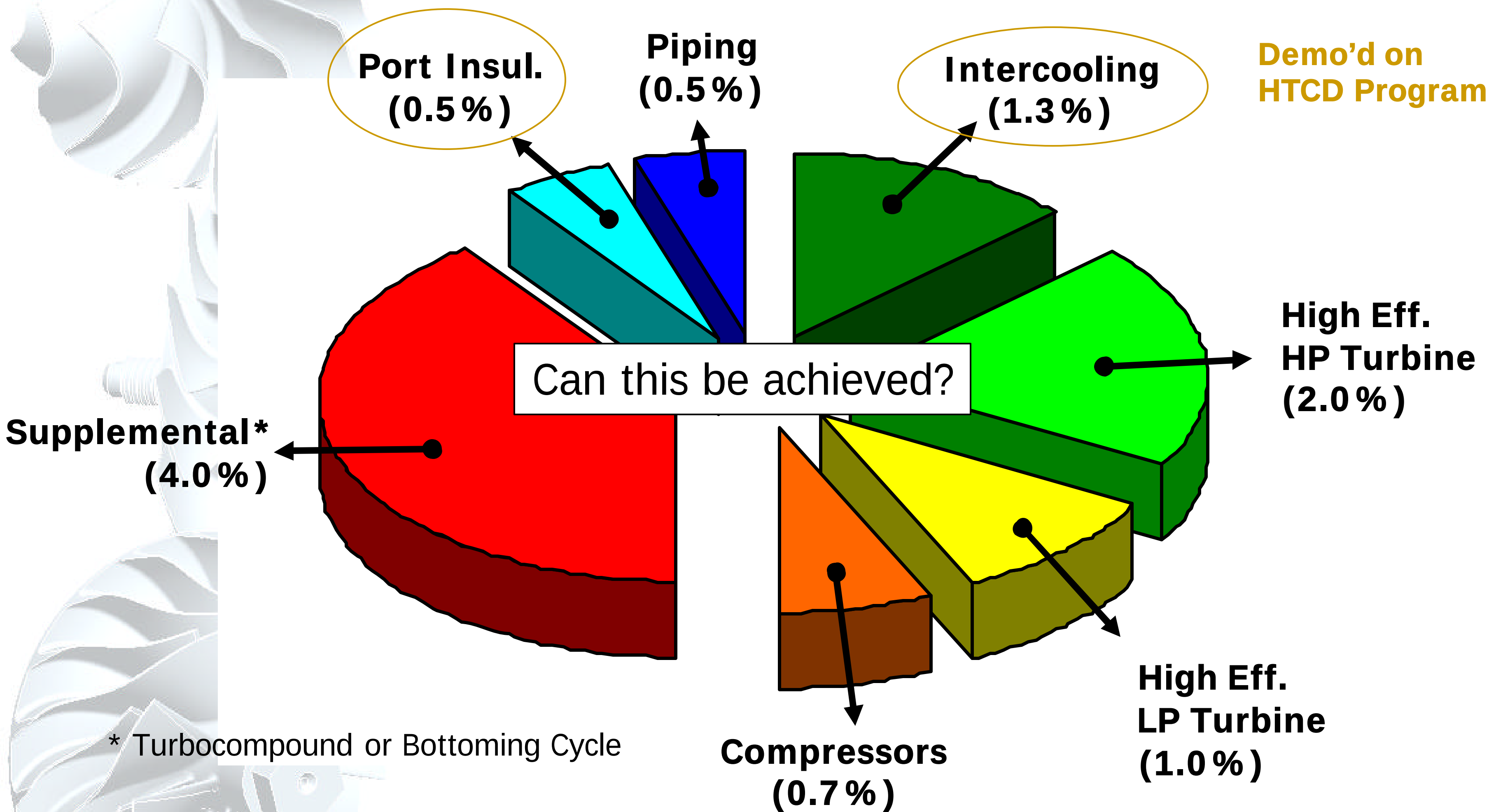


Baseline '07 C15 Engine Configuration

Exhaust Energy and Availability



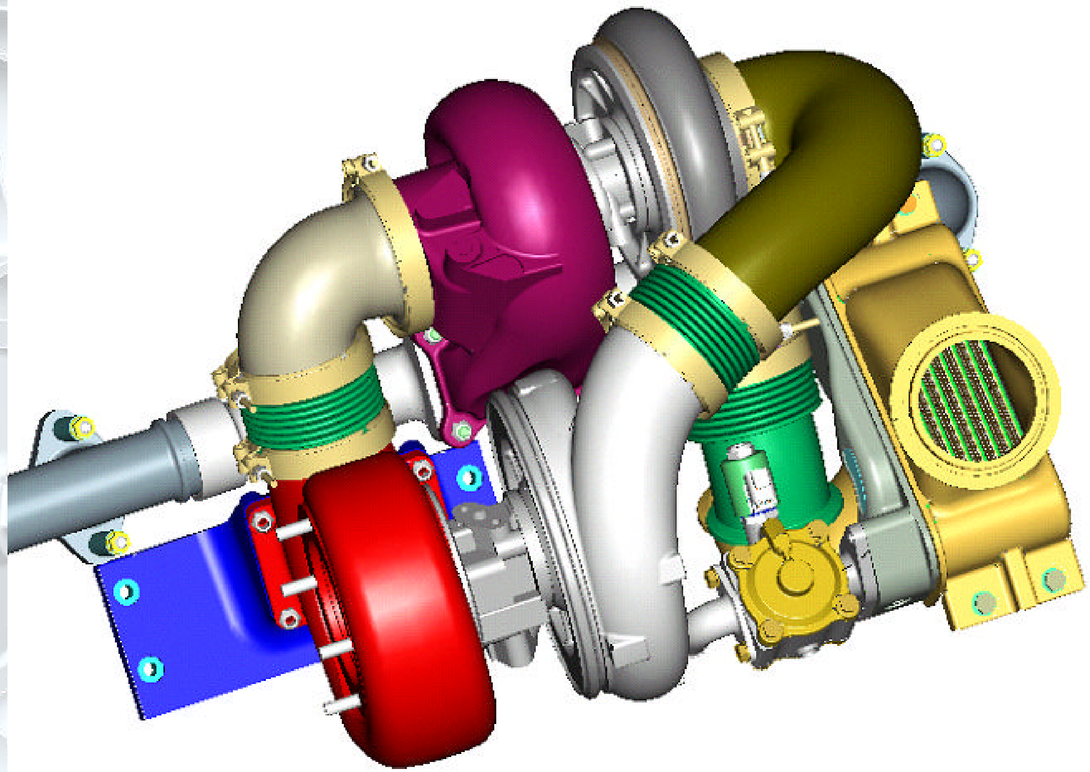
Path to +10% Overall Thermal Efficiency



* Turbocompound or Bottoming Cycle

Baseline is '07 C15 On-Highway

Component Analysis - Piping



Target: +0.5% overall thermal efficiency

- Focus on interstage ducts
  - Lower losses
  - Improved flow distribution
  - Turbines – low exit Mach #

System Integration and optimization of turbocharger component selection

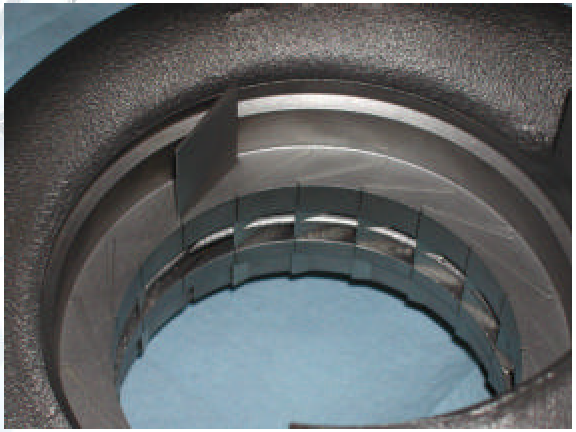
Component Analysis – HP Turbine

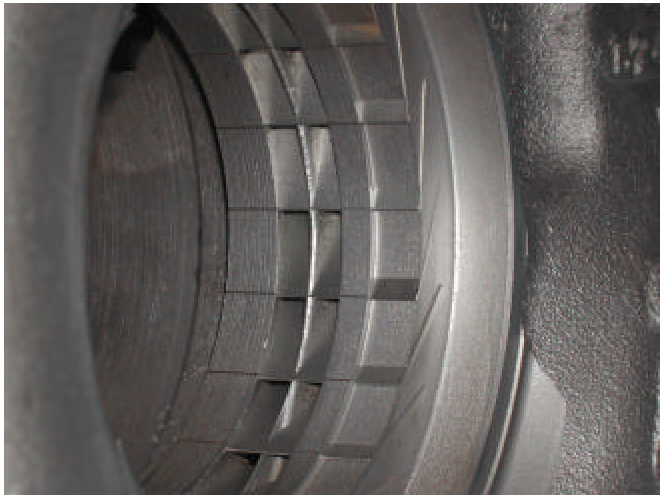
Target: +2.0% overall thermal efficiency

- Translates to ~ +10% turbine stage efficiency improvement

HTCD 50% OTE HP Turbo

- High-efficiency radial wheel – Caterpillar design
- Divided housing for blowdown pulse utilization, engine breathing
- Nozzled inlet for incidence control – *same OD as production HP*
- Parts procured, ready for G.S. test
- +5% T-S vs production predicted ← **Need more!**





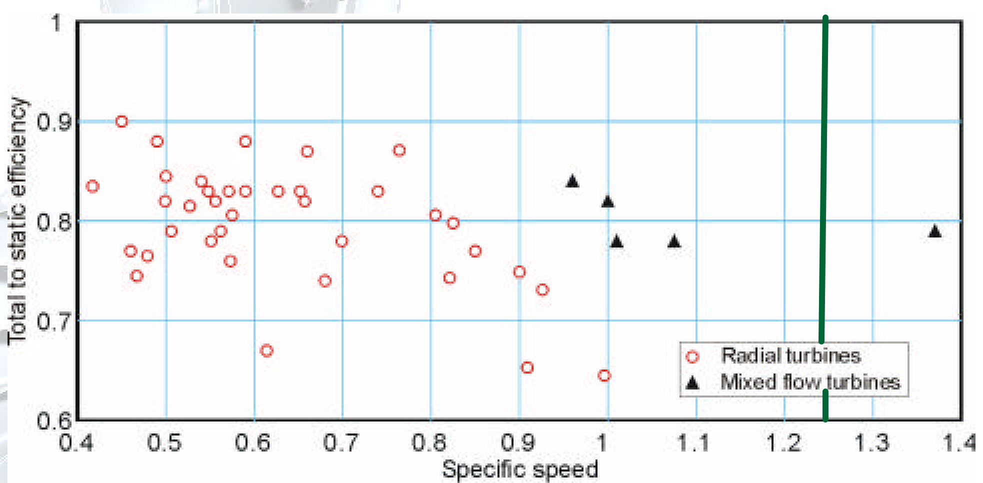
Component Analysis – HP Turbine

Target: +2.0% overall thermal efficiency

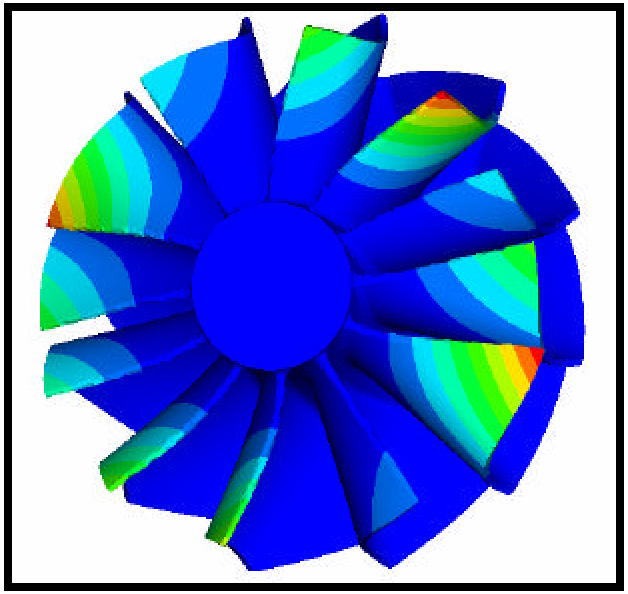
- Translates to ~ +10% turbine stage efficiency improvement

Mixed-Flow Turbine

- High Efficiency at high specific speeds
- Aero design and structural analysis complete
- *same OD as production HP*
- + 3-5% efficiency relative to radial



From Baines, Fundamentals of Turbocharging



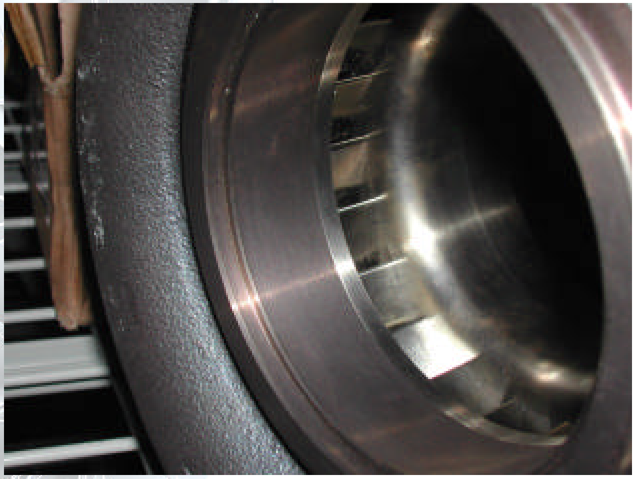
Component Analysis – LP Turbine

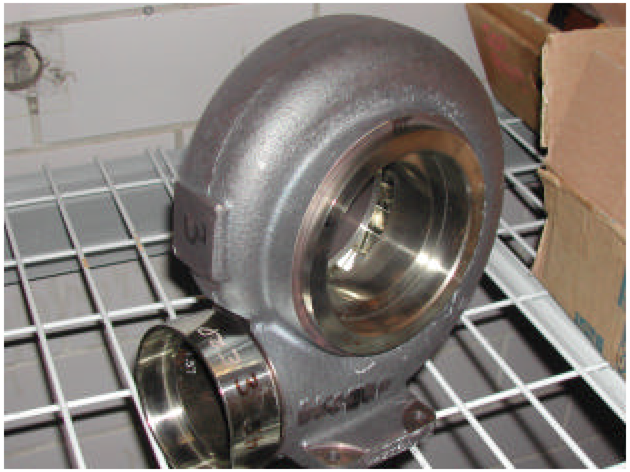
Target: +1.0% overall thermal efficiency

- Translates to ~ +6.5% turbine stage efficiency improvement

HTCD 50% OTE LP Turbine

- High Efficiency radial wheel – Caterpillar design
- Nozzled inlet for incidence control – *same OD as production LP*
- +5% T-S vs production LP ← **Need more!**





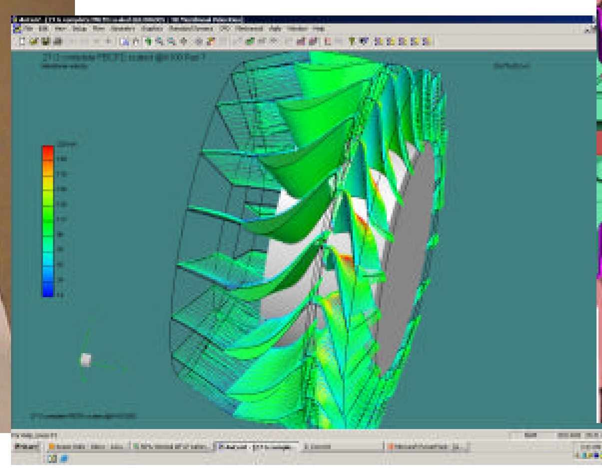
Component Analysis – LP Turbine

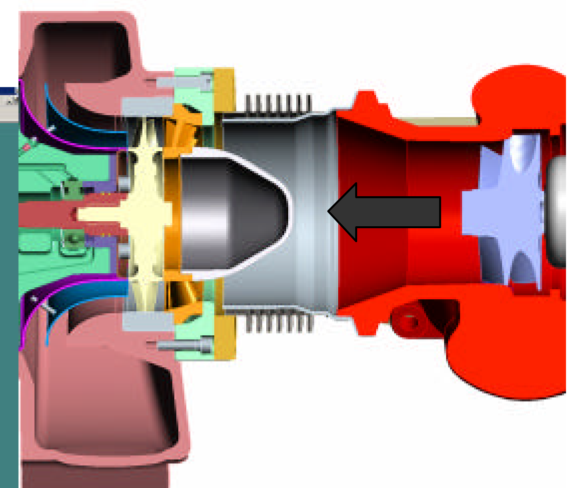
Target: +1.0% overall thermal efficiency

- Translates to ~ +6.5% turbine stage efficiency improvement

Axial Turbine

- High Efficiencies
  - 84-86% T-S efficiencies demo'd on Caterpillar prototypes
- Potential for reducing interstage duct losses
  - Combination of radial HP feeding axial LP





Component Analysis - Compressors

Target: +0.7% overall thermal efficiency

- Translates to ~ +2.5% compressor efficiency improvement

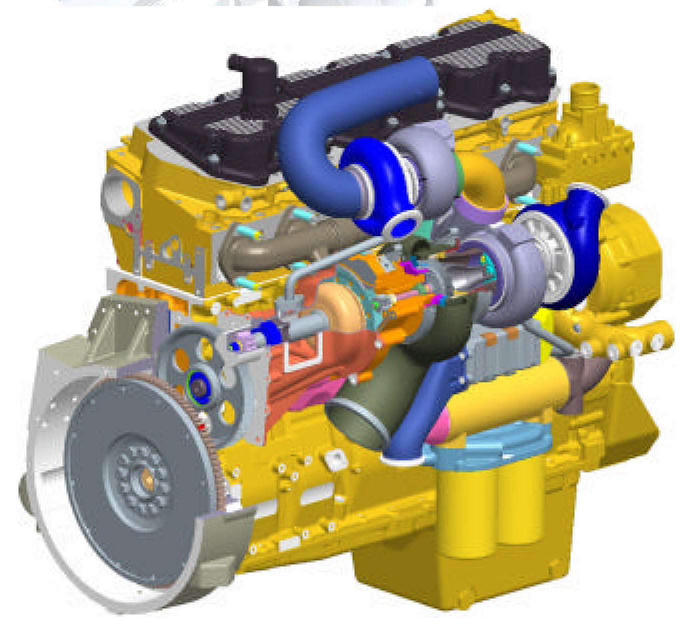
<u>High Efficiency Compressor Design</u>

- Caterpillar design
- High blade backsweep
- Low solidity vaned diffuser
- *Same OD as today's production*
- +2-3% efficiency predicted
- Design/analysis complete, Procurement underway

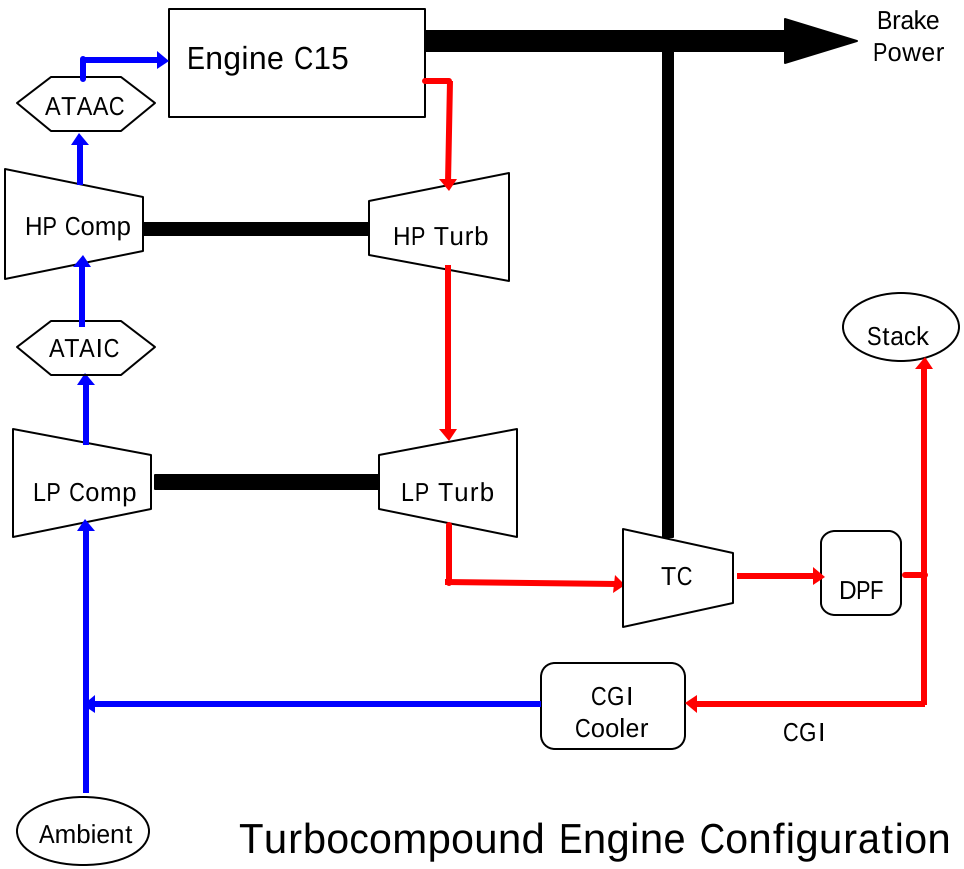
Component Analysis - Turbocompound

Target: +4.0% overall thermal efficiency

Caterpillar Experience



Mechanical
2006 HTCD Program

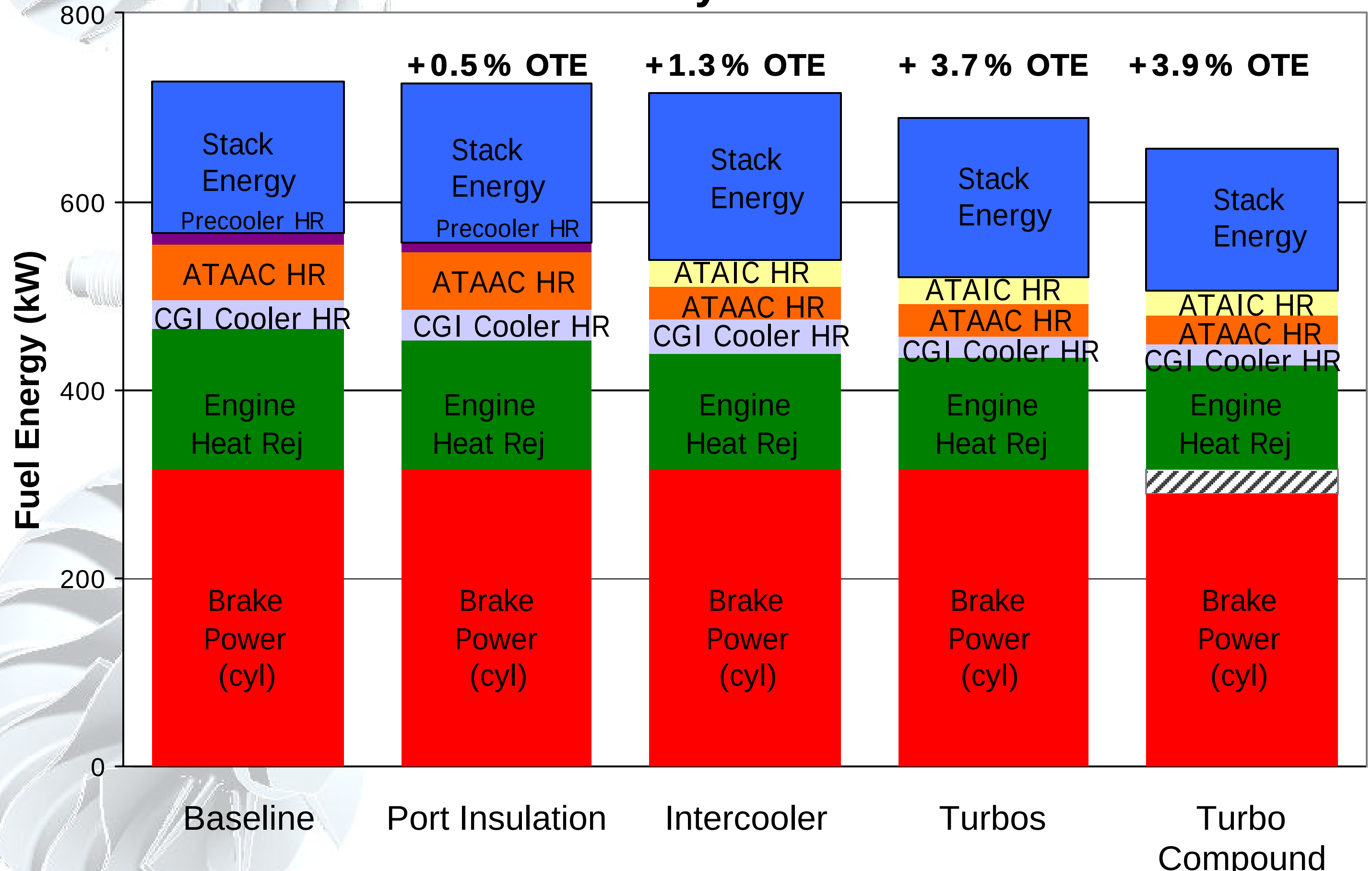


Turbocompound Engine Configuration

Component Analysis - Turbocompound

Target: +4.0% overall thermal efficiency

- **83% efficient compound turbine**
- **93% mechanical efficiency**



+9.1% OTE overall

+0.5% Piping

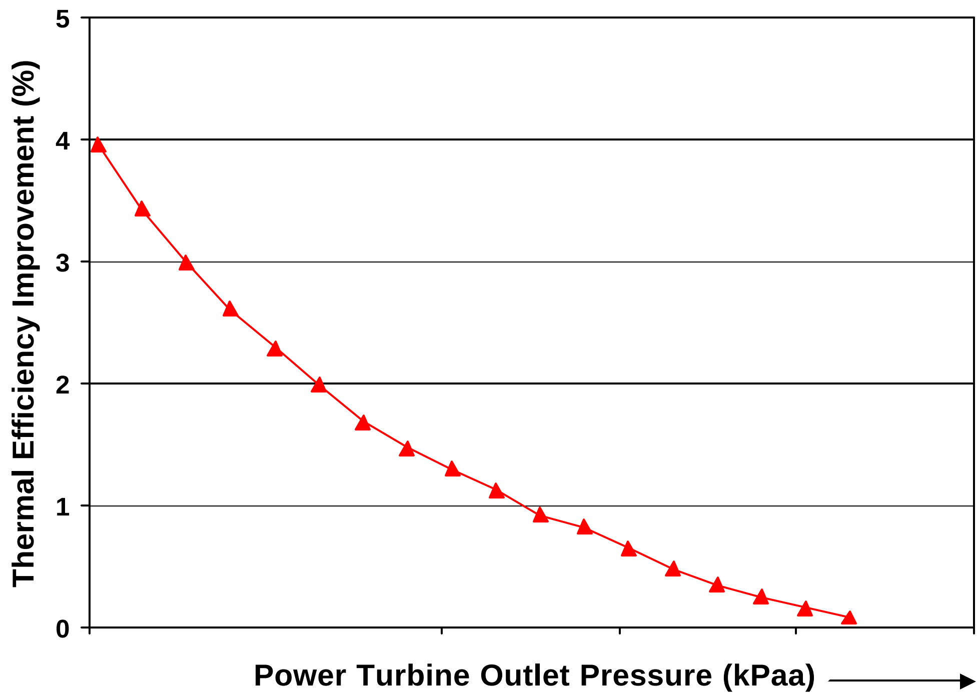
+9.6% OTE overall

BUT……..

Component Analysis - Turbocompound

Target: +4.0% overall thermal efficiency

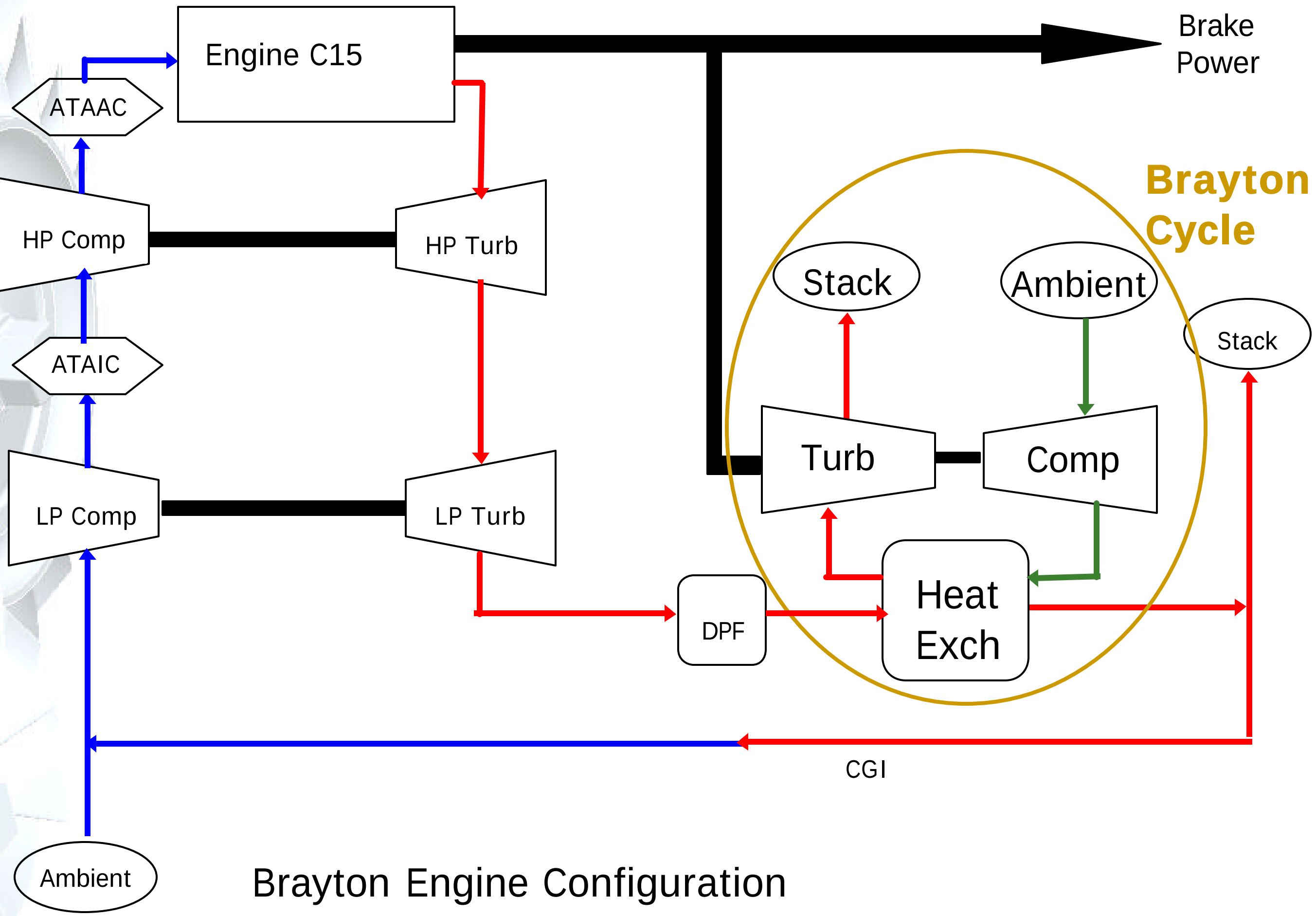
- **Turbocompound benefit highly sensitive to backpressure**
- **Additional 30KPa backpressure cuts benefit by half**



OTE improvement with turbocompound could fall 1-3% short of +10% goal, depending on aftertreatment DP

Component Analysis – Bottoming Cycle

Target: +4.0% overall thermal efficiency



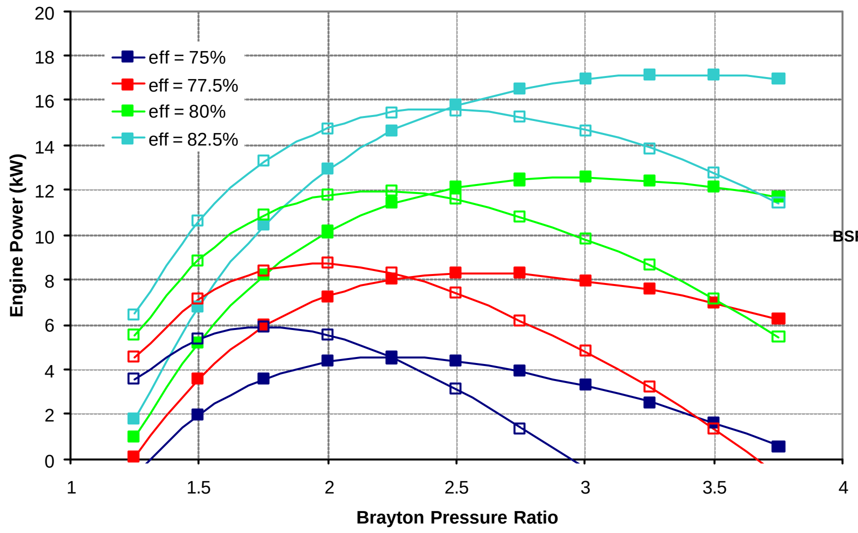
Brayton Engine Configuration

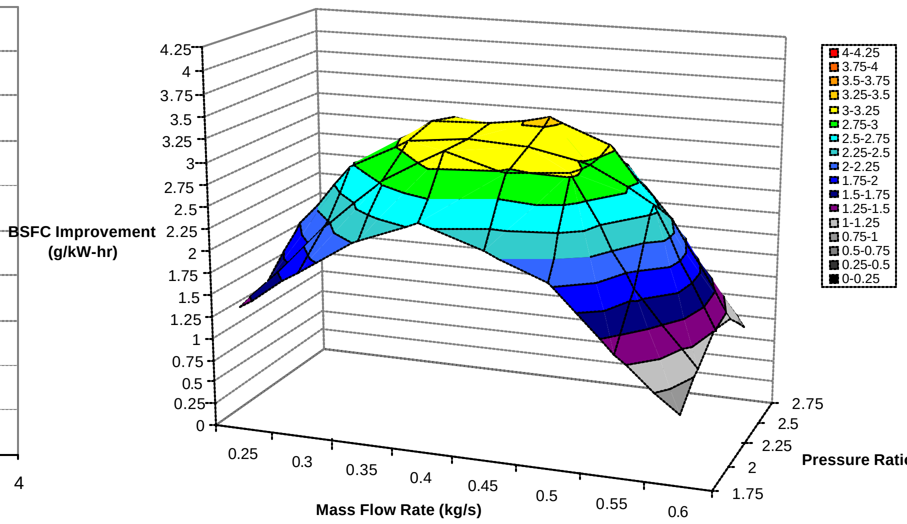
Component Analysis – Brayton Cycle

Target: +4.0% overall thermal efficiency

Brayton Cycle

- **Difficult to achieve high cycle efficiencies at 'low' heat source temps**
- **Highly sensitive to turbo efficiencies, heat exchanger effectiveness, operating conditions**
- **Extensive sensitivity conducted to optimize system**

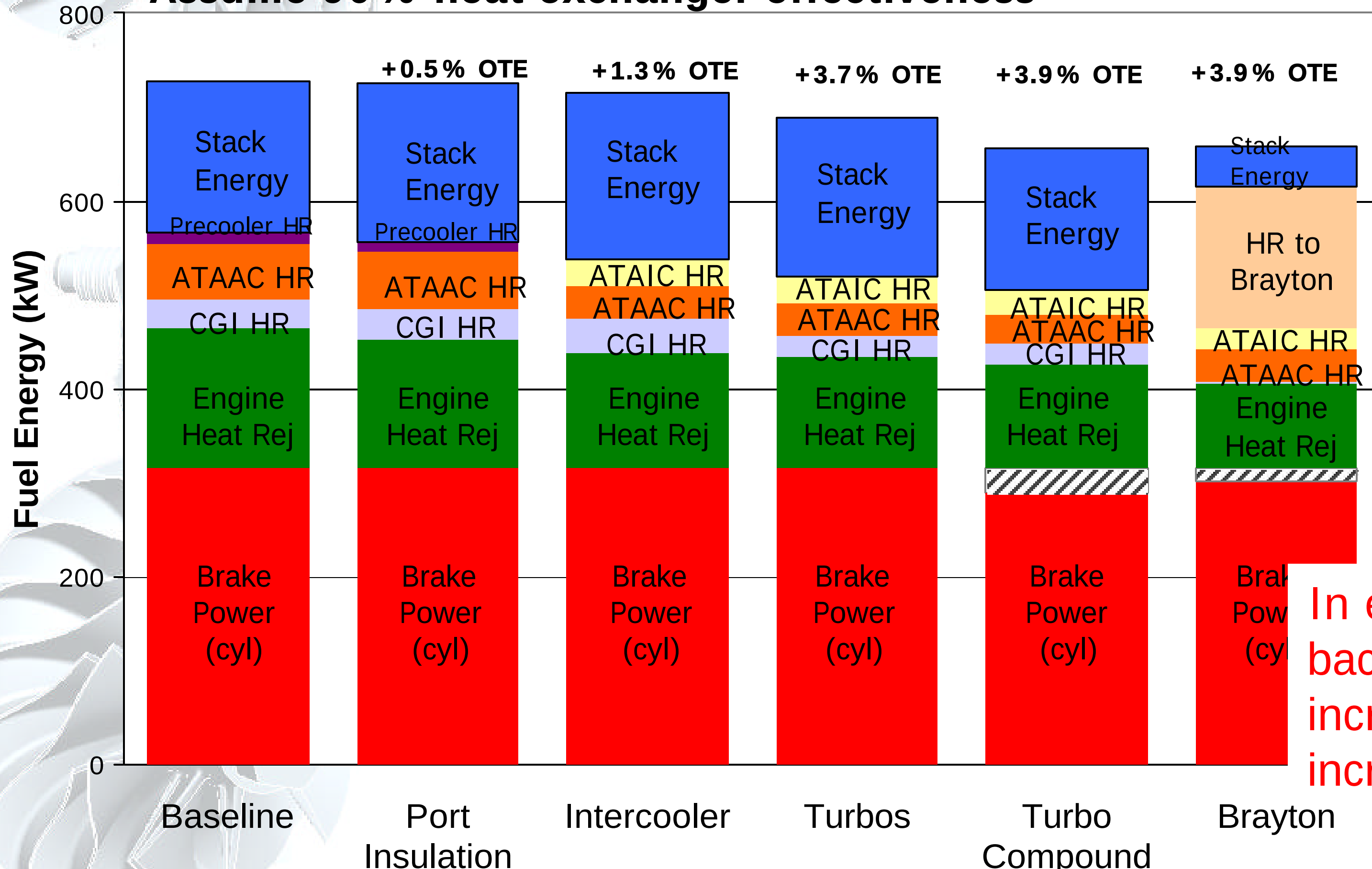




Component Analysis – Brayton Cycle

Target: +4.0% overall thermal efficiency

- **Assume 83% efficient Brayton turbo components**
- **Assume 90% heat exchanger effectiveness**



+9.1% OTE overall

+0.5% Piping

+9.6% OTE overall

In event of +30kPa back pressure, incremental benefit increases to +4.6%

Summary

- Goal of +10% OTE via improved WHR can be achieved
  - Line of sight to 9-10% improvement via analysis
  - Additional system optimization investigations ongoing
- Multiple paths to reach goal
  - Brayton cycle offers most potential
    - Highly sensitive to component performance
    - Must be combined with other technologies (port insulation)
  - Turbocompound similar efficiency benefit as Brayton
    - Highly sensitive to backpressure
    - Offers additional benefit of response improvement, especially ETC

Acknowledgements

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  - Ralph Nine