An Engine System Approach to Exhaust Waste Heat Recovery

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

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.

AGENDA

- EWHR Program Objectives, Timeline, Scope
- Technical Developments
- Summary and Conclusions

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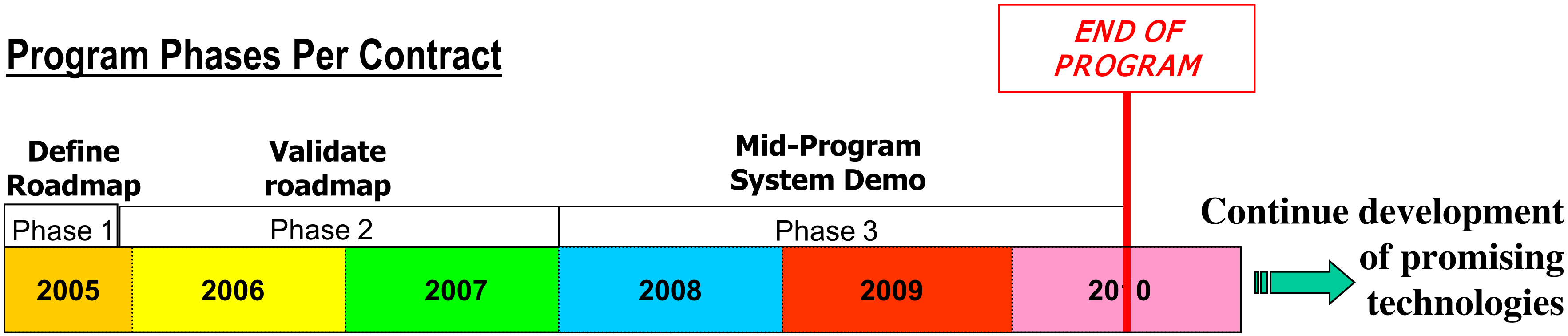
Program Objective

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 rate
- No reduction in power density
- Compatible with anticipated aftertreatment

Program Timeline

Program Phases Per Contract

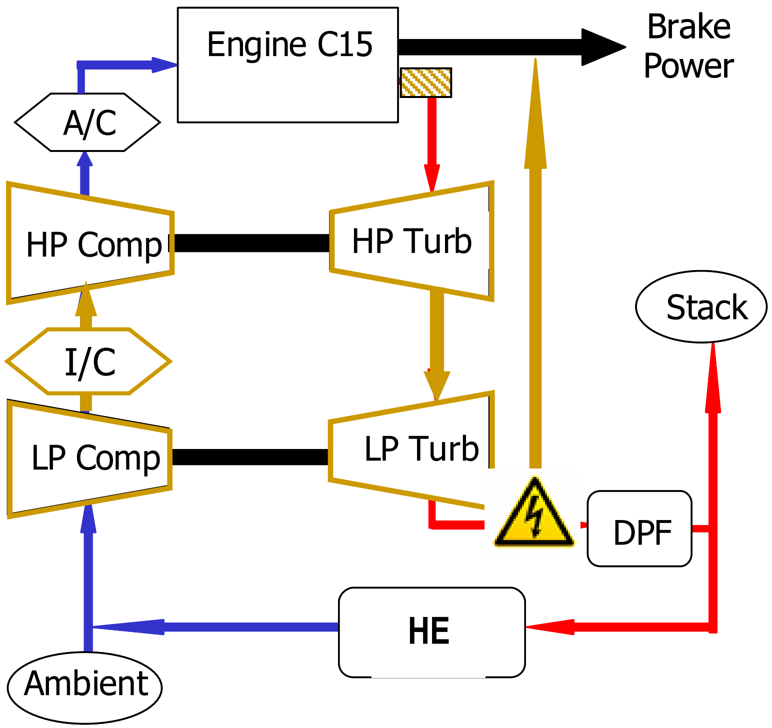


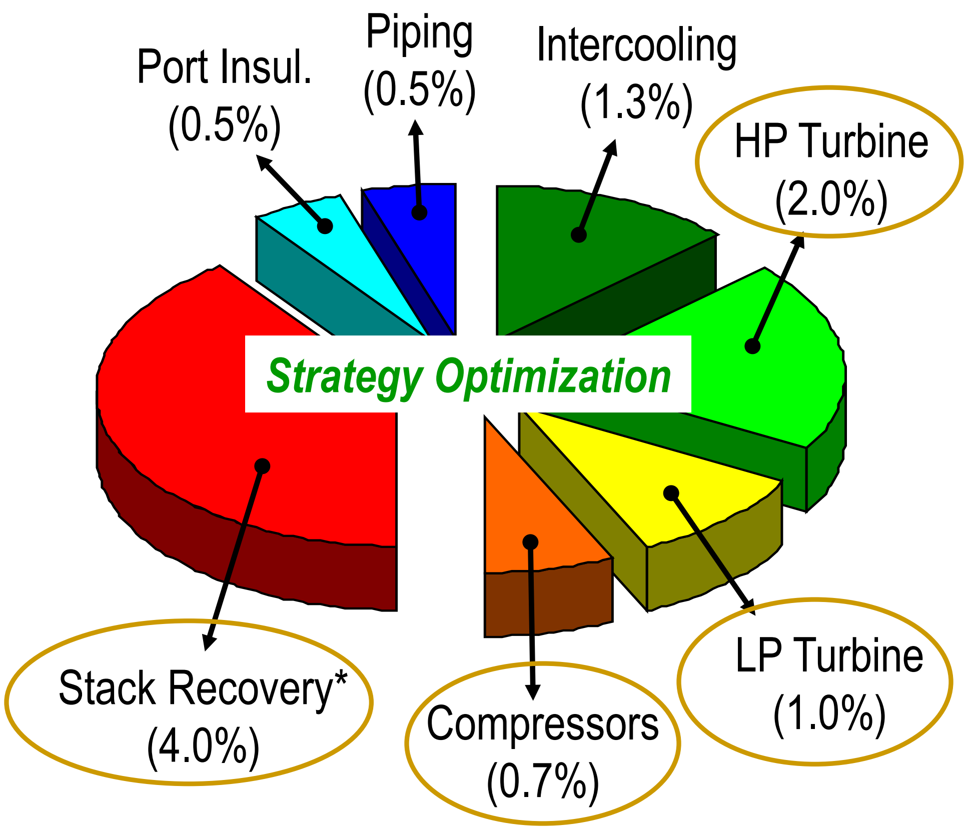
- Originally planned as a 5 Phase Program
- Truncated to 3 Phases – migration to Supertruck
- Final program report
  - Technologies developed
  - Key results & lessons learned

Approach

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

An integrated system solution to waste heat recovery





Baseline C15
15.2L On-Highway Truck Engine
LPL (low pressure loop) configuration

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

Program Philosophy

- **“System” Solution**
  - Modular; “Best” elements can be carried to production
- **Production-Viable Technologies**
  - Cost, Packaging, Manufacturing
- **Broad Emissions Architecture Applicability**
  - Viable for HPL, LPL, or non-EGR solutions
  - Compatible w/ Aftertreatment

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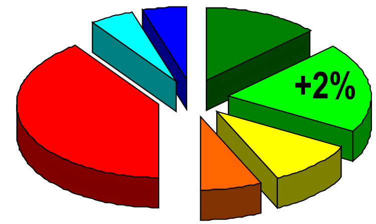
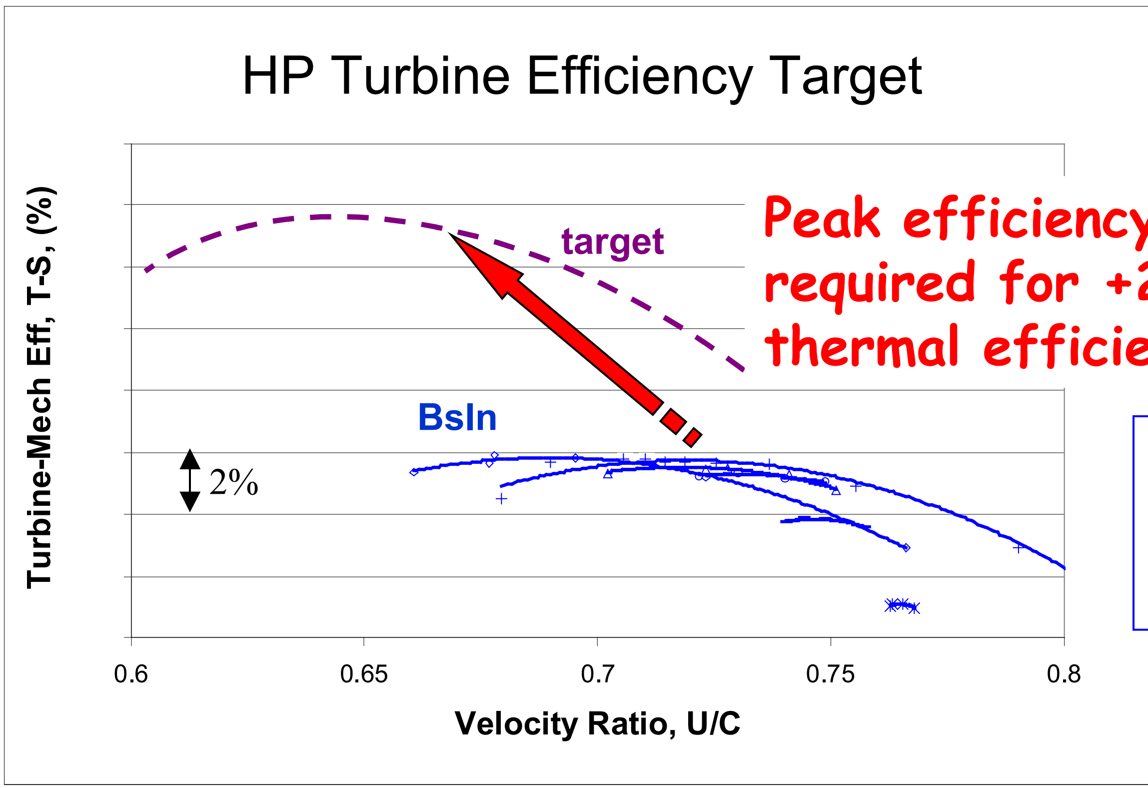
Technical Progress – HP Turbine



Target: + 2% Engine Thermal Efficiency:

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

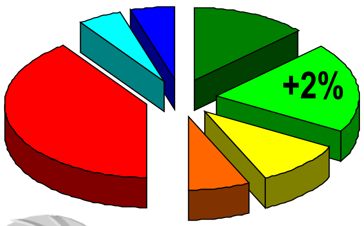


Peak efficiency shift required for +2% engine thermal efficiency

Technologies

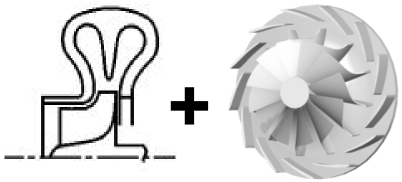
- RND turbine
- Mixed Flow turbine

Technical Progress – HP Turbine

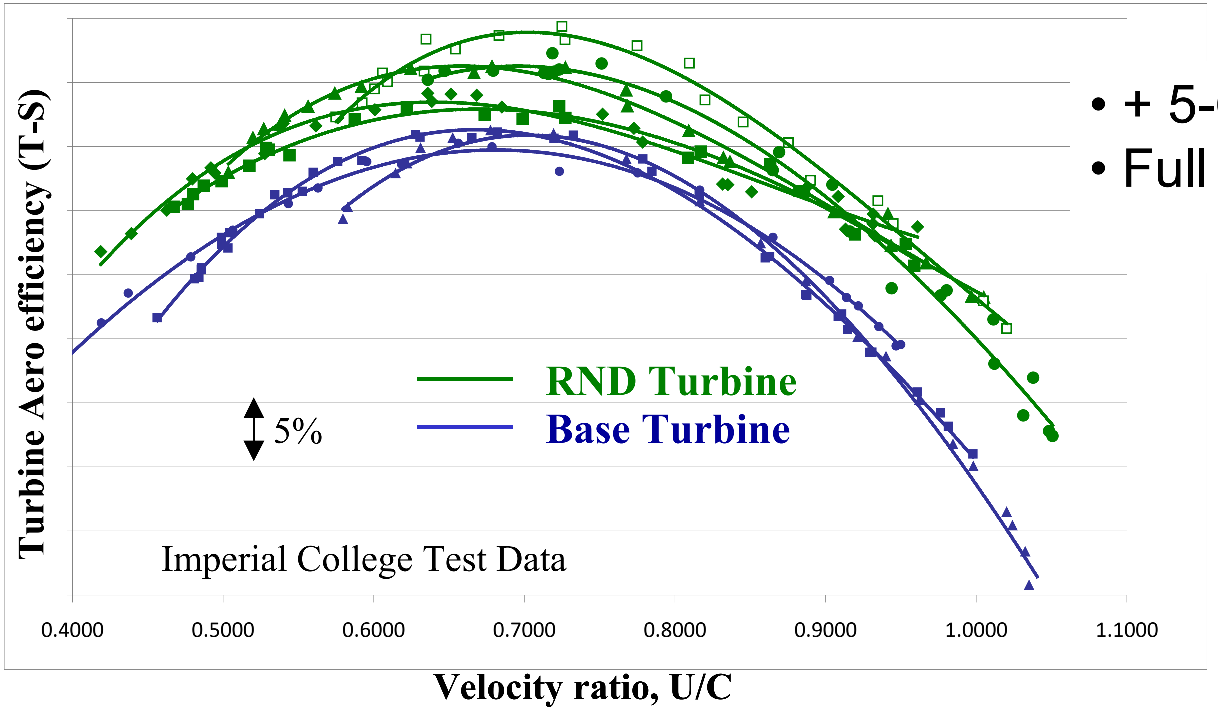


Technology 1 – Radial, Nozzled, Divided (RND) Turbine

- High efficiency turbine wheel
- Nozzled and divided turbine housing

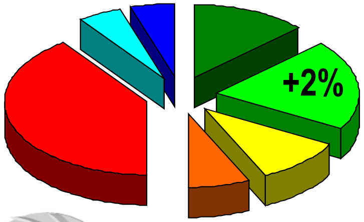


Gas Stand Test Results



- + 5-6% turbine efficiency
- Full map width benefits

Technical Progress – HP Turbine



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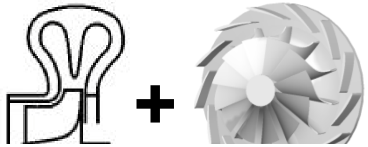
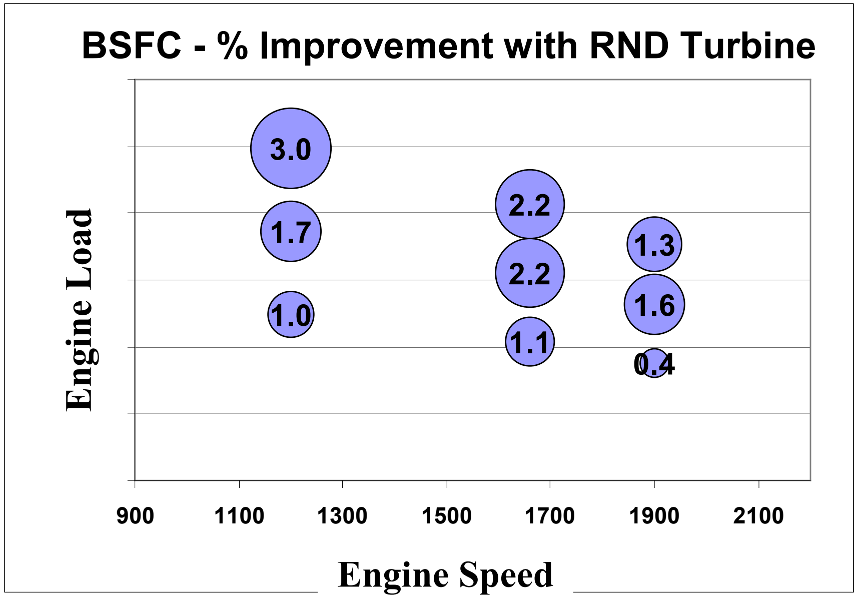
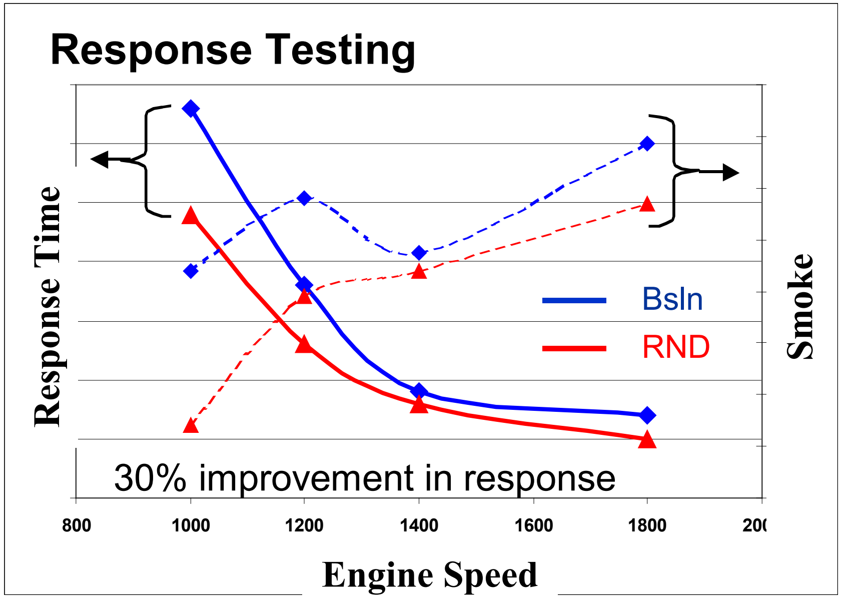


On-Engine Test Results: Single-stage turbo HPL EGR engine

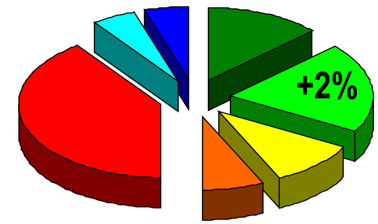




Durability testing underway

- Successful completion of nozzle ring thermal cycle test

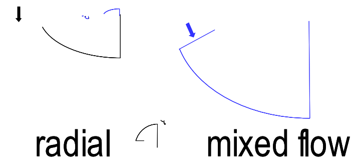
Technical Progress – HP Turbine

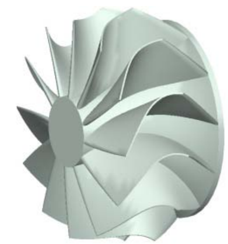


Technology 2 – Mixed Flow Turbine

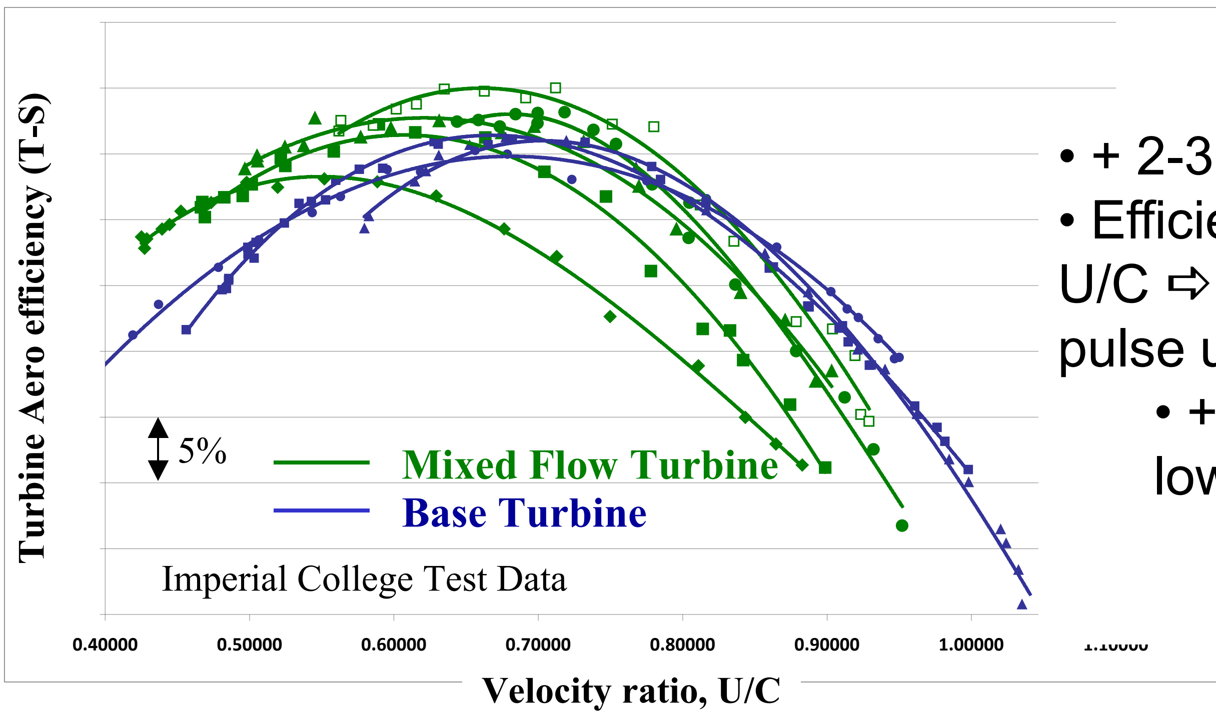
- Nozzle-less, divided volute

first-pass



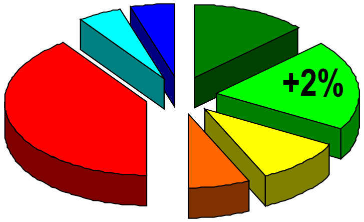


Gas Stand Test Results



- + 2-3% turbine efficiency
- Efficiency peak at lower U/C ⇨ improved exhaust pulse utilization
  - + 5-6% efficiency at lower U/C

Technical Progress – HP Turbine



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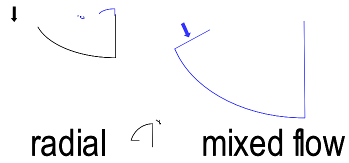
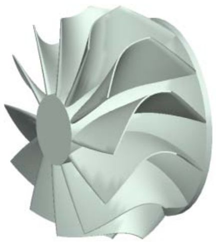
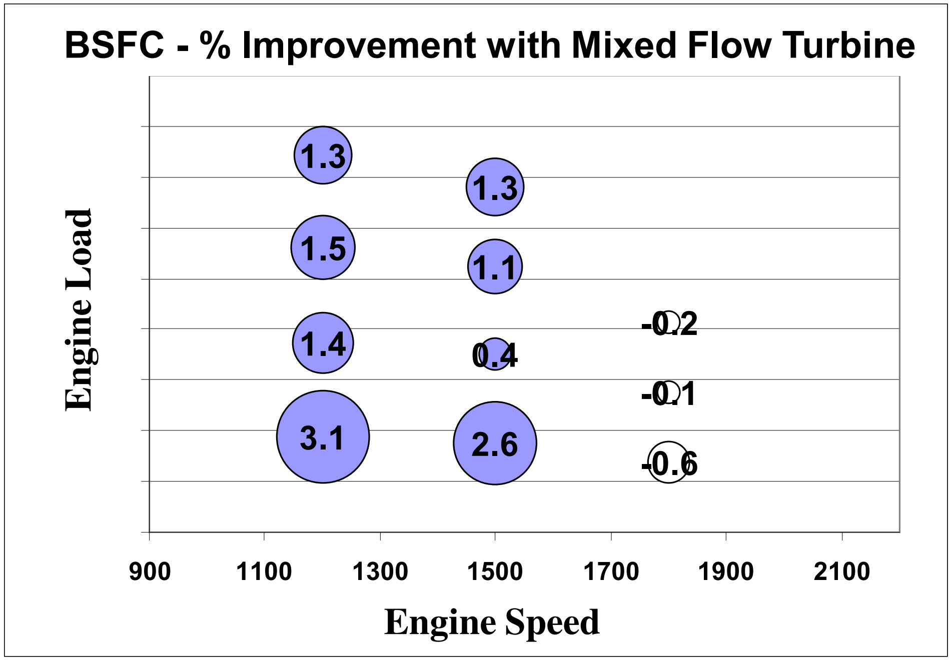




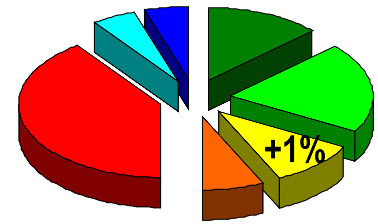
On-Engine Test Results: Series turbo LPL EGR engine



- 1 to 1.5% fuel economy benefit at low and mid speed range where exhaust pulse energy is significant

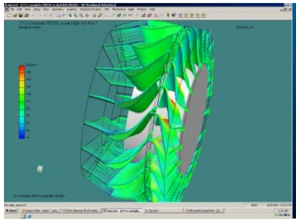
Development of mixed-flow, nozzled, divided turbine is underway

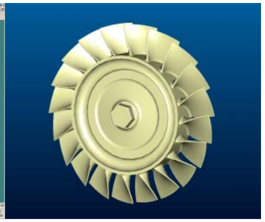
Technical Progress – LP Turbine



Target: + 1% Engine Thermal Efficiency:

- + 6% Turbine Stage Efficiency





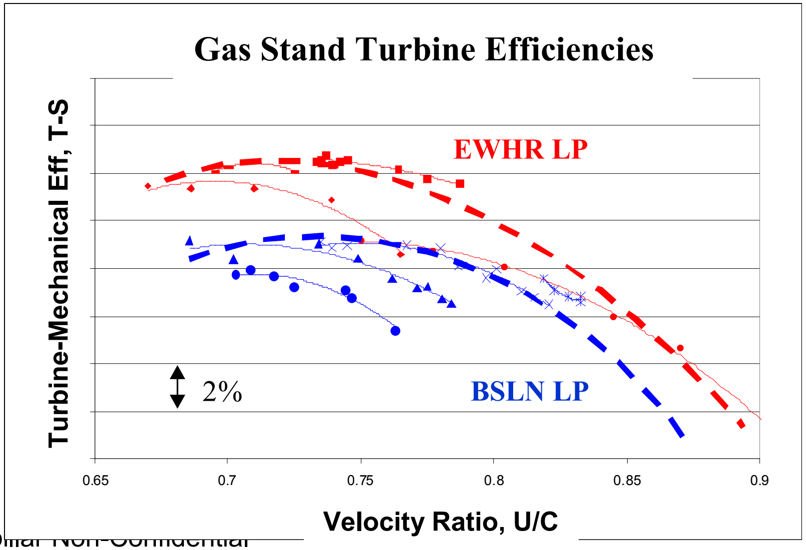
Technology 1 – High Efficiency Axial Turbine

- +6% turbine efficiency verified – analysis, test
- Packaging concerns w/ series turbos

Technology 2 – High Efficiency, Nozzled, Radial Turbine

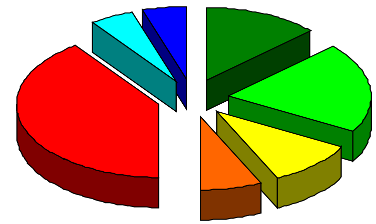
- Minimal impact on response – design freedom

Gas Stand Test Results



- + 4% peak turbine efficiency

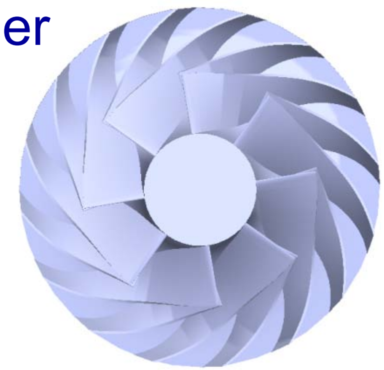
Technical Progress – Compressors



Target: + 0.7% Engine Thermal Efficiency:

- + 2.5% Compressor Stage Efficiencies

HP Technology – Highly backswept wheel w/ vaned diffuser



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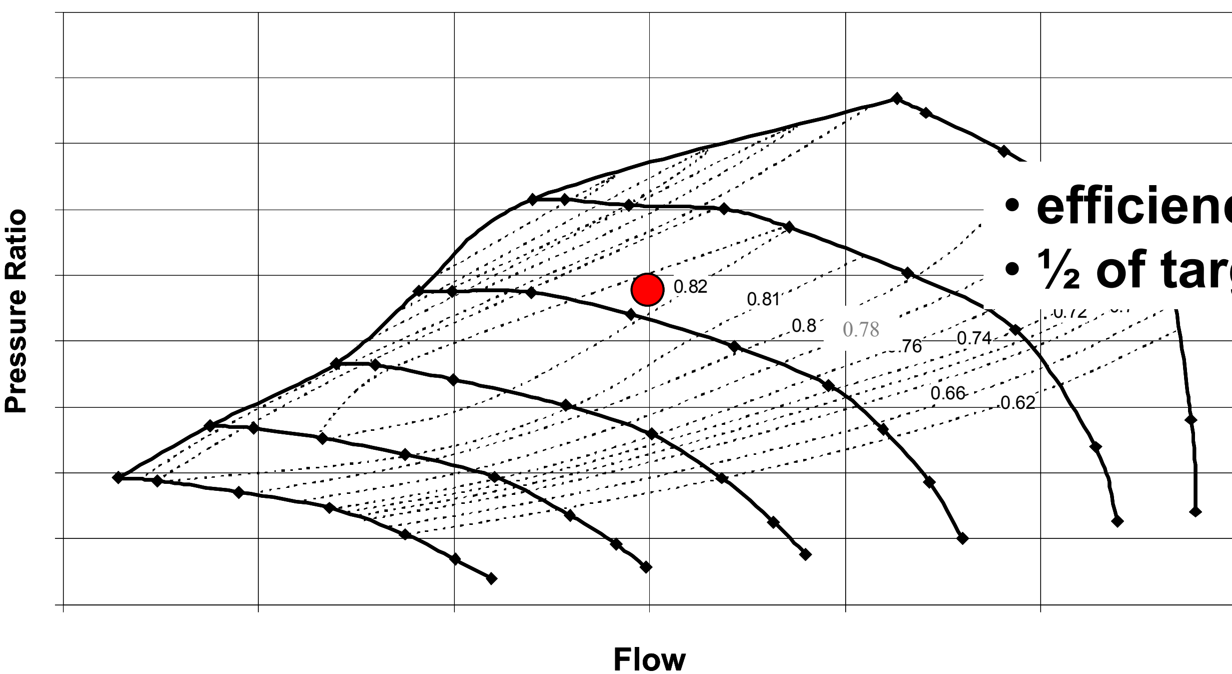
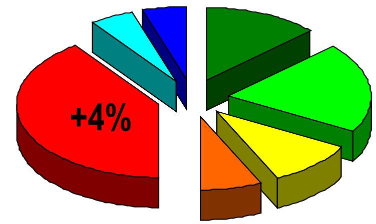


- efficiency 1-1.5% > production
- ½ of target achieved

Technical Progress – Stack Recovery

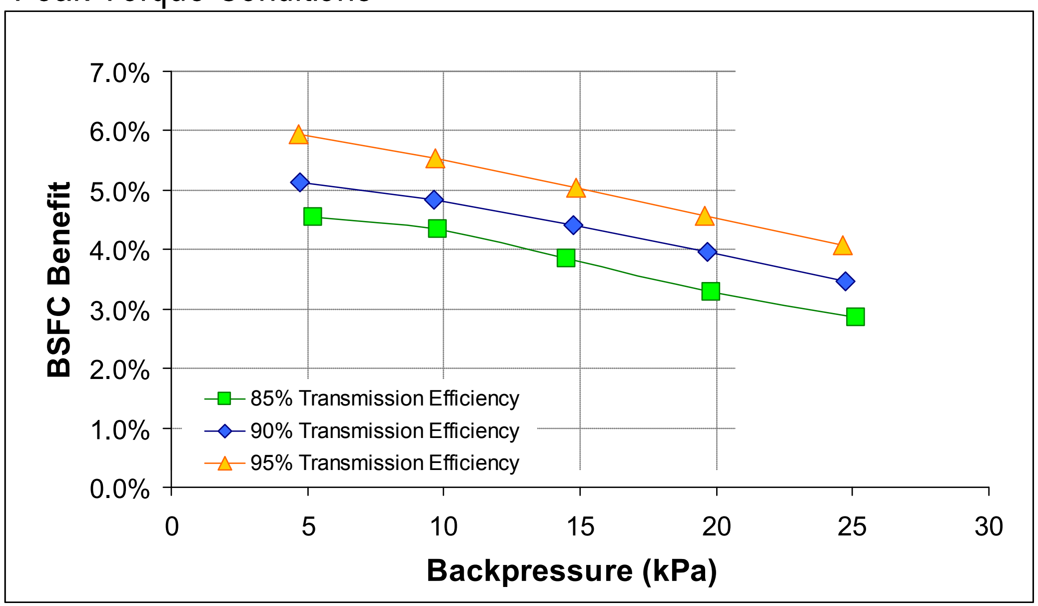


Target: + 4% Engine Thermal Efficiency

- Stack recovery on baseline LPL engine
- Turbocompound downselected
    - Brayton Cycle investigated – packaging challenges

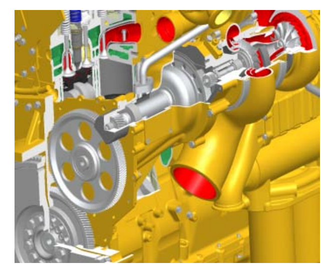
Engine Simulation Results

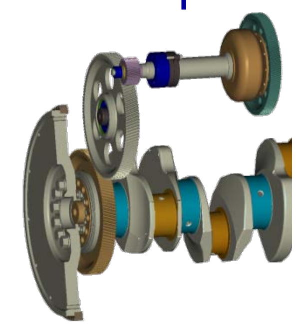
Peak Torque Conditions



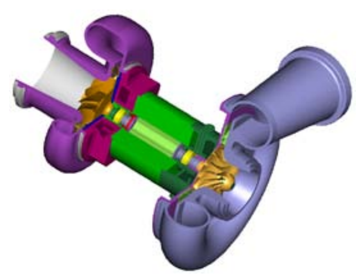
Technologies

- Mechanical Turbocompound

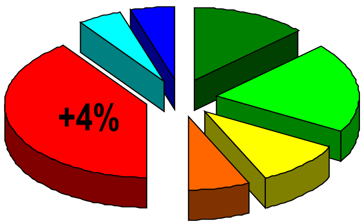




- Electrical Turbocompound



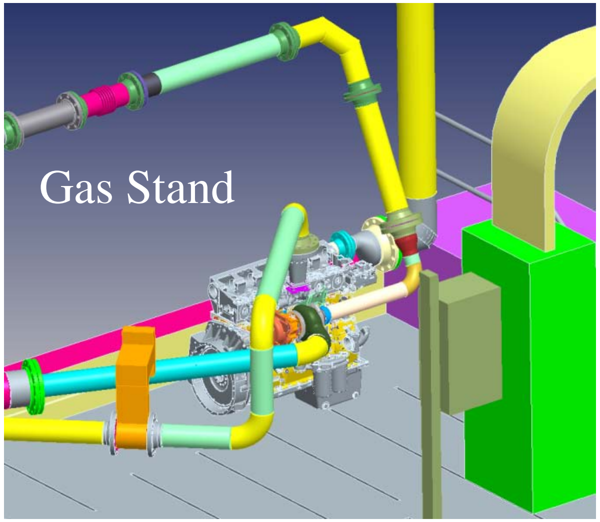
Technical Progress – Stack Recovery



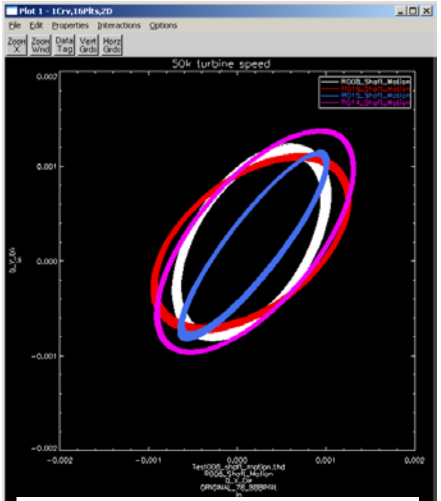
Target: + 4% Engine Thermal Efficiency

- Stack recovery on baseline LPL engine

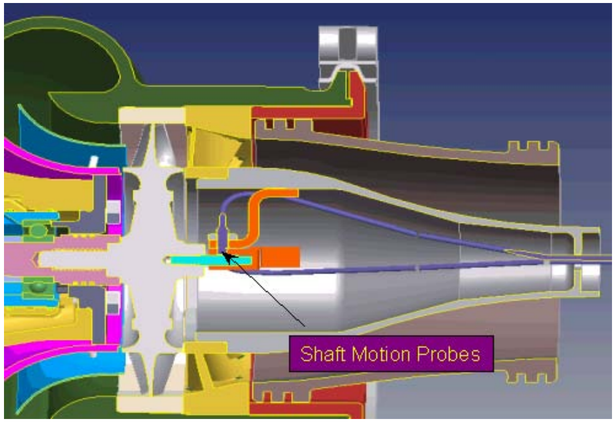
Technology 1 – Mechanical Turbocompound



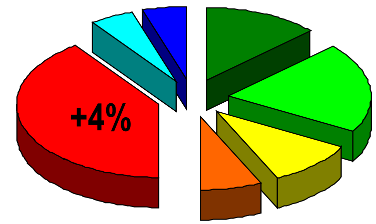
- Robust, high-efficiency bearing is challenge
- Developed power turbine gas stand test method
  - Detailed shaft motion measurements
- Test Conditions
  - 5 bearing systems
  - Speeds from 25-60krpm
- Gas Stand Test Results
  - < 0.002" shaft motion
  - 80-84% aero efficiency



Shaft Motion Results



Technical Progress – Stack Recovery

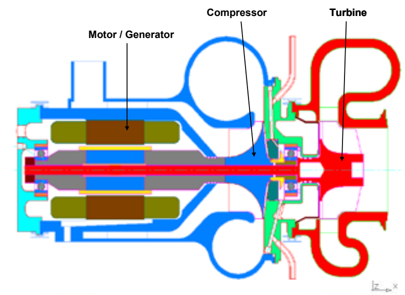


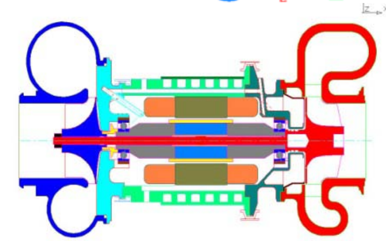
Target: + 4% Engine Thermal Efficiency

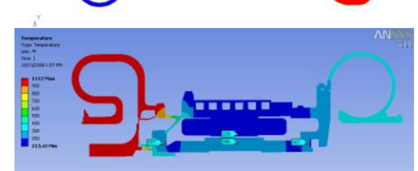
- Stack recovery on baseline LPL engine

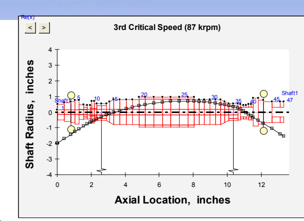
Technology 2 – Electrical Turbocompound

- Two concept designs developed / analyzed
  - Concept 1: Generator in front of compressor
    - Rotordynamic / packaging challenges
  - Concept 2: Generator between wheels
    - Thermal management challenges
- Concept 2 analysis results
  - Generator efficiencies > 96%
  - Peak rotor stress acceptable
  - Peak stator temperature acceptable
  - Peak magnet temperature acceptable
  - Bending critical speed acceptable



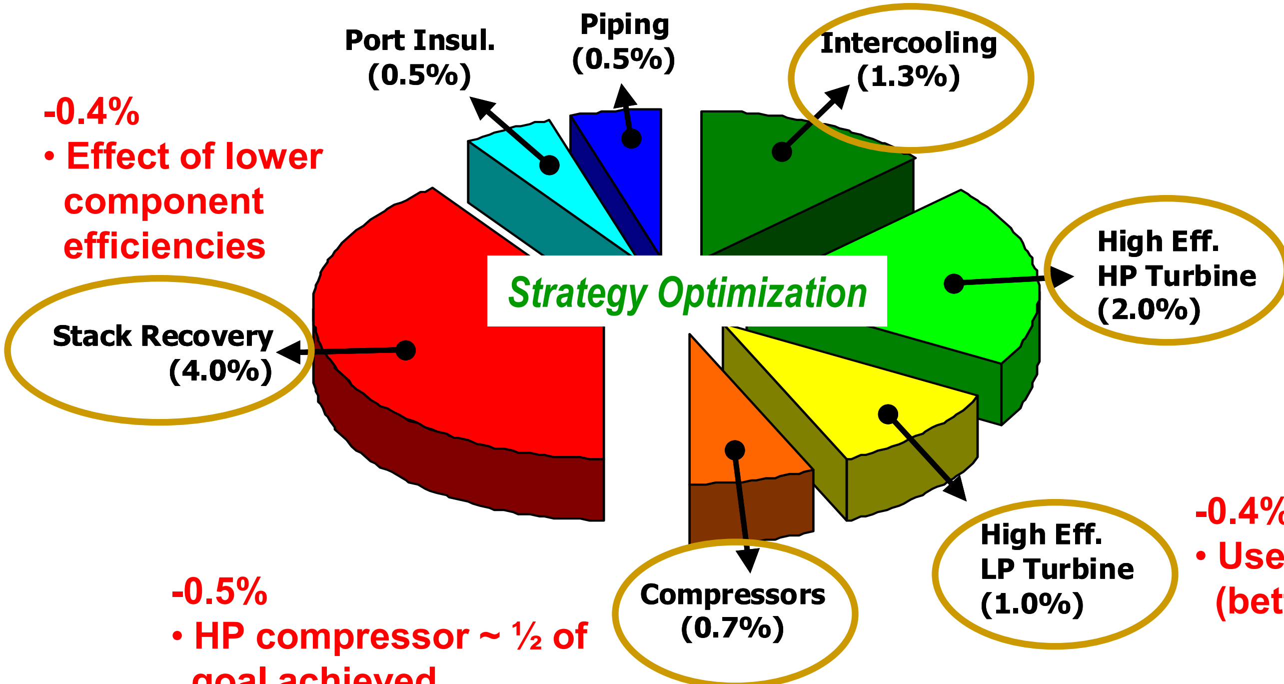






Development Ongoing: TSB-Funded Program

Summary



-0.4%
- Effect of lower component efficiencies

-0.7%
- Used RND turbine
- Mixed Flow ND will improve

-0.4%
- Used radial turbine map (better packaging vs axial)

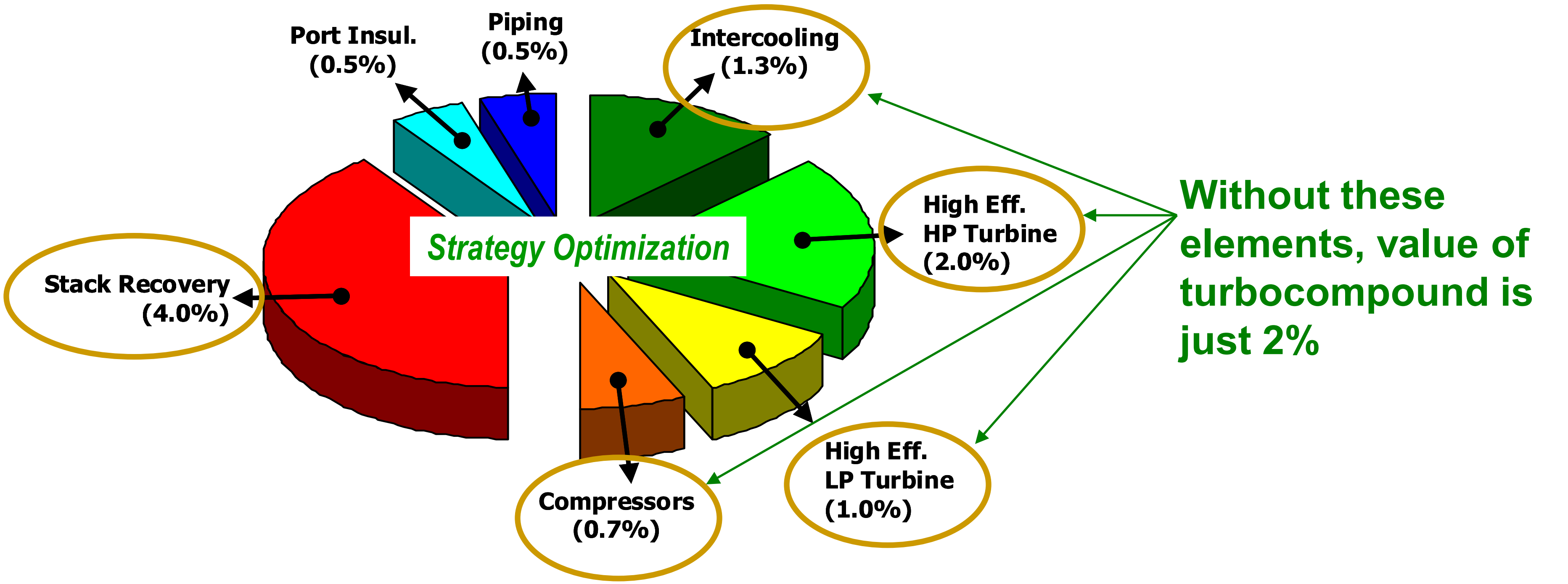
-0.5%
- HP compressor ~ ½ of goal achieved
- No change yet to LP compressor

<u>"Mid-Program" Proof-of-Concept Demo*</u>	<u>Thermal Eff. Improvement</u>
Design point demo - target:	+9.0%
Design point demo - achieved:	+7.0%

"Virtual" Demo: Engine Simulation using measured component performance maps

*Not commercially validated

Summary



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Acknowledgements

Caterpillar Thanks:

Barber-Nichols Inc.	Electric turbocompound design consulting
ConceptsNREC	Turbomachinery design consulting & optimization.
Honeywell	Turbomachinery design consulting, component procurement and integration.
Imperial College	Gas stand testing of advanced turbomachinery components
Oak Ridge National Lab	On-engine testing of advanced turbomachinery components
Turbo Solutions	Turbomachinery design consulting & optimization.

Acknowledgements

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  - **Gurpreet Singh**
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