Diesel Engine Waste Heat Recovery Utilizing Electric Turbocompound Technology

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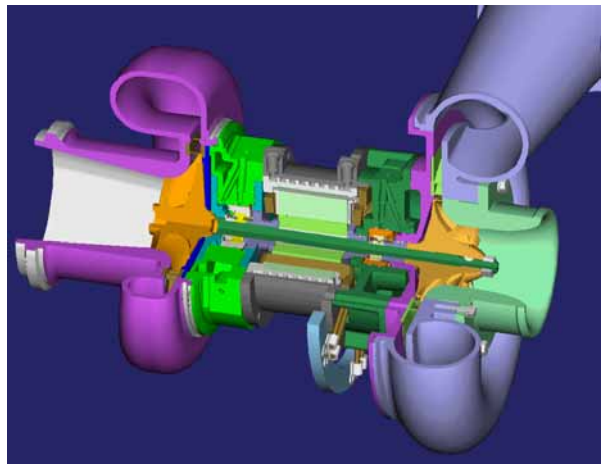
Agenda

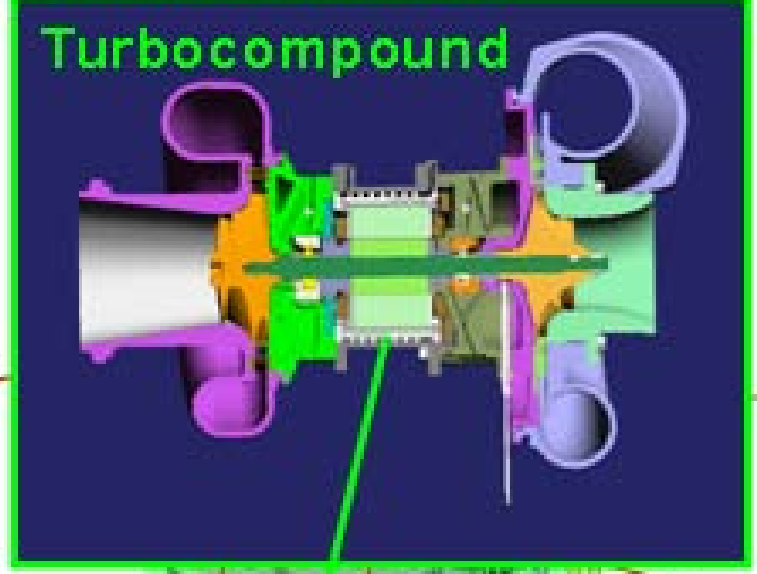
- Program Objectives and Electric Turbocompound (ETC)
  - System Background
- Update on Component Developments
  - Turbo-shaft generator and crankshaft motor
  - Air handling system
  - Control system
  - Component testing
- Cost/Value Study
- Next Steps and Summary

Diesel Electric Turbocompounding (ETC)

- **Primary Objectives:**
  - Demonstrate technical feasibility
  - Improve fuel economy



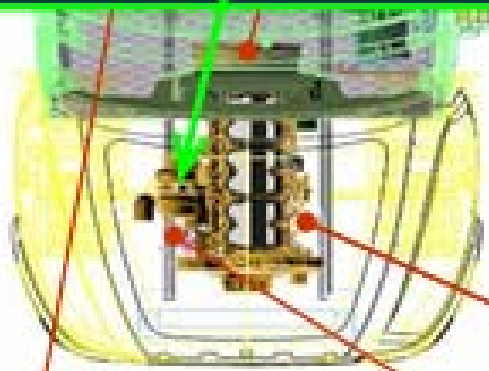
- **Program Goals and Milestones:**
  - Conceive and design optimum ETC system
  - Develop and bench test turbomachinery
  - Develop control system and strategy
  - Rig test ETC hardware
  - Lab engine test of ETC system



Modular HVAC
Variable speed compressor more efficient and serviceable
3X more reliable compressor no belts, no valves, no hoses leakproof refrigerant lines instant electric heat

Starter Generator Motor
Beltless engine product differentiation improve systems design flexibility more efficient & reliable accessories

Shore Power and Inverter
Supplies DC Bus Voltage from 120/240 Vac 50/60 Hz Input Supplies 120 Vac outlets from battery or generator power



Auxiliary Power Unit
Supplies DC Bus Voltage when engine is not running - fulfills hotel loads without idling main engine overnight

Down Converter
Supplies 12 V Battery from DC Bus

Compressed Air Module
Supplies compressed air for brakes and ride control

Electric Water Pump
Higher reliability variable speed faster warm-up less white smoke lower cold weather emissions

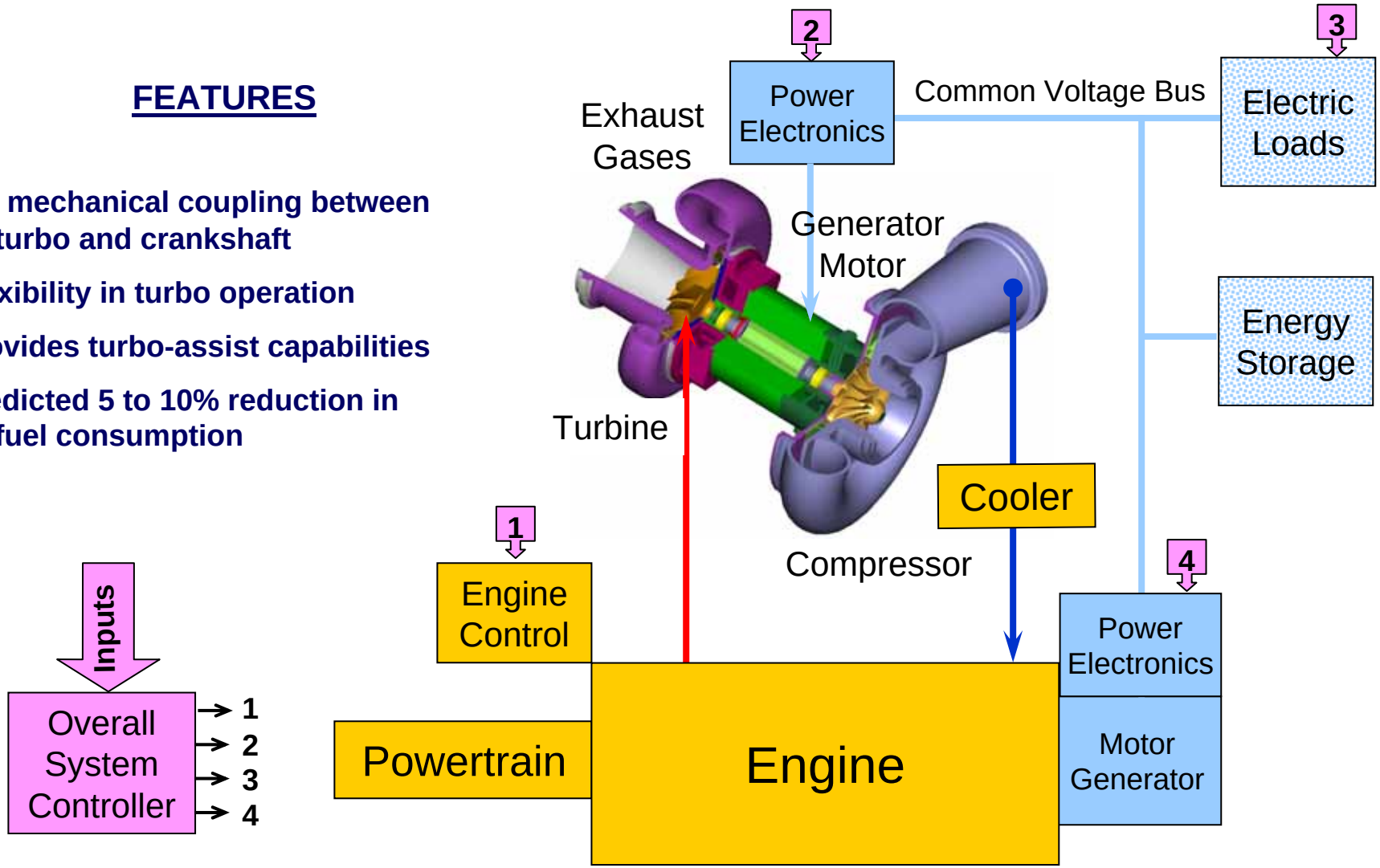
Electric Oil Pump
Variable speed
Higher efficiency

CATERPILLAR

Working Principle

FEATURES

- No mechanical coupling between turbo and crankshaft
- Flexibility in turbo operation
- Provides turbo-assist capabilities
- Predicted 5 to 10% reduction in fuel consumption



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- **Update on Component Developments**
  - **Turbo-shaft generator and crankshaft motor**
  - **Air handling system**
  - **Control system**
  - **Component testing**
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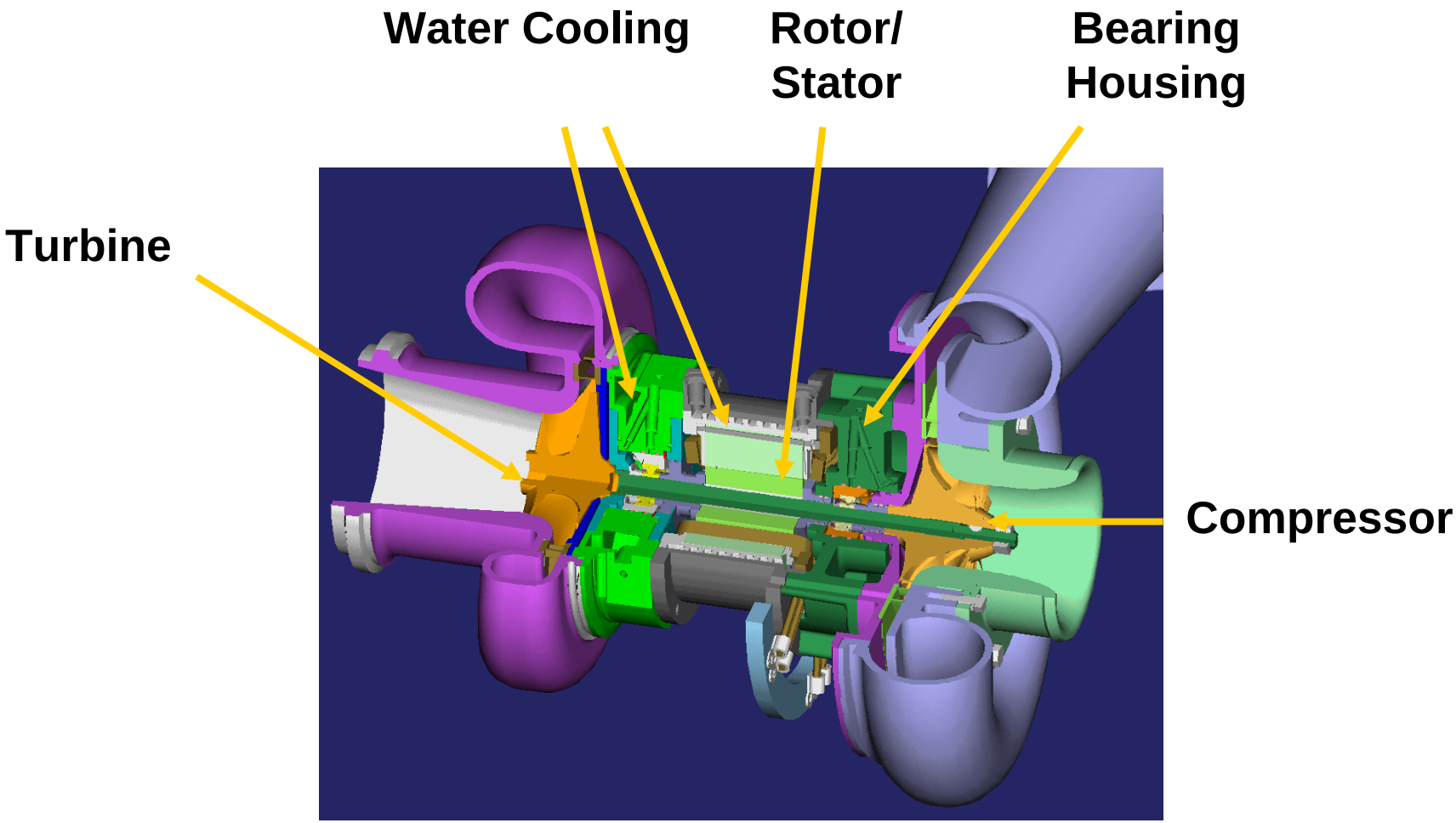
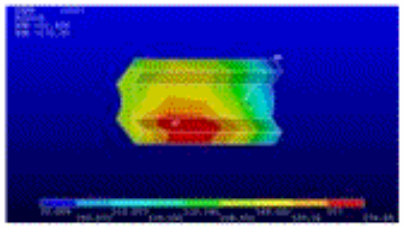
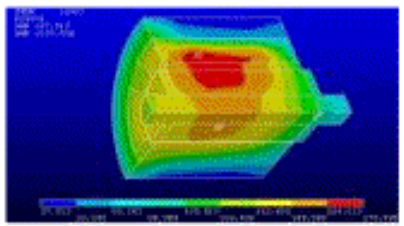
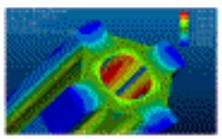
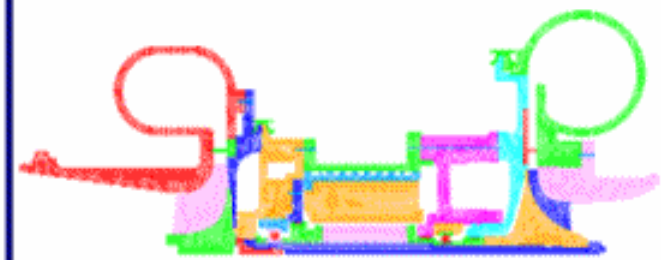
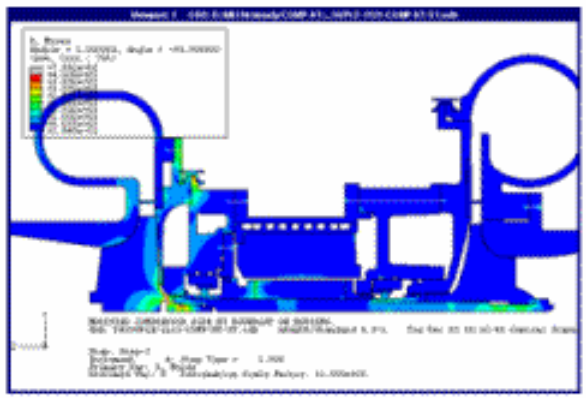
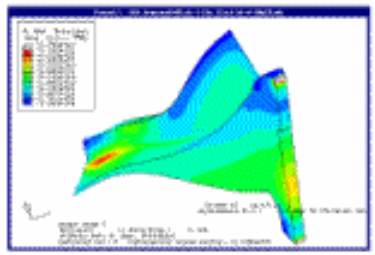
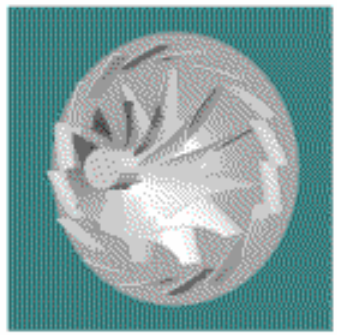
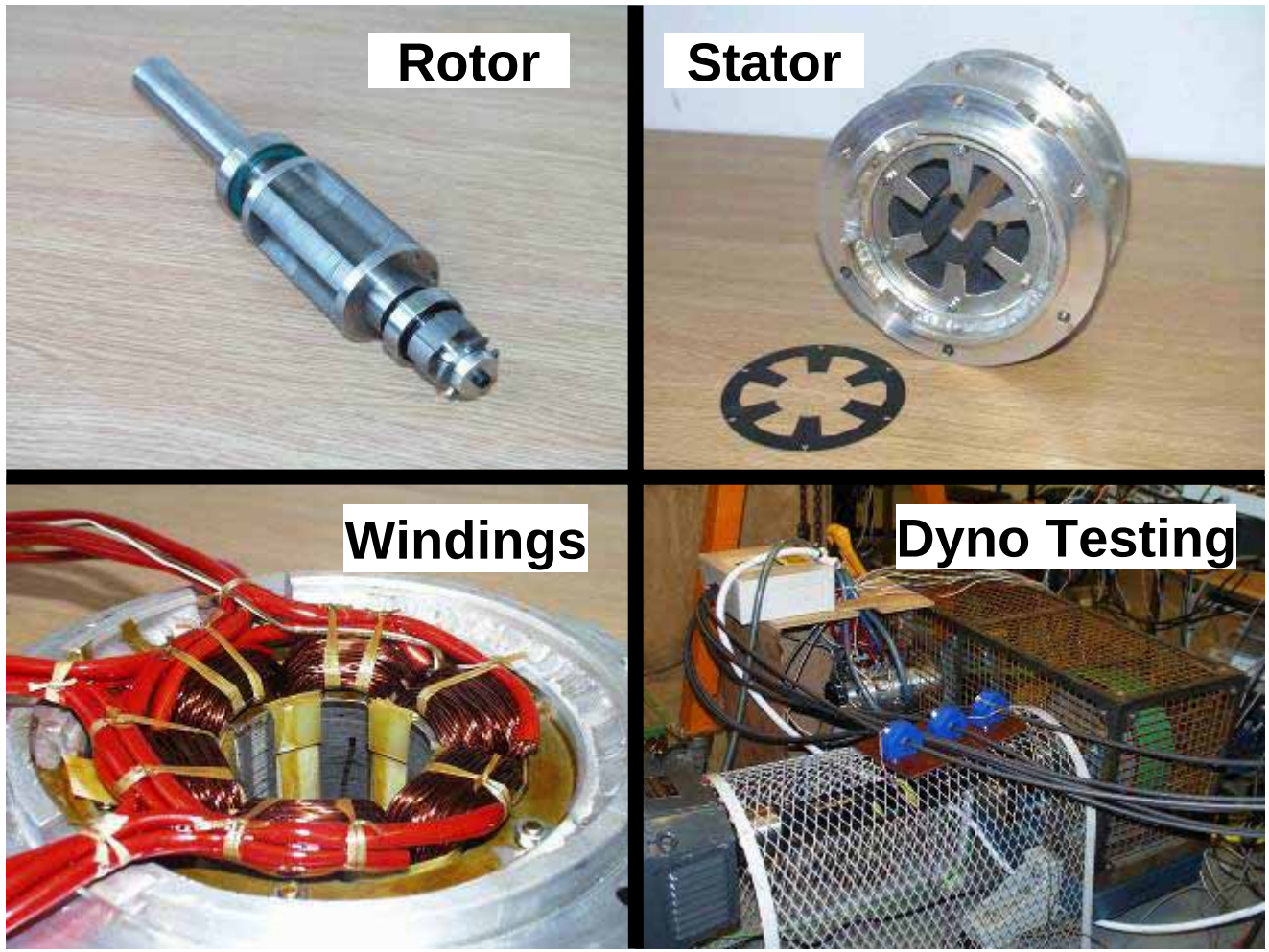
Final Design



Final Design

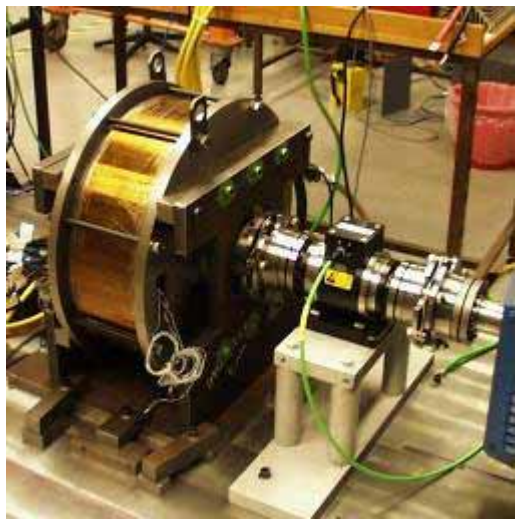
Turbo Shaft M/G	Turbocharger Structure	Aero Components
   Voltage: Voltage: 340 V Power: 40 kW / 60kW Rotor Length: 70 mm	 	 

Turbo Shaft – Generator/Motor



Crank Shaft - Motor/Generator

Flywheel Housing with
Crank Shaft M/G



340 Vdc Crank Shaft M/G

Electronics

Compressor and Turbine

Compressor Scroll and Compressor Wheel with Diffuser

Design Point

- Pressure Ratio (t-s) 3.1
- Efficiency (t-s) 82%, max. 85%

Turbine Scroll and Turbine Rotor with Nozzle

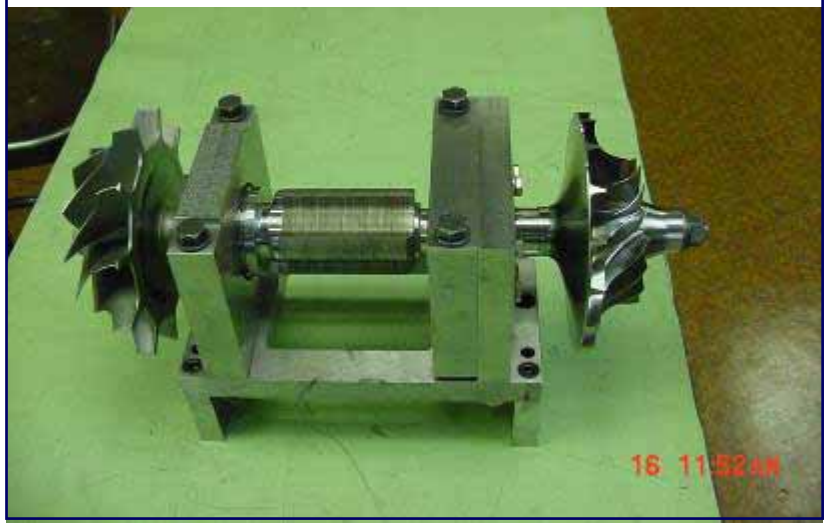
Design Point

- Pressure Ratio (t-s) 3.7
- Efficiency (t-s) 84%, max. 85%

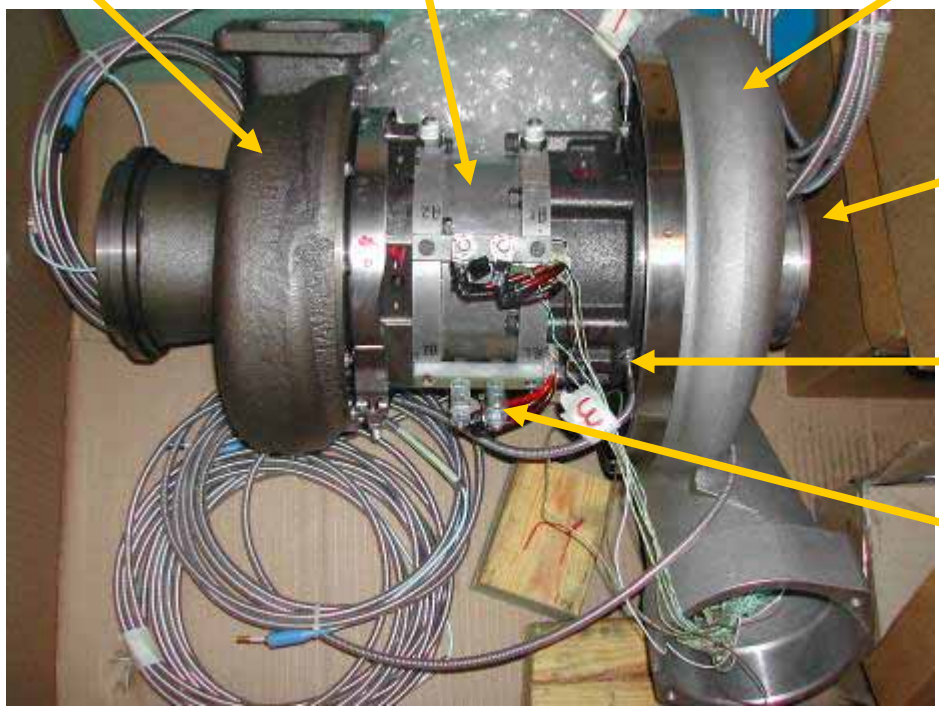
Turbo Shaft & Bearing Housing

Turbo Shaft w/ Ball Bearings

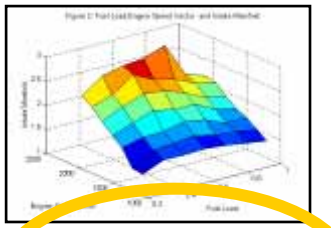
Rotor Assembly with Balancing Fixture



Assembled ETC Turbocharger



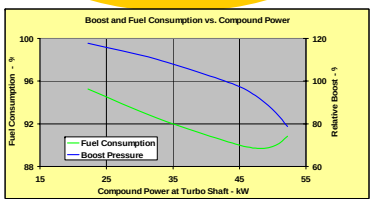
ETC Control System

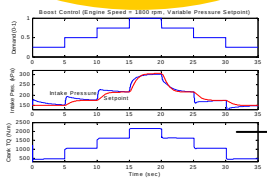


Map Boost / Speed / Load

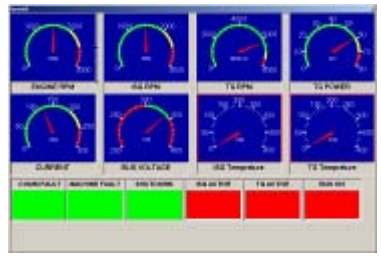
Boost at Optimum Fuel Consumption

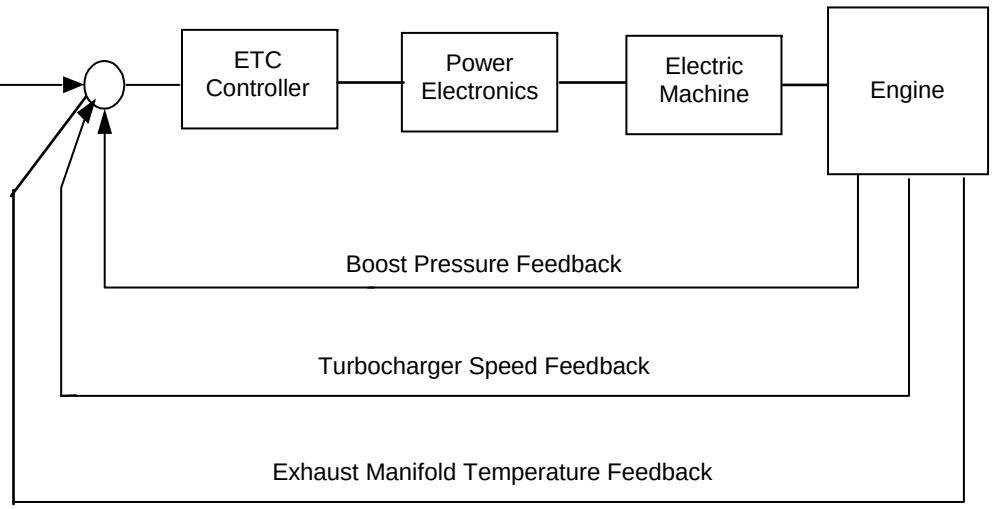
Set Point for Transient Behavior





- System Simulation in Simulink
- Controller Implemented in dSpace
- Virtual Instrumentation Capabilities





Component Testing

- Turboshaft and crankshaft motor/generator (M/G) have been tested on separate test rigs
- Measured peak efficiency of crankshaft M/G at target level
- ETC turbocharger is being tested on gas stand
  - Rotor dynamics check
  - Compressor map
  - Turbine map
- Engine test planned for October 2004

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Cost/Value Study

Value of ETC Technology

- 3 to 5% bsfc reduction

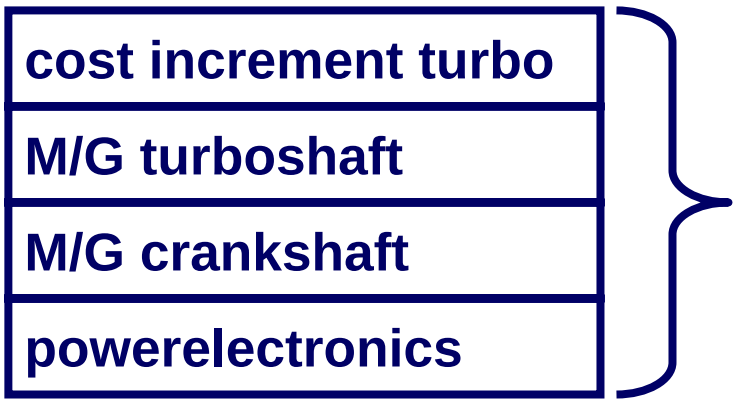
Program is based on MY 2000 engine

- No need for waste gate
- Enhanced braking power through
  - Higher boost
  - Regenerative braking with crank m/g

- Turbo assist capabilities
- Control A/F ratio (gas engines)
- Improved cold startability
- Altitude capability

System – Cost/Value: Example On-Highway Truck

- ETC system cost



  - System cost: $ 2000 to $ 3400
  - Powerelectronics account for half the cost

- Customer Benefit
  - Payback period between 13 (best case) and 38 months

Next Steps for ETC Development

- Complete test of ETC turbocharger in gas-stand lab-setting
- Complete engine testing with ETC system
- Assess ETC on low emission engine
  - Packaging
  - Aerodynamics
  - Cost effective design
  - Reliability/durability demonstration

Summary

- Turbocharger and ETC system have been designed and analyzed
- Performance predictions indicate 3 to 5% fuel economy improvement for cycle, 10% at key operating point
- Opportunity for reduced emissions and improved drivability
- E-Machine hardware testing completed
- Cost/value analysis shows high customer value