Diesel Engine Waste Heat Recovery Utilizing Electric Turbocompound Technology

Department of Energy Contract DE-SC05-00OR-22810

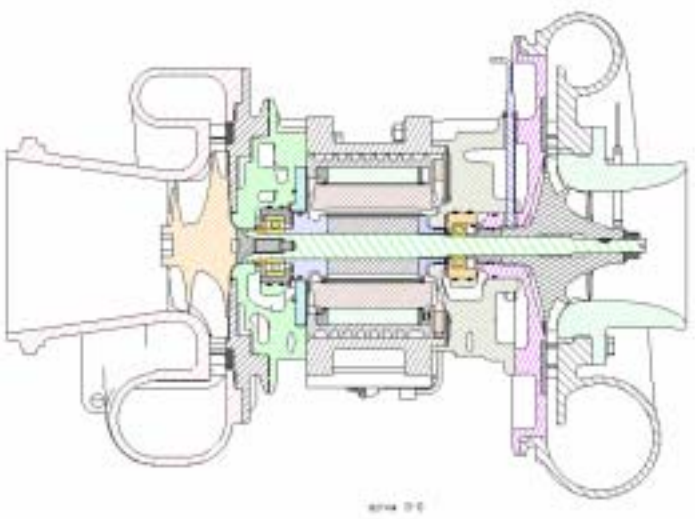
Marcelo Algrain and Ulrich Hopmann
Caterpillar Inc.

2003 DEER Conference
August 25-28, 2003
Newport, Rhode Island

Agenda

- Program Objectives
  and ETC System Background
- Update on Component Developments
  - Air Handling System
  - Turbo-Shaft Generator and Crankshaft Motor
  - Control System
- Next Steps and Summary

Diesel Electric Turbocompounding (ETC)



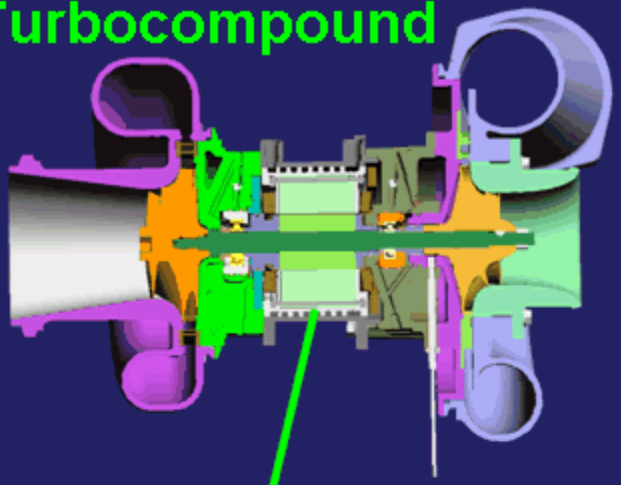
Primary Objectives

- 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 Electric Turbocompound System

Turbocompound



Modular HVAC

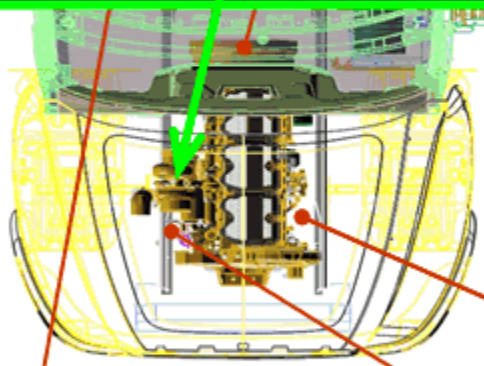
Variable speed compressor more efficient and serviceable
3X more reliable compressor no belts, no valves, no hoses leak-proof refrigerant lines instant electric heat

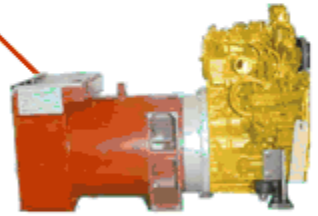
Starter Generator Motor

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

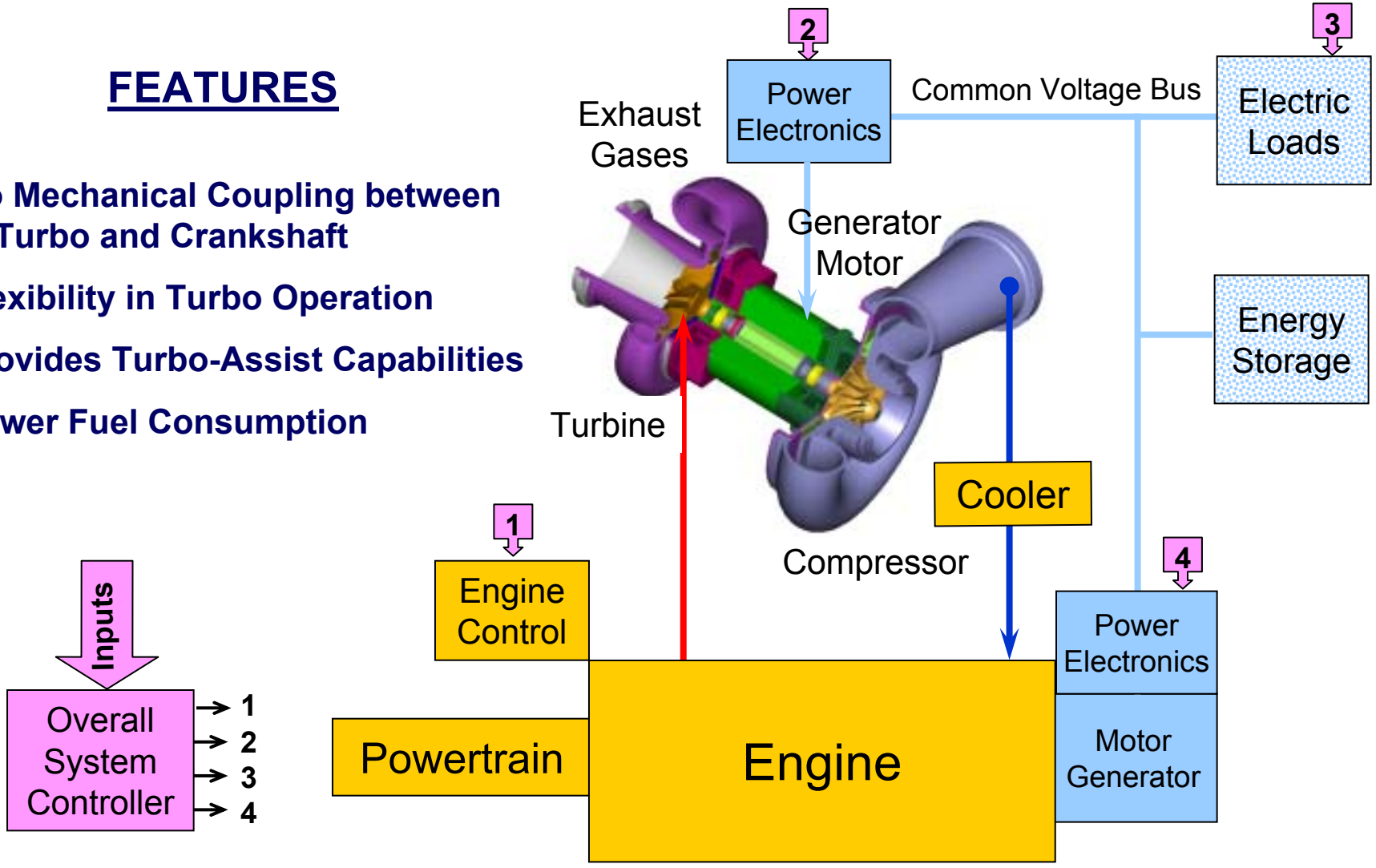
CATERPILLAR

Caterpillar Engine Research
Diesel & Emissions Technology

Working Principle

FEATURES

- ❑ No Mechanical Coupling between Turbo and Crankshaft
- ❑ Flexibility in Turbo Operation
- ❑ Provides Turbo-Assist Capabilities
- ❑ Lower Fuel Consumption



Electric Turbocompound System

FEATURES

- No Mechanical Coupling between Turbo and Crankshaft
- Flexibility in Turbo Operation
- Provides Turbo-Assist Capabilities

BENEFITS

- Lower Fuel Consumption
  - Predicted 5% improvement
- Controlling Boost enables strategies for reducing transient Particulate Emissions
- Lower CO_2 due to lower Fuel Consumption
- Potential for enhanced Engine Braking with Control of Boost

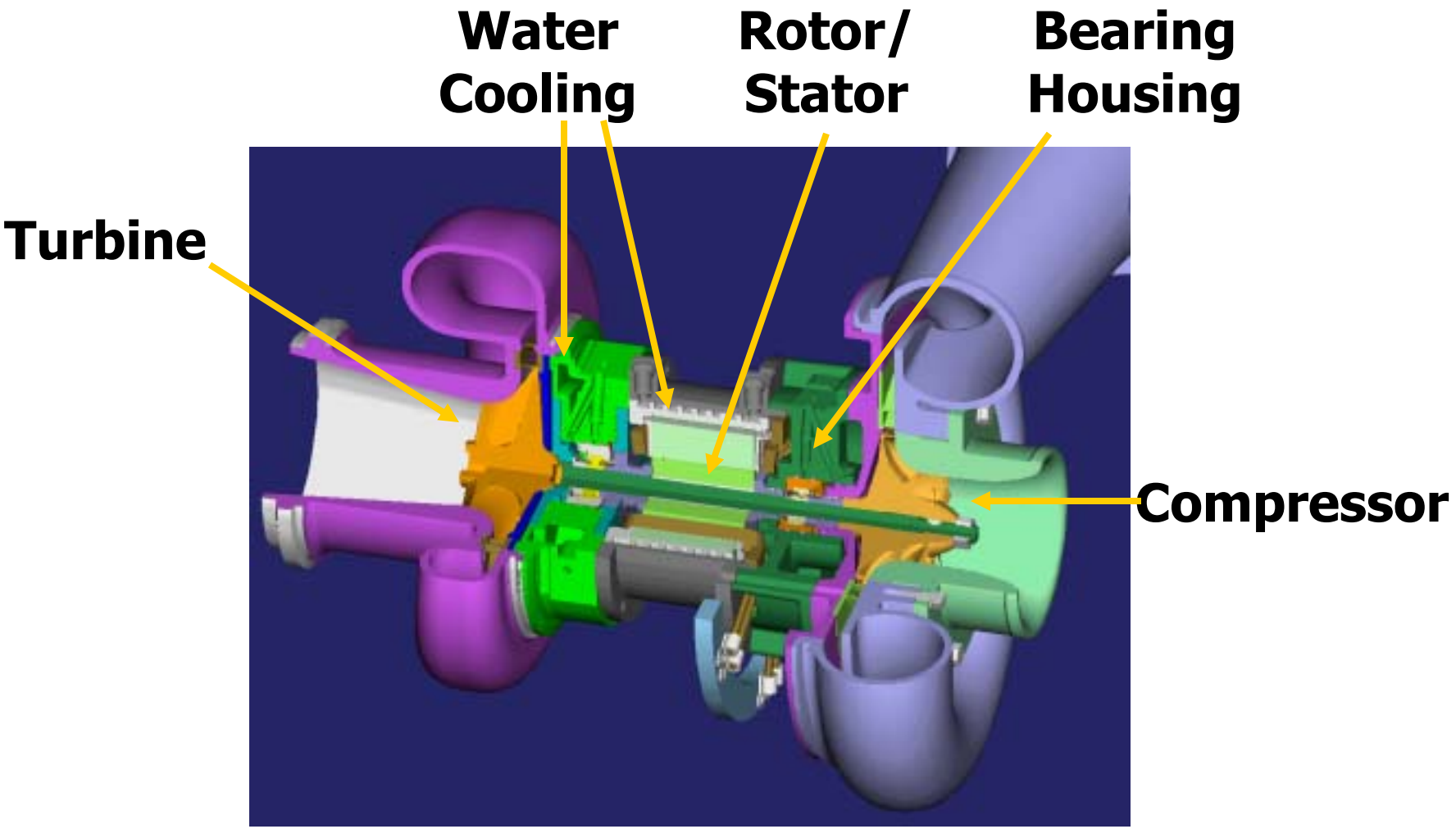
Progress to Date

- Completed Design of Components
  - Air handling system
  - Electric Machinery and Power Electronics
  - Control System
- Run Computer Simulations for Engine Performance Analysis and Dynamic Control Evaluation
- Identified Opportunity for Reduced Emissions and Improved Drivability
- Built Generator, Crankshaft Motor, and Electronics
- Remaining Hardware is Being Procured
- System Lab Test Planned for 2003 and Engine Test in 2004

Agenda

- Program Objectives and ETC System Background
- **Update on Component Developments**
  - **Air Handling System**
  - **Turbo-Shaft Generator and Crankshaft Motor**
  - **Control System**
- Next Steps and Summary

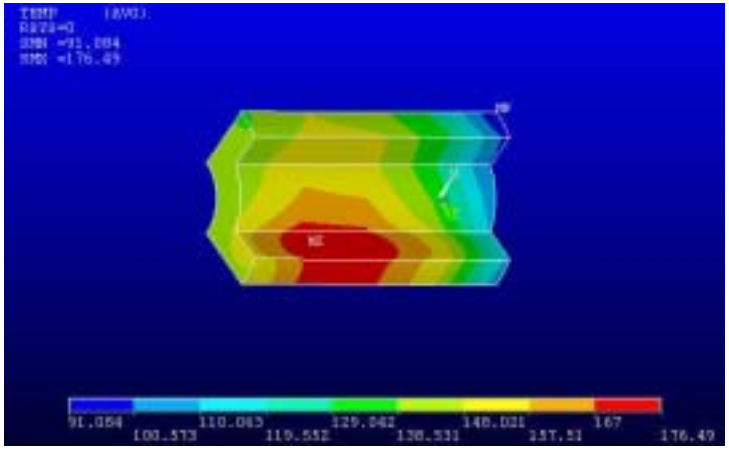
Final Design



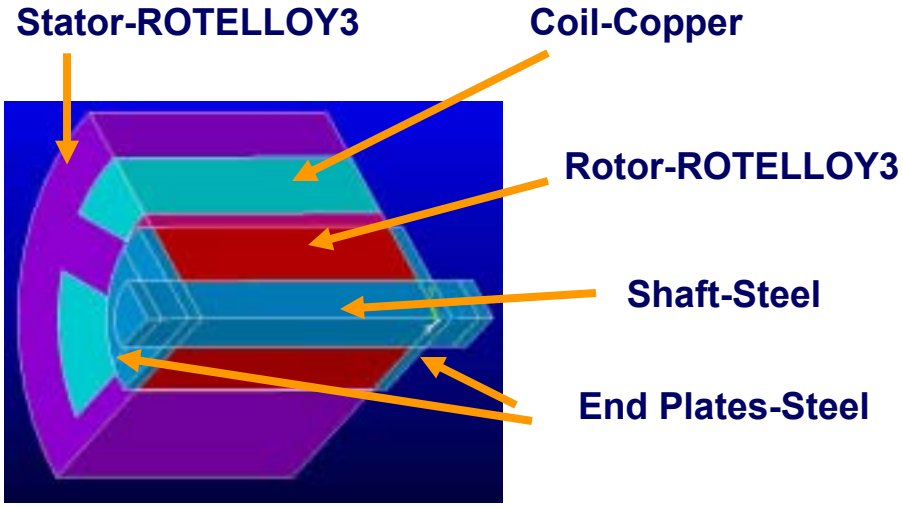
Turbo Shaft Generator Heat Transfer

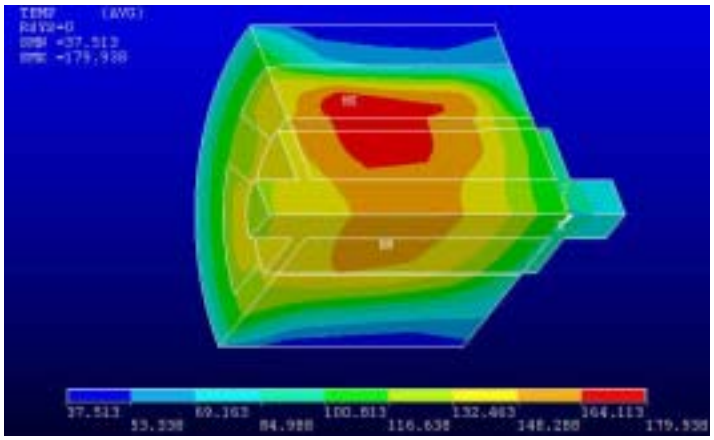
Voltage: Voltage: 340 V
Power: 40 kW / 60kW max.
Rotor/Stator Length: 70 mm 340 V

	Coil	Stator/Rotor
Density (kg/m^3)	7800	7980
Thermal Conductivity (W/mK)	4.6	29
Magnetic Permeability	1	6000
Electrical Resistivity (ohm-m)	1.7e-8	4e-7



Rotor: Temperatures at 60kW



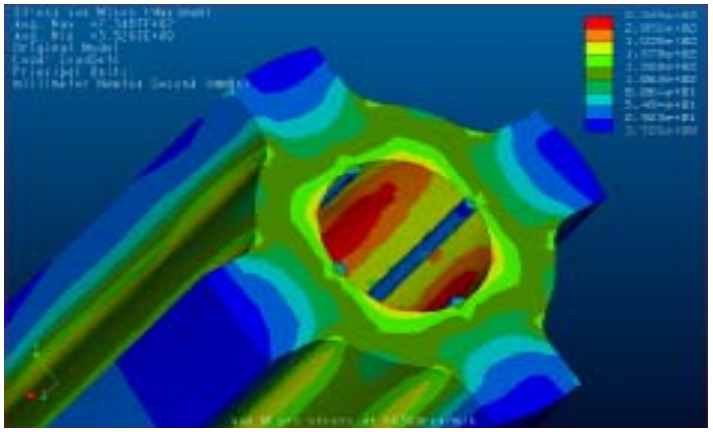


Rotor&Stator: Temperatures at 60 kW

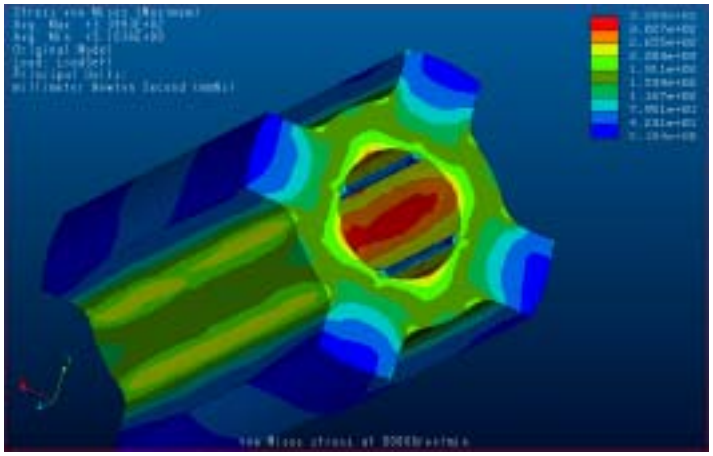
Turbo Shaft Rotor Lamination

FE Analysis

- 4/6 machine, 4 rotor poles
- OD and shape designed for low stress
- Material is ROTELLOY3
- Max operating stress below limit



Stress @ 66,500 rpm design speed

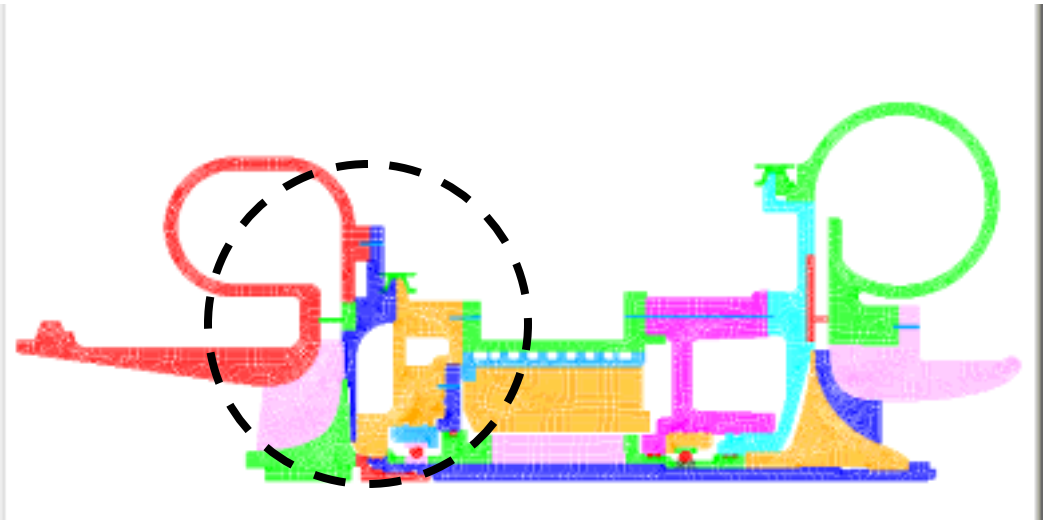


Stress @ 80,000 rpm over speed

Modified FE Model

Baseline Model

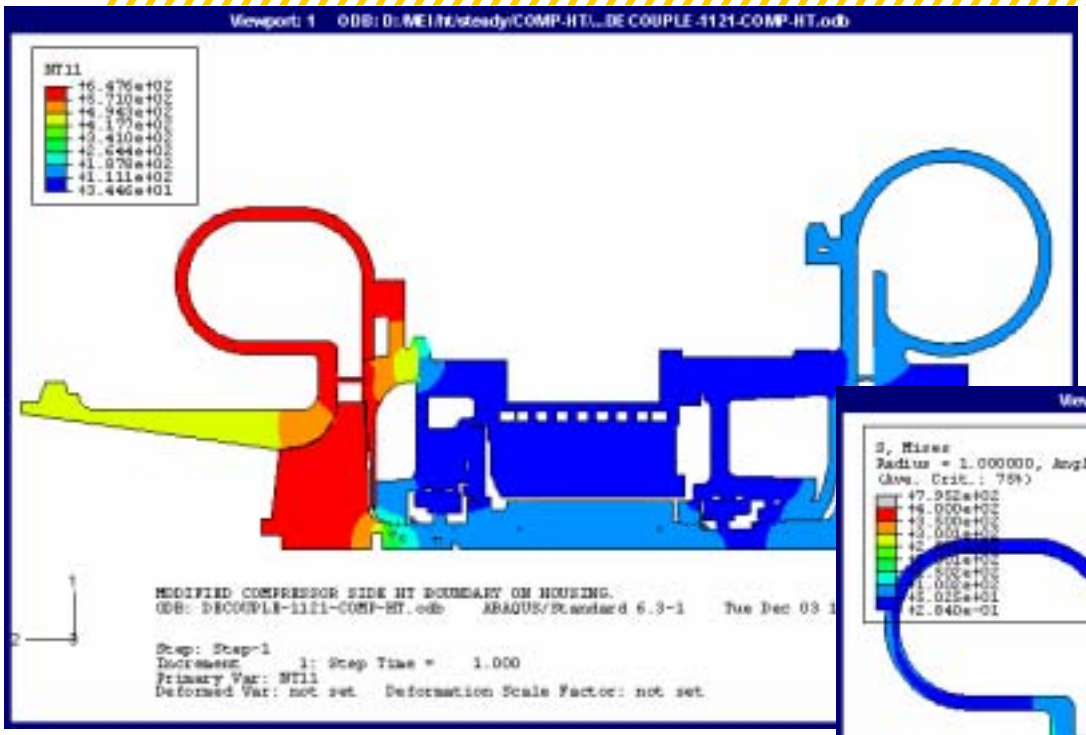
- High Temperature and Stress Gradients



Decoupled Model

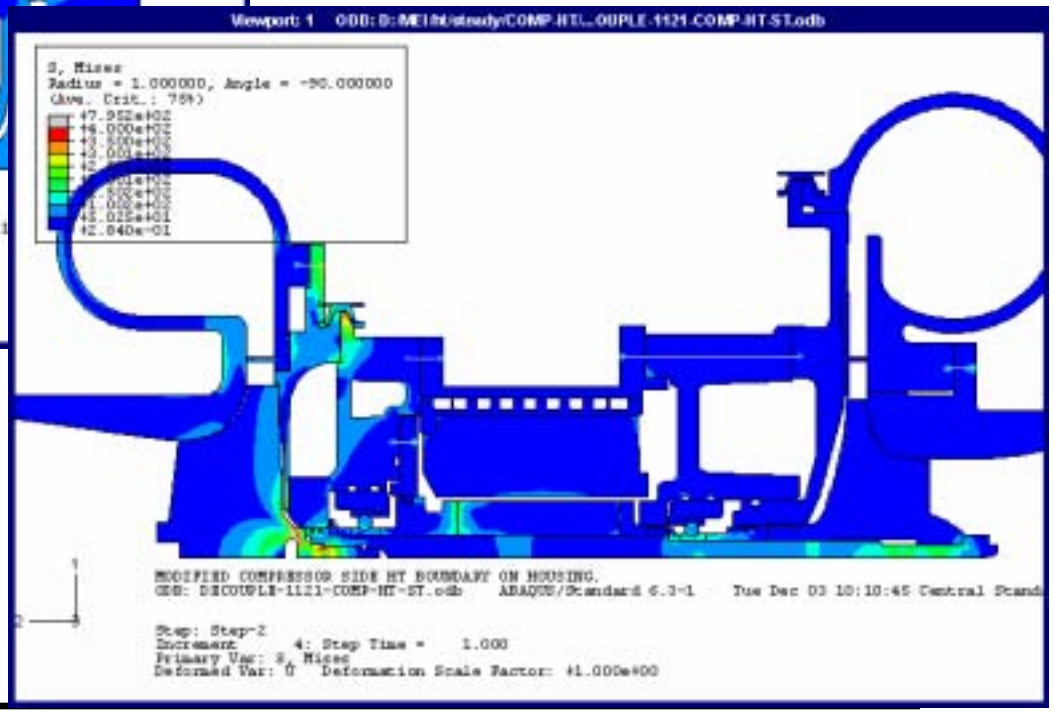
- Turbine Housing decoupled from Bearing Housing
- Decreased Waterpassage
- Lower Stresses

FE Analysis Steady State



Thermal Analysis

Stress Analysis



Compressor and Turbine

Compressor Scroll and
Compressor Wheel with Diffuser

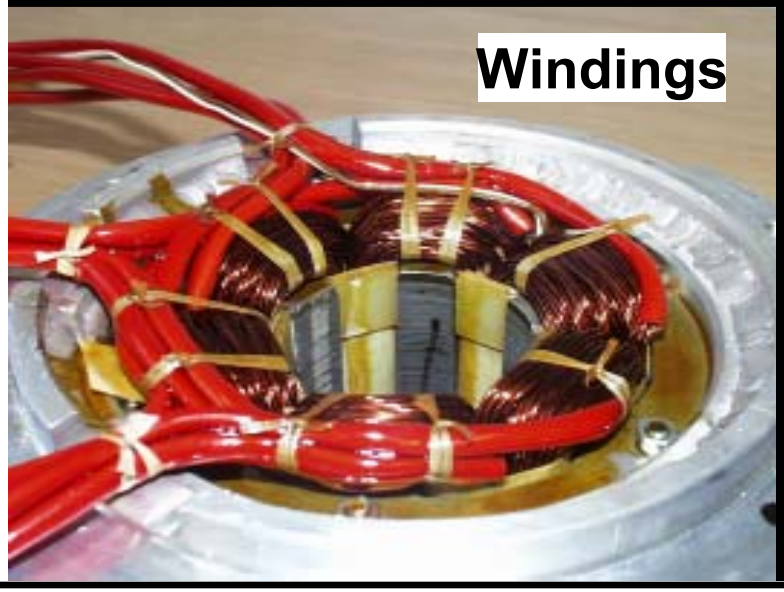
Turbine Scroll and
Turbine Rotor with Nozzle

Turbo Shaft

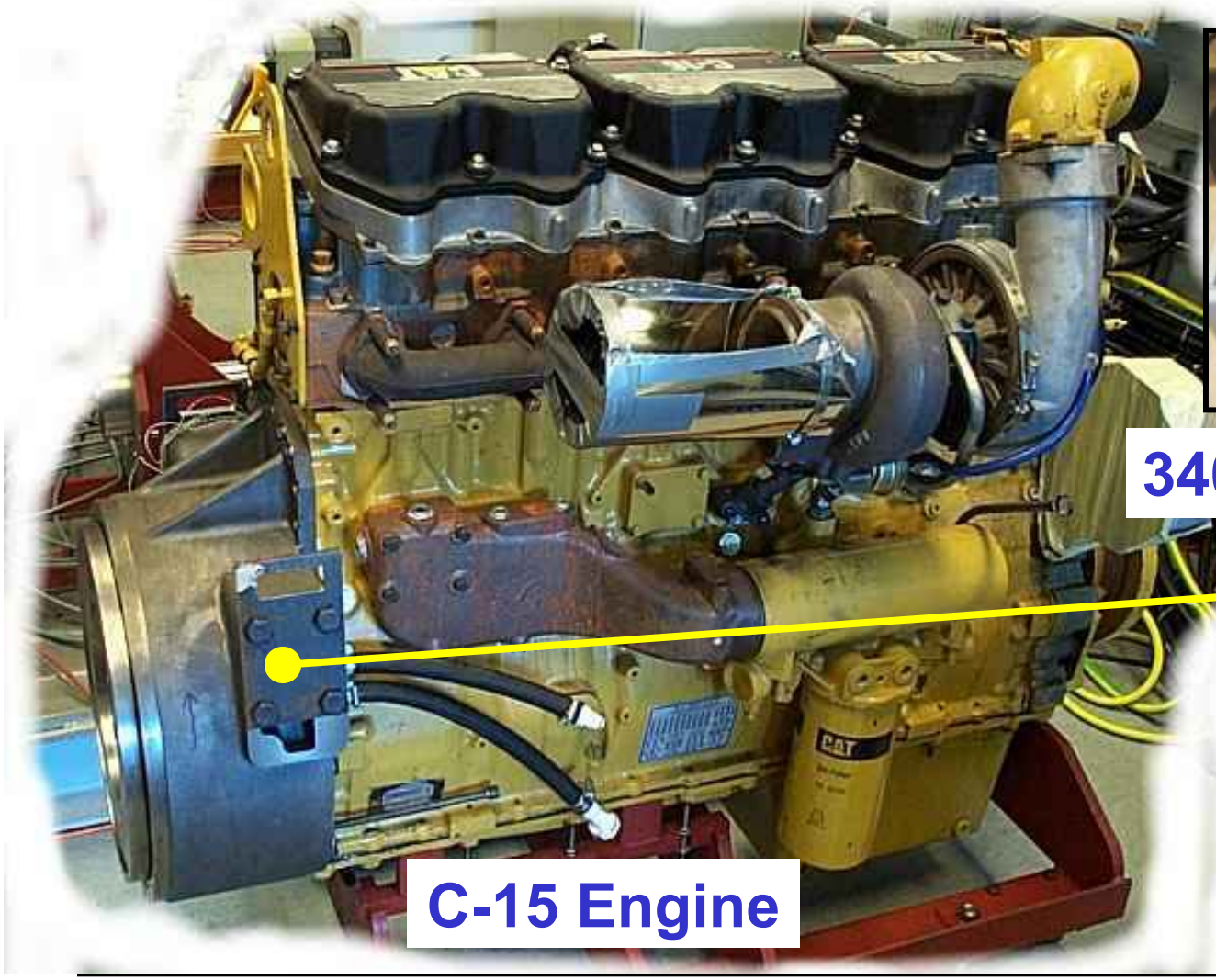
Turbo Shaft w/ Ball Bearings

Compressor Wheel on Shaft

Turbo Shaft – Generator/Motor

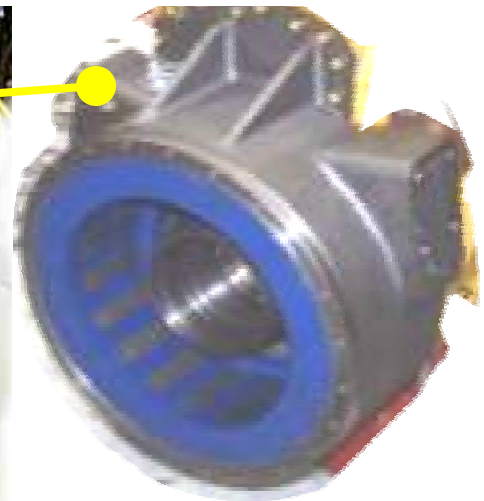


Crank Shaft - Motor/Generator & Housing



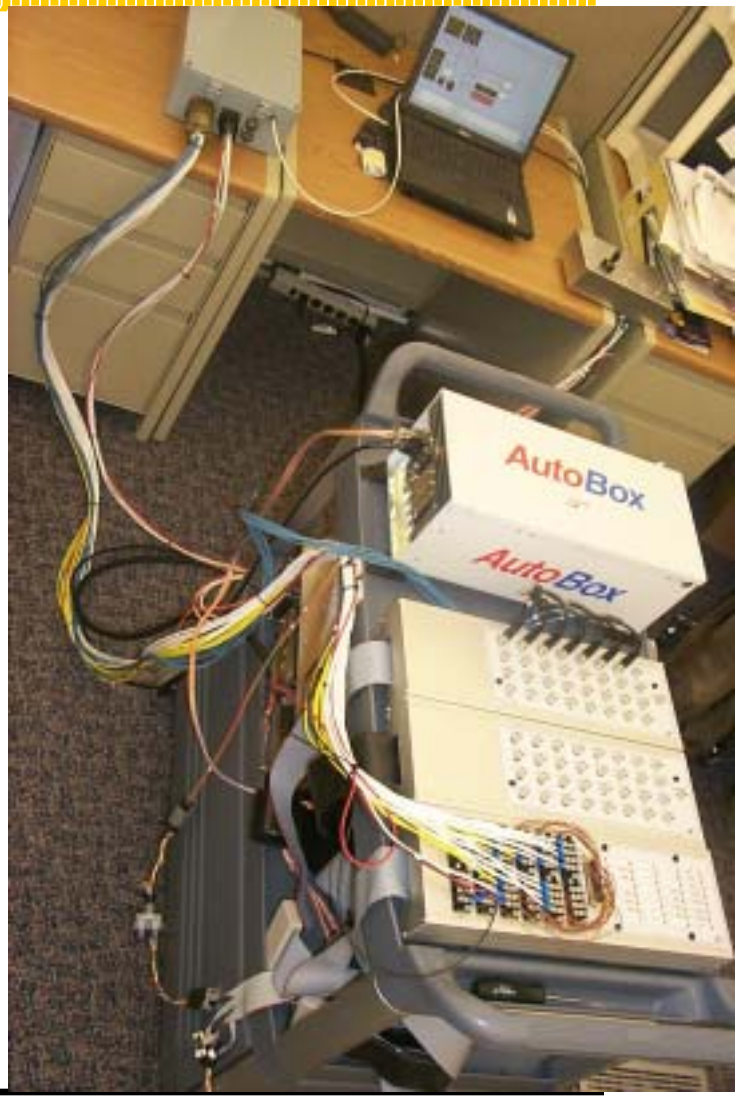
Electronics

340 Vdc Generator

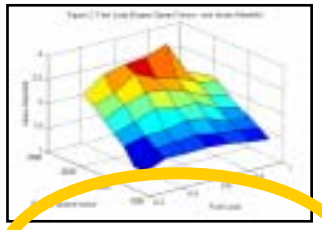


Control System Development

- Engine and Vehicle
  - Engine ECU and Fuel Control
  - Engine Combustion & Dynamics
  - Driveline and Vehicle Dynamics
  - ETC Components
    - Turbomachinery maps
    - Generator and Motor Models
- Simulated Overall Functionality and Operation of ETC System
- Modeled for testing ETC Controller Algorithms

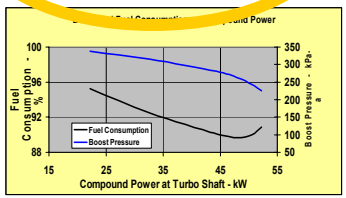


- System Simulation in Simulink
- Controller Implemented in dSpace
- Virtual Instrumentation Capabilities

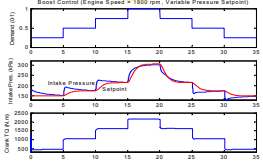


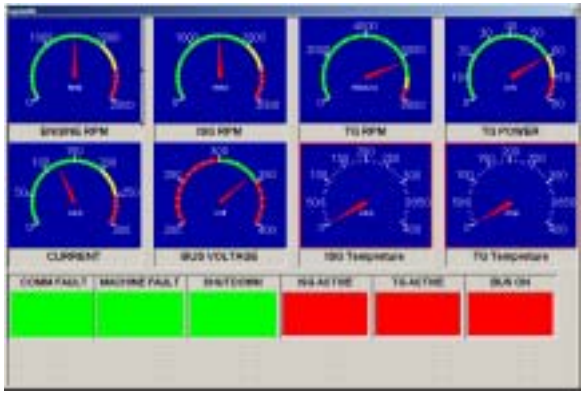
Map Boost / Speed / Load

Boost at Optimum Fuel Consumption

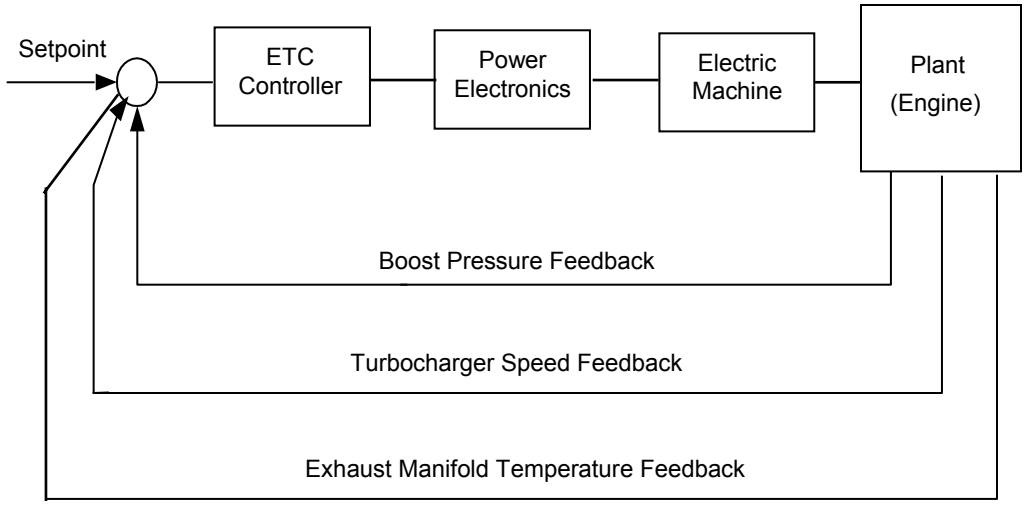


Set Point for Transient Behavior





ETC Control System

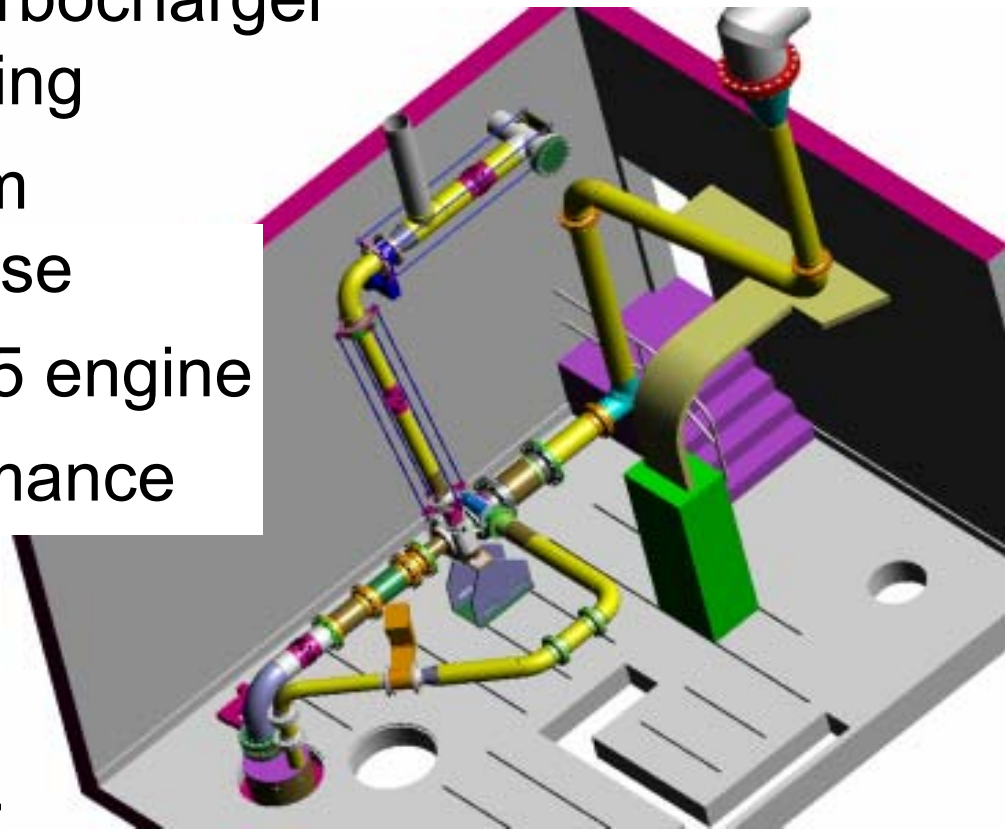


Agenda

- Program Objectives and ETC System Background
- Update on Component Developments
  - Air Handling System
  - Turbo-Shaft Generator and Crankshaft Motor
  - Control System
- **Next Steps and Summary**

Next Steps for ETC Development

- Complete electric machinery test on dynamometer
- Add air-handling components to generator housing
- Conduct SS test of E-turbocharger in gas-stand lab-setting
- Test ETC control system and transient response
- Incorporate ETC to C-15 engine
- Measure engine performance with ETC in test-cell
- Deploy ETC-engine on future test vehicle



CATERPILLAR

Summary

- Turbocharger and ETC System have been Designed and Analyzed
- Performance Predictions Indicate 5% Fuel Economy Improvement
- Opportunity for Reduced Emissions and Improved Drivability
- Electric Machine Hardware Available
- Remaining Hardware is Being Procured
- System and Engine Test Planned for 2003 and 2004
- Cost/Value Analysis Shows High Customer Value