



Diesel Engine Waste Heat Recovery Utilizing Electric Turbocompound Technology

**Department of Energy Contract
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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)

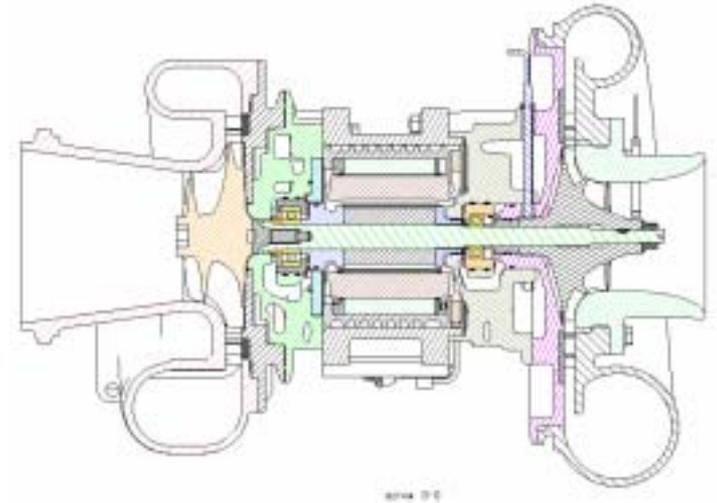


Primary Objectives

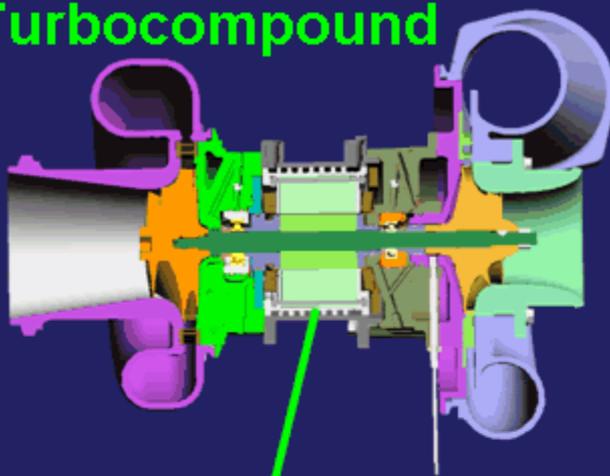
- ❑ Demonstrate Technical Feasibility
- ❑ Improve Fuel Economy

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



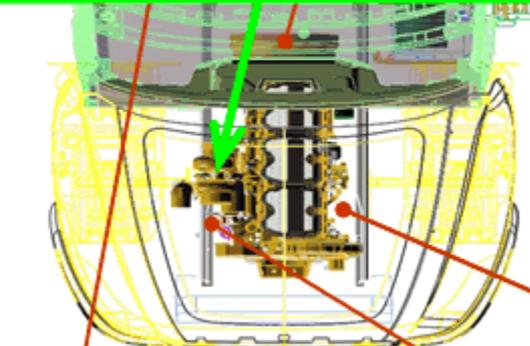
Shore Power and Inverter

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



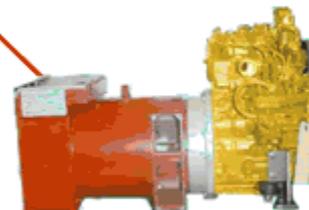
Down Converter

Supplies 12 V Battery from DC Bus



Starter Generator Motor

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



Auxiliary Power Unit

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



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



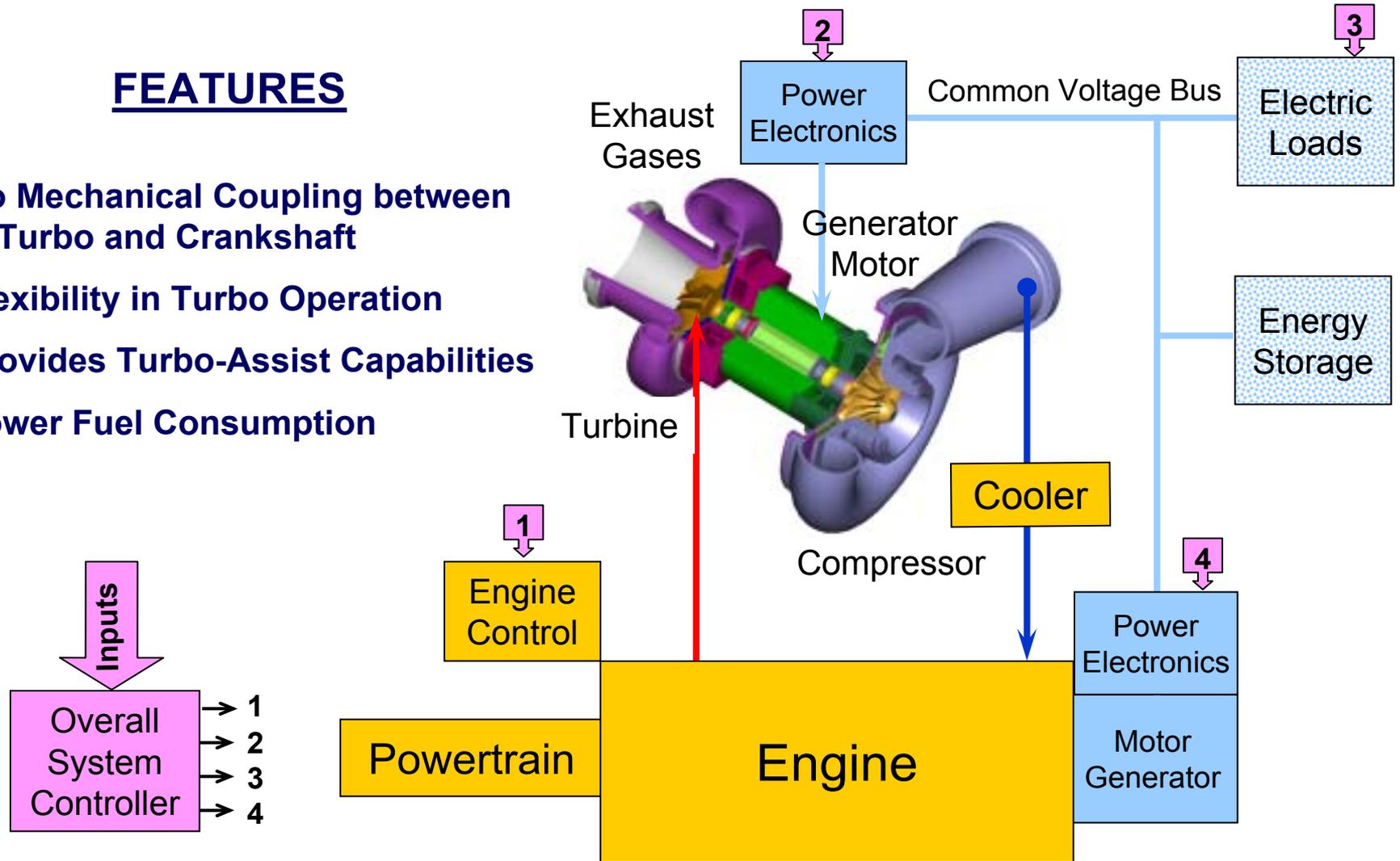
Electric Oil Pump

Variable speed Higher efficiency

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

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BENEFITS

- ❑ Lower Fuel Consumption
 - Predicted 5% improvement
- ❑ Controlling Boost enables strategies for reducing transient Particulate Emissions
- ❑ Lower CO₂ due to lower Fuel Consumption
- ❑ Potential for enhanced Engine Braking with Control of Boost

Progress to Date

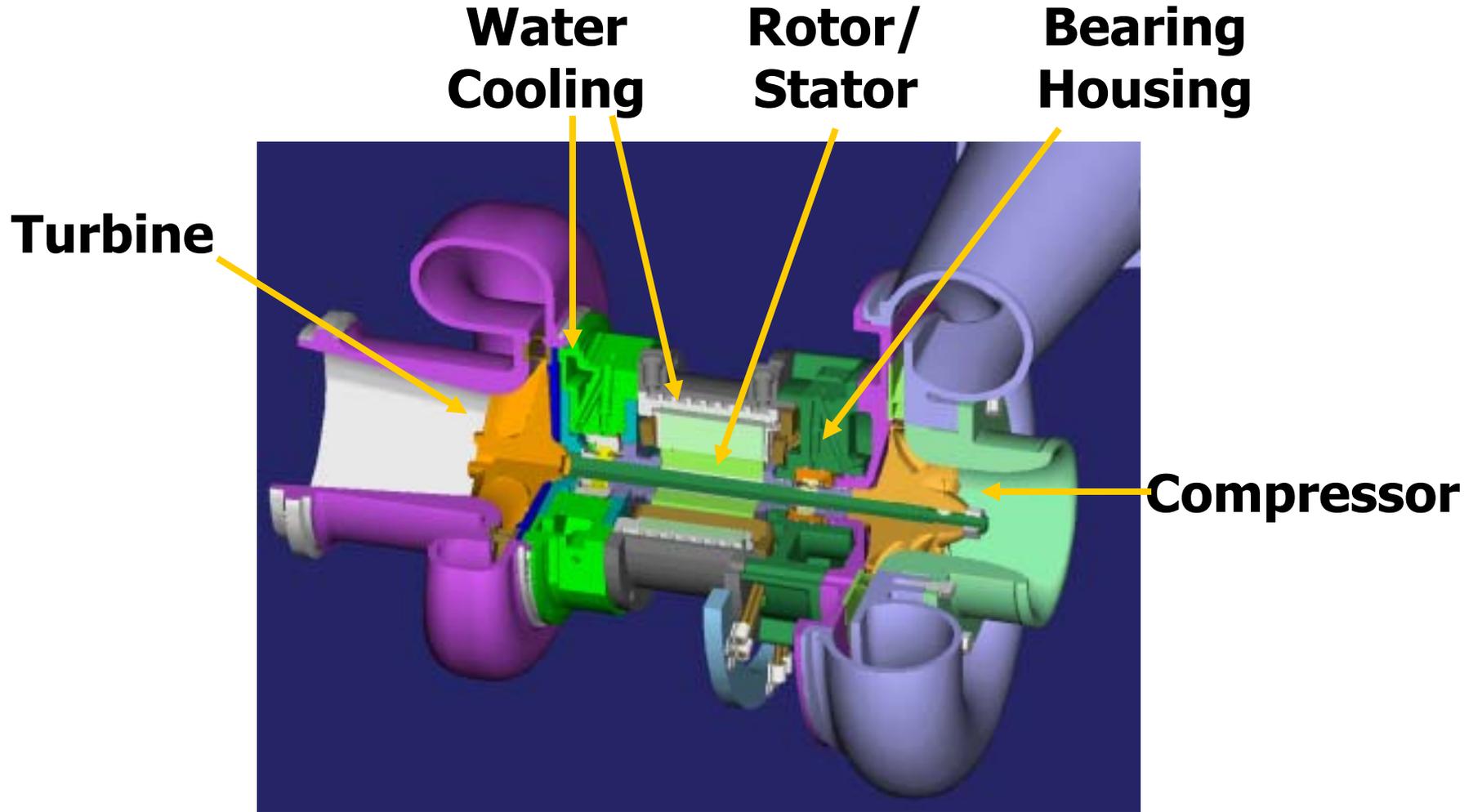


- Completed Design of Components**
 - Air handling system**
 - Electric Machinery and Power Electronics**
 - Control System**
- Run Computer Simulations for Engine Performance Analysis and Dynamic Control Evaluation**
- Identified Opportunity for Reduced Emissions and Improved Drivability**
- Built Generator,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

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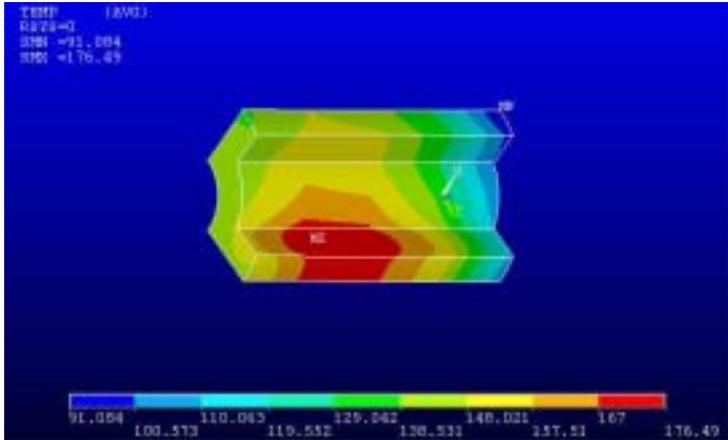
Final Design



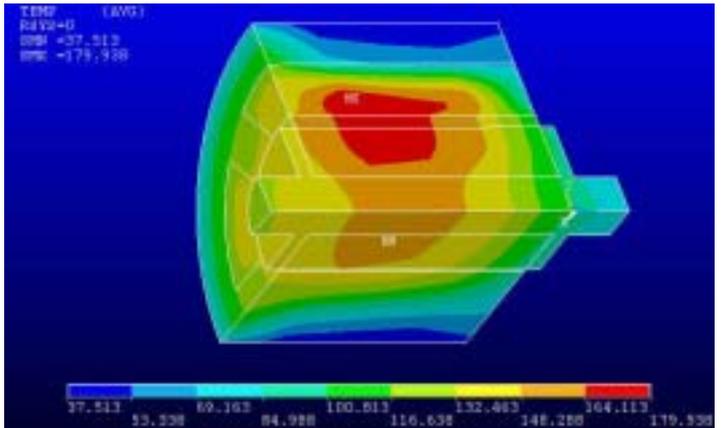
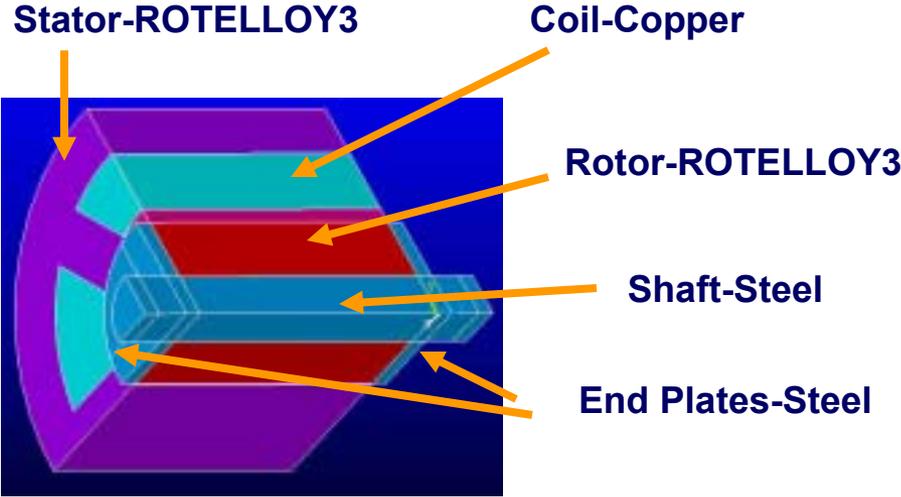
Turbo Shaft Generator Heat Transfer



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



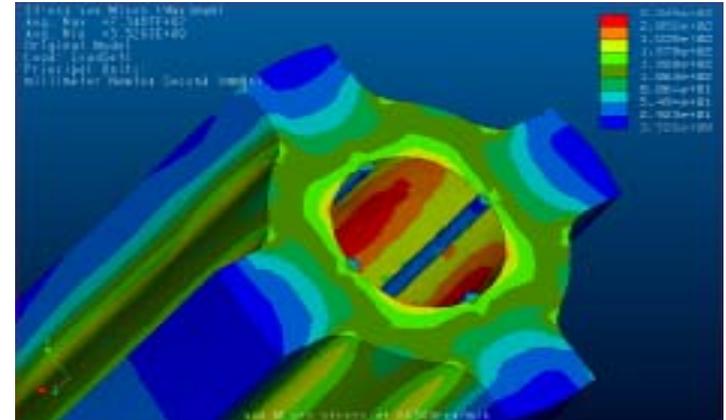
Rotor&Stator: Temperatures at 60 kW

Turbo Shaft Rotor Lamination

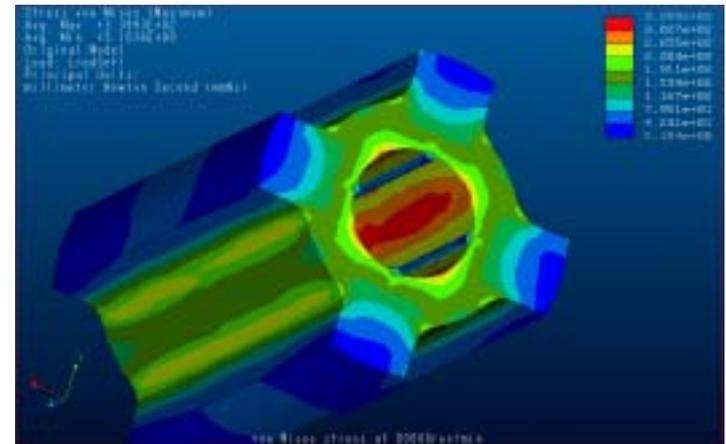


FE Analysis

- ❑ 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



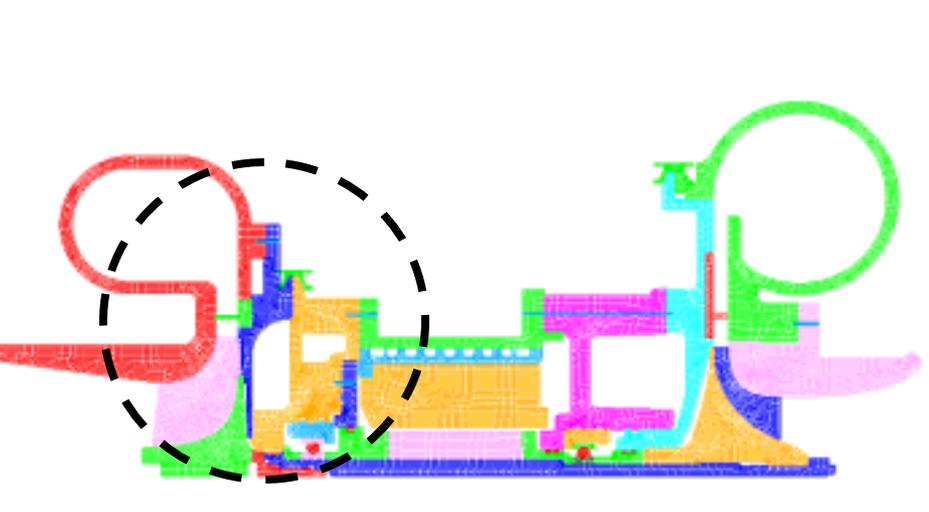
Stress @ 80,000 rpm over speed

Modified FE Model



Baseline Model

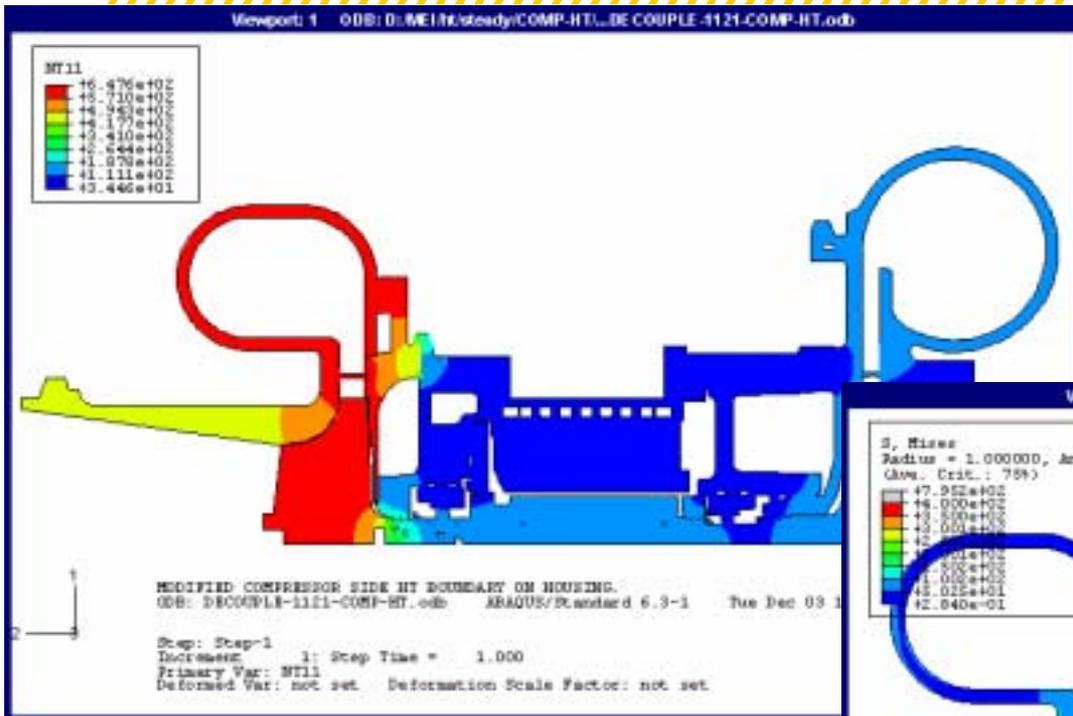
- ❑ High Temperature and Stress Gradients



Decoupled Model

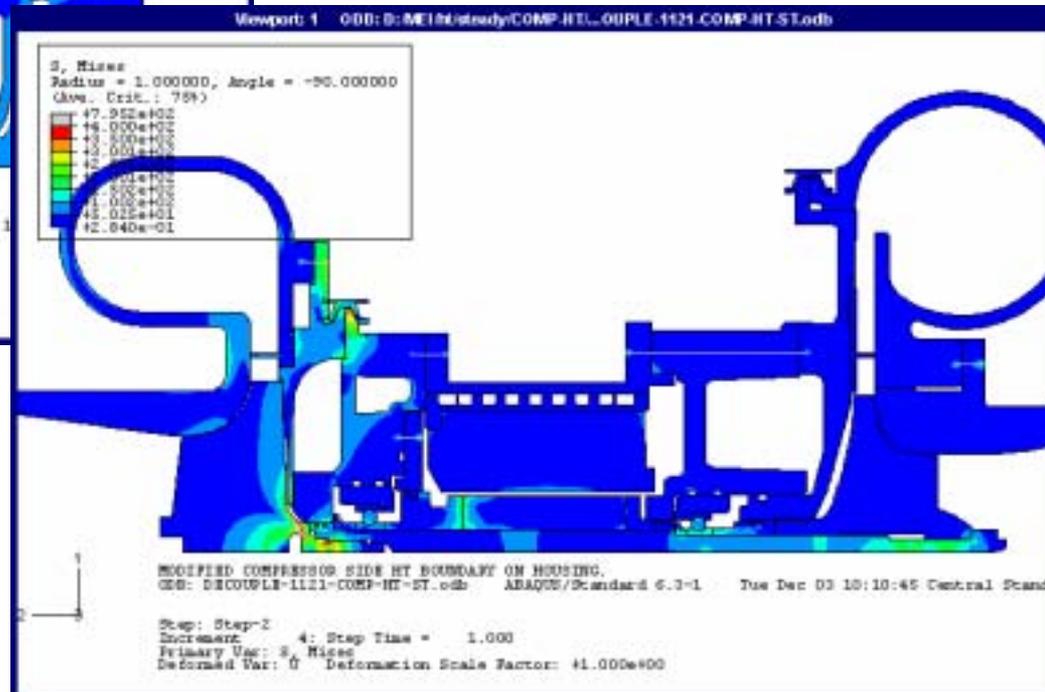
- ❑ Turbine Housing decoupled from Bearing Housing
- ❑ Decreased Waterpassage
- ❑ Lower Stresses

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



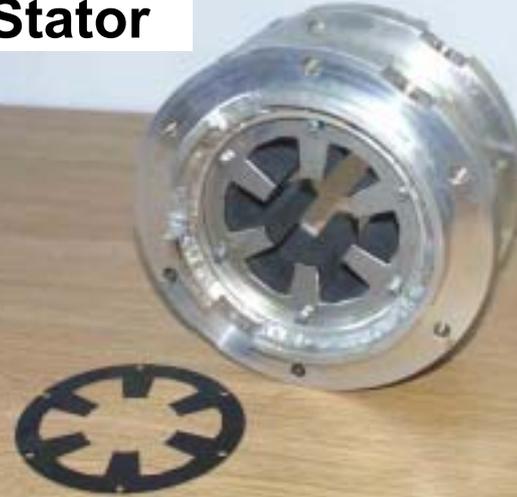
Compressor Wheel on Shaft

Turbo Shaft – Generator/Motor

Rotor



Stator



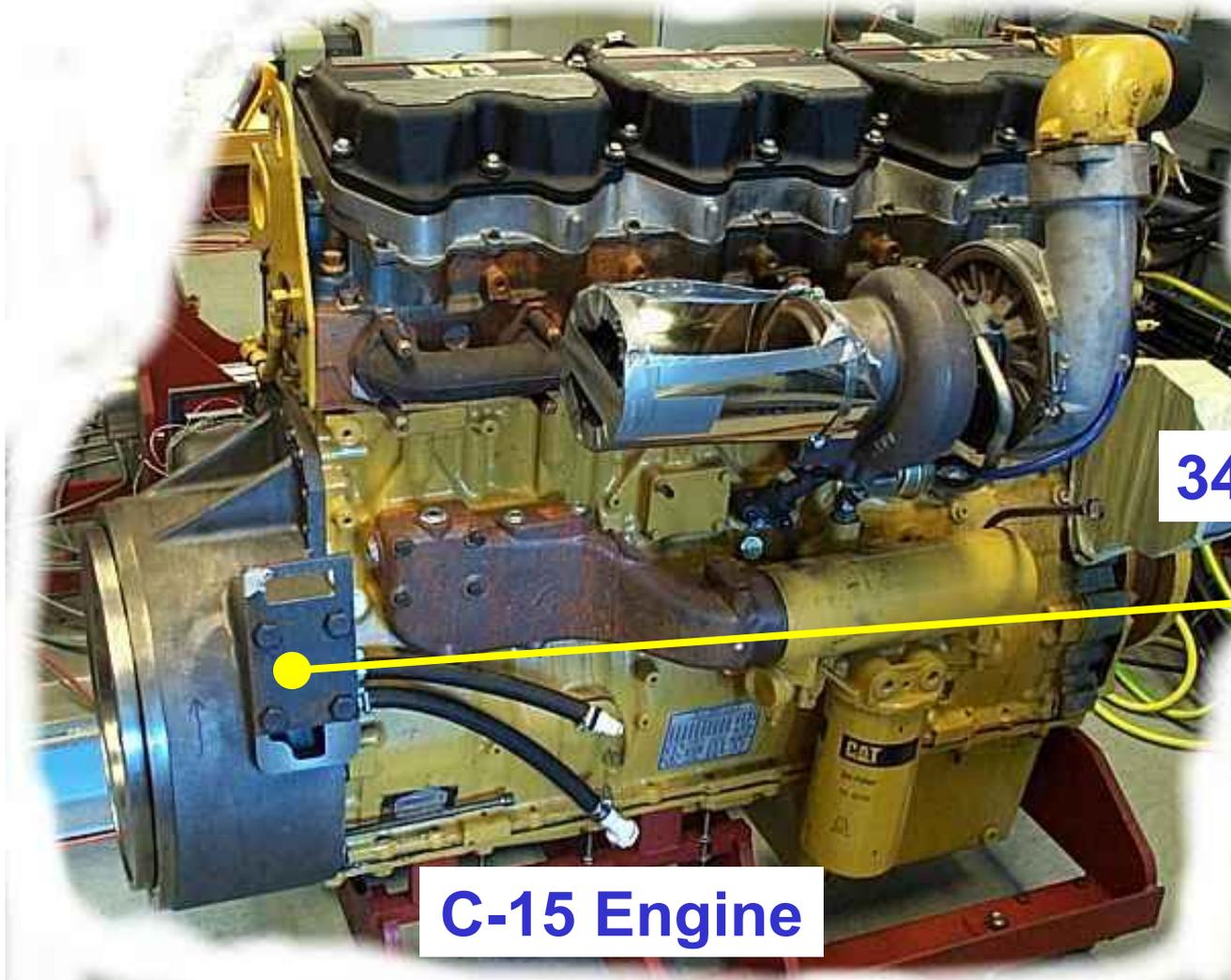
Windings



Dyno. Testing



Crank Shaft - Motor/Generator & Housing



C-15 Engine



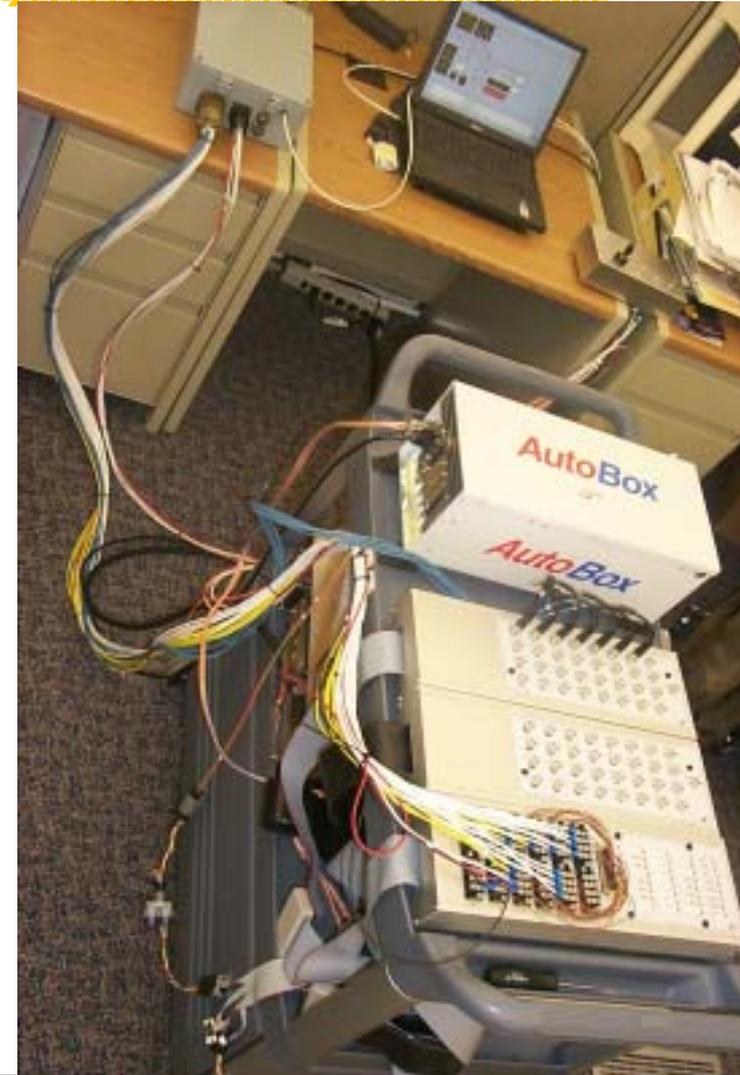
Electronics

340 Vdc Generator

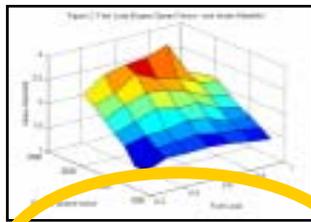


Control System Development

- ❑ 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

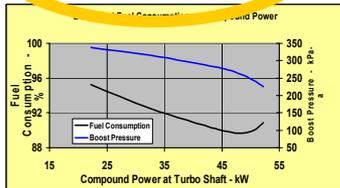


- ❑ System Simulation in Simulink
- ❑ Controller Implemented in dSpace
- ❑ Virtual Instrumentation Capabilities

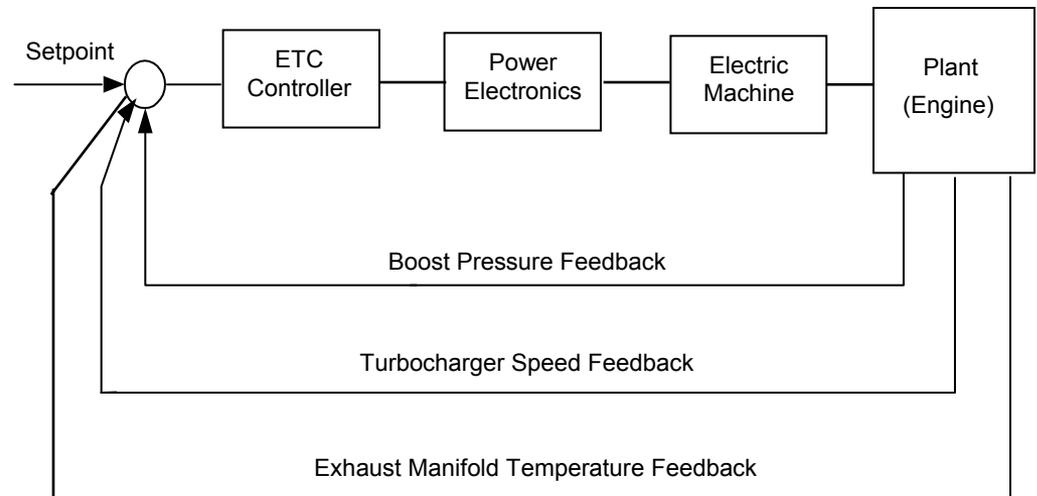
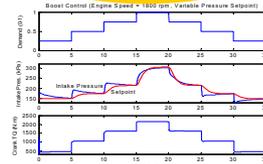


Map Boost / Speed / Load

Boost at Optimum Fuel Consumption



Set Point for Transient Behavior



ETC Control System

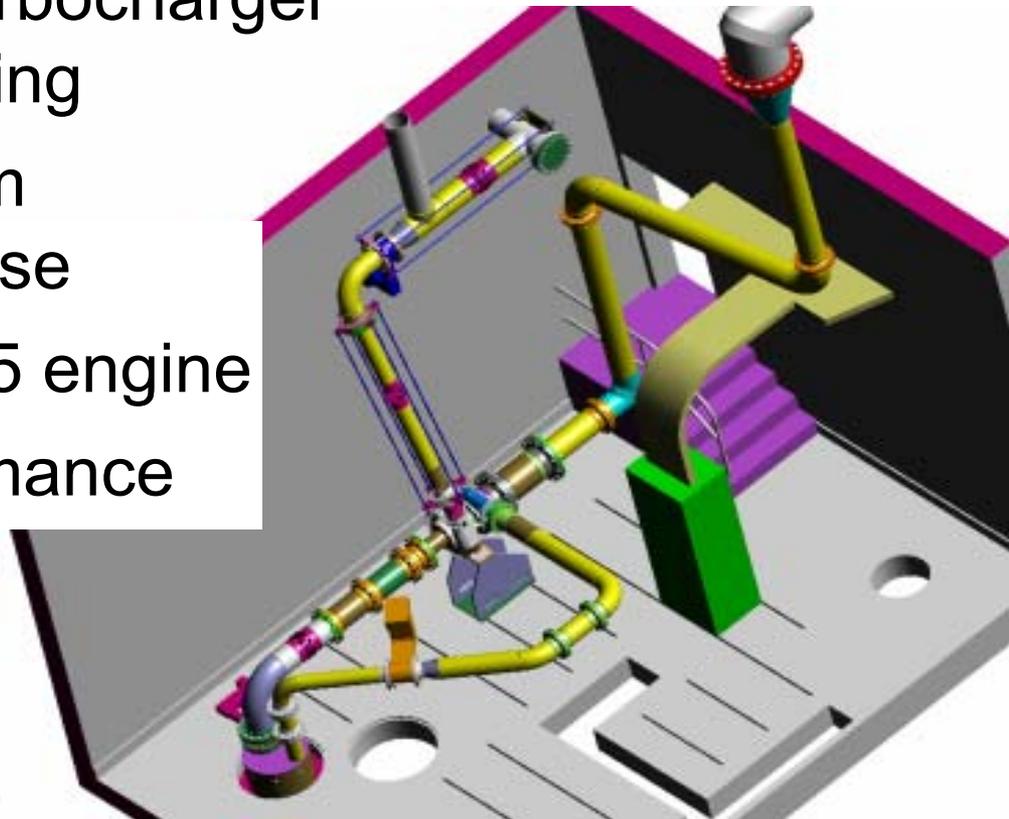
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Next Steps for ETC Development



- ❑ 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



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