Diesel Engine Waste Heat Recovery Utilizing Electric Turbocompound Technology

Department of Energy Contract
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Caterpillar Inc.

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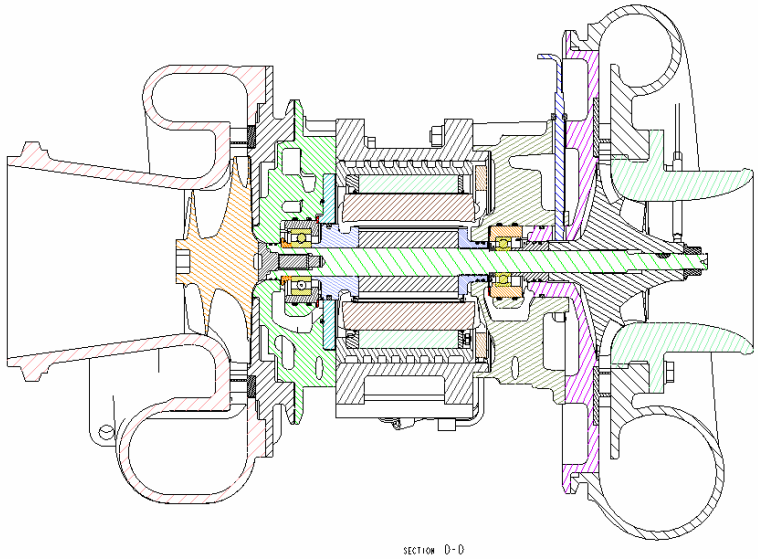
Agenda

- 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

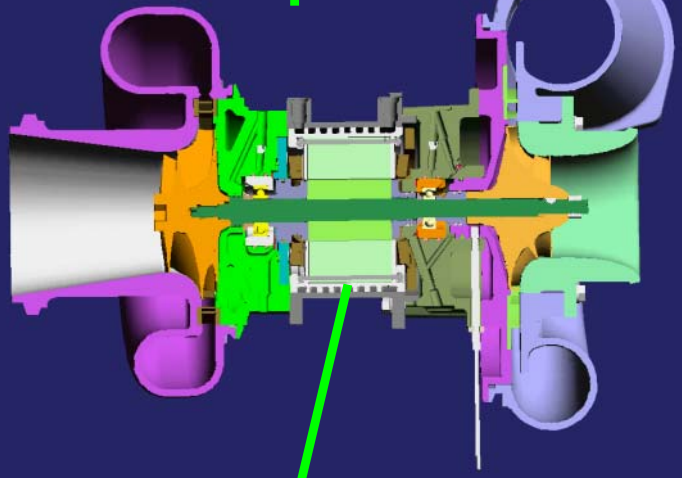
- Demonstrate Technical Feasibility
- Improve Fuel Economy

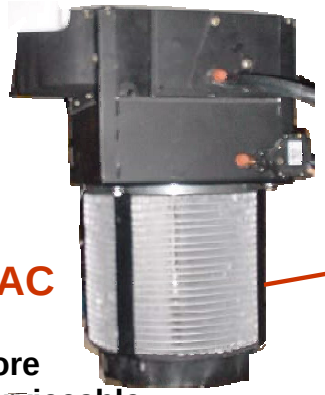


Program Goals and Milestones

- 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

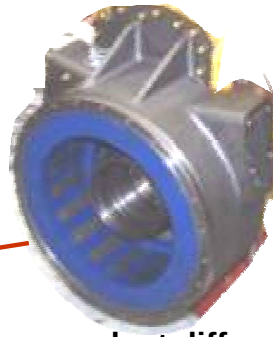




Modular HVAC

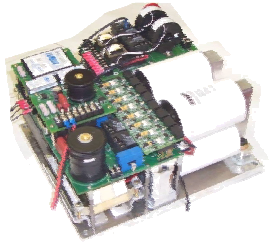
Variable speed compressor more efficient and serviceable

3X more reliable compressor no belts, no valves, no hoses leak-proof refrigerant lines instant electric heat



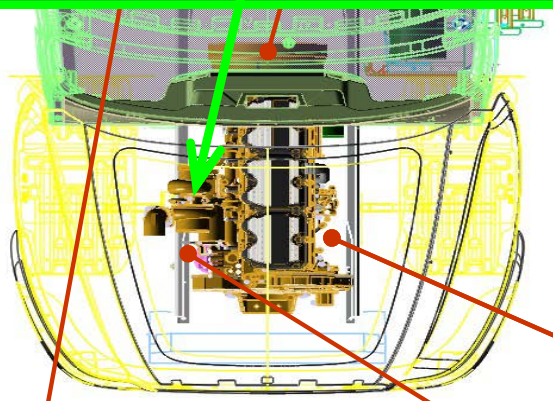
Starter Generator Motor

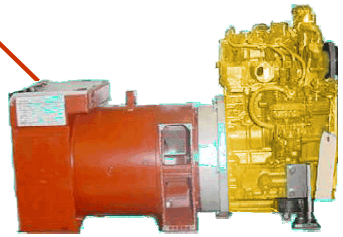
Beltless engine product differentiation improve systems design flexibility more efficient & reliable accessories



Shore Power and Inverter

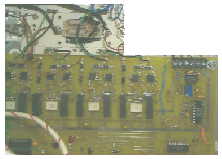
Supplies DC Bus Voltage from 120/240 Vac 50/60 Hz Input Supplies 120 Vac outlets from battery or generator power





Auxiliary Power Unit

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



Down Converter

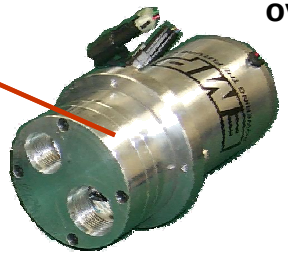
Supplies 12 V Battery from DC Bus

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

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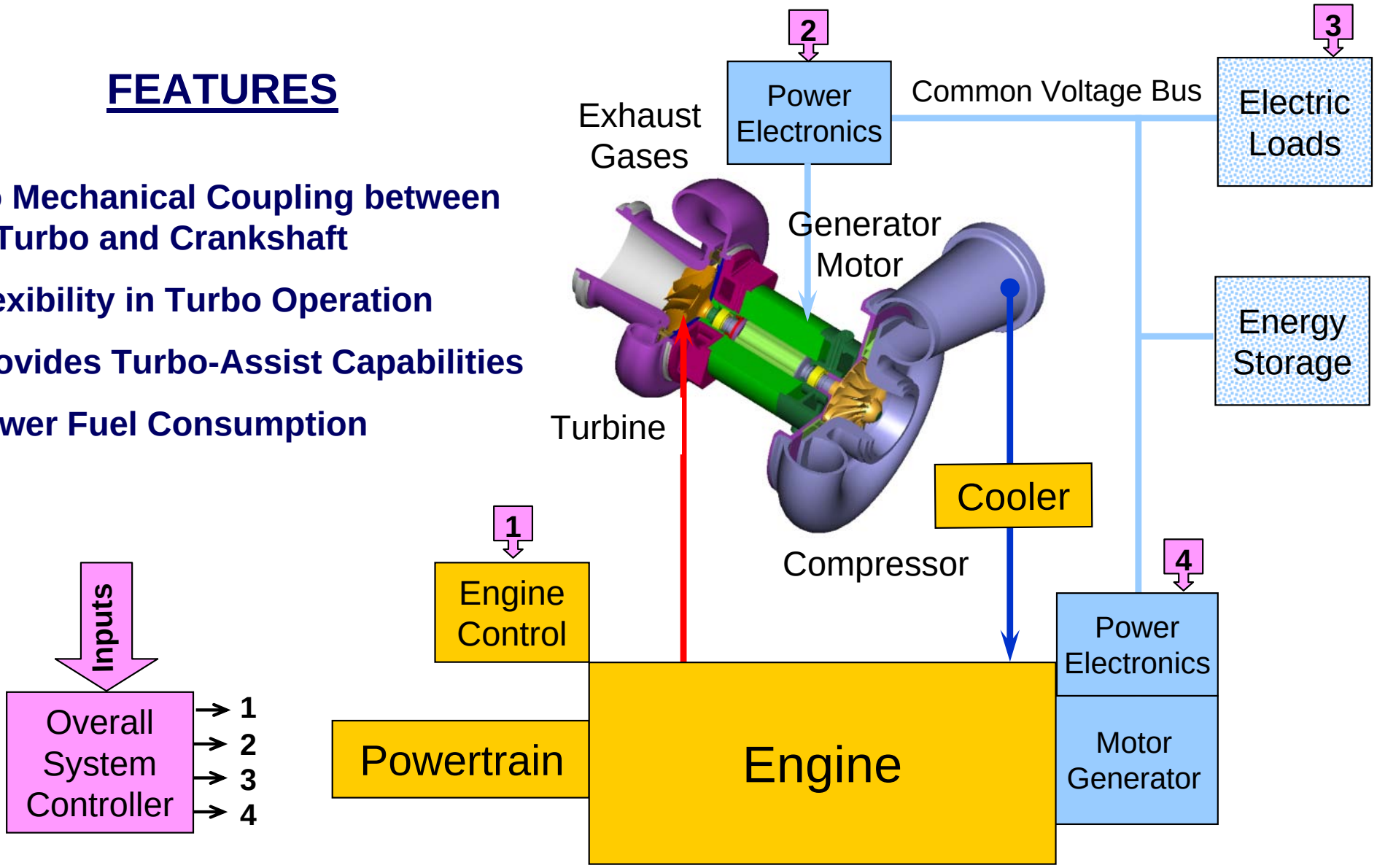
Caterpillar Engine Research
Diesel & Emissions Technology

Working Principle

FEATURES

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



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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

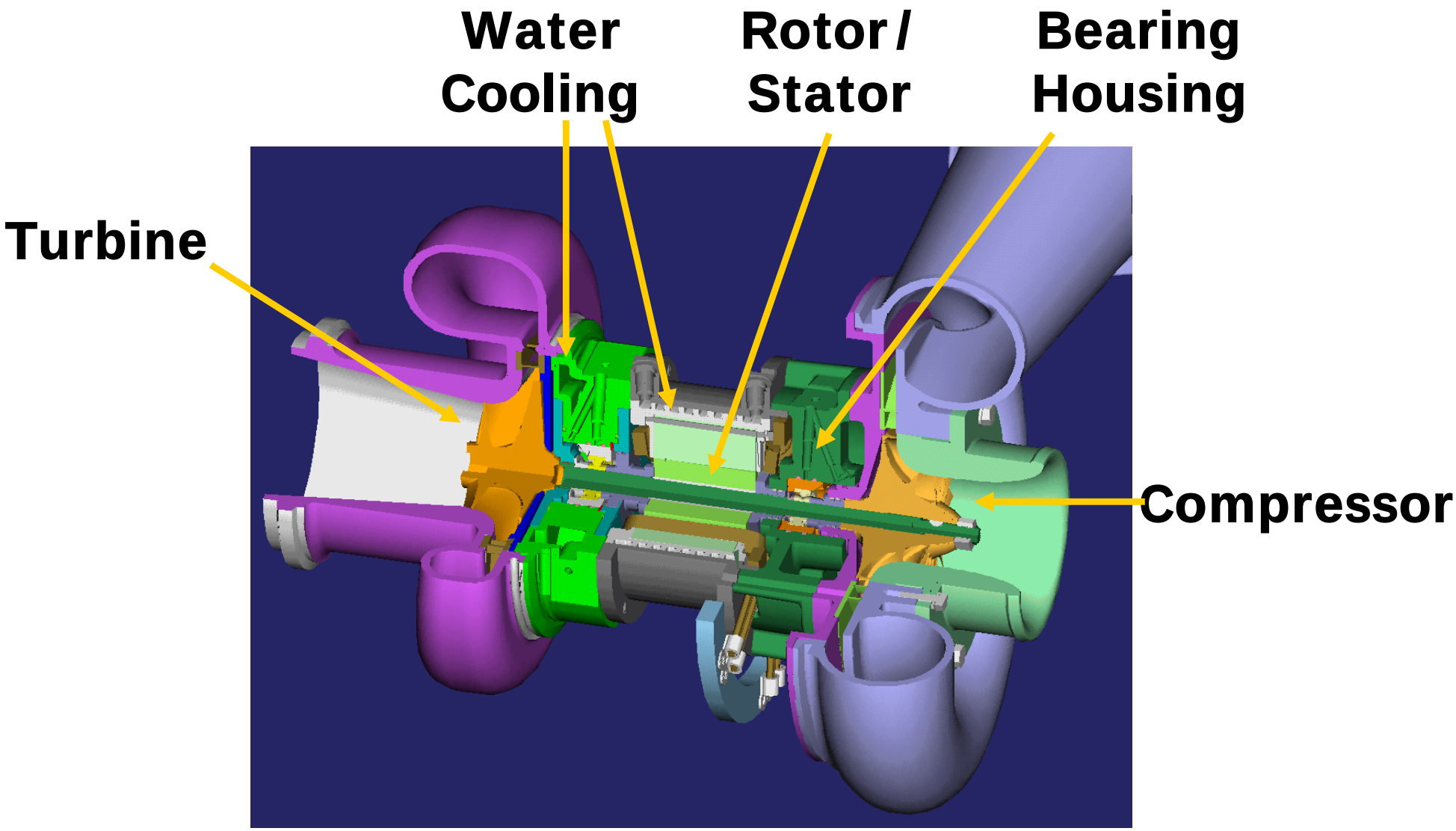
Progress to Date

- 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

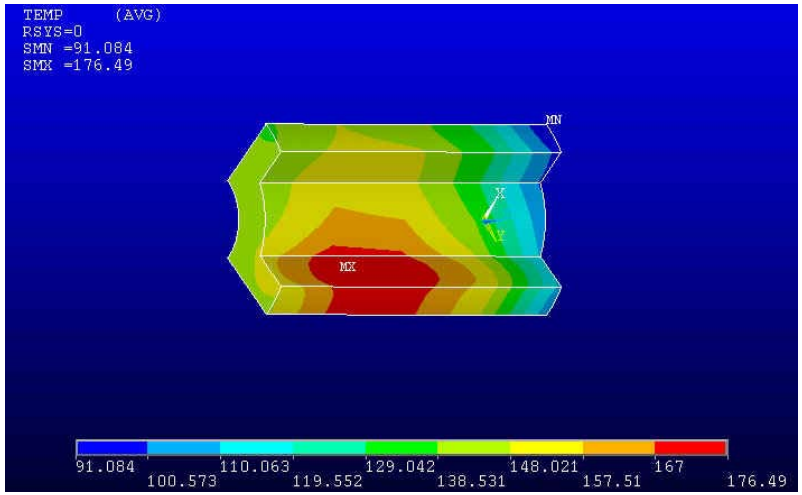
Final Design



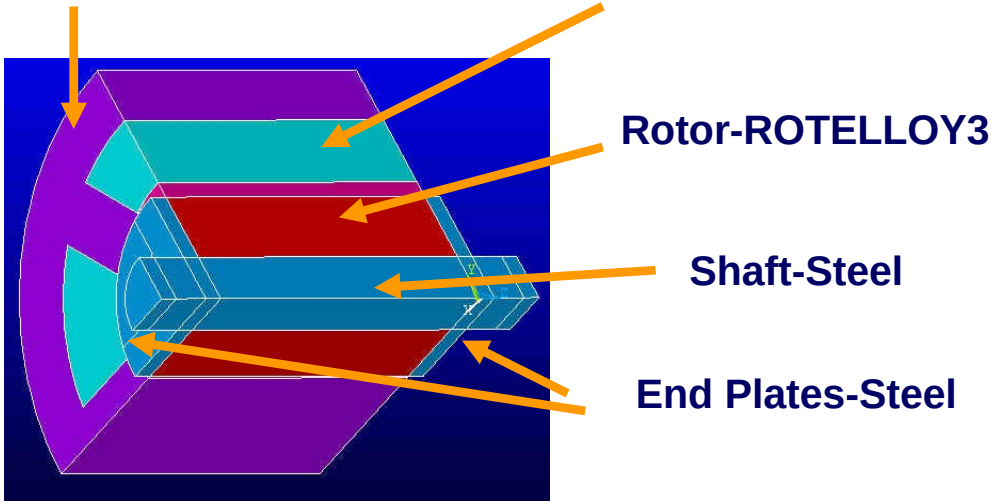
Turbo Shaft Generator Heat Transfer

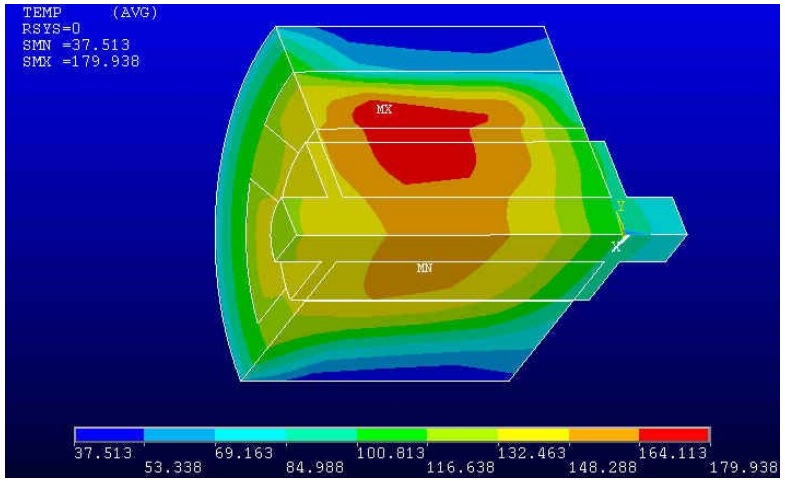
Voltage: Voltage: 340 V
Power: 40 kW / 60kW max.
Rotor/Stator Length: 70 mm 340 V

	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

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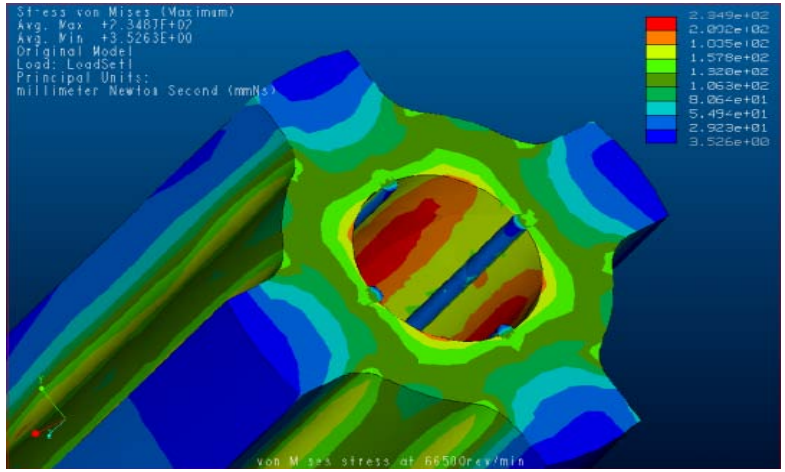
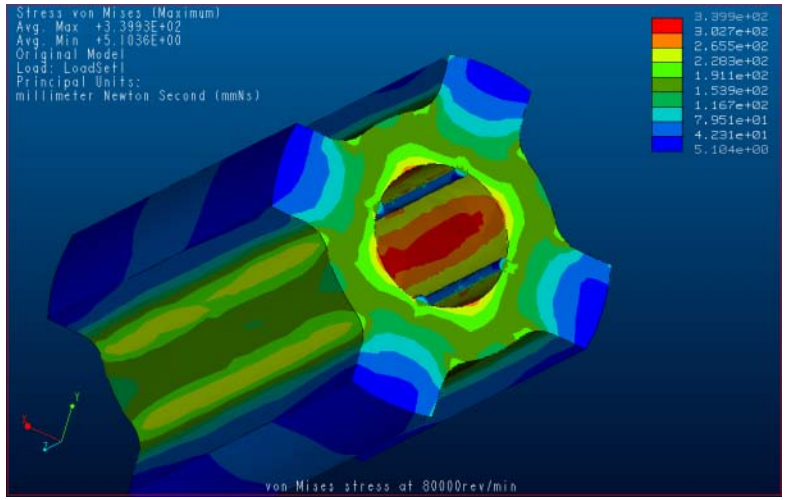
Turbo Shaft Rotor Lamination

FE Analysis

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

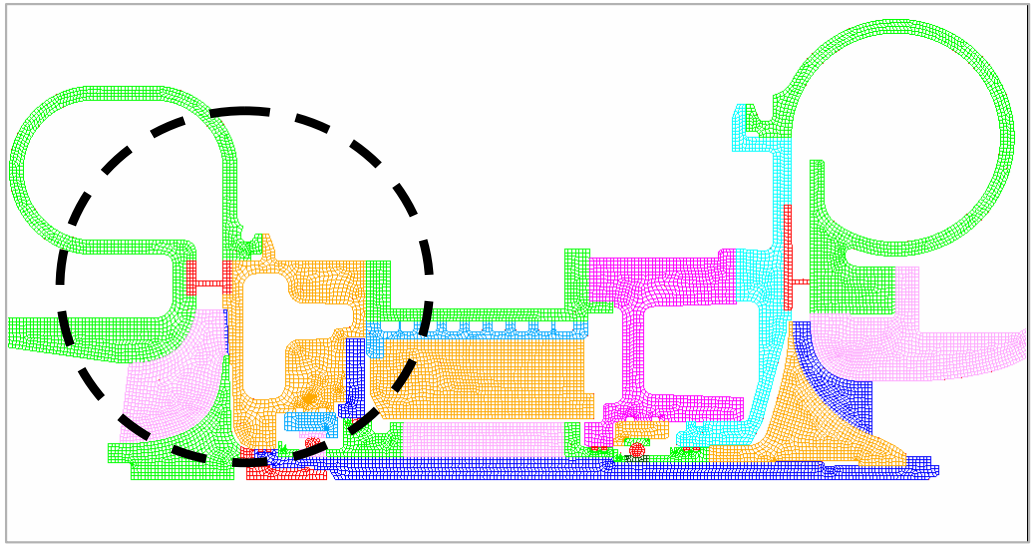


Stress @ 66,500 rpm design speed



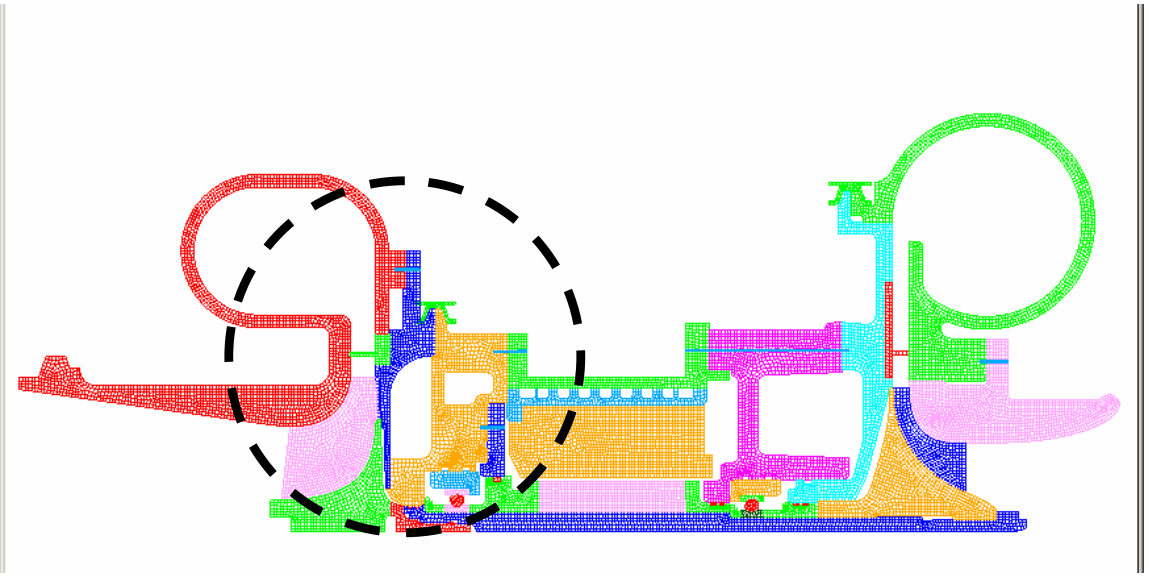
Stress @ 80,000 rpm over speed

Modified FE Model



Baseline Model

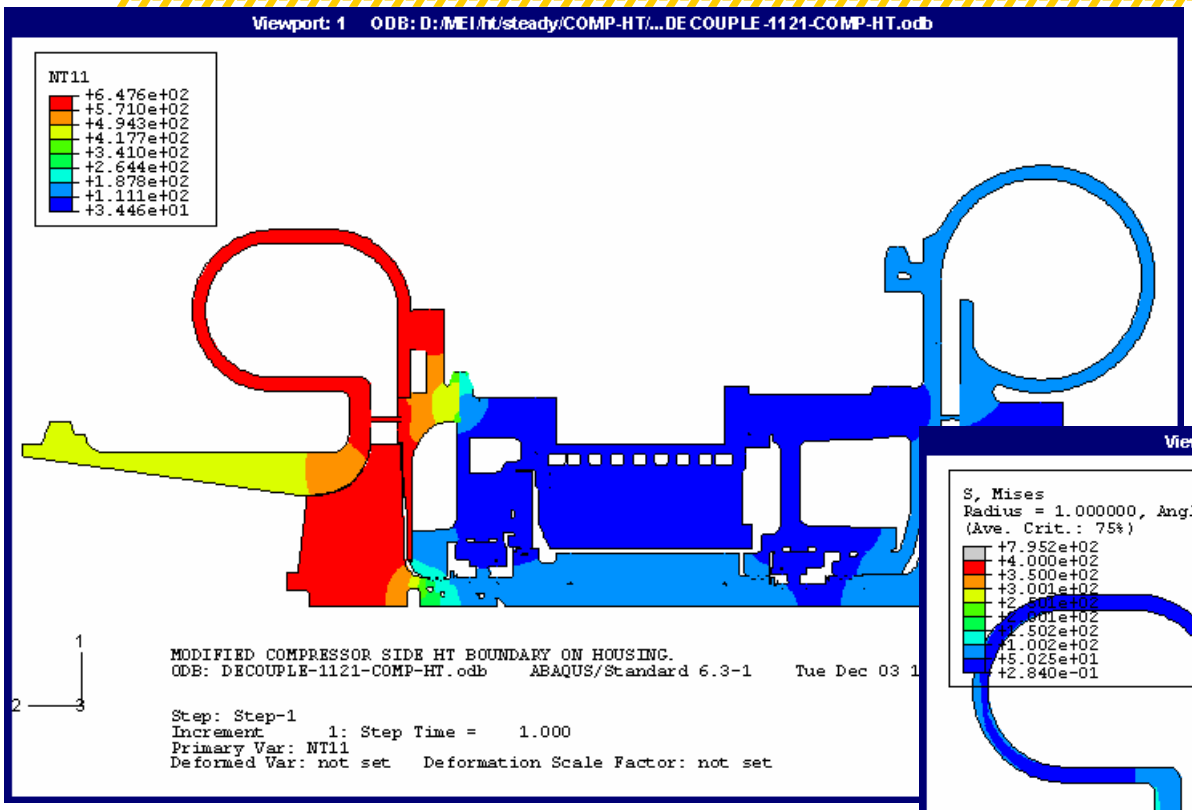
- High Temperature and Stress Gradients



Decoupled Model

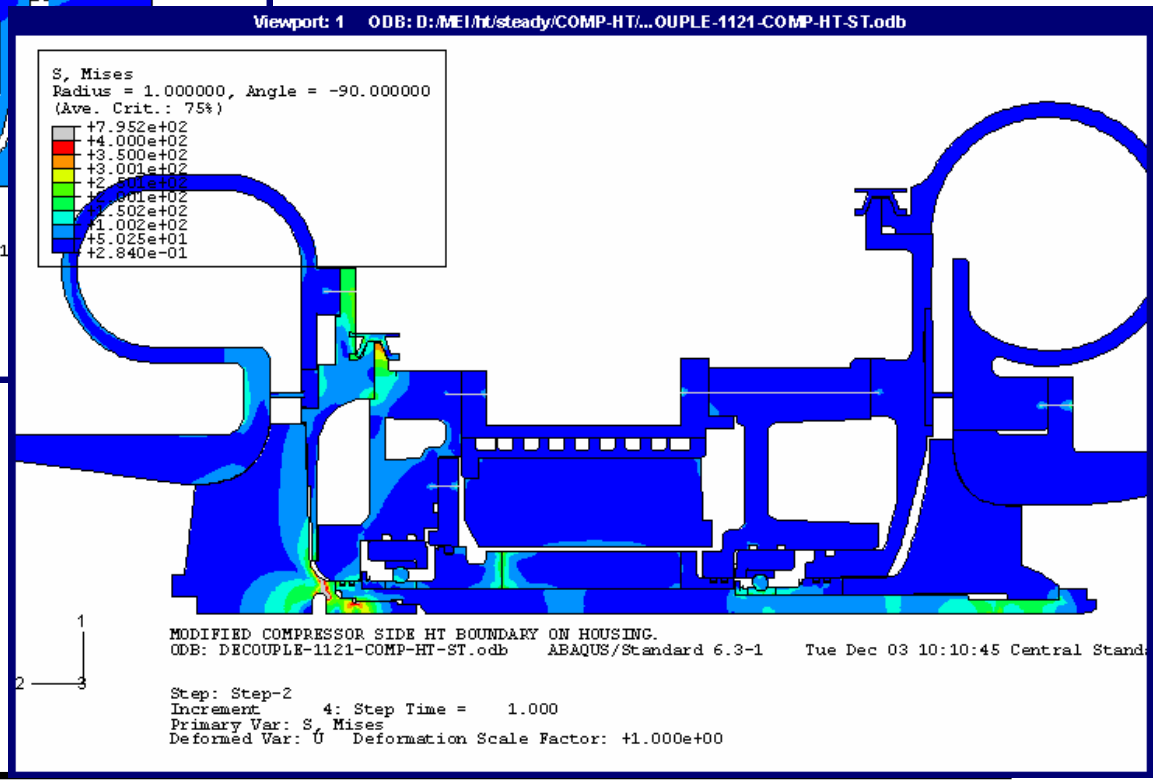
- Turbine Housing decoupled from Bearing Housing
- Decreased Waterpassage
- Lower Stresses

FE Analysis Steady State



Thermal Analysis

Stress Analysis



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Compressor and Turbine

Compressor Scroll and
Compressor Wheel with Diffuser

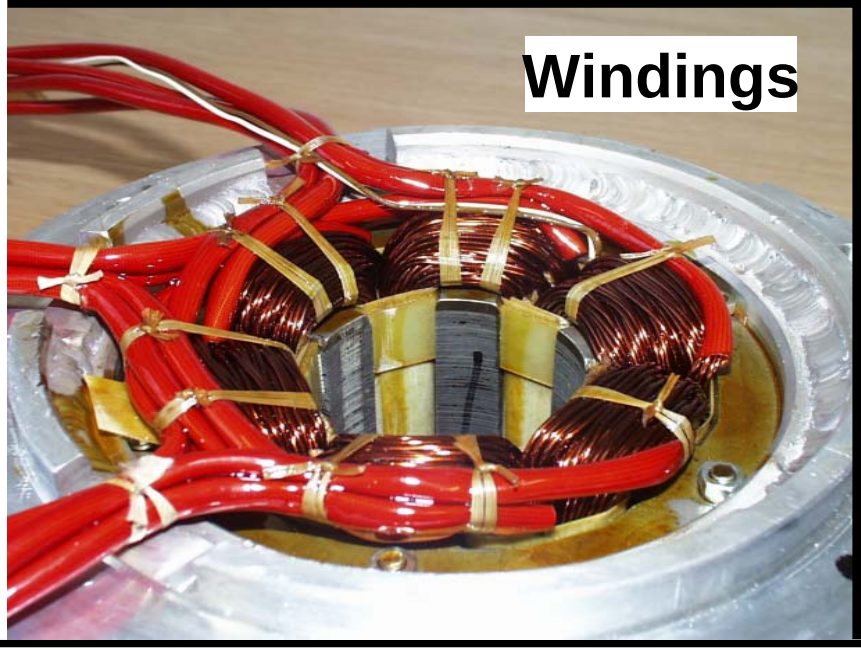
Turbine Scroll and
Turbine Rotor with Nozzle

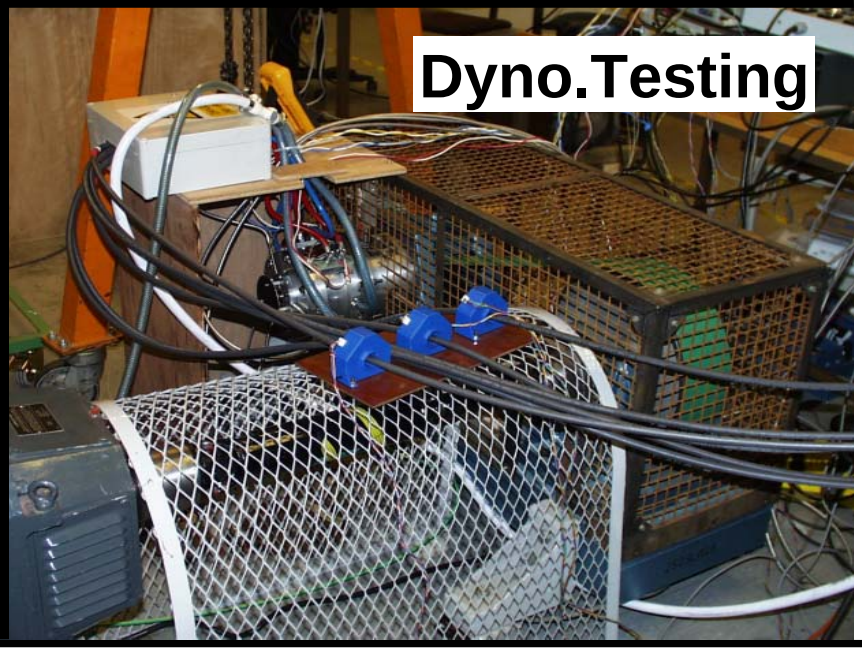
Turbo Shaft

Turbo Shaft w/ Ball Bearings

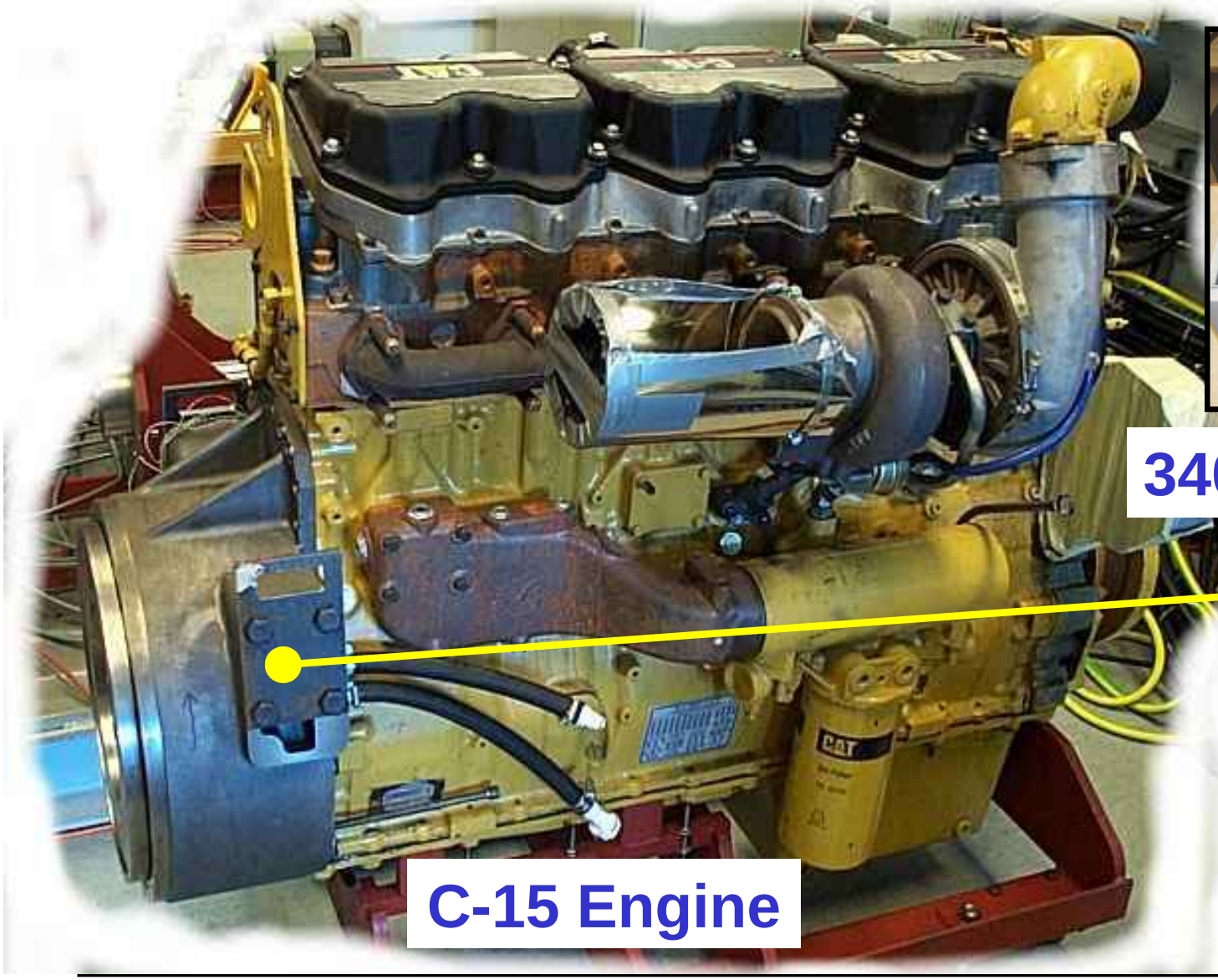
Compressor Wheel on Shaft

Turbo Shaft – Generator/Motor



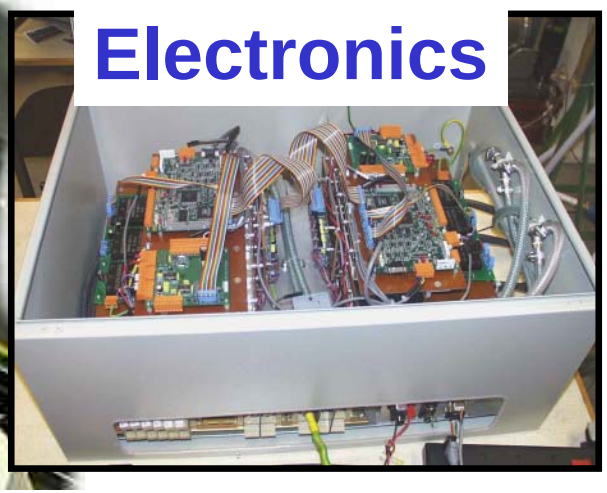


Crank Shaft - Motor/Generator & Housing

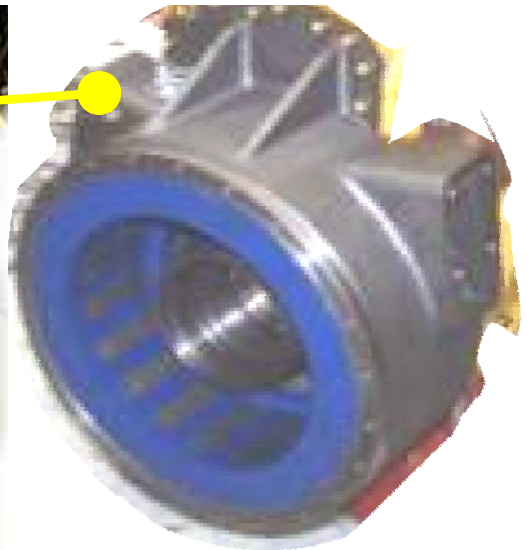


C-15 Engine

Electronics

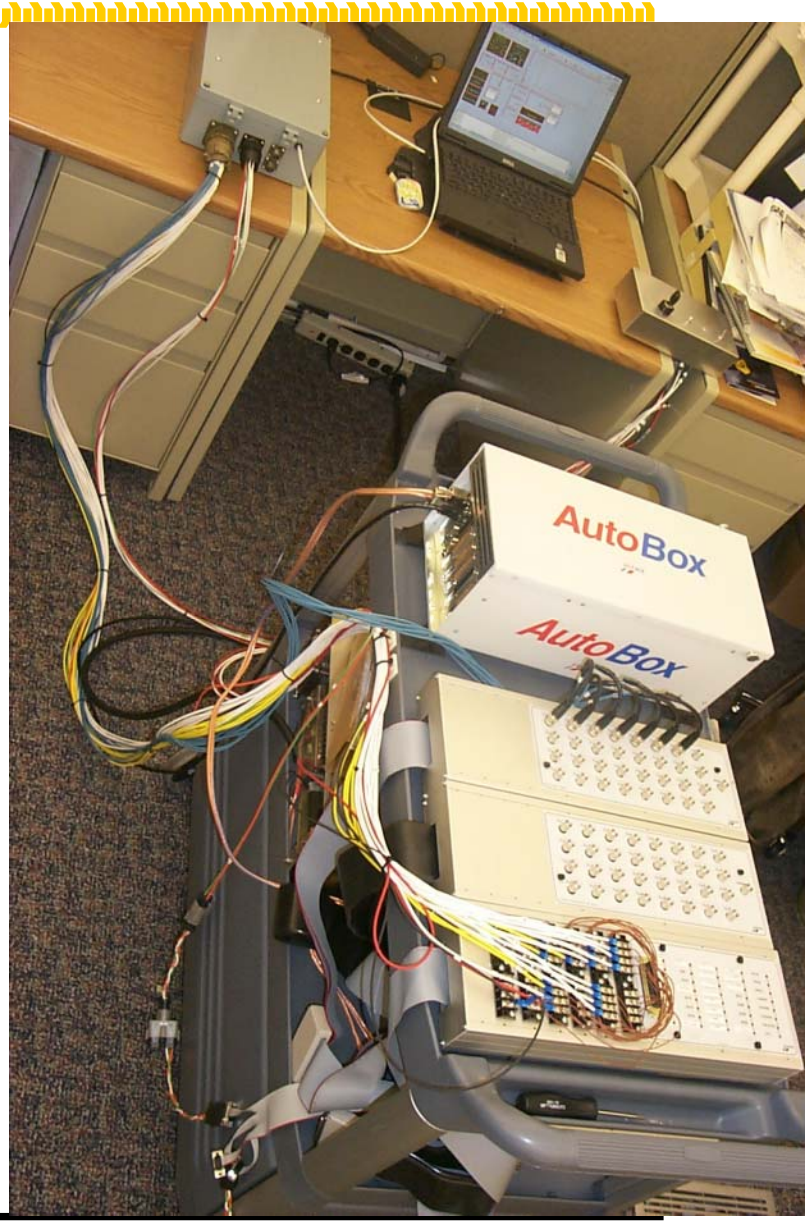


340 Vdc Generator



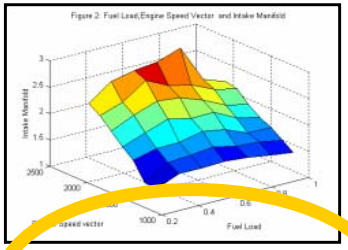
Control System Development

- 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



ETC Control System

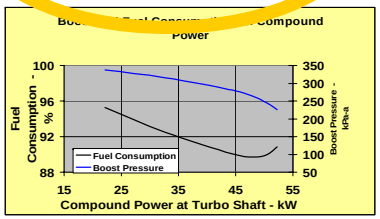
- System Simulation in Simulink
- Controller Implemented in dSpace
- Virtual Instrumentation Capabilities

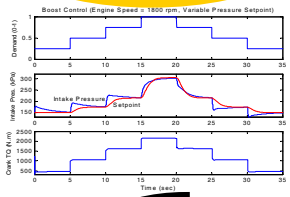


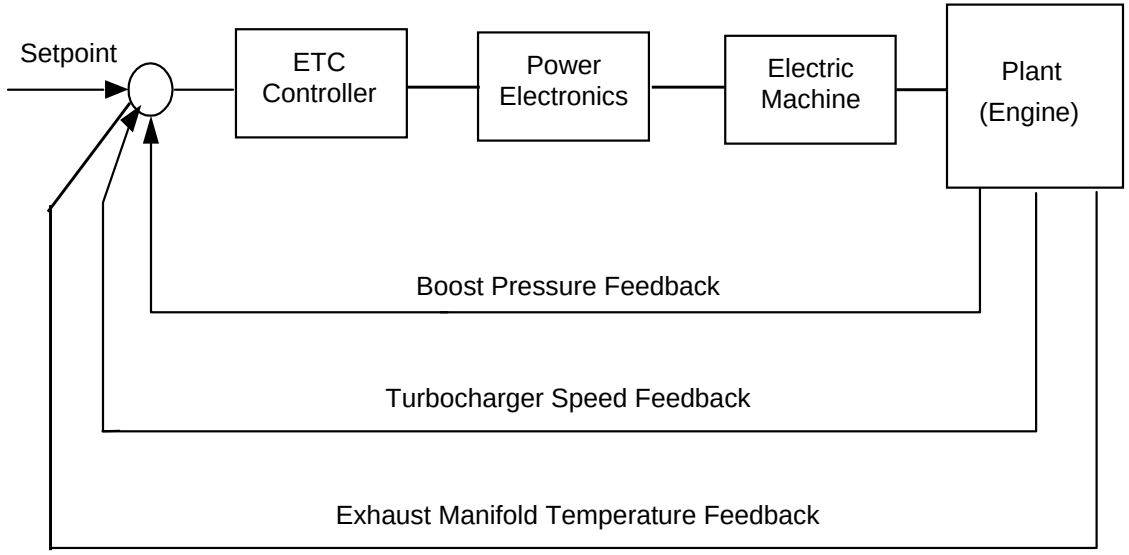
Map Boost / Speed / Load

Boost at Optimum Fuel Consumption

Set Point for Transient Behavior







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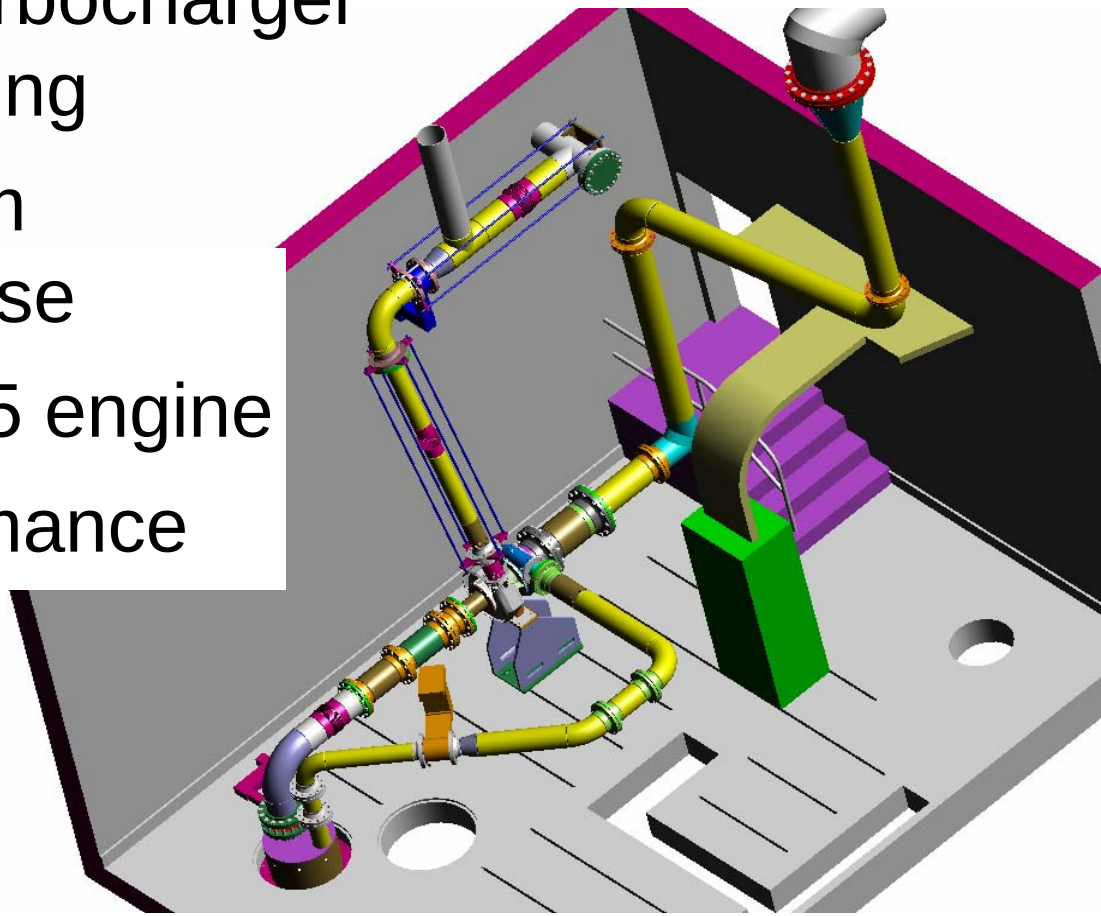
Next Steps for ETC Development

- 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



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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