**2006 Diesel Engine-Efficiency and Emissions Research (DEER) Conference**

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J. LaGrandeur

# Automotive Waste Heat Conversion to Electric Power using Skutterudites, TAGS, PbTe and $Bi_2Te_3$

BSST innovative solutions in temperature control

Visteon

NETL

NREL

Jet Propulsion Laboratory
California Institute of Technology

# Discussion Outline

Background program information and system architecture

System modeling (bumper to bumper vehicle model inclusive of thermoelectric system)

Key Subsystems:

- Primary Heat Exchanger (PHx)
- Thermoelectric Generator Module (TGM)
- Power Control System (PCS)

Conclusions and further work

Acknowledgements

# Program Timing and Objectives

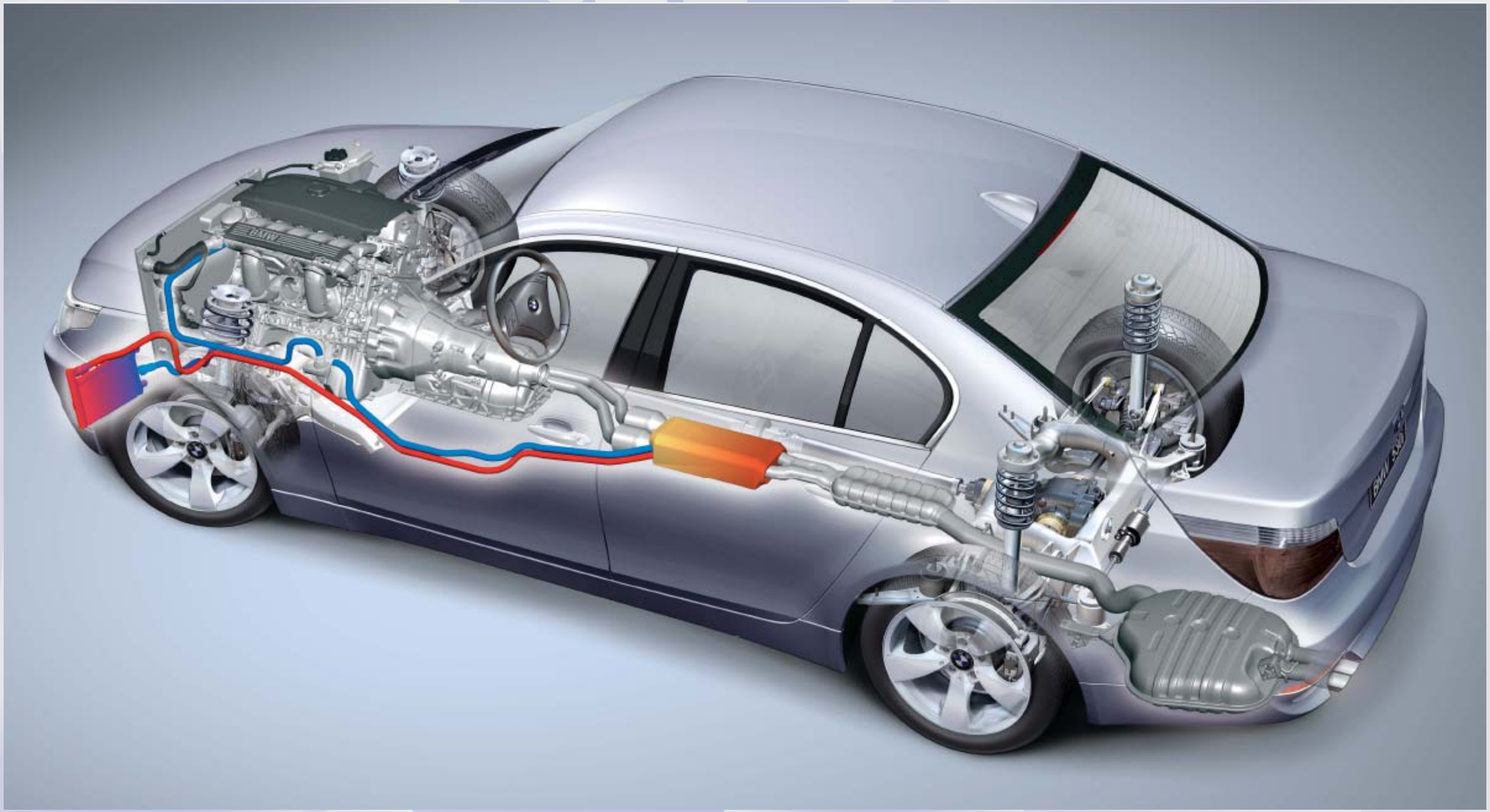
**Phase 1:**
modeling & prelim. design
11/04 to 5/05

**Phase 2:**
bench system build and test
6/05 to 12/06

**Phase 3:**
Design iteration, system integration & test
1/07 to 8/07

**Phase 4:**
Engine integration and system test at NREL
9/07 to 8/08

# Thermal Management.
# Thermoelectric Generator.



# Vehicle / Engine Selection

***Selected vehicle platform (BMW 530i, MY2006)***

***Selected engine platform (Inline 6 cylinder, 3.0 l displacement)***

The selected vehicle is a state-of-the-art BMW sedan with a 3 liter displacement engine (BMW 530i, MY 2006, automatic transmission).

The engine is the newest generation of highly efficient, in-line, 6-cylinder engines with characteristics representative of engines in the 2010 to 2015 timeframe

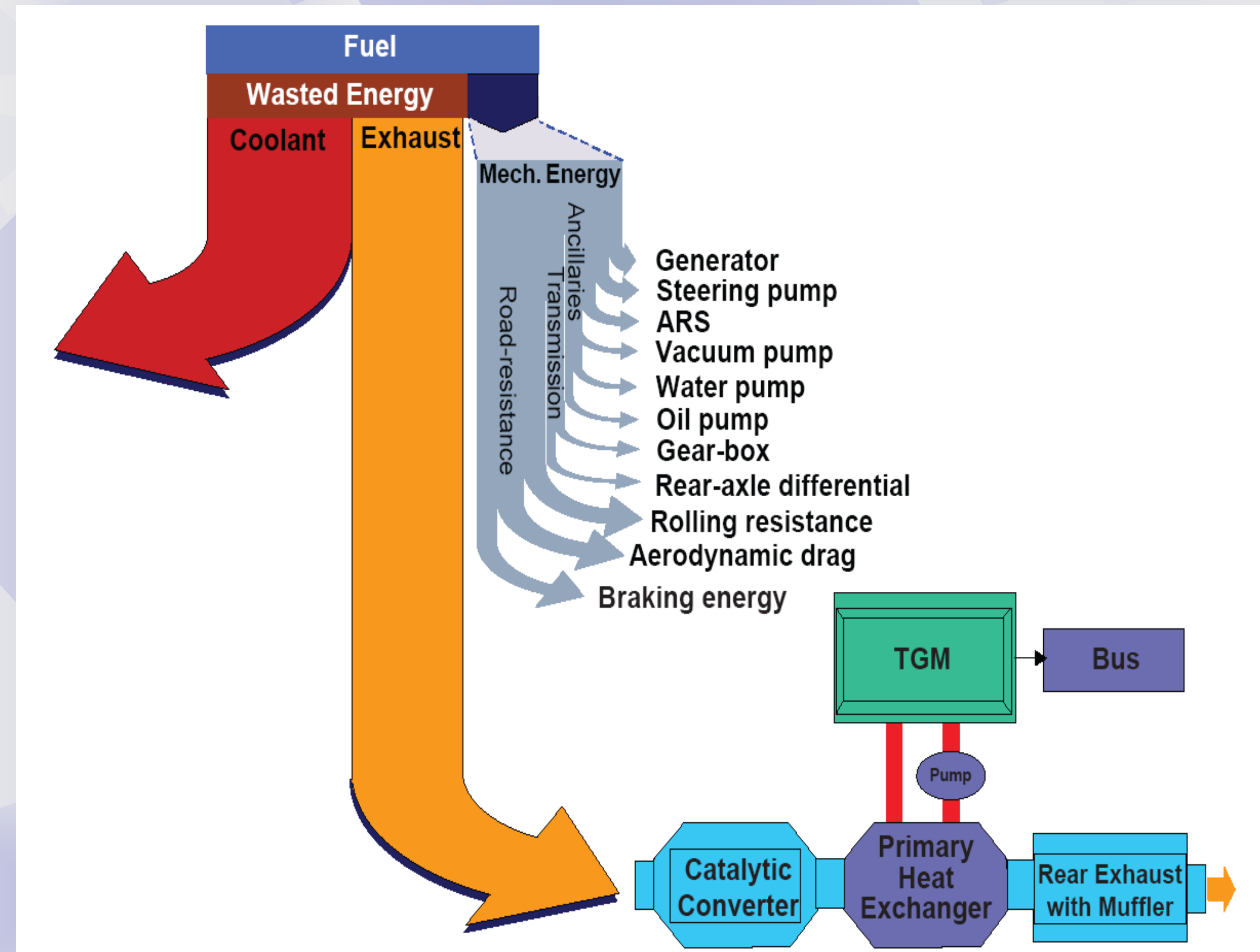
# System Development Challenges

A simulation tool needs to be created that integrates a thermoelectric waste heat recovery system within a bumper to bumper vehicle model

Wide variations in exhaust gas mass flow must be managed to optimize the efficiency of the thermoelectric generator module (TGM)

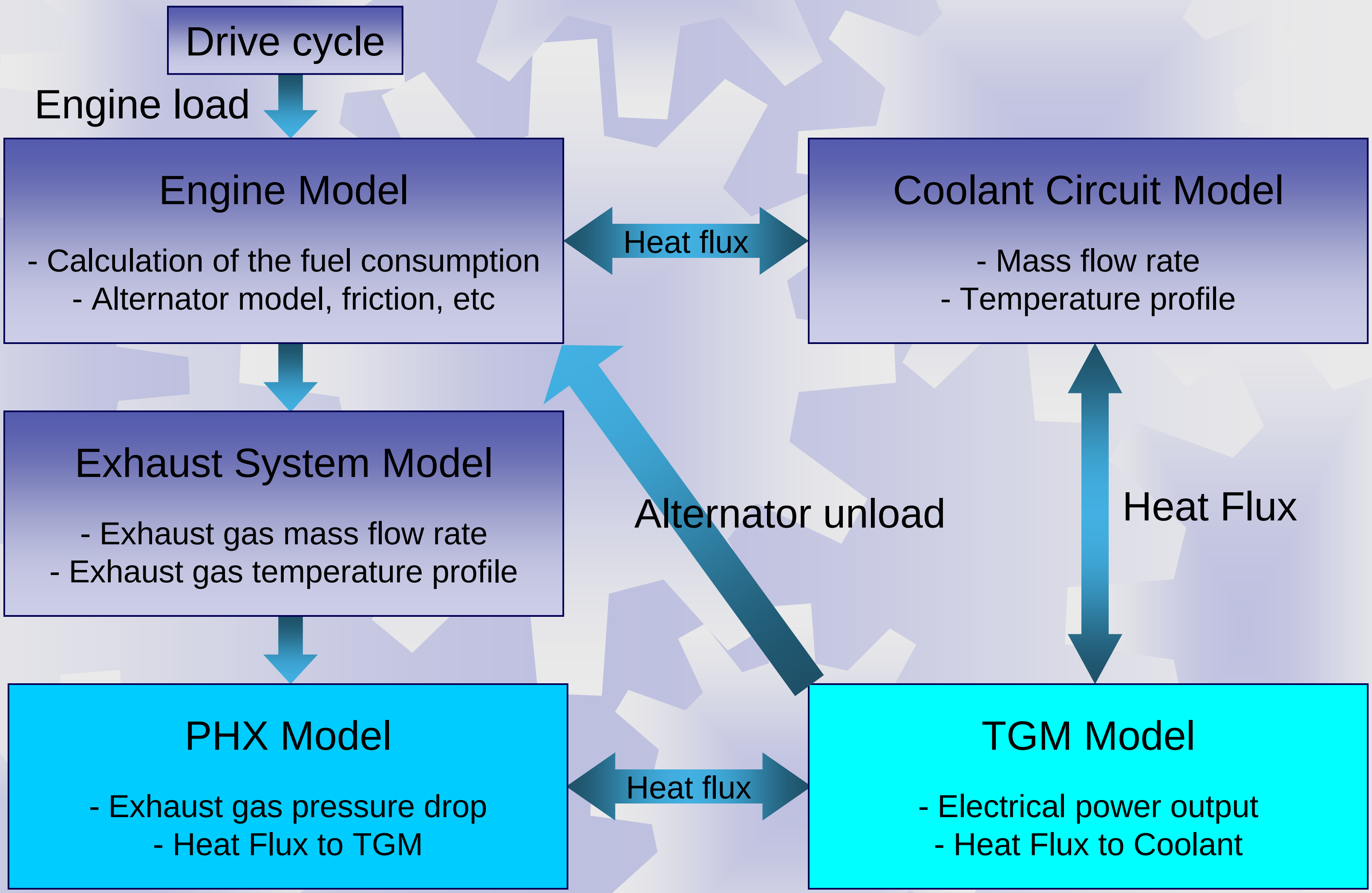
The TGM output power, which varies according to driving conditions/exhaust gas mass flow, must be integrated with as little loss as possible with the vehicle power bus.

# System Block Diagram



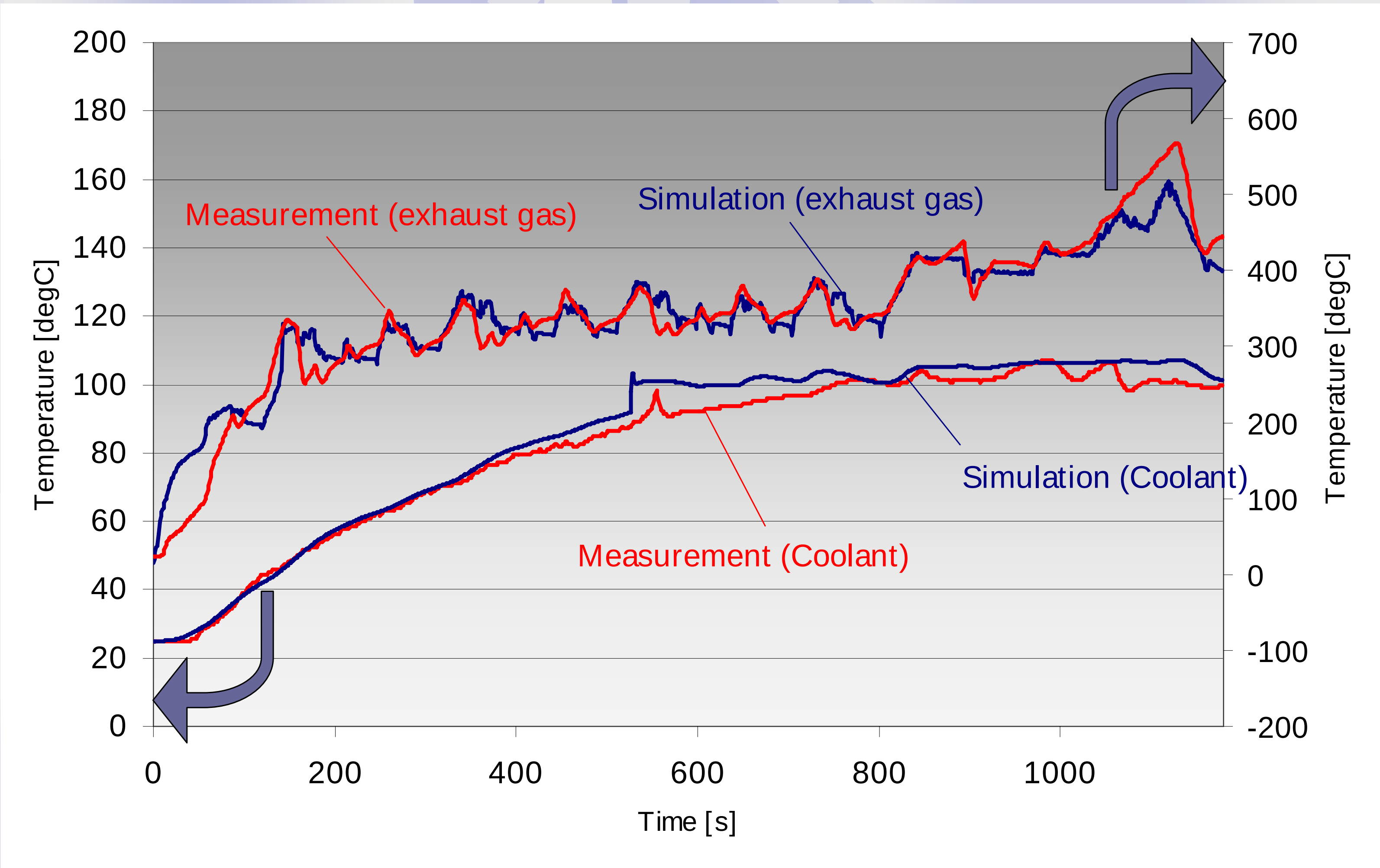
# System Modeling

# GT Cool Simulation Overview



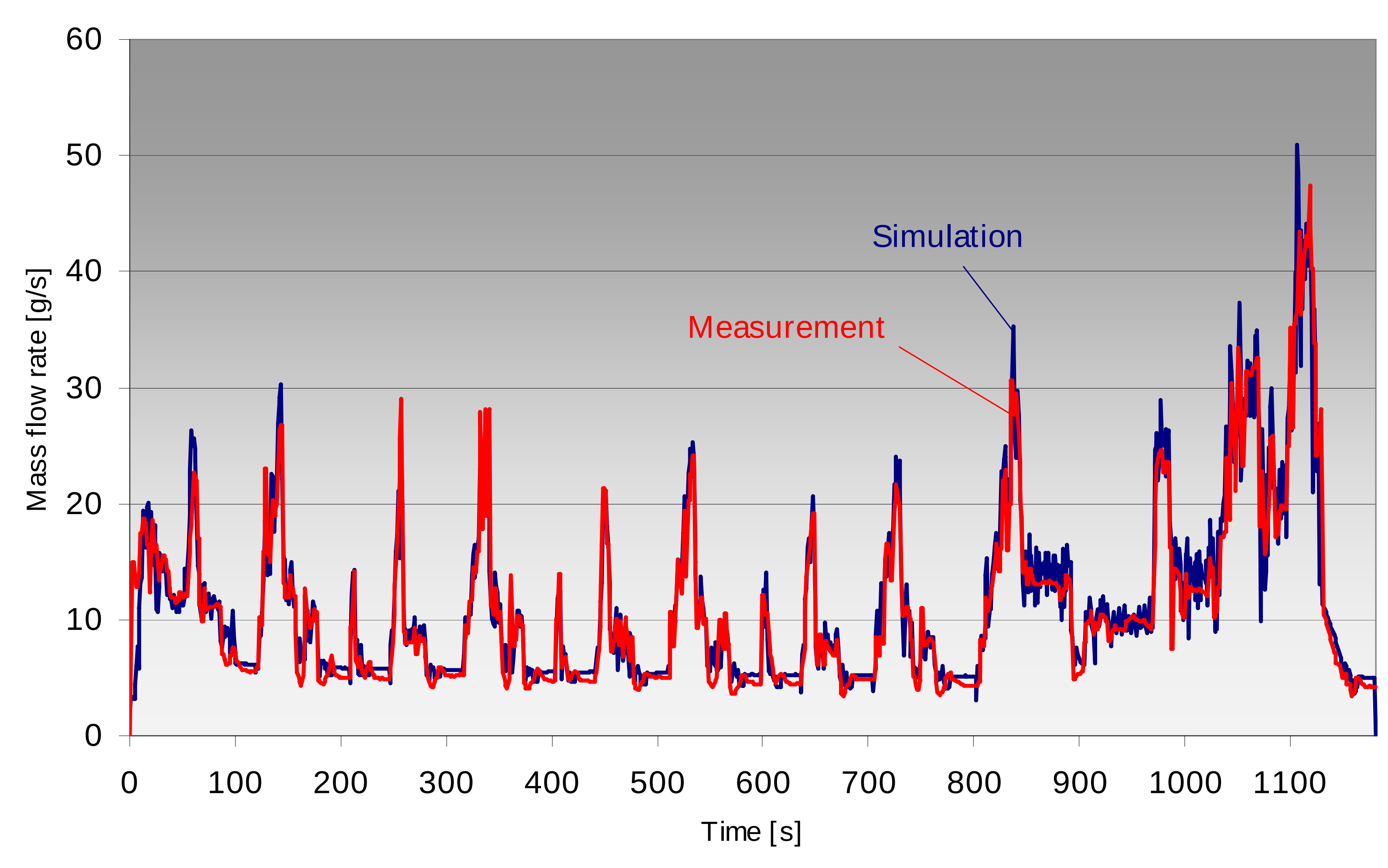
# System Model- Validation

**Coolant and exhaust gas temperature (for NEDC)**



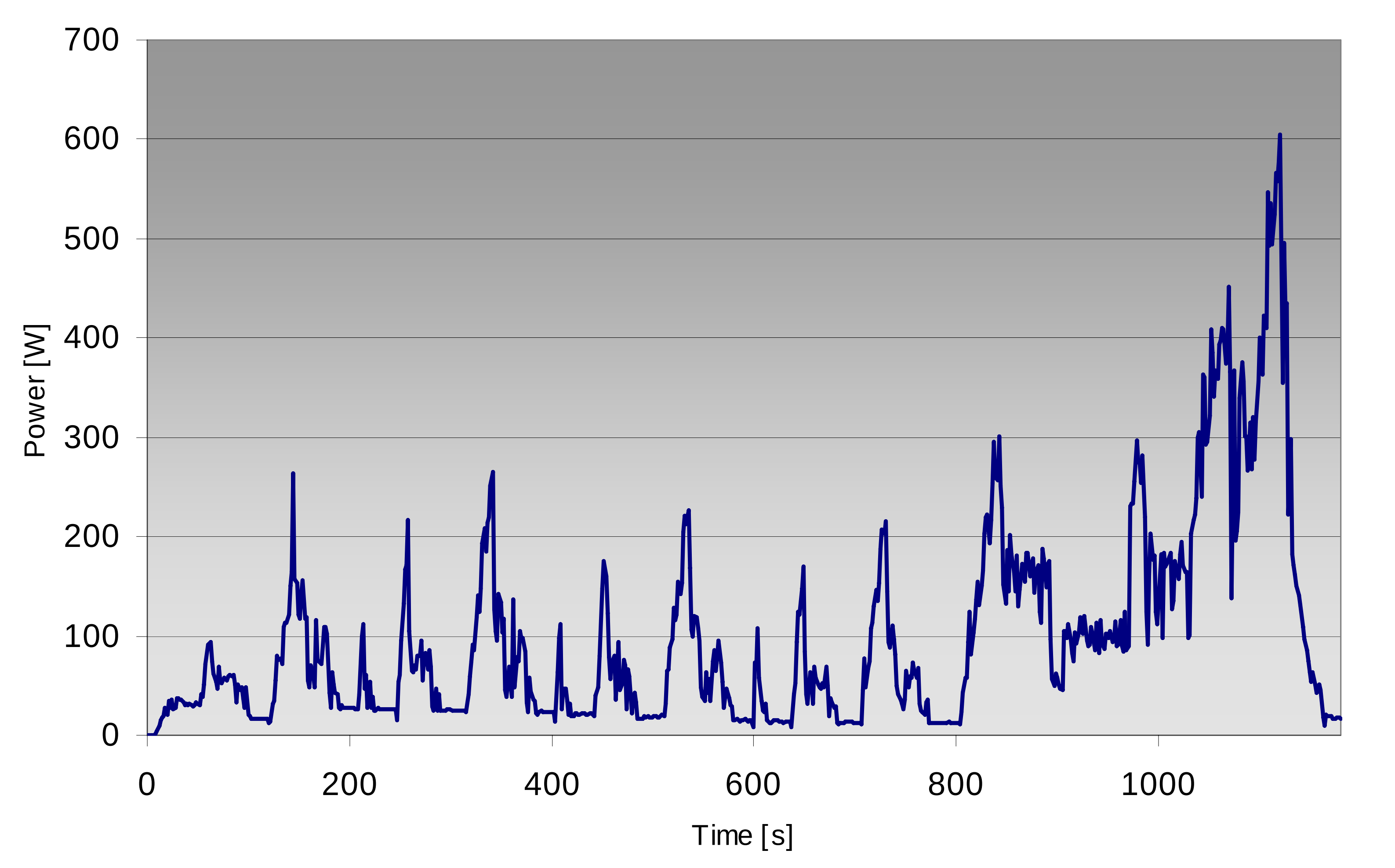
# System Modeling

**Exhaust gas mass flow rate (for NEDC)**



# System Modeling

**Electrical power output of the TGM (for NEDC)**



# Primary Heat Exchanger (PHx) and Pump

# Primary Heat Exchanger and Pump Functions

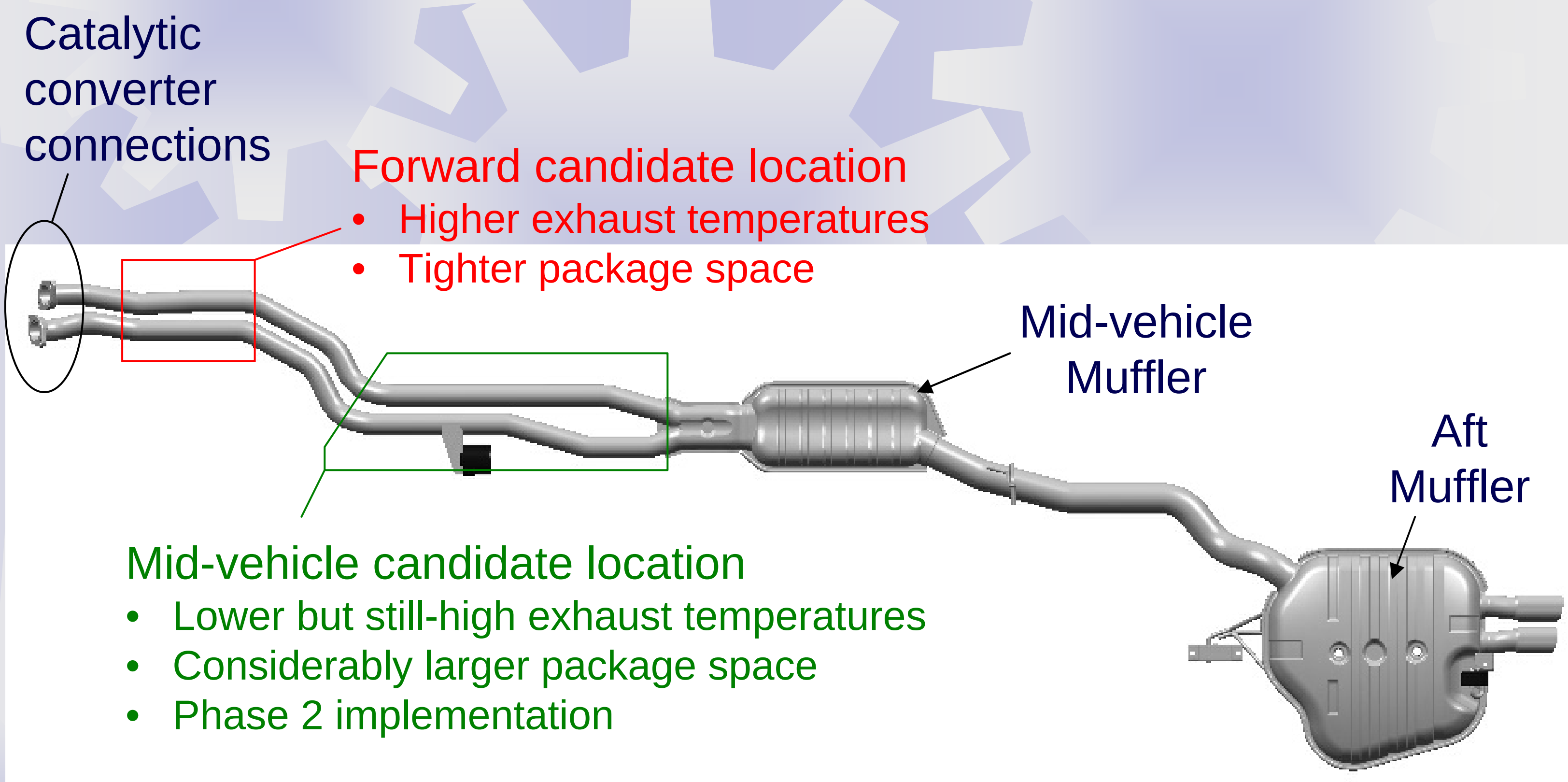
## Primary Heat Exchanger

- Extracts heat energy from vehicle exhaust gas stream.
- Transfers exhaust heat energy to the TGM hot-side via a gaseous working fluid, designated as 75% He/ 25% Xe.

## Hot side working fluid pump

- Located downstream from the TGM
- Circulates hot working fluid between the PHX and TGM.
- Mechanism for controlling heat energy transfer rate from PHX to TGM.

# Primary Heat Exchanger Location




BMW 530i Exhaust System
← Front of Vehicle

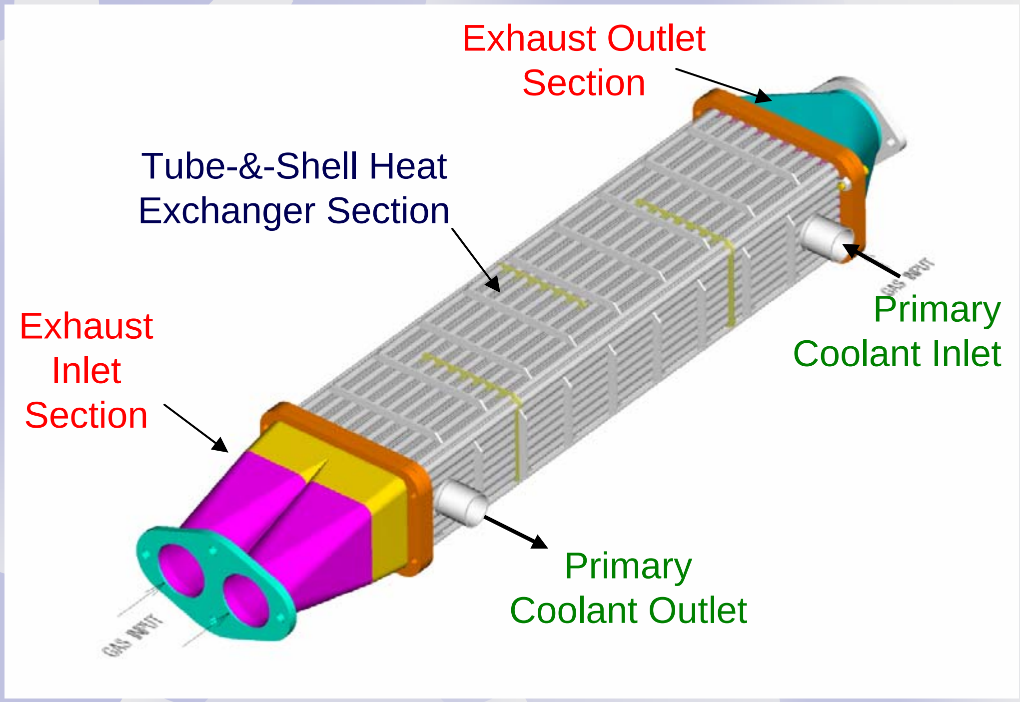
# Primary Heat Exchanger Description

Requirements:

- Exhaust inlet temperatures up to 750°C
- Exhaust path pressure drop <100mbar
- TGM hot-side working fluid temperatures up to 700°C with pressure up to 12.2bar

Implementation:

- Modified Visteon EGR Cooler technology

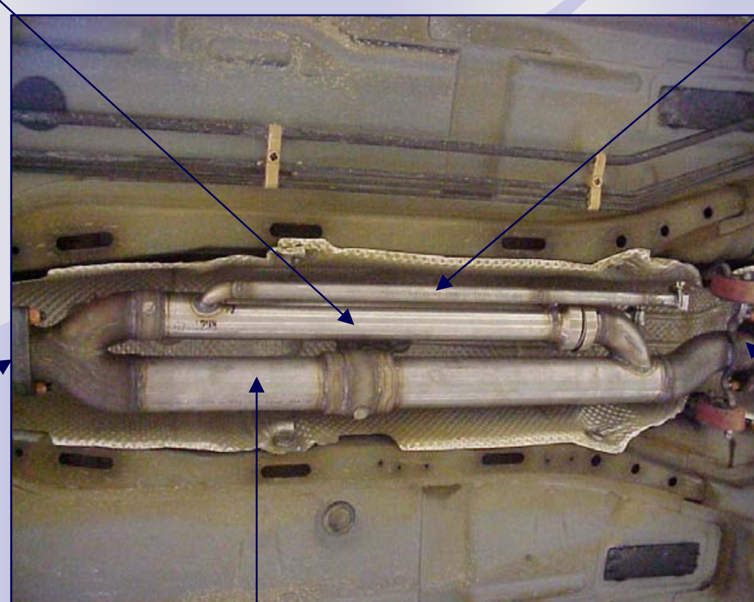



- Stainless steel tube-&-shell heat exchanger.
- Dual inlet accepts 530i dual catalytic converter outlet streams
- Single outlet feeds the 530i mid-vehicle muffler.

# PHx With Exhaust Gas By-Pass

Shell & tube heat exchanger for exhaust gas heat transfer

Working fluid transports thermal energy



Cat converter

Muffler

Exhaust gas bypass flow

# Thermoelectric Generator Module (TGM)

# TGM Development Methodology

- Model, design and build fractional generator (1/35$^{th}$ of full-scale)
- Validate performance model
- Replicate fractional generator to scale up to ~ 750 watts
- Integrate fractional generators with tube-style liquid heat exchangers on the cold side, metal fin heat exchangers on the hot side
- Test and revalidate the performance model

# Fractional Generator Design Basics

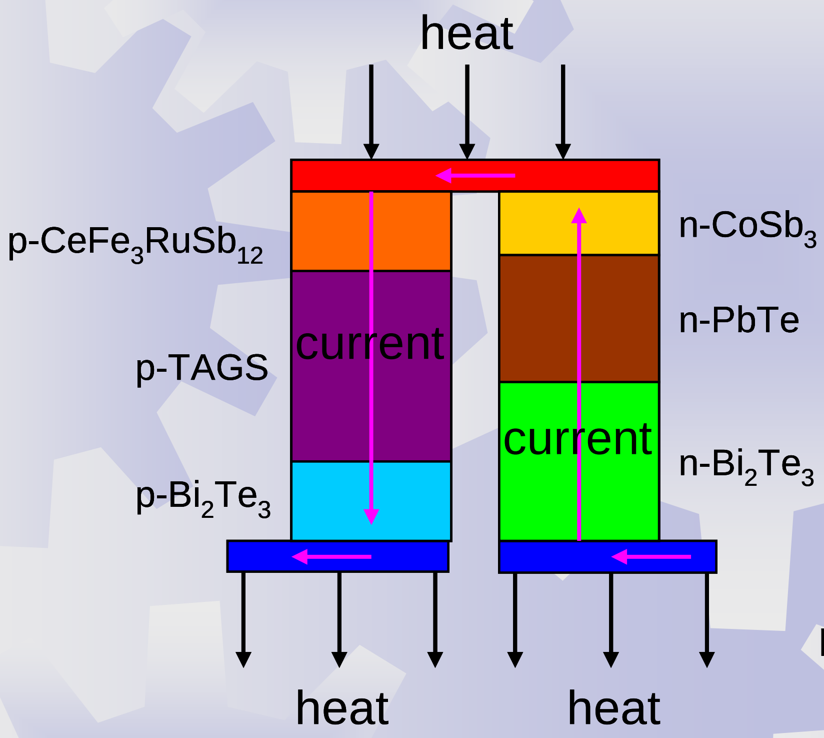
Segmented TE elements comprised of p & n type Skutterudites and $Bi_2Te_3$, TAGS and n type PbTe

- Thermally isolated elements in the direction of flow
- High power density configuration
- Methods to combat TE material incompatibility and thermal expansion mismatch

Hot side working fluid temperature decreasing

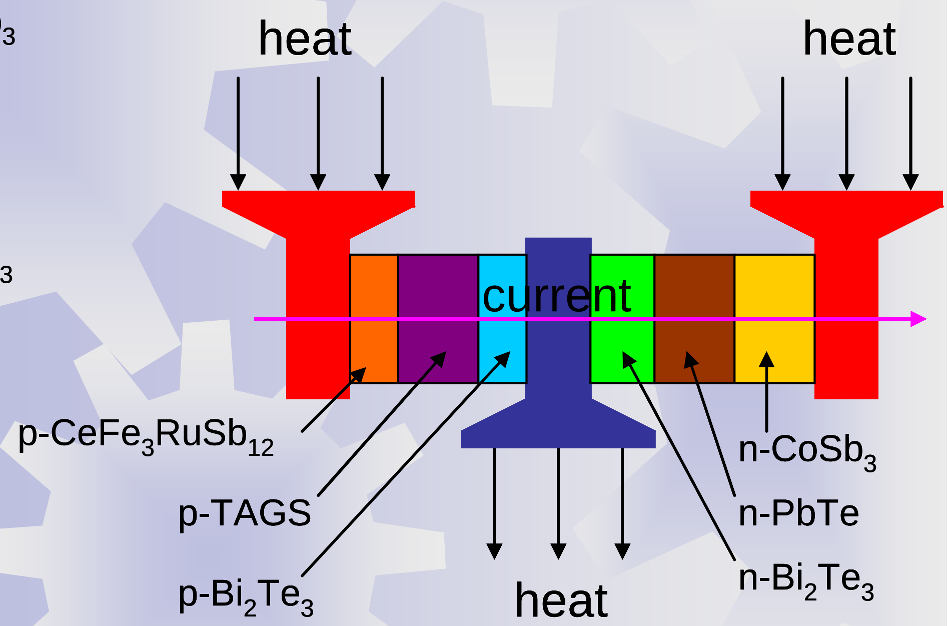
Cold side working fluid temperature increasing

# TE Couple Configuration Alternatives with Segmented Elements




Traditional configuration

Alternative "Y" configuration



# TE Device-Level Model

Steady-state numerical model comprised of simultaneously solved, non-linear, energy balance equations- will be evolved to provide transient analysis capability by 2006-end

Advanced multi-parameter, gradient-based optimization techniques are used to better understand the interactions between various design variables and parameters.

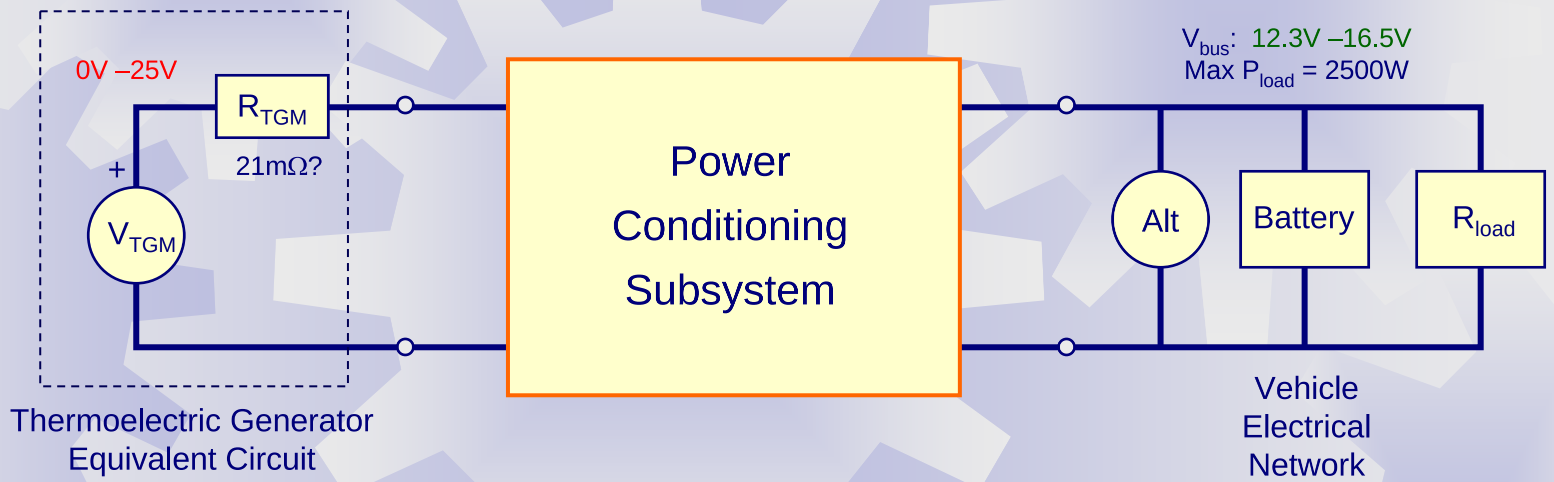
- Fin material/density
- Heat transfer fluids density, viscosity, K, $C_p$
- TE element quantity, geometry, ZT, K, seebeck and resistivity
- Interfacial materials, solder, braze, thermal greases, liquid metals

# Fractional Generator Status/Summary

- Power curves have been generated for low temperature and limited high temperature materials with results matching the model predictions
- The fractional device will be completed with 35-40 stacks comprising a full scale TGM to deliver a nominal power output of 750 watts at a $\Delta T$ of ~ $500^0$C
- Hot side gas and cold side liquid heat exchangers will be integrated with careful management of thermal boundaries and stresses
- Series and parallel redundancy will be incorporated to supply a target voltage of 12 VDC

# Power Conditioning Subsystem (PCS)

# Power Conditioning Subsystem
## Architectural Overview




- Accepts power from TGM over 0V-25V range.
- Delivers up to 1500W to vehicle electrical power bus at bus voltage over 12.3V-16.5V range.
- Potential (MY2012) vehicle electrical load forecasted to be as high as 2500W.

# Power Conditioning Subsystem Implementation

Simple control strategy

- PCS acts like a voltage source when the TGM can supply enough power to support the vehicle electrical load
- PCS acts like a current source when the TGM can supply less than the full vehicle electrical load. The alternator acts as the electrical system voltage reference in this case.
- PCS draws maximum power from the TGM under the above two conditions at all times.

Virginia Tech is developing a high-efficiency implementation of the PCS.

# Conclusions and further work

- A thermoelectric waste heat recovery system has been modeled and key subsystem designs established with a path outlined to meet the program goal of 10% fuel efficiency improvement
- A vehicle simulation capability has been established in GT Cool that has been validated and may be used to predict and optimize system performance
- The TGM has been designed incorporating thermal isolation and high density design principles
- A secondary loop has been implemented to improve system efficiency, reduce material usage and to address potential environmental issues. The performance and behavior of this architecture will be evaluated in phase 2 using build and test results fed back into the GT Cool model