

Automotive Thermoelectric Generator Design Issues

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Why develop automotive TEG's?

- **Improve vehicle fuel efficiency**

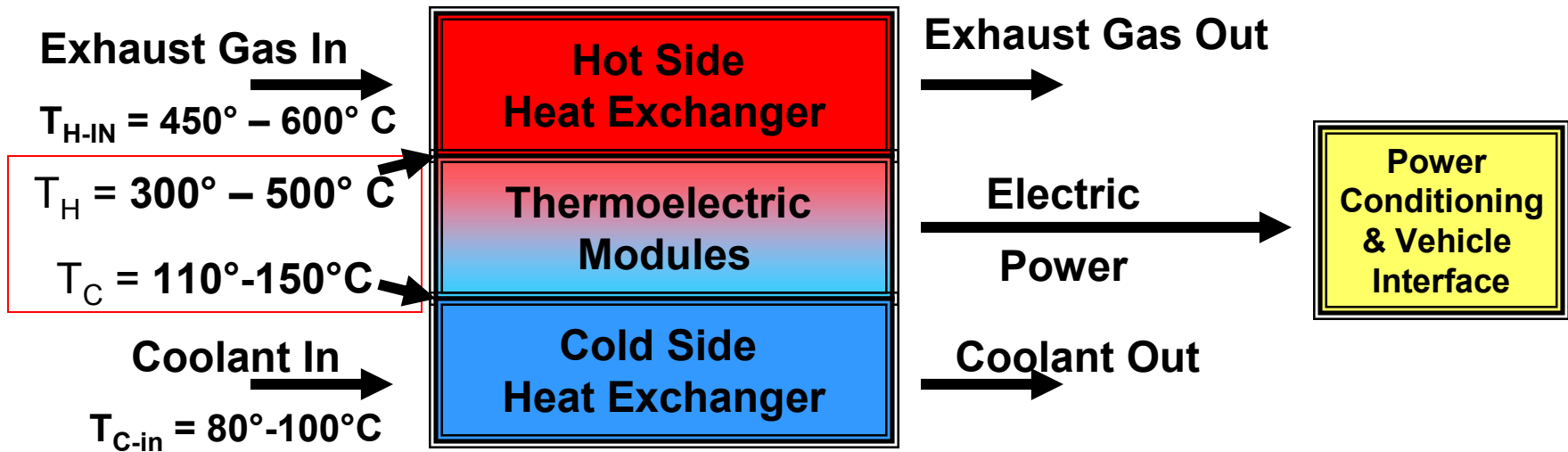
- Customer driven requirement
- Government driven requirements
- Requirements to lower CO₂ emissions
- Green image to help vehicle sales
- Support increased vehicle electrification
- Simpler than alternative systems:
 - Rankine, Stirling, Turbo-generator, thermo-acoustic, etc.

What are the major components of a production thermoelectric generator (TEG) system?

- TEG Unit
 - Hot side heat exchanger & flow controls
 - Thermoelectric modules & thermal management
 - Cold side heat exchanger and flow controls
 - Enclosure
- Hoses, pipes, flow management
- Thermal management components (optional)
- Vehicle mechanical interface - mounting
- DC to DC converter & electrical interface

Generic Exhaust Gas TEG

Representative TEG Temperatures for a Gasoline Fueled Vehicle



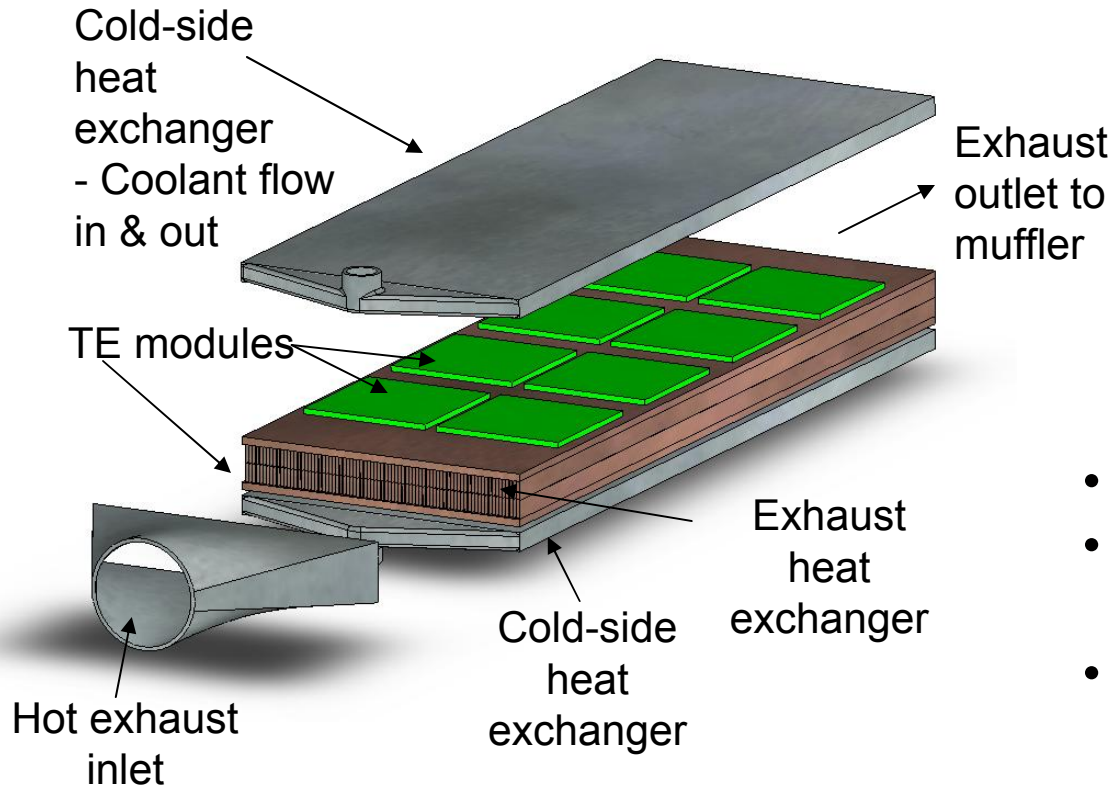
Start up temperatures lower
Peak temperatures higher

Typical Heat Exchanger Loses

$$\Delta T_{HS} = 100^\circ \text{ to } 150^\circ \text{ C}$$

$$\Delta T_{CS} = 30^\circ \text{ to } 50^\circ \text{ C}$$

Example of Exhaust TEG Basic Geometry



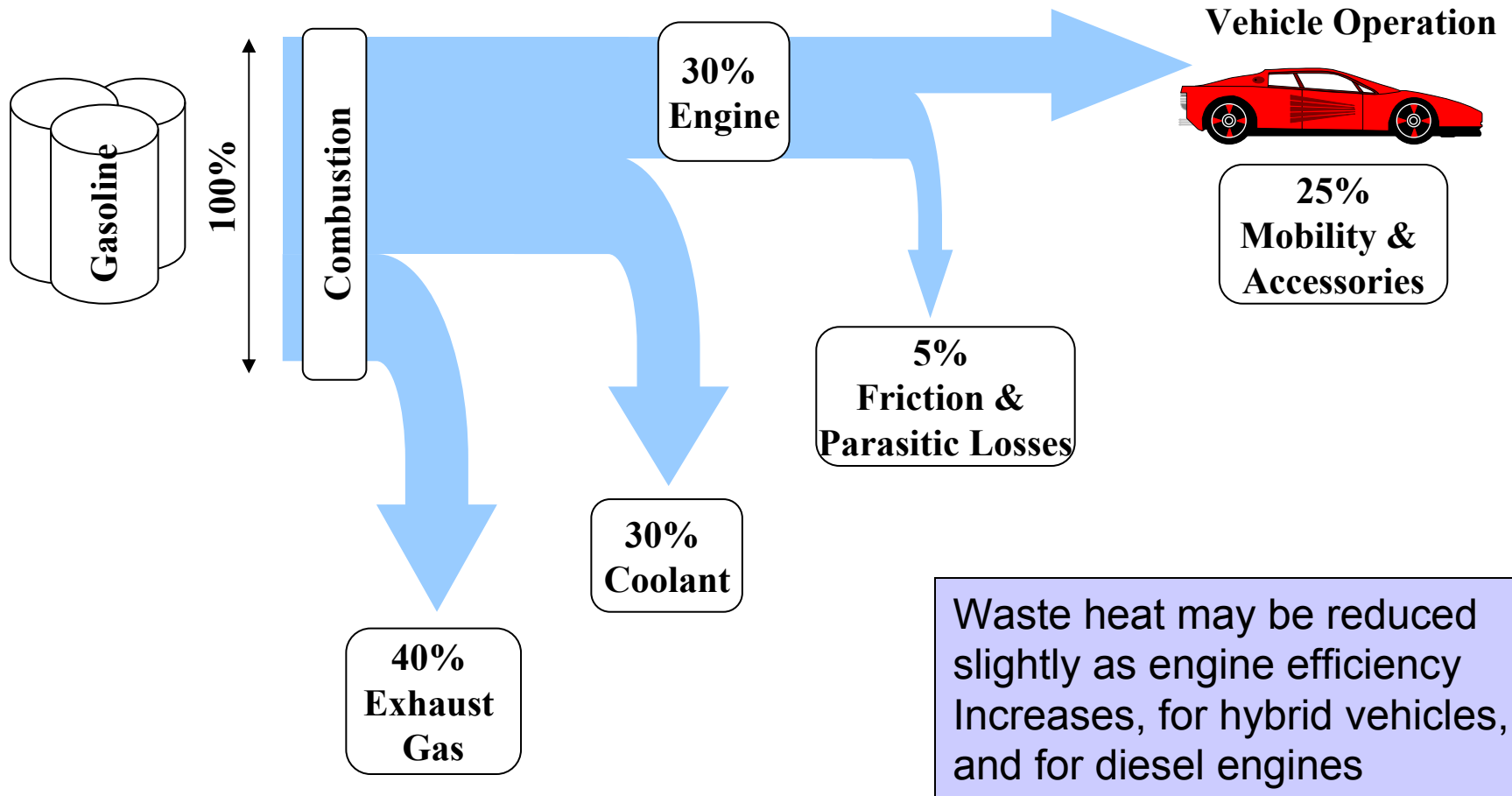
- High performance compact exhaust gas heat exchanger
 - high heat transfer coefficient at average flow
 - high surface area
 - meets pressure drop requirements at max flow
- Dual surface configuration
- Scalable, manufacturable design
- Geometrically compatible with vehicle

Slide courtesy of General Motors Corp.

TEG Design Issues

- Heat source
- Cooling source
- Heat exchangers
- Thermoelectric modules
 - Selection, placement, & thermal management
- Electrical power output
- Automotive environment
- Economic considerations

Typical Energy Path in Gasoline Fueled Internal Combustion Engine Vehicles



Exhaust Heat Energy Source

(Only source currently being worked for TEG applications)

- Energy available is dependent on gas temperature and mass flow
 - Temperature range - ambient to 600°C with rare excursions to 1000°C under extreme operating conditions
 - Flow and temperature are unpredictably time varying for cars & light duty trucks in normal use
 - Predictable in standard government testing

Cooling of TEG - Possible Methods

- Ambient air, blower, & TEG cooling fins
 - Lowest temperature potential, **vehicle problem with cost, space, noise, environment, & power**
- Dedicated liquid cooling loop
 - Higher temperature than air cooling, **added cost and vehicle space**
- ➔ • Engine coolant & vehicle radiator using engine coolant pump or an added pump
 - Lowest cost approach, higher temperature
 - **Concern that radiator capacity may have to be increased**

Heat Exchanger Considerations (1)

- Minimize exhaust heat loss from engine to TEG
- We need to efficiently transfer heat
 - From the exhaust gas flow to TE modules
 - From the TE modules to the cooling system
- Prototype TEG heat exchangers have demonstrated 40% to 70% efficiency
- Thermal interface issues
 - Module to heat exchanger

Heat Exchanger Considerations (2)

- Reliability and durability – no significant degradation over life of TEG (10 to 20 years)
 - Potential problems include mechanical or chemical degradation of heat exchanger surfaces or build-up of foreign material that degrades heat transfer
- Limit the impact on the vehicle operation that could reduce engine efficiency
 - Flow restrictions in the exhaust (backpressure)
 - Increased radiator size
 - Added vehicle weight

Thermoelectric Module Requirements

- **Functionality**
 - Efficient at available temperatures (high ZT)
- **Availability**
 - Moderate volume now & very high volume in long term
- **Economics**
 - Low \$/Watt installed capability
- **Reliability and Durability**

Thermoelectric Module Selection

- Match TE modules (material & ZT) to the available temperature range at the modules
 - Take into account the temperature drop across the heat exchangers
 - Exhaust gas to module & module to cooling system
 - Need peak ZT at the optimum temperature expected at the modules
 - No degradation over the range of module temperatures
 - Consider temperature differences based on location
 - Lower temperatures downstream in the exhaust heat flow
 - Potential to use two or more types of modules
 - Take design steps to equalize the temperature at all TE modules

Thermoelectric Modules

- Availability of modules in the necessary quantity
 - Existing manufacturing facilities
 - None or very limited today?
 - Ability to expand manufacturing facilities
 - Supply a significant portion of the over 50 million vehicles produced globally each year
 - Available material supply as volume increases
- For cost estimates:
 - A complete TEG system will cost approximately twice as much as the TE modules

Other TE Module Considerations

- Effective insulation to avoid heat loss around the modules
 - Stop radiation from heat source to cooling system
- Reliability and durability of the modules
 - 10 Years minimum life and 20 years expected life without maintenance
 - Sealing of modules to avoid oxygen or water degradation
- Material safety considerations for manufacturing, use, in accidents, and “end of life” disposal

Electric Power Output of TEG System

- Power from the TE modules cannot be used directly; therefore, a DC to DC converter is needed as part of the TEG system
 - A conventional “12 volt” vehicle uses electrical power at 13.5 to 14.5 volts (temperature dependent)
 - Hybrid vehicles use much higher voltages for propulsion, but “12 volts” for vehicle systems (accessories & engine)
- Electrical considerations:
 - Variation in module output as temperature and flow changes
 - Module connections: Parallel, series, or a combination
 - Power loss in the conversion
 - Load matching to minimize losses

Electric Power Considerations

- How much electrical power is needed?
 - Examples of demand to consider:
 - 250 to 350 Watts needed to operate during government regulatory testing (~ 1 to 4% FE increase)
 - An added 200 to 800 Watts needed if coolant pump converted from mechanical to electric drive
 - 300 to 1500 Watts needed during typical customer driving
 - An additional 3000 to 5000 watts needed if air conditioning converted from mechanical to electric operation
- For Fuel Economy calculations, use average power delivered to vehicle, not maximum power possible from the modules under optimum conditions
- TEG output improves vehicle fuel economy by reducing generator and other mechanical loads on the engine

Automotive Environment

- Limited space to install added equipment
- Shock and vibration
 - Requires a rugged design or isolation from vehicle
- Ambient air thermal extremes (-40° to 50° C)
- Thermal shock
 - Typical: 20° to 400° C; extreme: -40° to 400° C in less than 2 minutes
- Thermal cycling
 - Average 1500 cycles per year for at least 10 years,
 - More cycles for frequent short trips or hybrid vehicles
- Long life
 - Minimum 5000 operating hours
 - Minimum design life 10 years or 150,000 miles
 - Target 20 year life and 200,000 miles

Economic Considerations

- The customer must perceive sufficient benefit to pay for the cost of a TEG
- The real number to focus on is \$ per MPG (miles per gallon) improvement
 - May use \$ cost per Watt output for the complete TEG system
- Some of the benefit may be “Green Image” but most of the benefit has to translate into actual fuel savings
 - Eliminating the use of the conventional generator for a vehicle on the US Government fuel economy test (FTP) will improve fuel economy 1% to 4% depending on the type of vehicle
 - Real world driving may provide additional fuel savings
 - Ex.: Steady state freeway driving

Summary

- Address the complete TEG system
 - Consider all of the changes and components to be added to a vehicle
- Design for cost effective manufacturing and vehicle customer use (total \$/watt on vehicle & \$/mpg improvement)
- Need higher ZT and lower cost/watt
- Design for quality, reliability, and durability

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- Dr. Jihui Yang for strong support of TE applications and many useful discussions

Vehicle Packaging Examples

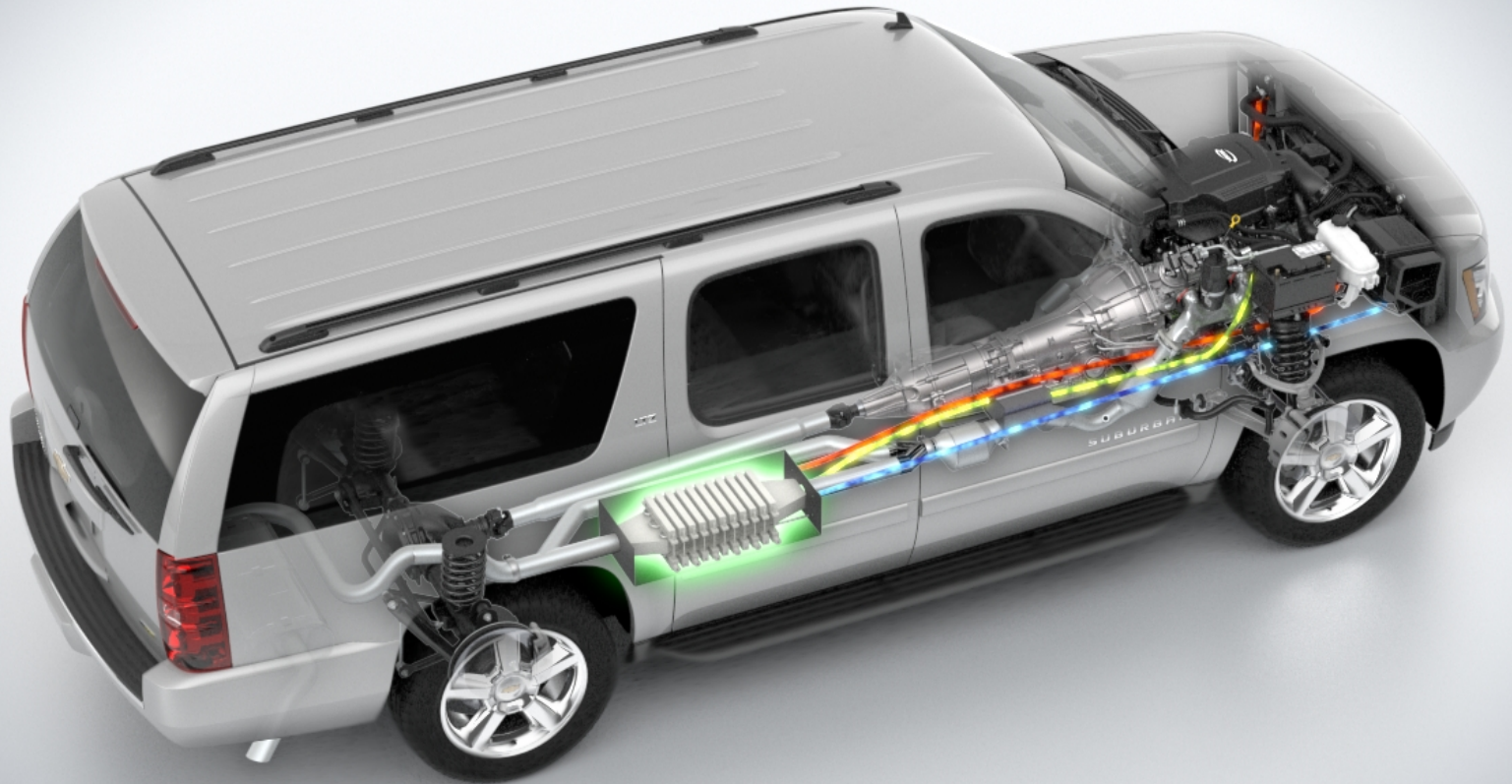
- BSST / BMW TEG mounting
- GM TEG mounting - Suburban

BSST TEG mounted in BMW



Slide courtesy of BSST



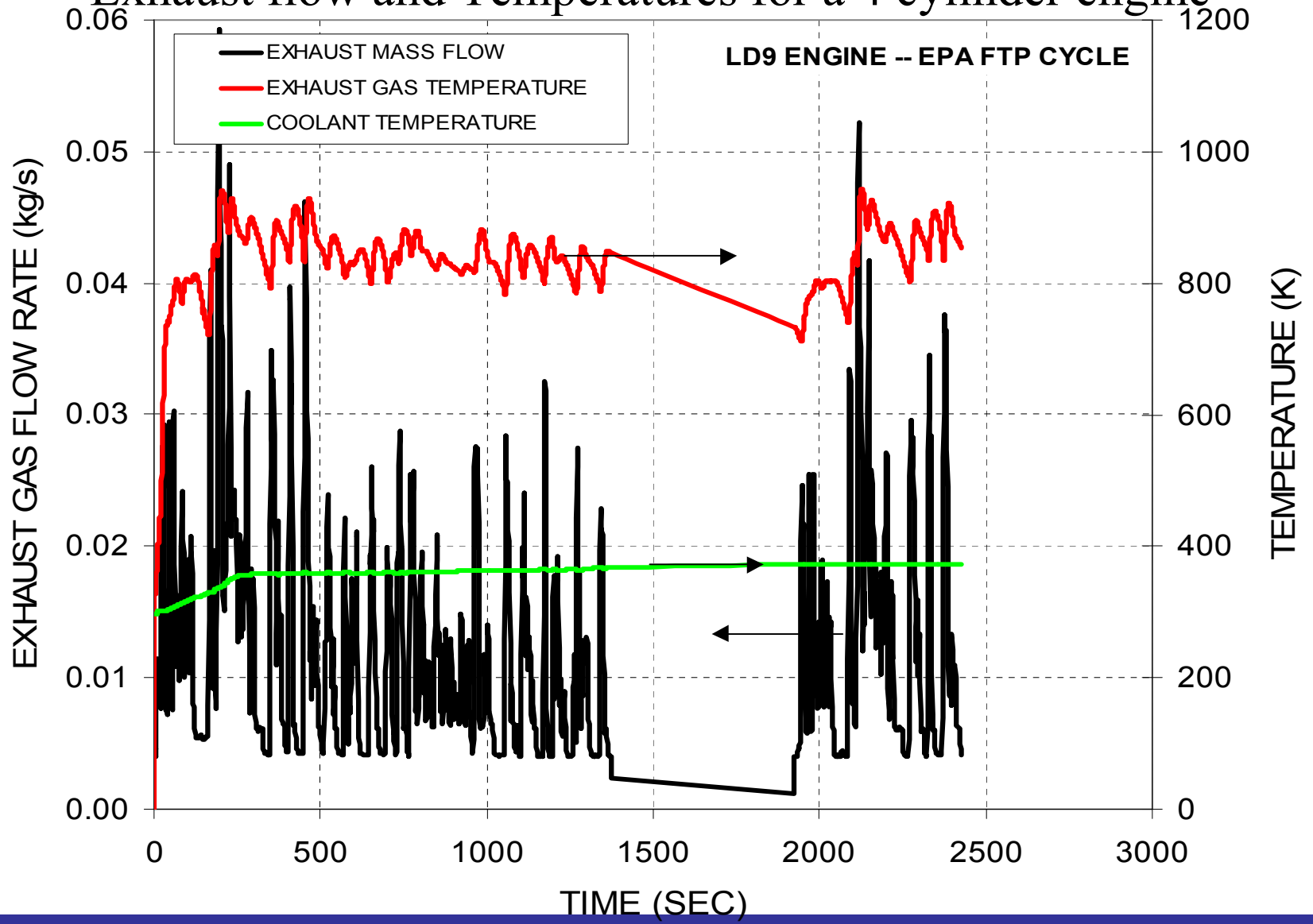


Slide courtesy of General Motors Corp.

TEG Installation in GM Suburban



Exhaust flow and Temperatures for a 4 cylinder engine



Generic Representation of a TEG

Thermoelectric Generator (TEG) Functions

