Automotive Thermoelectric Generator Design Issues

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Why develop automotive TEG's?

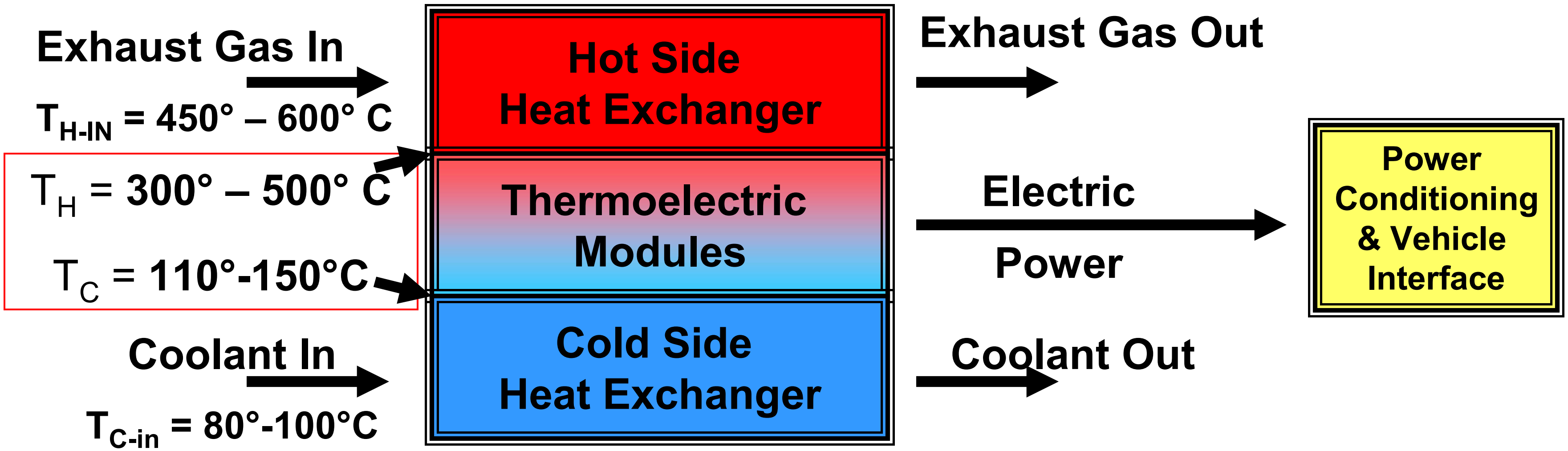
- **<u>Improve vehicle fuel efficiency</u>**
  - Customer driven requirement
  - Government driven requirements
- Requirements to lower CO_2 emissions
- Green image to help vehicle sales
- Support increased vehicle electrification
- Simpler than alternative systems:
  - Rankine, Stirling, Turbo-generator, 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

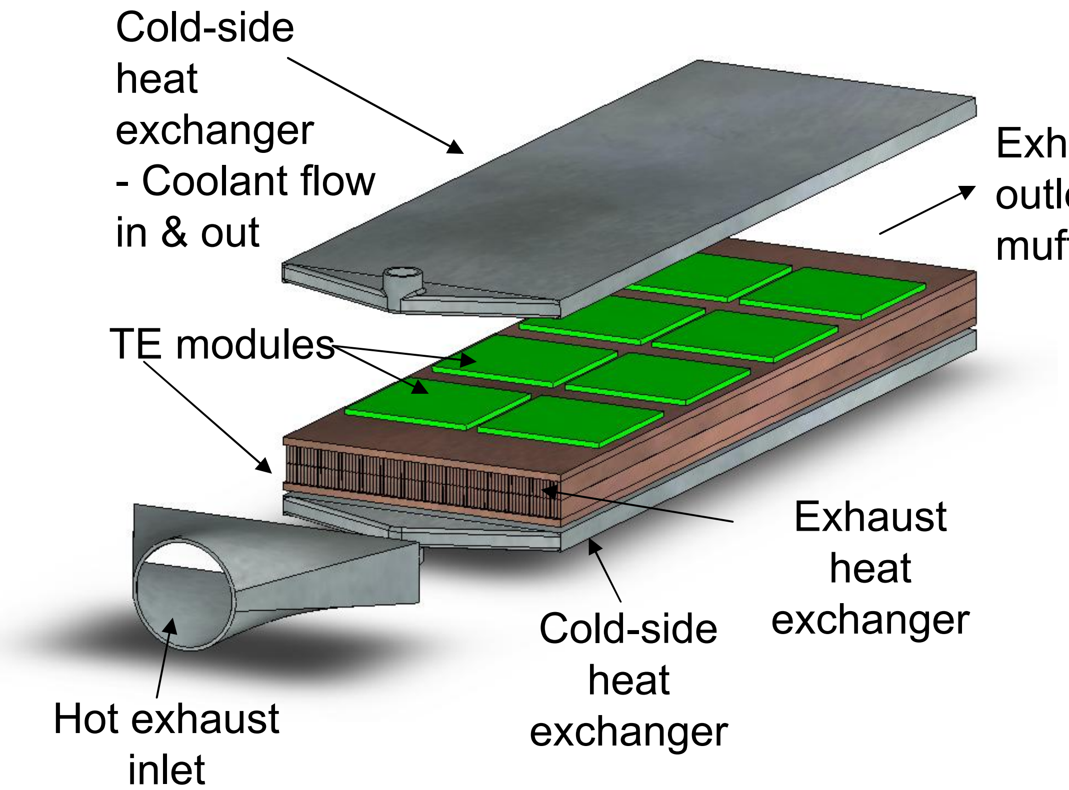
Representative TEG Temperatures for a Gasoline Fueled Vehicle



Typical Heat Exchanger Loses
ΔT_{HS} = 100° to 150° C
ΔT_{CS} = 30° to 50° C

Start up temperatures lower
Peak temperatures higher

Example of Exhaust TEG Basic Geometry



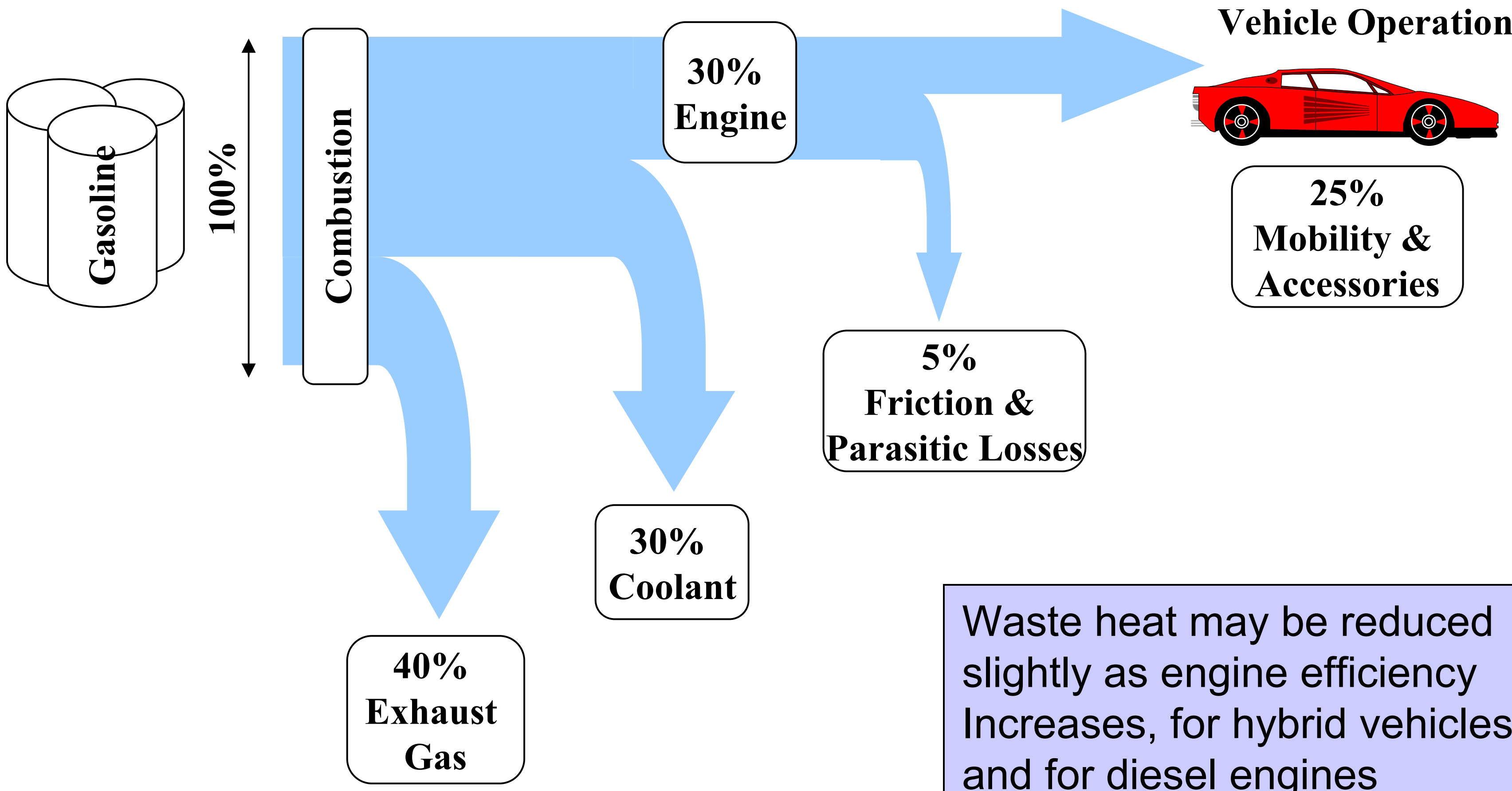
- High performance compact exhaust gas heat exchanger
  - high heat transfer coefficient at average flow
  - high surface area
  - meets pressure drop requirements at max flow
- Dual surface configuration
- Scalable, manufacturable design
- Geometrically compatible with vehicle

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



Waste heat may be reduced slightly as engine efficiency Increases, for hybrid vehicles, and for diesel engines

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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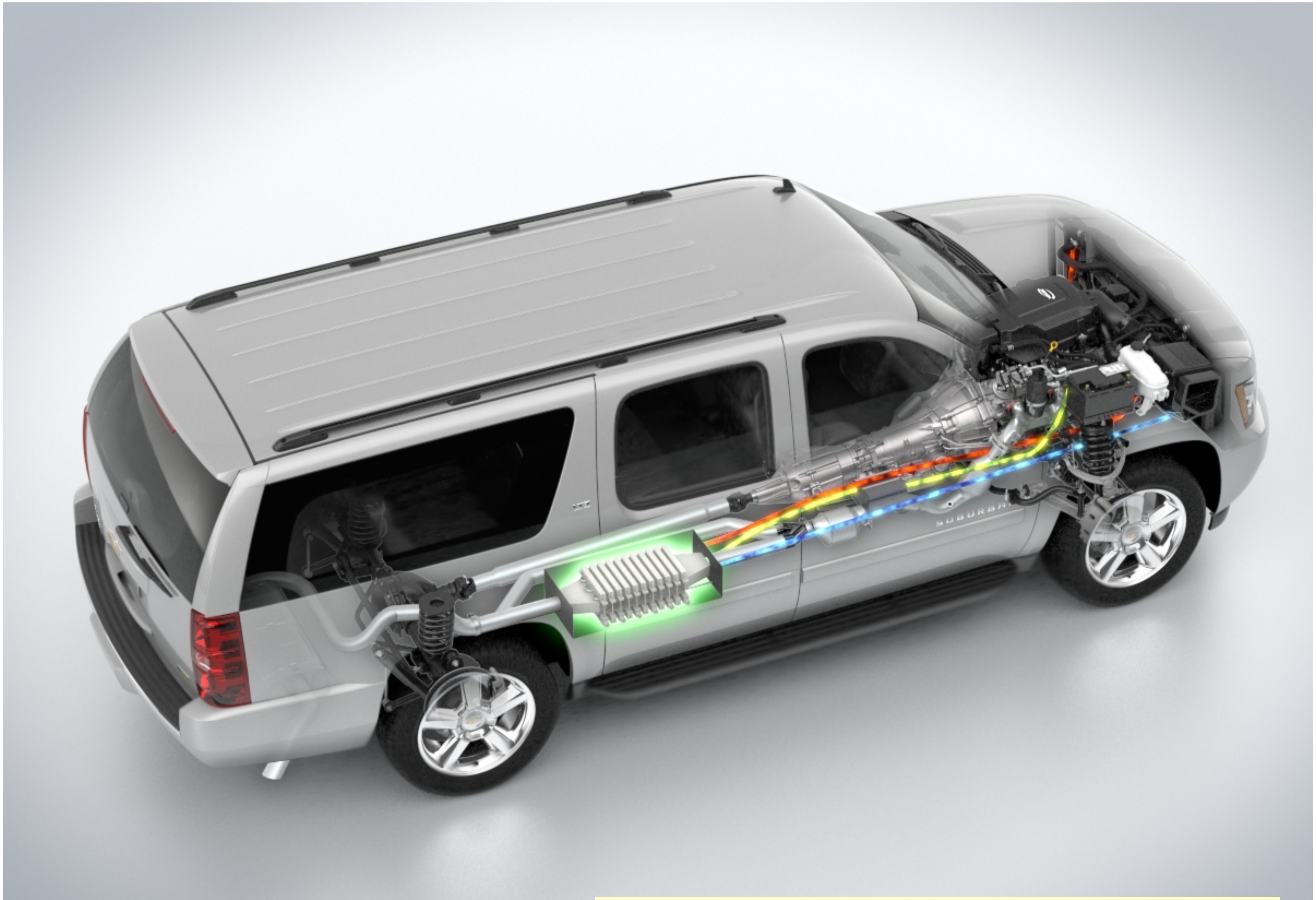
Vehicle Packaging Examples

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

BSST TEG mounted in BMW

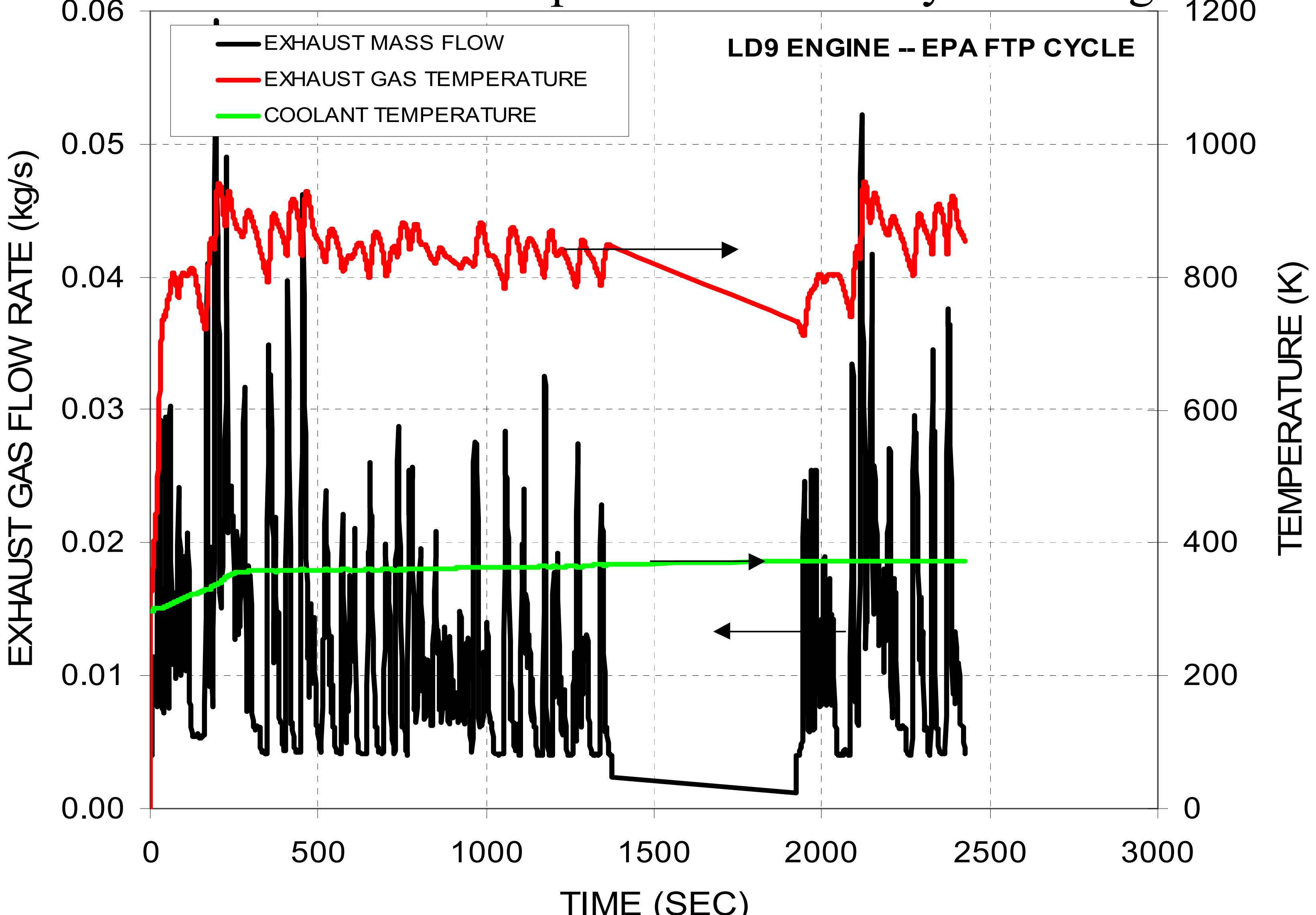
Slide courtesy of BSST



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