WASTE ENERGY RECOVERY CONCEPTS FOR MILITARY VEHICLES

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Agenda

1. Introduction
2. Waste Heat Recovery Rational & System Impact
3. Waste Energy Recovery Technologies
4. TEG Technology Approach
5. Conclusions

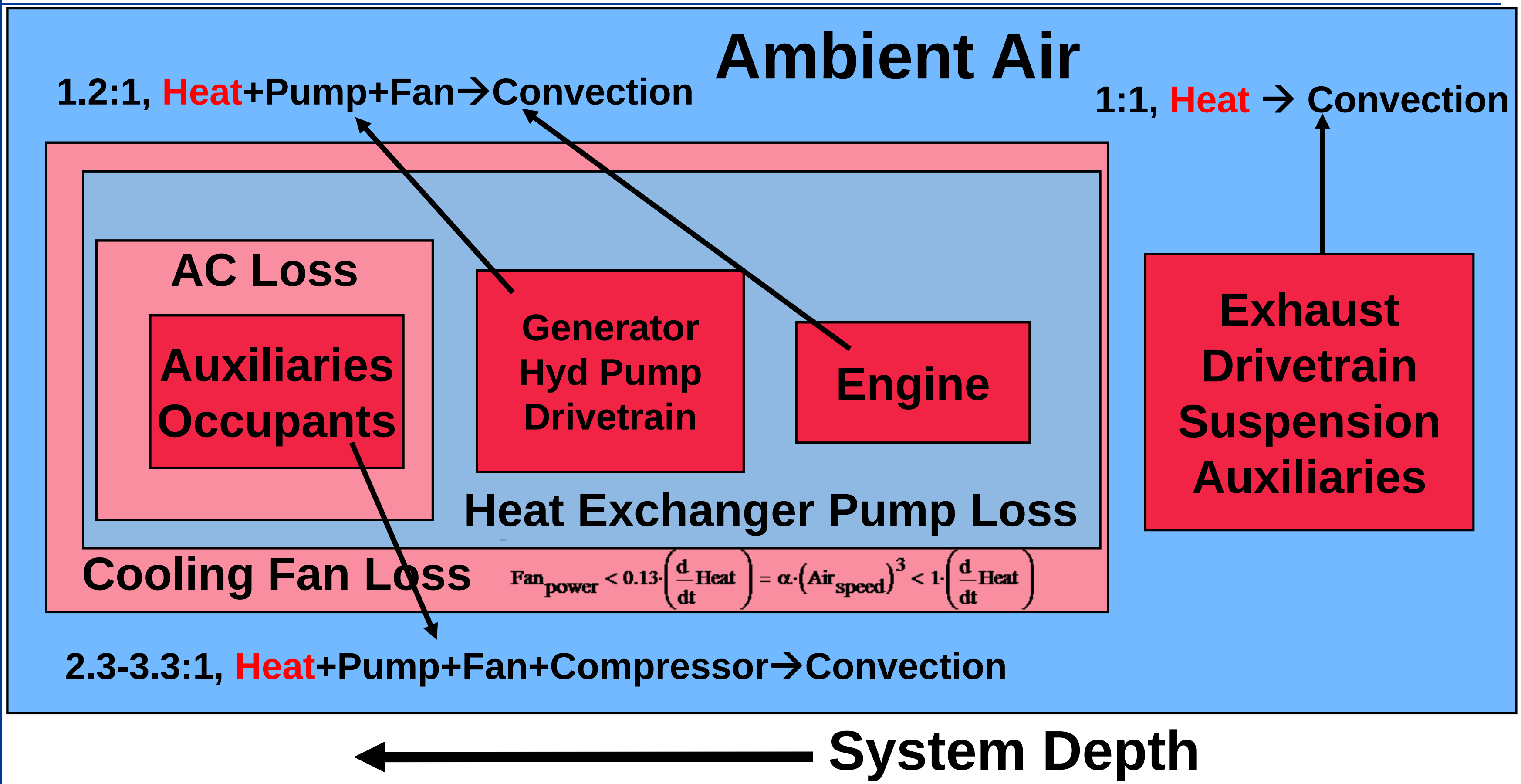
The Changing Energy Landscape

- Economic and Political Issues Affecting Petroleum Availability
  - Instability of Nations Owning Oil Reserves
  - Economic Growth Affecting Cost and Availability
  - Dollar Value Eroded by Trading Imbalance
- DoD Energy Issues
  - DoD Largest Energy Consumer (75% Mobility; 50% Jet Fuel)
  - $ 5/gal Pump Cost Becomes > $200/gal Delivered
  - Vehicle Hotel Power Requirements Growing Rapidly (50+ kW/vehicle)
- DoD Energy Initiatives
  - Fully Burdened Fuel Cost For Weapons Systems
  - Army Energy Task Force
    - Improve System Efficiency (Vehicles and Installations)
    - Increase Utilization of Renewable Fuels
    - Reduce Environmental Impact

Alternative to Status Quo

- Internal Combustion Engines Convert At Best 30% of the Utilized Fuel into Useful Energy
- Significant Improvement in IC Engine Efficiency is Unlikely
- Address 70% Waste (Harmful) Energy From IC Engines
  - Results in Higher “Hotel Loads” (fans, compressors, etc.)
  - Increases System Weight and Cost
  - Creates Vulnerabilities to Threat Sensors
  - Reduces Component Reliability
- Recover and Convert Waste Energy to Usable Power

System Effect of Heat → Useful Energy



10% thermal-electric efficiency → 10% to 33% effective efficiency in terms of power replaced

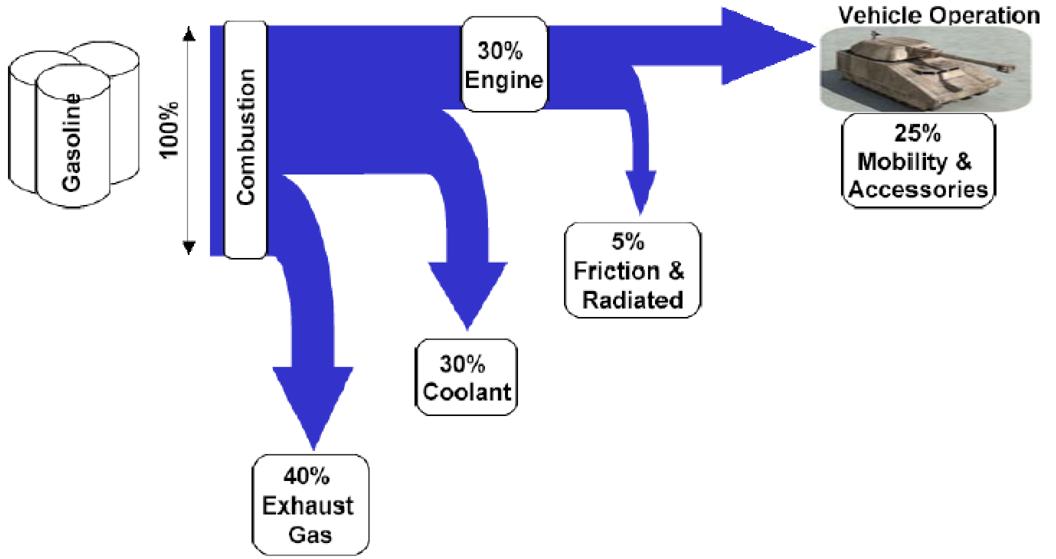
System Costs

- $Cost
  - Fuel Cost Factors
    - Cost= fuel purchase + storage + protection + transport
    - Deployed $Cost >> Stateside $Cost
  - Waste Heat Recovery Device $Cost Test

$$\left(\text{Cost}_{\text{device}} + \text{installation}\right) \cdot \int_0^{t_{\text{life}}} (\text{interest} + \text{maintenance})\, dt < \int_0^{t_{\text{life}}} \frac{\text{Cost}_{\text{fuel}}(t)}{\text{gal}} \cdot \text{usage}(t)\, dt$$

    - $ Cost effectiveness depends on usage and deployment
- Weight & Volume (Range) Cost
  - To be cost effective an energy recovery device must produce the energy of its weight and volume in fuel within the context of a fuel limited mission
- Other Costs
  - Survivability (Sigman), Reliability, and Maintainability

Energy Path for an IC Engine Vehicle

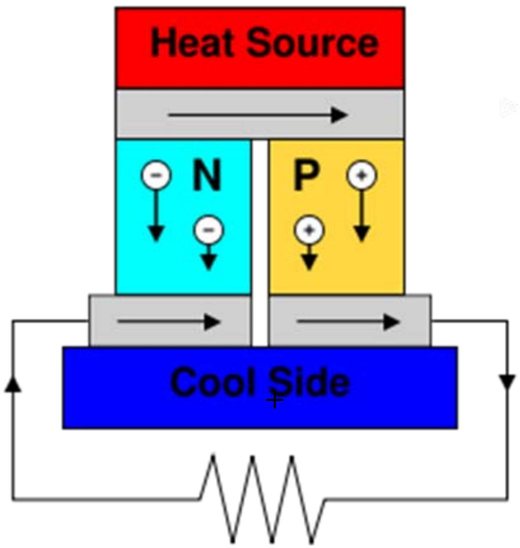


- Only less than 30% of the energy used for vehicle operation
- Wasted energy (+70%)
  - ↗ Exhaust: 40%
  - ↗ Coolant: 30%
  - ↗ Friction, radiation, NVH: 5%

Waste Energy Recovery Review

Conversion Method	Processes
Thermal to Thermal	Heat Storage, Absorption Refrigeration, Thermal Acoustics
Thermal to Mechanical	Rankine Cycle, Stirling Cycle, Gas Turbine
Thermal to Electrical	Thermoelectric Devices
Thermal to Chemical	Fuel Reforming
Kinematic to Electrical	Regenerative Magnetic and TEG Shock Absorbers
Kinematic to Electrical/ Hydraulic	Regenerative Braking in Electric and Hydraulic Hybrid Vehicles

Thermoelectricity and TEGs



Typical Thermoelectric Device

- A Thermoelectric generator is a device that converts thermal energy into electricity.
- It is based on the Seebeck effect and hence the thermoelectric power or Seebeck coefficient of a material is a measure of the induced thermoelectric voltage due to a temperature difference across that material.
- It can be calculated using $$S = \frac{V}{\Delta T}$$

  where, S is the Seebeck coefficient, V is voltage, and ΔT is the temperature difference.

Thermoelectric Efficiency (η) = $\dfrac{M-1}{M+\frac{T_C}{T_H}}\left(1-\dfrac{T_C}{T_H}\right)$, where

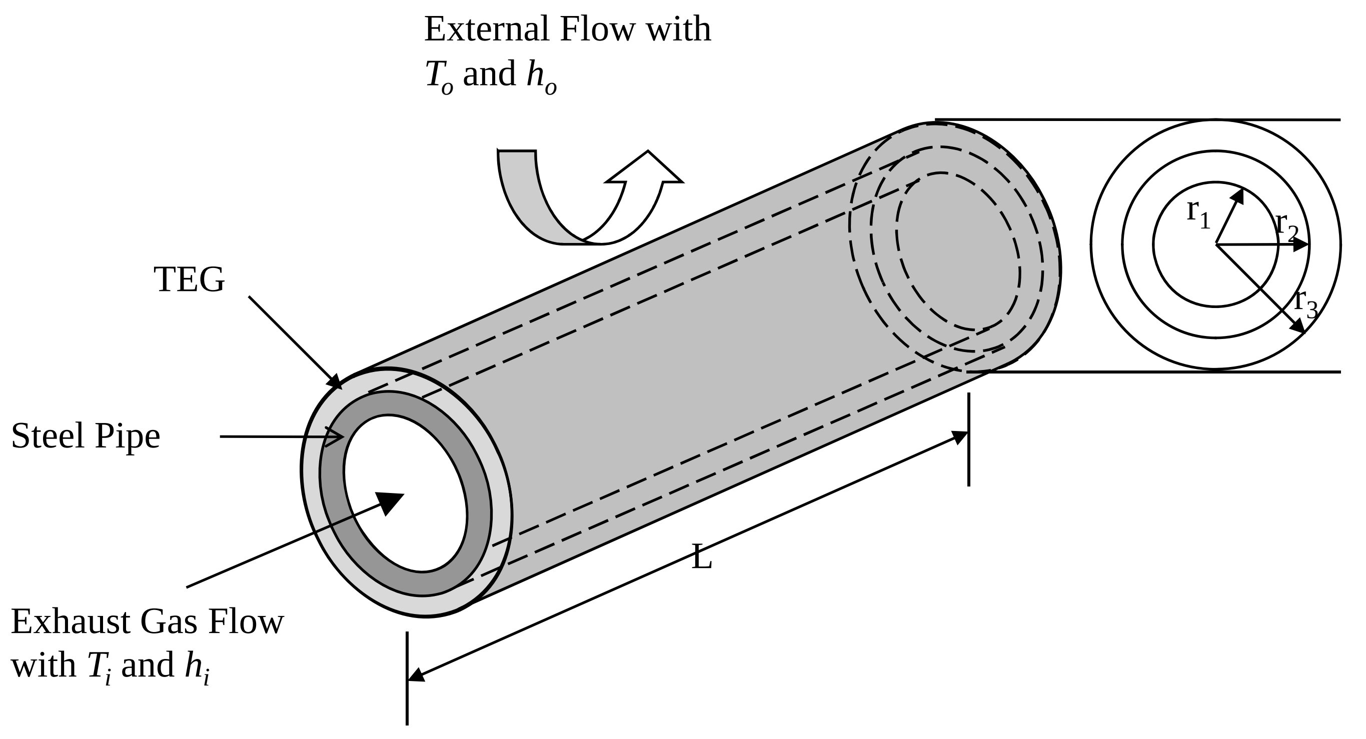
$$M = \sqrt{1+Z\left(\frac{T_C+T_H}{2}\right)}$$

$$Z = \frac{S^2}{\sigma k}$$

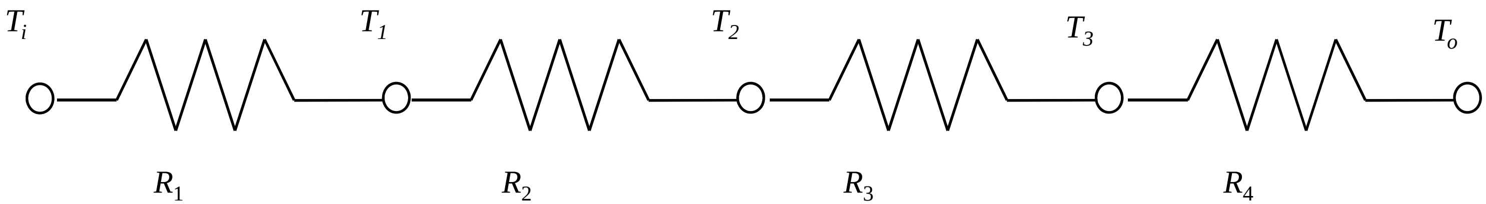
Comparison between performance of Quantum Well and Bi_2Te_3 modules

Thermoelectric Module Material	Temperature Difference °C	Voltage at Maximum Power	Maximum Efficiency %	Maximum Power W
N & P-type bulk Bi_2Te_3	200	1.6	5.8	14
	Hi-Z's Commercial Alloys		**Module dimensions are 6.3x6.3 cm**	
N type Si/SiGe & P-type B_4C/B_9C Quantum Well Kapton Substrate 25 μm thick	200	10.0	17	60
	250	12.4	20.9	72
	Under Development			
N type Si/SiC and P-type B_4C/B_9C Quantum Well SiGe Subsrate ~5 μm thick (too hot for Kapton)	450	22.6	32.5	338
	Under Development			

Thermal Model of Exhaust Pipe with TEG



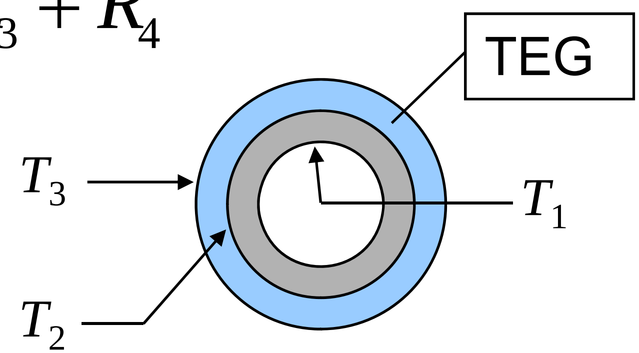
Equivalent Thermal Circuit of Exhaust Pipe with TEG



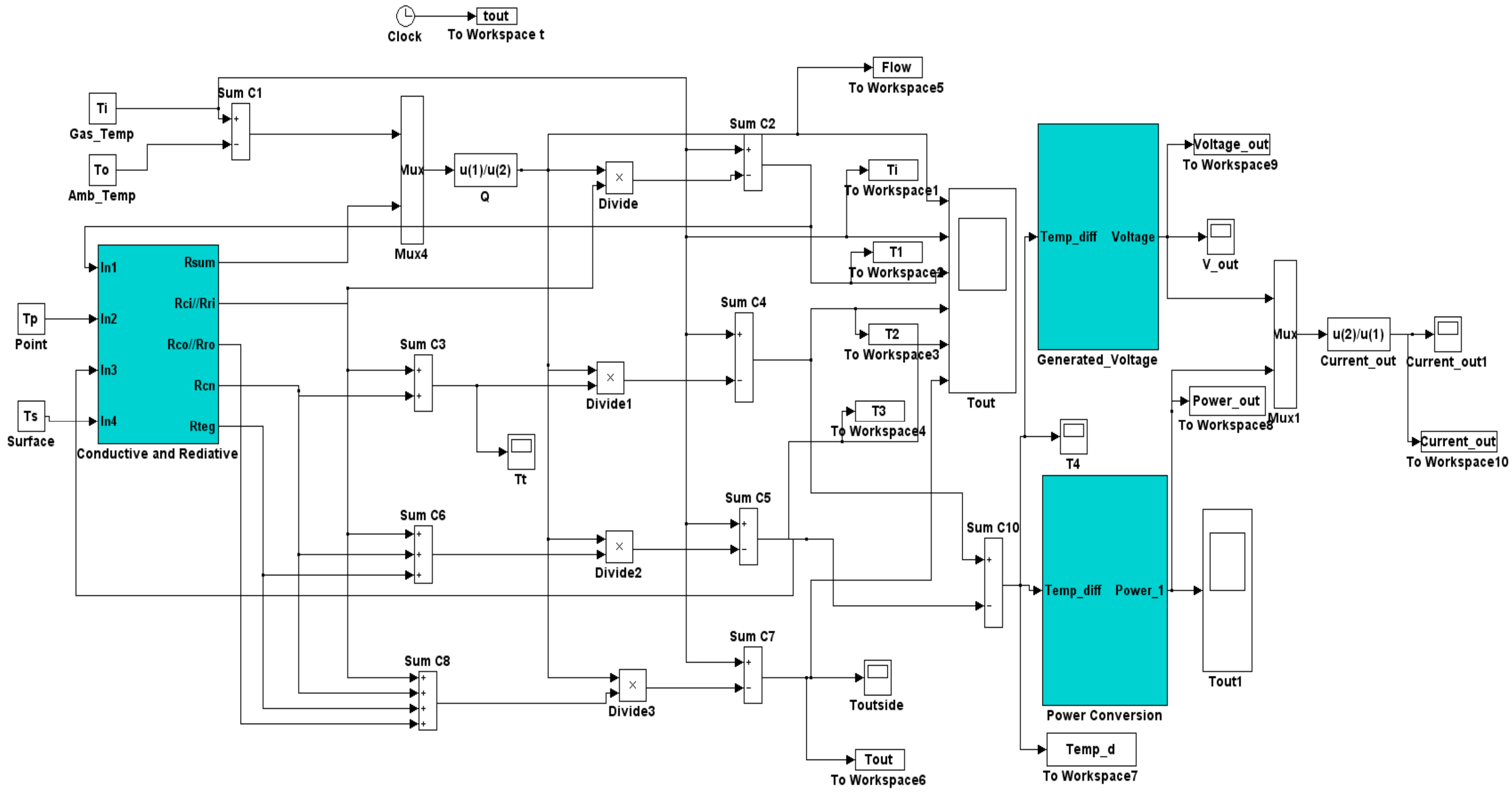
$$R_1 = \frac{1}{h_i A_i}\ , \quad R_2 = \frac{\ln\left(r_2 / r_1\right)}{2\pi L k_s}\ , \quad R_3 = \frac{\ln\left(r_3 / r_2\right)}{2\pi L k_t}\ , \quad R_4 = \frac{1}{h_o A_o}$$

$$Q = \frac{T_i - T_o}{\Sigma R_t} \qquad \Sigma R_t = R_1 + R_2 + R_3 + R_4$$

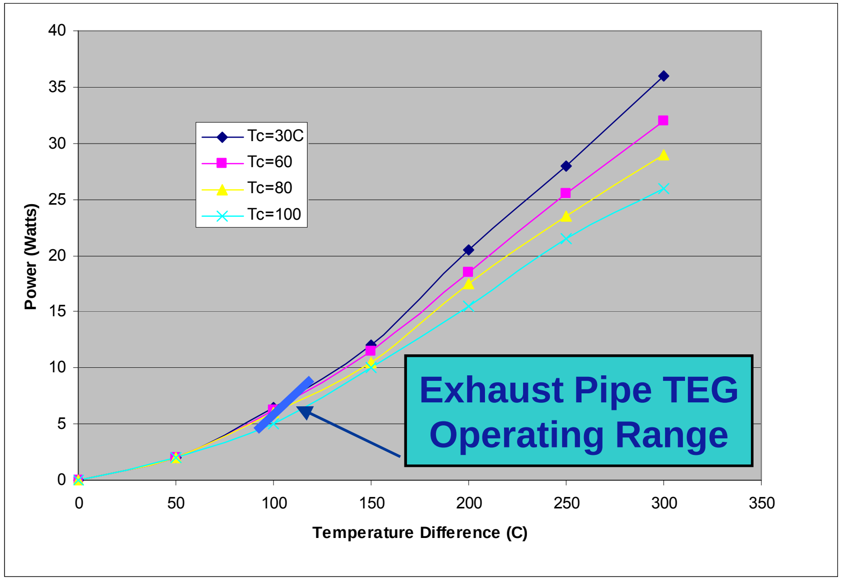
$$\Delta T = T_2 - T_3 = Q \times R_3$$

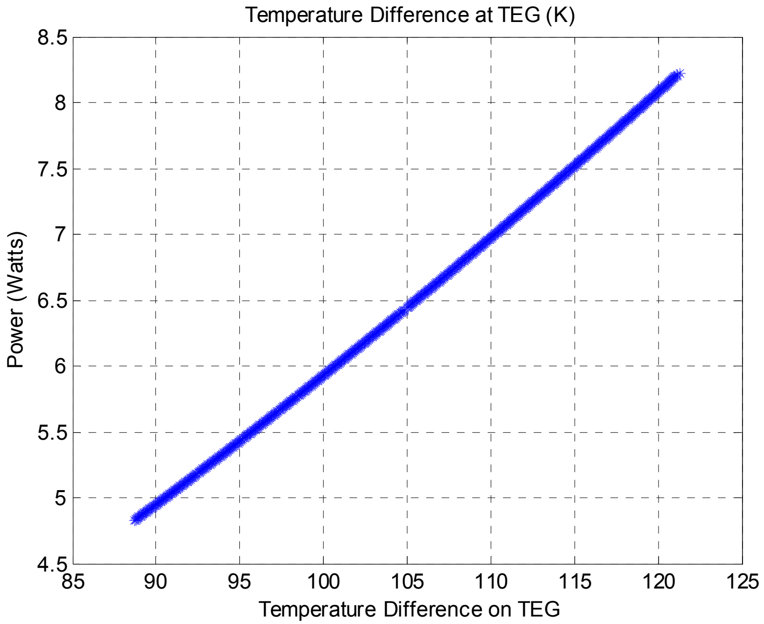


MATLAB/SIMULINK Model of Exhaust Pipe with TEG



MODELING RESULTS OUTPUT POWER VS.TEMPERATURE DIFFERENCE AT TEG ON EXHAUST PIPE





HZ-20 TEG Power-dT data

Surface area: 8.2 in^2 (56 cm^2)

Volume: 1.6 in^3 (28 cm^3)

Weight: 115 grams

Exhaust pipe power generation using a HZ-20 TEG

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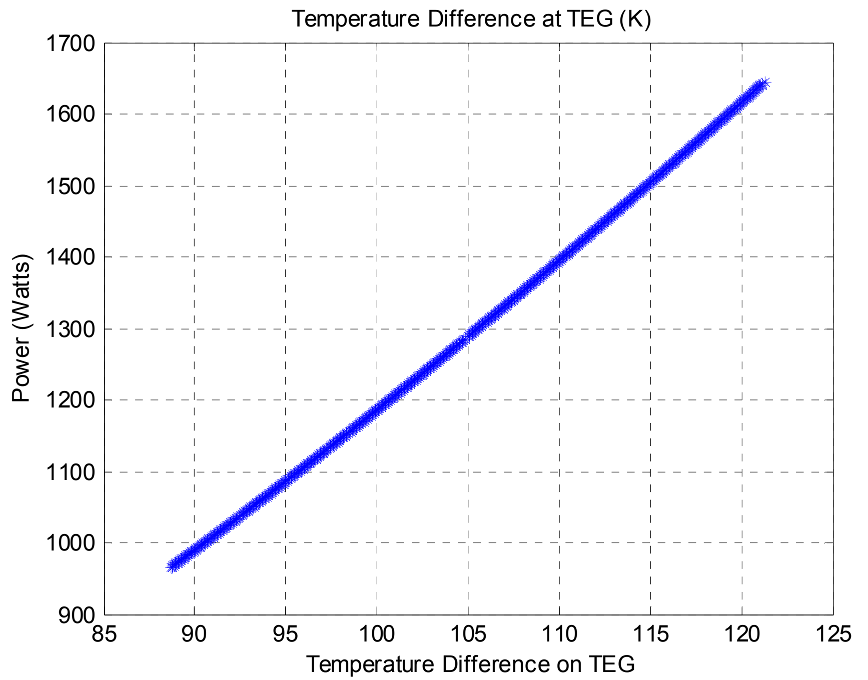
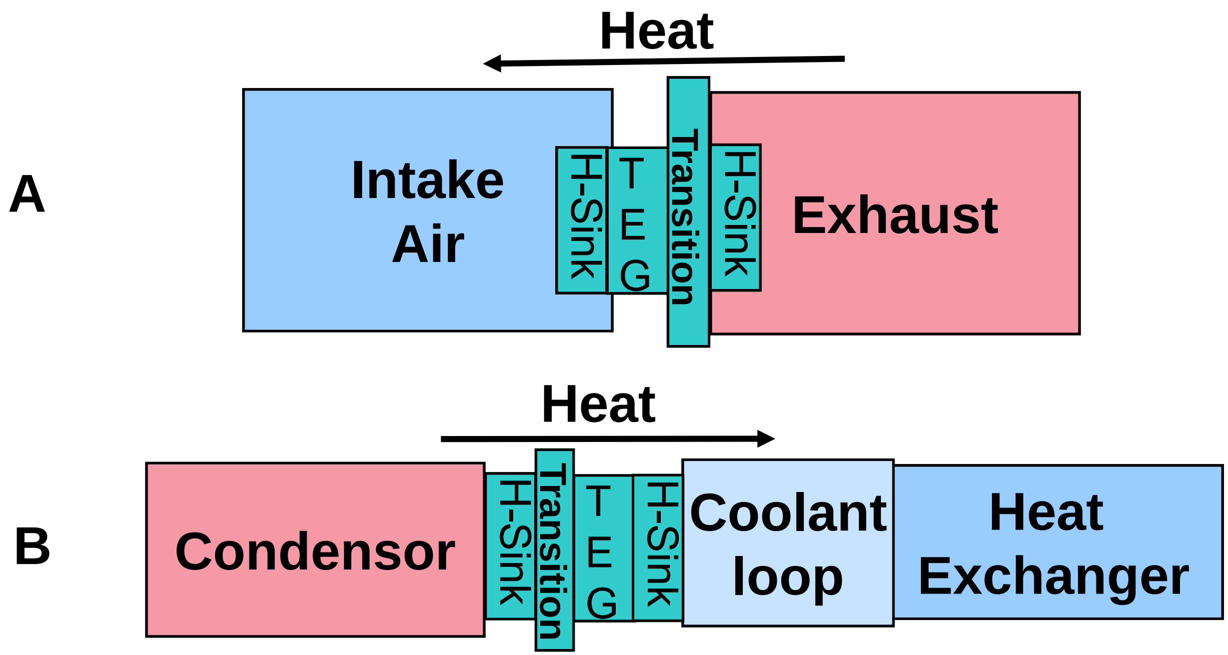


Total power generated using 10x20 HZ-20 TEG Matrix (10 in parallel, 20 in series)

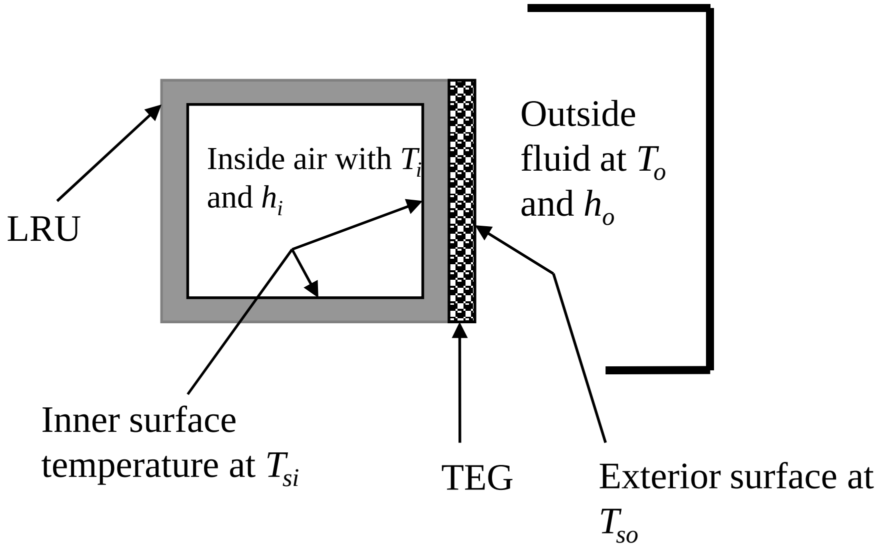
Vehicle Modes & Application

- Silent Watch (engine off)
- Combat Idle (low power)
- Combat (partial to full power)



High Delta T & dQ/dt with Low System Efficiency

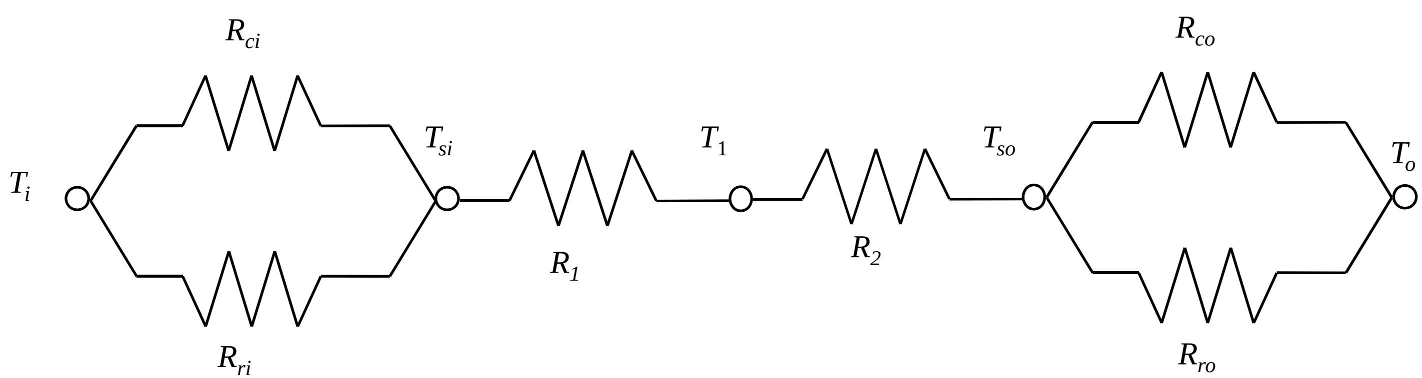
Thermal Model of LRU with TEG



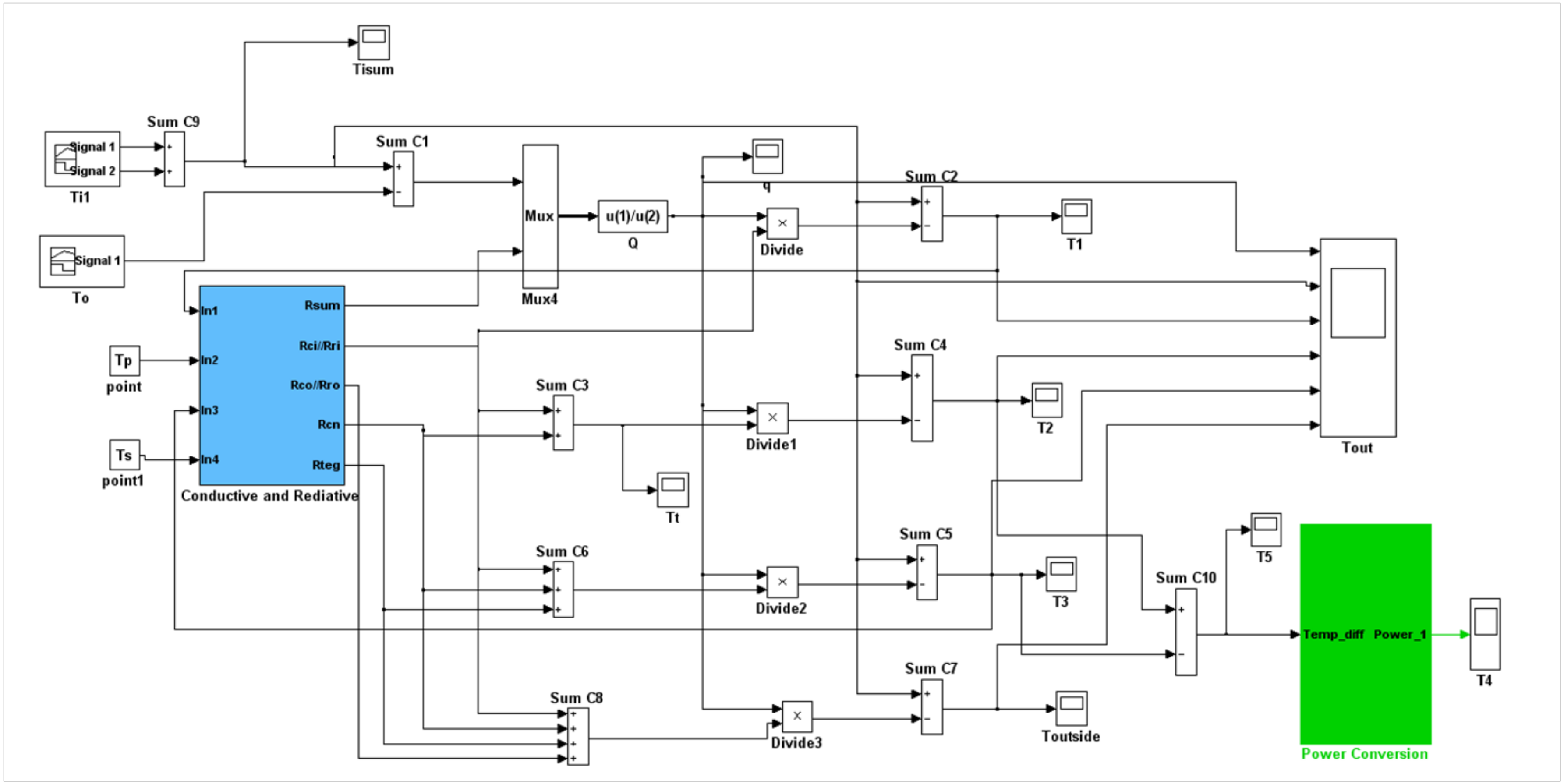
$$Q = \frac{T_i - T_o}{\Sigma R_t}$$

$$\Sigma R_t = R_i + R_1 + R_2 + R_o$$

$$\Delta T = \left(T_1 - T_{so}\right) = Q \times R_2$$



MATLAB/SIMULINK Model of LRU with TEG



Conclusions

- Recovering waste heat is an untapped resource
- Thermoelectric Generation is a Low Burden Method of Converting Waste Heat to Usable Power ($P \propto \Delta T$)
- Exhaust Heat Offers the Highest ΔT, But Recovery Will Be on a 1:1 Basis
- Removing heat at the LRU level will have lower ΔT s, but the payoff in system efficiency Improvement could be 2-3X
- Practical Approaches such as Simulink Modeling can Provide Prediction of Heat Recovery
- GDLS Currently Evaluating TEGs on the Abrams Recuperator to Validate Energy Recovery