Potential Thermoelectric Applications in Diesel Vehicles

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Automotive Technology Drivers

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- Requirements for reduced emissions and environmental impact
- Increasing markets for alternative propulsion systems and energy sources
- Needs for greater fuel efficiency
- Marked increase in automotive electronics
- Continuous need for improved passenger comfort

Advantages of TE’s in Vehicle Applications

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- Solid-state
- Simple – few or no moving parts
- Able to provide distributed cooling and heating
- Compatible with new vehicle types
- Systems do not produce emissions, are recyclable and exemplify environmental friendliness

Thermoelectric Fundamentals

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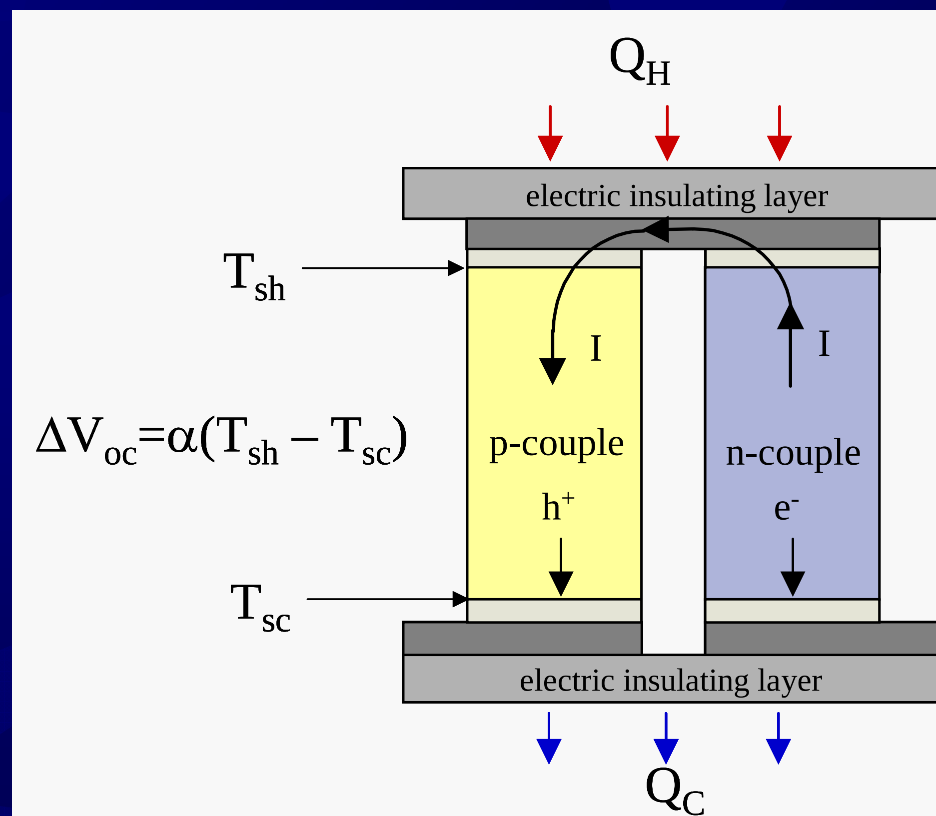
- Thermoelectrics are couples of n- and p-type semiconductors
  - generate voltage ∝ (T_{sh} – T_{sc}) across the junctions
  - generate current as a function of heat flux through couples
  - ideally with low thermal conductivity and high electrical conductivity



Thermoelectric Efficiency

- Thermoelectric efficiency is based on the material's non-dimensional figure of merit (ZT) and the ΔT across the device
- From the late 1950's until the late 1990's, the highest ZT achieved in practice was ~ 1, with little improvement during that time.
- With a ZT = 1 and a $\Delta T = 100^{o}C$, a device efficiency of ~ 5% can be achieved with current technology.

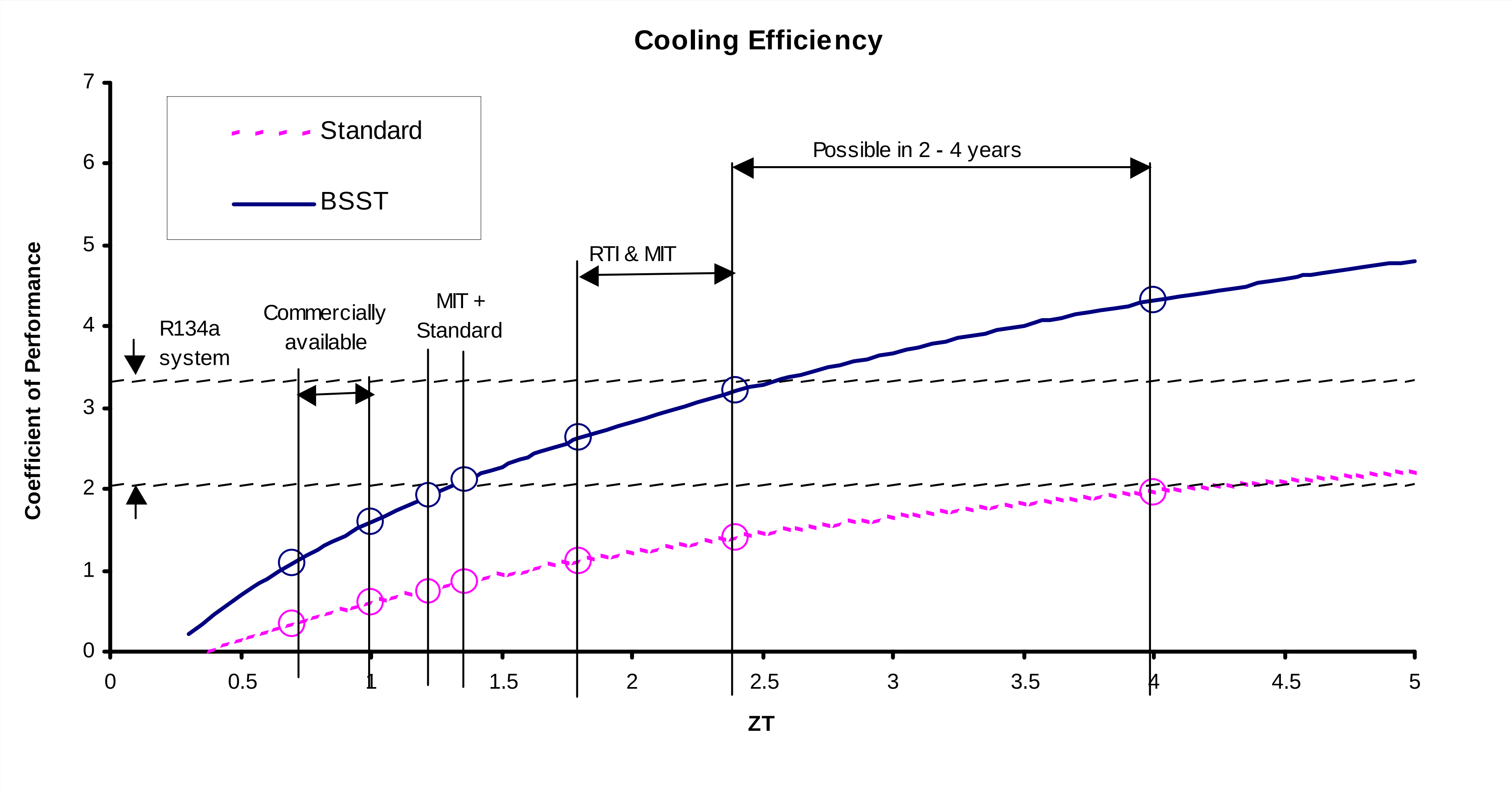
Promising Developments in Thermoelectric Materials

- Quantum well devices (MIT)
  - Harman et al. (2002) conservatively estimated that ZT=2.0 at 300 K could be achieved with quantum well devices.
- Superlattice thin-film materials (RTI)
  - Venkatasubramanian et al. (2001) – demonstration of thin film TE's with ZT ~ 2.4 at near room temperature.
- Alternative materials (JPL)
  - Fleurial et al. (2001) – filled skutterudites (LnT_4Pn_{12}) with ZT of 1.8 at 650°C
- Efficiencies would approach the 20-25% range for large temperature differences (> 400 K).

Promising Developments in Thermoelectric Assembly Techniques

- Thermal isolation (BSST)
  - Bell (2002) predicts at least 50% and up to 120% improvement in performance by thermally isolating each TE couple in the direction of the fluid flow.
  - Higher efficiencies and coefficients of performance (COP) are achieved by progressively heating/ cooling operating fluid
- Used in conjunction with advanced thermoelectric materials could provide efficiencies approaching 50%.

Potential of Thermoelectric Energy Conversion



- Horizontal band represents the COP for a system using R134a.

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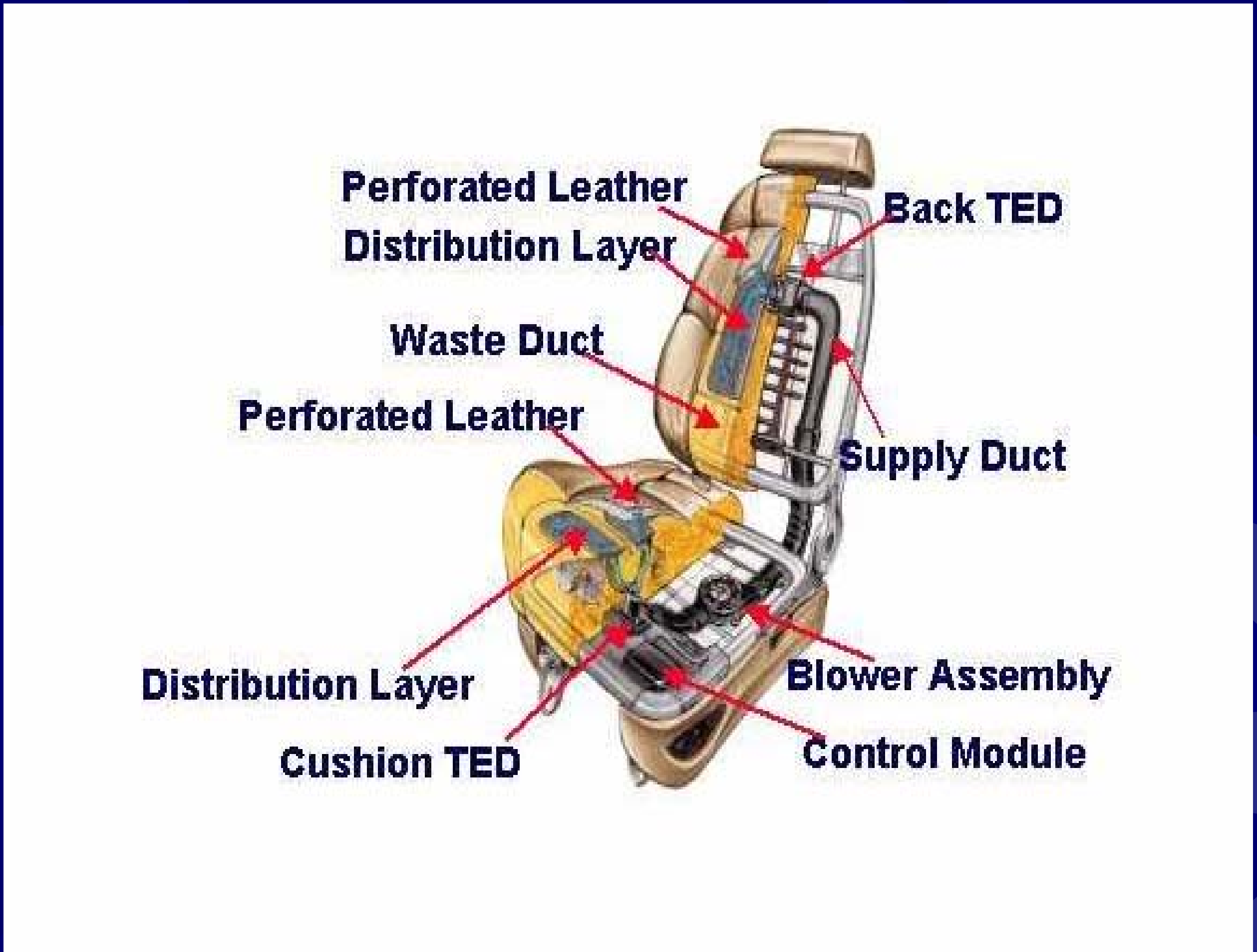
Amerigon Climate Control Seat (CCS™)



- Most successful and highest production volume thermoelectric system in vehicles today
- Mass production of thermoelectric materials will bring costs down.

CCS Advantages

- Improves passenger comfort by targeting strategic areas for climate control
- Decreases the use of standard HVAC systems, reducing greenhouse gas emissions created by R134a
- Improves fuel economy by reducing engine load required to drive HVAC system
- Vehicle weight can be reduced, translating into improved fuel economy

Current and Projected CCS Vehicle Platforms

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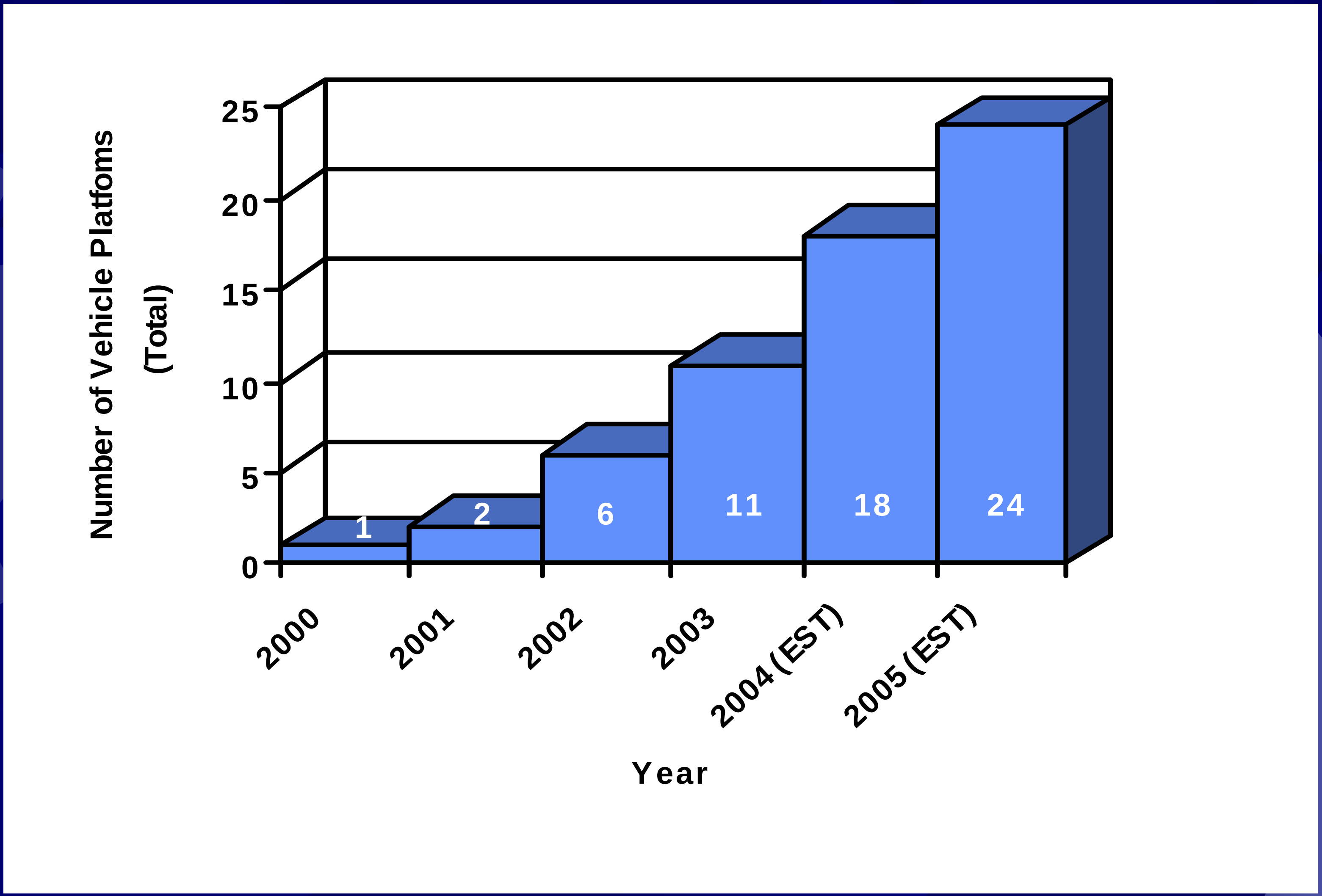
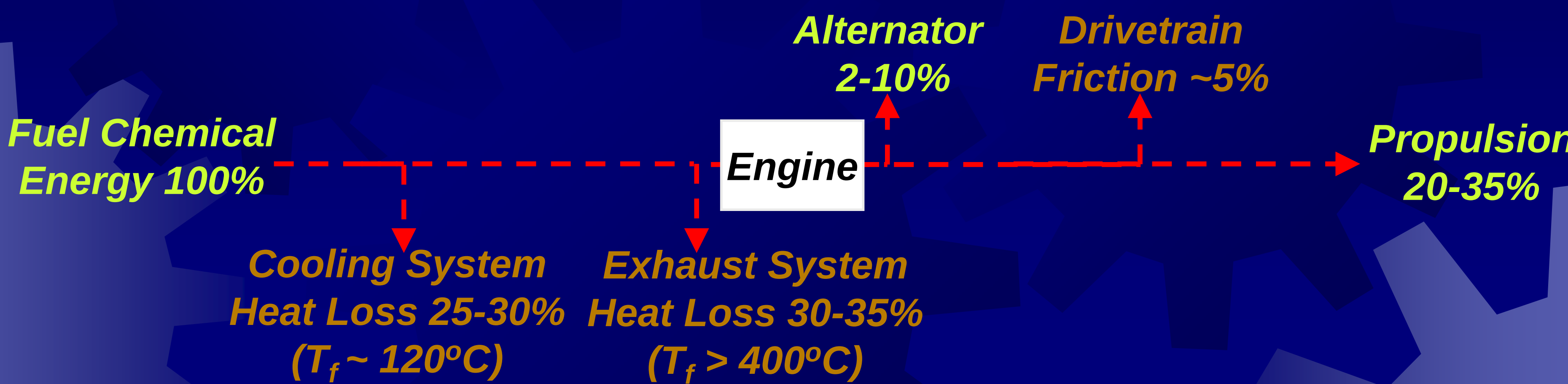


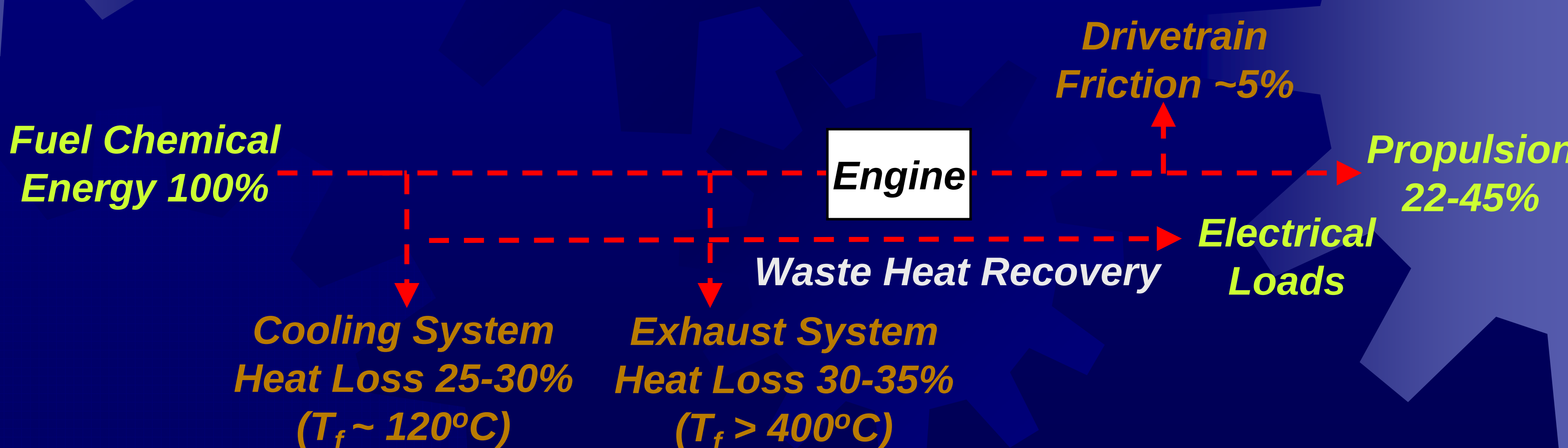
- Available in vehicle platforms made by Lincoln, Lexus, Ford, Toyota, and Infiniti
- Will be standard on the 2004 Cadillac Escalade

Motivation for Waste Heat Recovery

- Up to 65% of fuel chemical energy is lost as waste heat in a typical diesel vehicle
  - another 2-10% is used by the alternator to meet electrical loads



- If accessory loads can be met via waste heat recovery, more fuel energy could be converted directly to propulsion (an increase of 2-10%)



Motivations for Waste Heat Recovery (cont.)

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- Up to 10 kW of fuel chemical energy can be saved if a TE waste heat recovery system displaces an alternator used to produce 1kW of auxiliary power.
- Like regenerative braking, waste heat recovery can provide additional energy reserves for a hybrid electric vehicle battery pack

TE Radiator Cross-Section

(drawing not drawn to scale)

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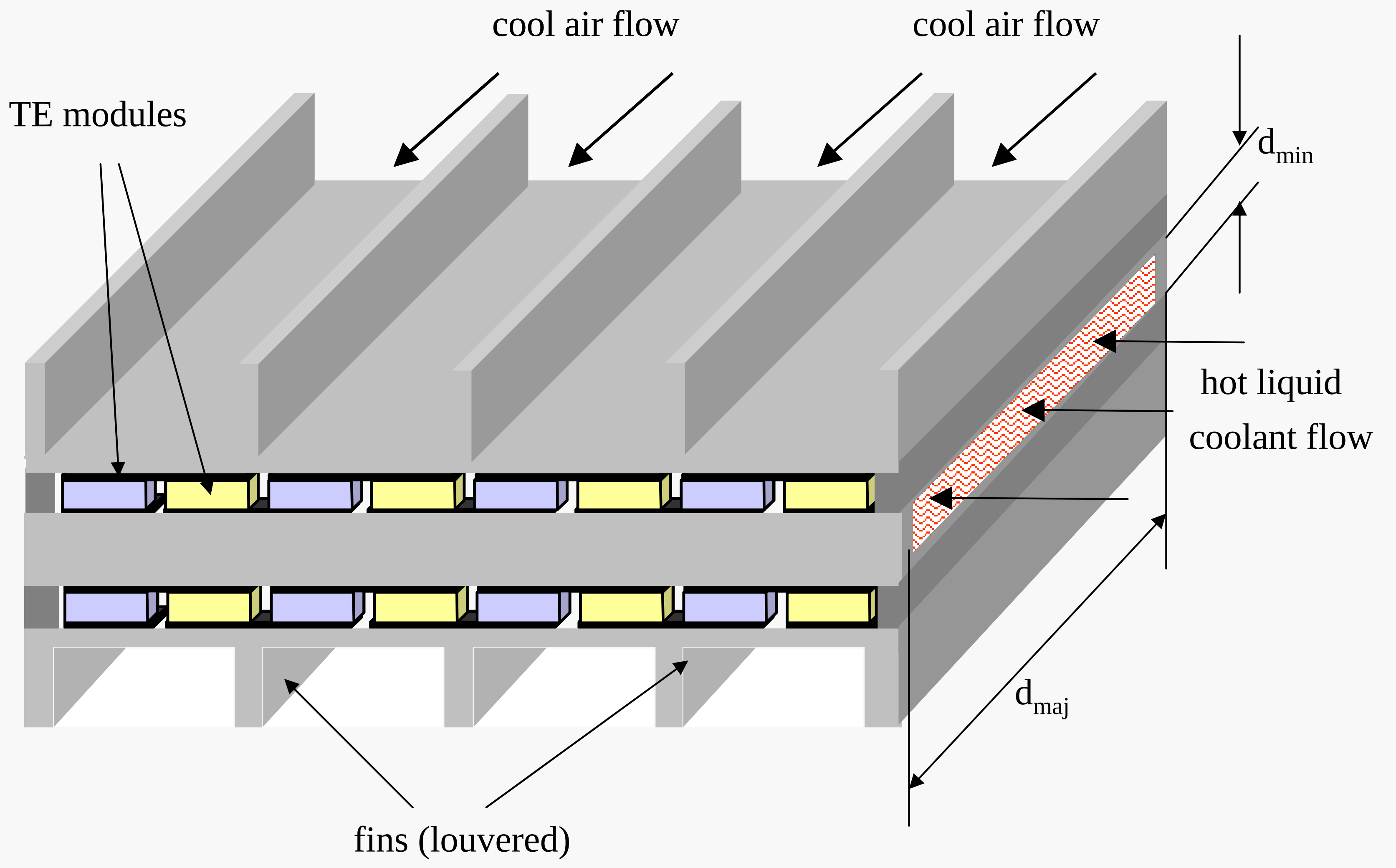
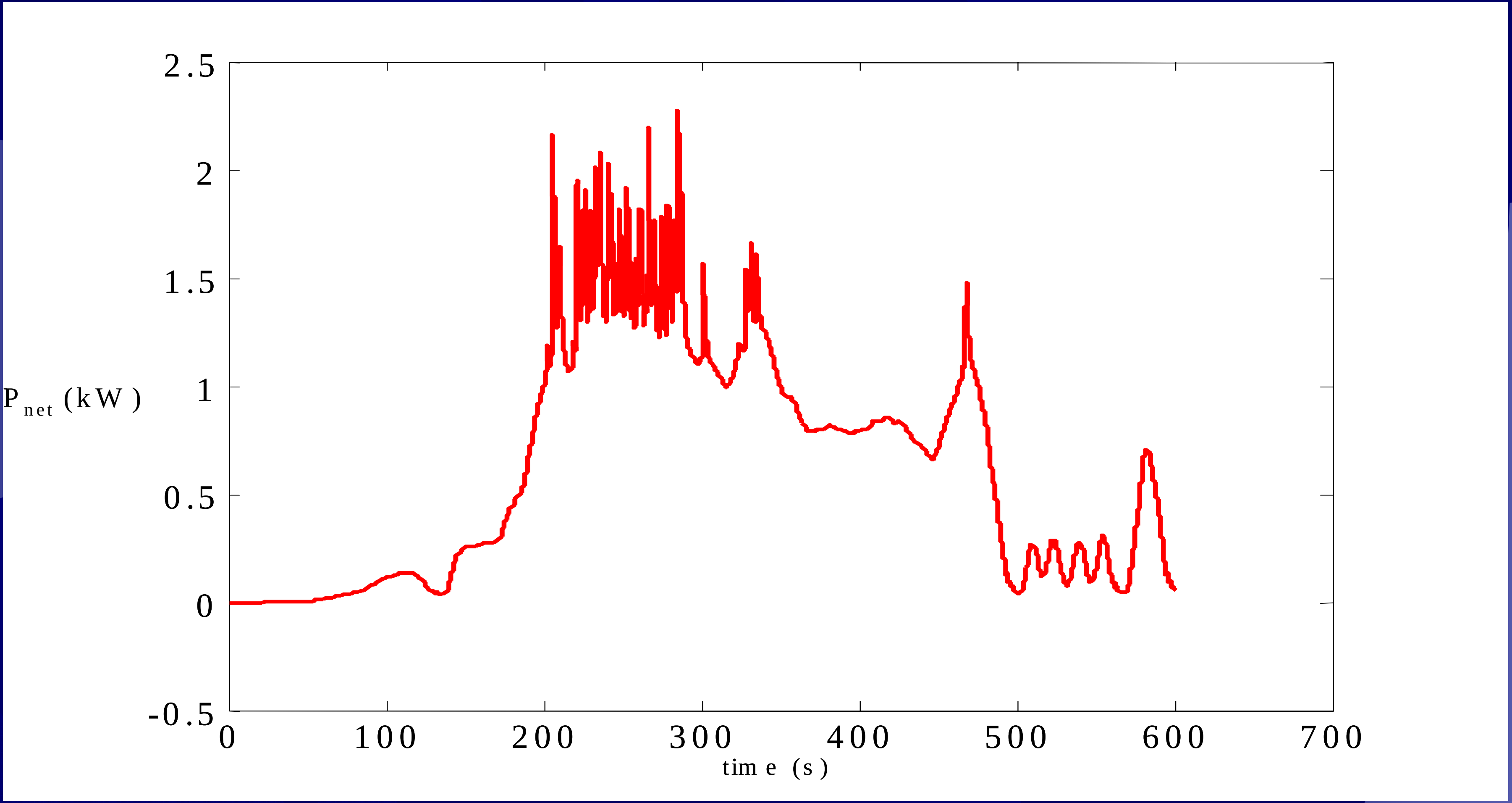


Systems-Level TE Waste Heat Recovery from the Automotive Cooling System



- Transient net power ($P_{TE} – P_{fan} – P_{pump}$) for the US06 drive cycle using RTI TE's with T_{amb} = 300 K and $T_{f,max}$ = 395 K.
- Overall vehicle efficiency was shown to improve by as much as 3.3% for standard driving cycles (does not include BSST thermal isolation).

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Previous Work on Automotive Waste Heat Recovery from the Exhaust System

- Embry and Tudor – Utah St. University and University of Missouri (1968)
  - Theoretically showed an exhaust waste heat TE generator could provide sufficient auxiliary electrical power for a vehicle
- Menchen et al. – Teledyne Energy Systems (1990)
  - Simulated TE muffler for a heavy diesel truck
- Haidar and Ghojel – Monash University – Austrailia (2001)
  - Predicted that a 1 kW alternator could be displaced by a TE waste heat recovery system based on a low-power diesel engine placed between the exhaust manifold and exhaust tube
- Hendricks and Lustbader – National Renewable Energy Laboratory (2002)
  - P_{TE} up to 0.9 kW for light-duty and 5–6 kW for heavy-duty vehicles were predicted using a modified ADVISOR vehicle simulator

Waste Heat Generation Challenges

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- Cooling the cold side in an exhaust system
  - Inconsistent airflow along the underside of the vehicle.
  - Increased complexity of additional coolant loop (i.e. pumps, tubing, and control systems).
- Extracting heat from hot side in exhaust system
  - Internal fins may create engine backpressure concerns
- Potential aerodynamic drag increase
  - Integrated thermoelectric radiator may further restrict cooling system airflow
  - Additional heat exchanger along underside of vehicle to extract heat from exhaust may restrict and/or disrupt airflow.
- Additional weight of thermoelectrics

Emissions Reduction Applications

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- 60% to 80% of all vehicle emissions occurs during cold-start
- Reduce cold-start emissions – catalyst light-off
  - Significant problem in hybrid electric vehicles used in urban driving where engine is turned on and off
  - Temperature control of catalytic converter for optimum performance
  - Dual-use device could be designed for waste heat recovery and temperature control
- Reduce cold-start emissions – fuel filter
  - Prevent obstruction of fuel filter by solidified fuel
  - Particularly a problem in diesel vehicles since the solidification temperature of diesel fuel is higher than that of gasoline
- Particulate trap regeneration
  - Raise temperature of particles to 500^{o}C in order to burn off device-clogging soot that reduces trap functionality.

Conclusions

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- Using BSST thermal isolation techniques in conjunction with advanced TE materials can provide efficiencies and COPs that will be competitive with or exceed the performance of current power generation and HVAC systems.
- BSST is also developing higher power density thermoelectrics, which will further reduce weight and cost.
- Thermoelectric applications in diesel vehicles can provide practical methods to improve fuel economy and reduce engine and HVAC emissions as well as increase user comfort.