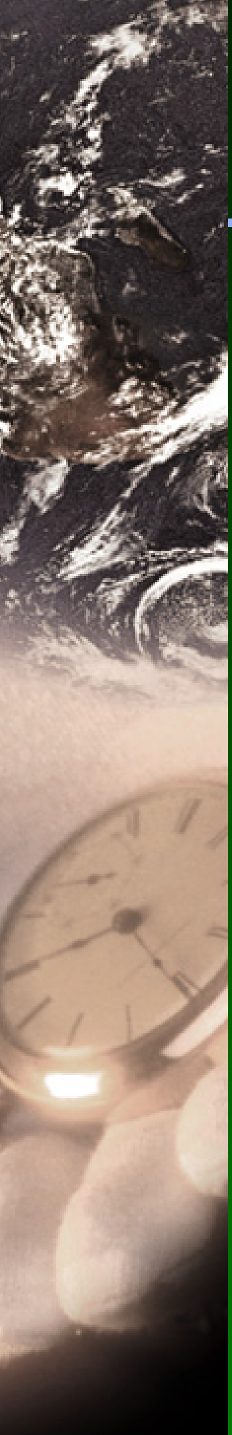


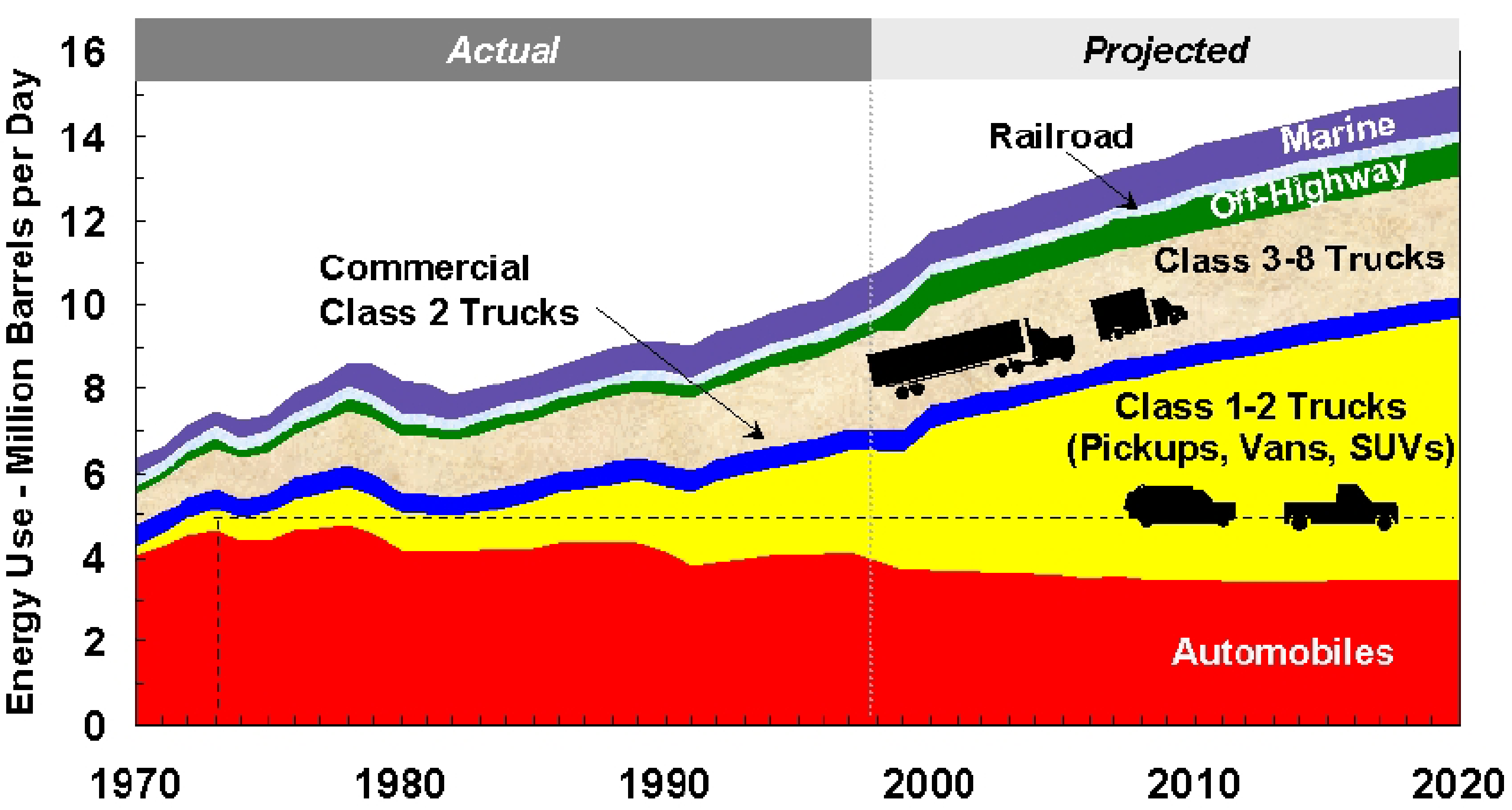
Time for World Class Solutions

Advanced Thermoelectric Energy Recovery Systems in Future Vehicle Systems

DOE/EPRI High-Efficiency Thermoelectrics Workshop
San Diego, CA
19 February 2004

U.S. Department of Energy's National Renewable Energy Laboratory
Terry J. Hendricks, Ph.D., P.E., Heavy Vehicle Power & Propulsion Task Leader
Ph. (303)-275-4419, terry_hendricks@nrel.gov

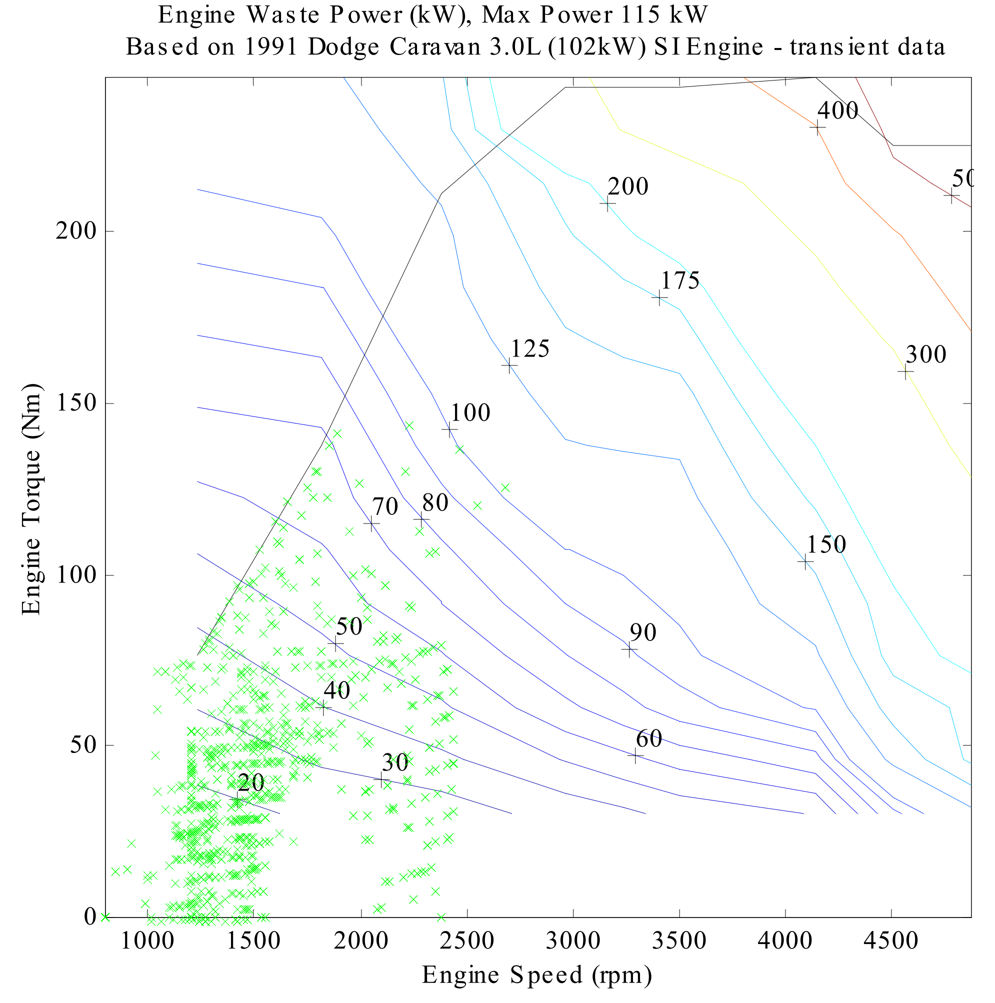
Breakdown of US Historical and Projected Fuel Use by Platform



Sources: *EIA Annual Energy Outlook 2000*, DOE/EIA-0383(2000), December 1999
Transportation Energy Data Book: Edition 20, DOE/ORNL-6959, October 2000

Waste Power Available in Representative 115 kW Engine

- 20-400 kW Waste Power Available Across The Engine Map
- Average of 23 kW Over an FTP Drive Cycle



Objective

Low Grade Thermal Energy From Various Automotive Systems

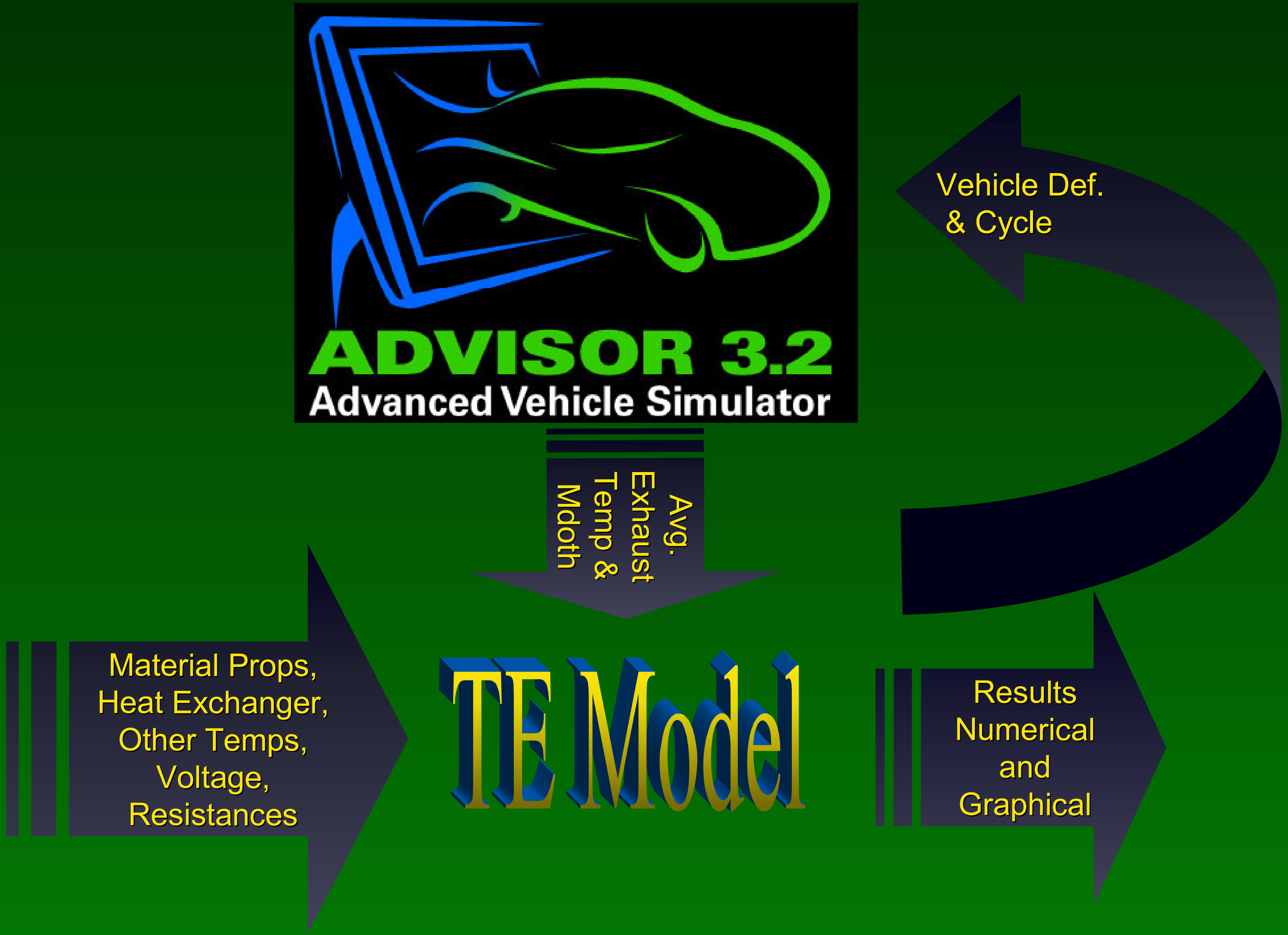
High Grade Electrical Energy To Operate Various Automotive Systems

- Relatively Low Cost
- Passive System
  - No Noise
  - No Vibration
- High Reliability
- Ideally No Fluids

Advanced Thermoelectric Systems

- **Convert Waste Thermal Energy Into High-Grade Electrical Energy**
  - Completely Solid State
  - No Moving Parts or Fluids
  - No Noise or Vibration
- **Latest Thermoelectric Materials Offer New Opportunity**
  - Skutterudites
  - Zn-Sb alloys
  - Quantum-Well Materials
    - Quantum Dots, 1-D Quantum Wires, 2-D Thin Film Superlattices
- **Automotive Exhaust Heat Temperatures 600-650 °C**
  - Interested in ~1000 W System
- **Heavy Vehicle Exhaust Heat Temperatures 500-550 °C**
  - APUs
  - Truck Electrification

Advisor Interface



Vehicle Def.
& Cycle

Avg.
Exhaust
Temp &
Mdoth

Material Props,
Heat Exchanger,
Other Temps,
Voltage,
Resistances

TE Model

Results
Numerical
and
Graphical

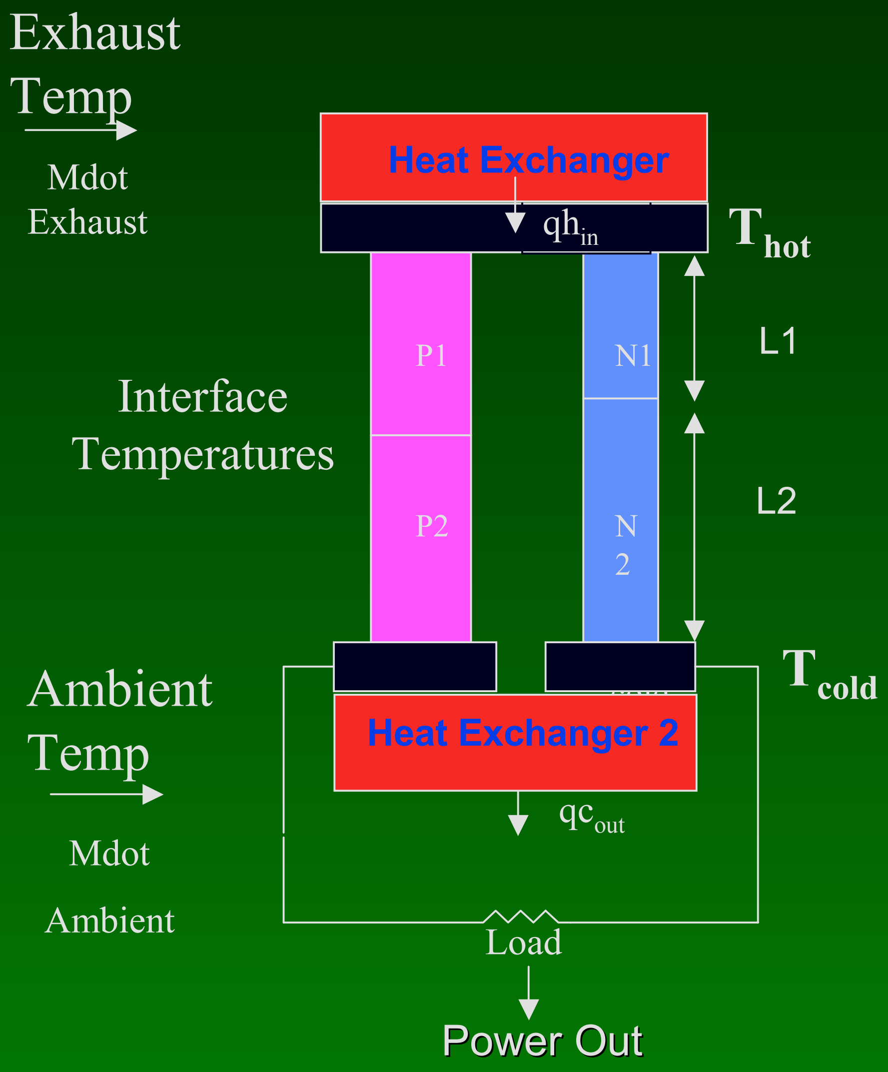
Light-Duty Vehicle Applications

Continuing National Security Issue

=

Advanced Thermoelectric System Design

- Initially Investigated Segmented TE Couple Designs
- Light-Duty & Heavy-Duty Vehicles



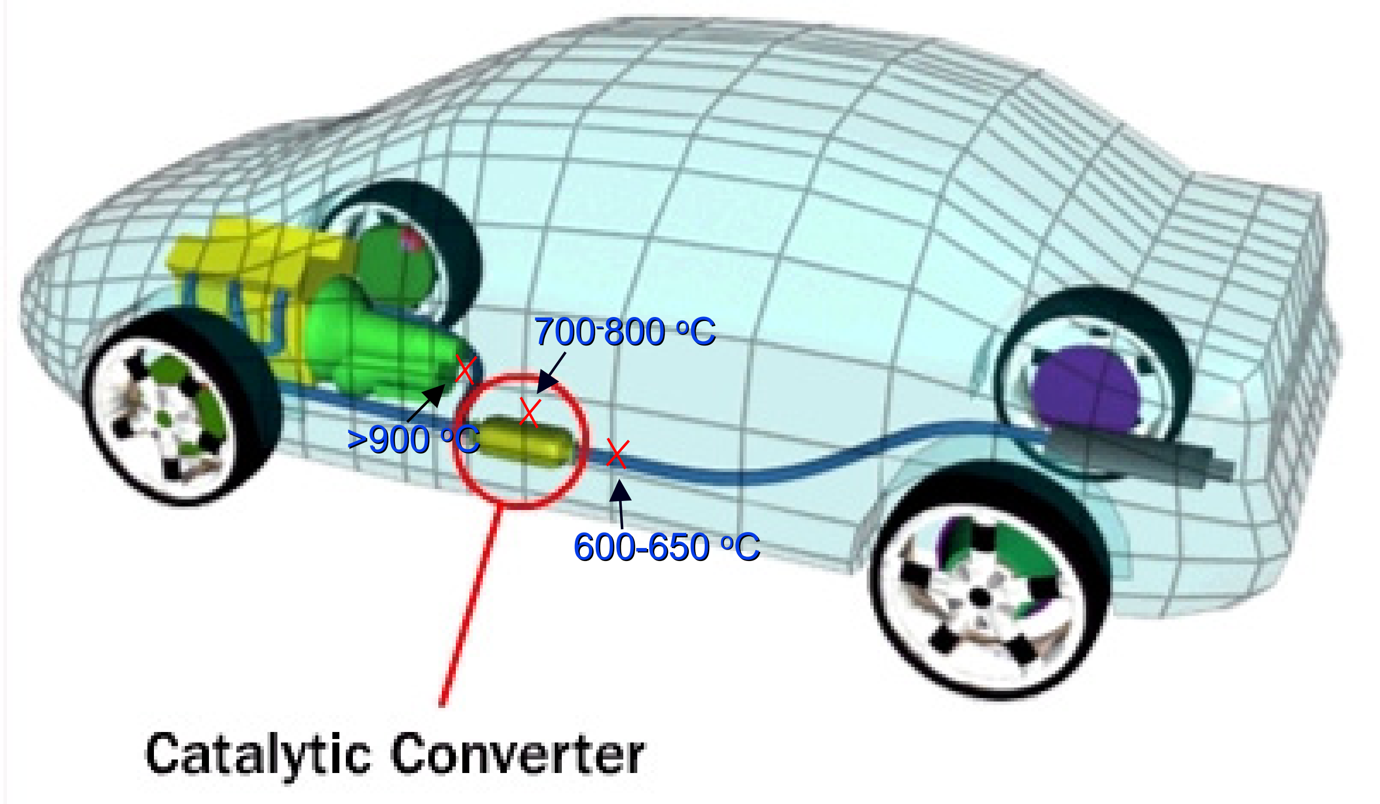
P1=CeFeSb

P2=BiTe

N1=CoSb

N2=BiTe

System Placement



Light Duty Automotive Vehicle Studies

Dodge Neon
Ford Focus
Honda Civic
Saturn S-Series SL

Ave Power = 120 (hp)
Ave Weight = 2500 (lbs)

Buick LeSabre
Cadillac DeVille
Ford Crown Victoria
Lincoln Continental

Ave Power = 250 (hp)
Ave Weight = 3900 (lbs)

Ford Explorer
Toyota 4 Runner
GMC Envoy
Land Rover Discovery

Ave Power = 211 (hp)
Ave Weight = 4300 (lbs)

See Hendricks & Lustbader, 2002, 2003 [1-3]

Advanced Heavy Hybrid Vehicle Applications

Continuing National Security Issue

=

Advanced Heavy Hybrid Propulsion Systems (AH^2PS)

- **AH^2PS Requires High-Grade Electrical Energy Sources from Waste Heat Recovery**
  - Secondary Energy Storage Charging – SOC Maintenance
  - Minimize Engine Use for Energy Storage Charging
  - Powering Auxiliary Loads
- **Long-Term (Phase II) Need for Next-Generation Heavy Hybrid Technology**
  - Advanced Thermoelectric Systems Offer Unique Opportunity
- **Time is Critical – Must Start Now to Have Any Hope of Having Viable Systems in Time to Impact Heavy Vehicle Hybridization**
  - TE Material R&D is Critical
  - Device-Level and System-Level R&D is Critical

Critical Technical Issues

- **Heat Exchanger / TE Device Integration**
  - Potential Electrical Power Available
  - Thermal / Power Integration
  - Physical Integration
    - How Big Could it Be? How Does It Fit Together?
  - Thermal & Structural Interfaces
    - It Is Never Too Early to Start Thinking About This!
  - Physical Location on a Vehicle
- **Exhaust Mass Flow Effects** – Variation in Flow & Temperature
- **Cooling Mass Flow Effects**
  - Air-Cooled vs. Water-Cooled
- **TE Material Combinations & Effects on Performance**
  - What's Best From Performance, Cost, Vehicle Integration

NREL System-Level Investigations in AH²PS Program

- **Preliminary Advanced TE System Analyses**
  - Exhaust Temperature & Mass Flow Rate Conditions in a Typical AH²PS Vehicle Case
  - Realistic Power Estimates
    - Accounting for Integrated Performance Effects
  - Preliminary System Sizing
  - Vehicle Systems Location Analysis
    - Exhaust Stream
    - Turbo Charger
    - EGR
  - Estimate Vehicle-Level Benefits
  - Material Property Effects on System Benefits & Performance
- **Integrate With AH²PS Project in Out Years**

Table 1 – Thin-Film Multi-Layer Thermoelectric Properties @ 300 °K [5]

	Seebeck Coefficient $[10^{-6}$ V/K]	Electrical Resistivity [Ohm-cm]	Thermal Conductivity [W/m-K]
Si/SiGe n-type	950	0.005	1.0-1.5
Si/SiGe n-type	900	0.0083	1.0-1.5
B_9C/B_4C p-type	800	0.020	1.0-1.5

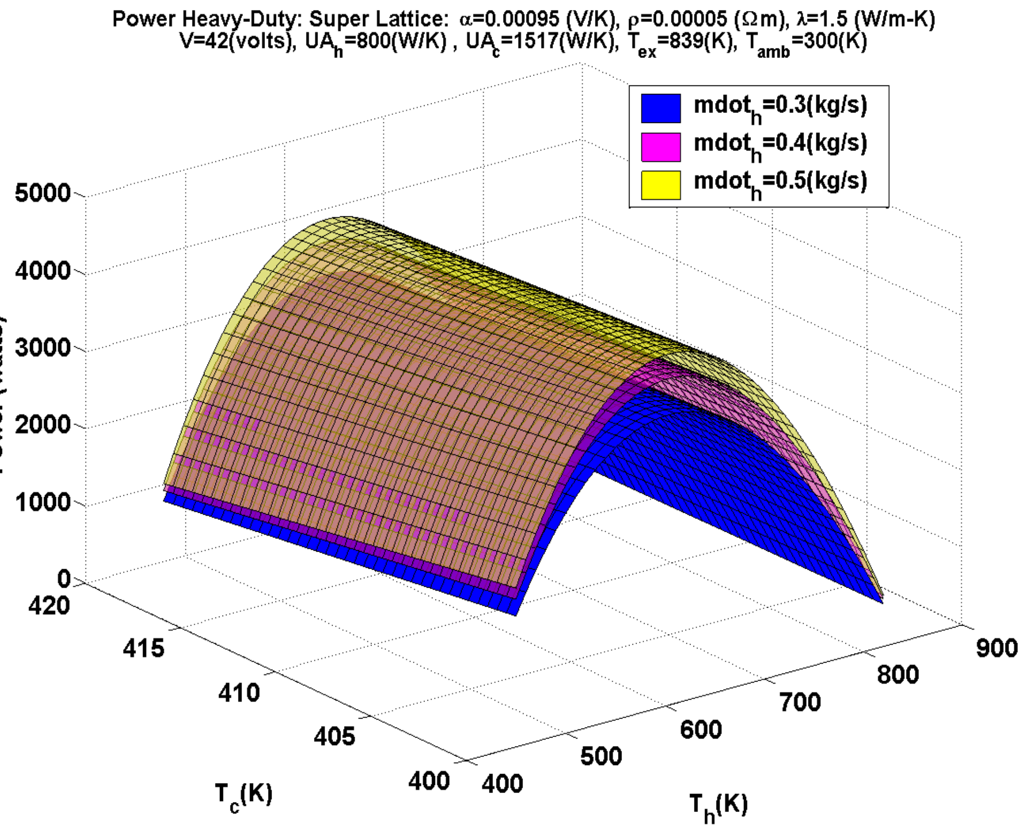
ZT) ≈ 1.1-1.6

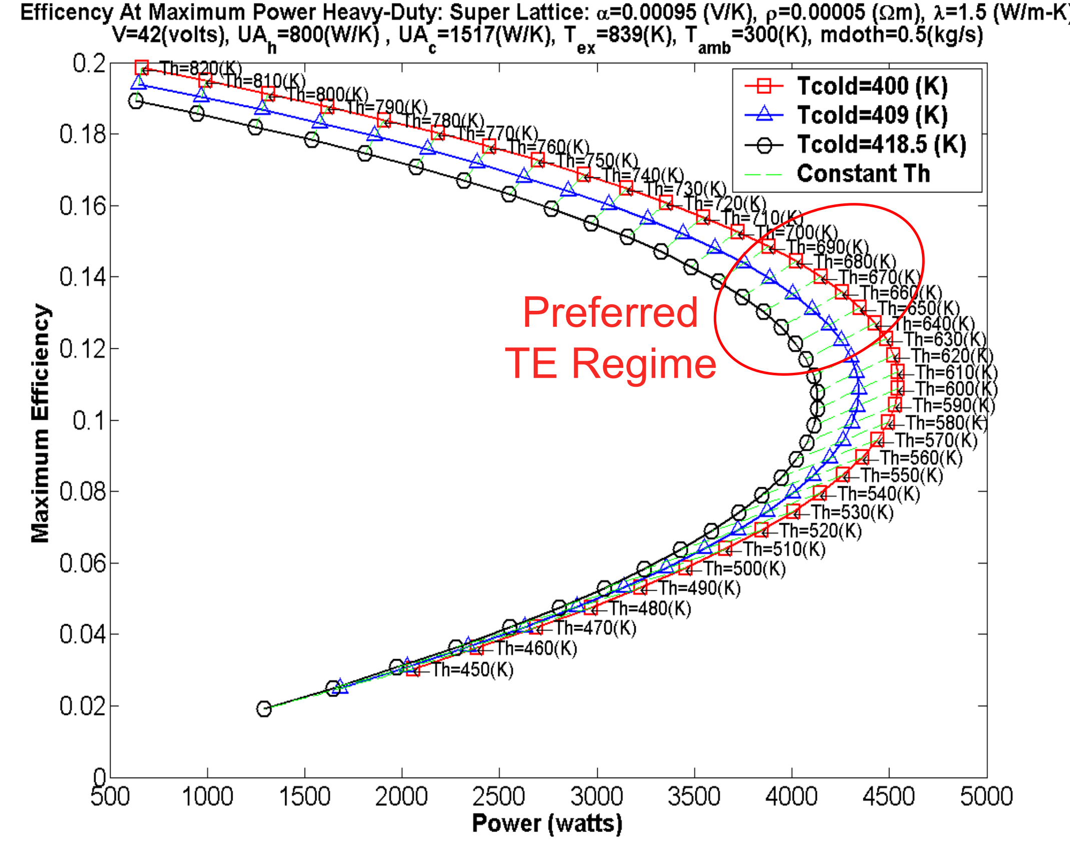
(ZT) ≈ 1.4-2.0

Acknowledgement to Peter Martin & L.C. Olsen, PNNL, DEER 2003 , Newport, RI

Potential Power Output & Efficiency

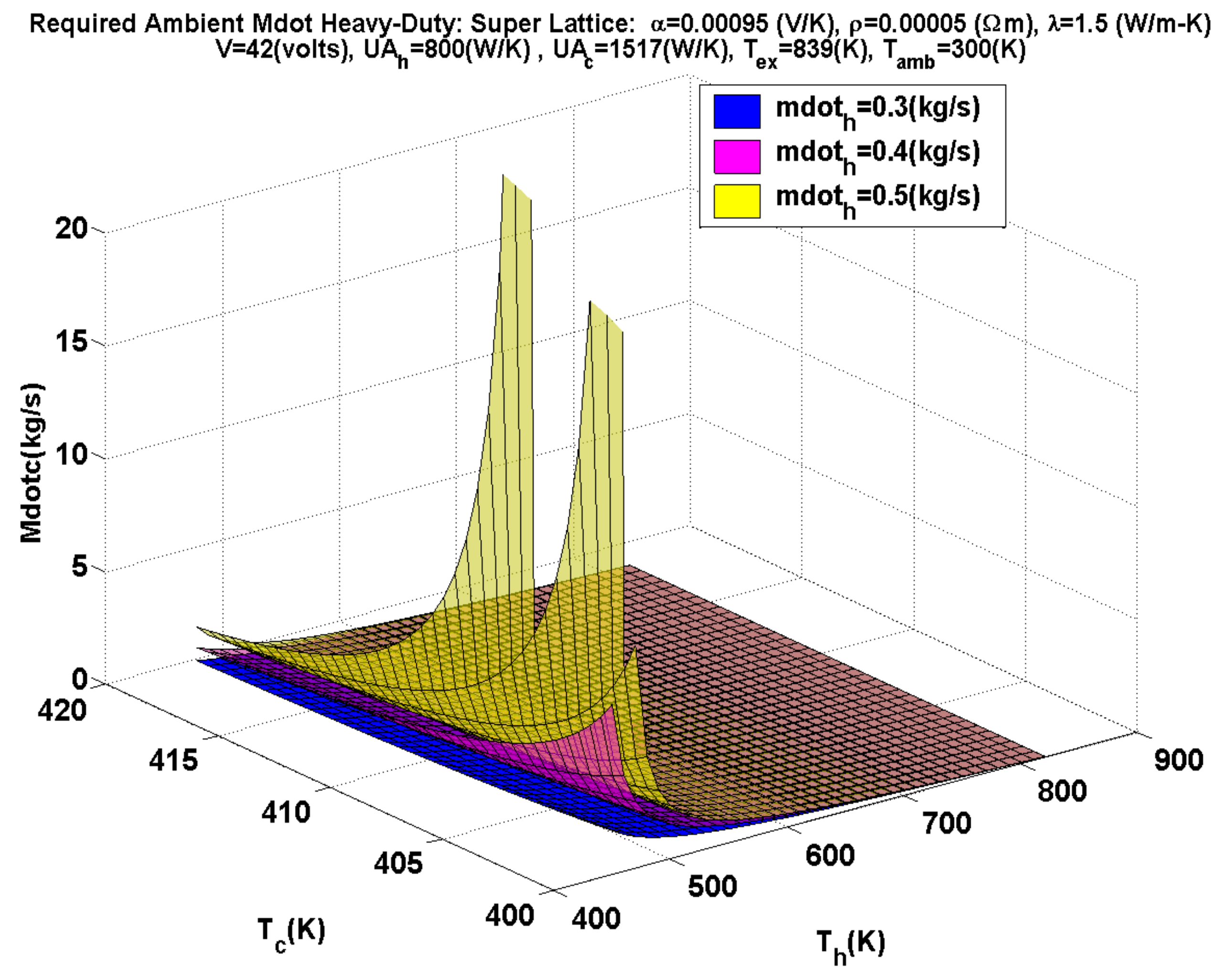
- Peak Powers in Optimized Systems: 4000-4500 Watts @ 12%
- Heat Exchanger & TE Device Interaction
- Peak Power & Peak Efficiency At Distinctly Different Points





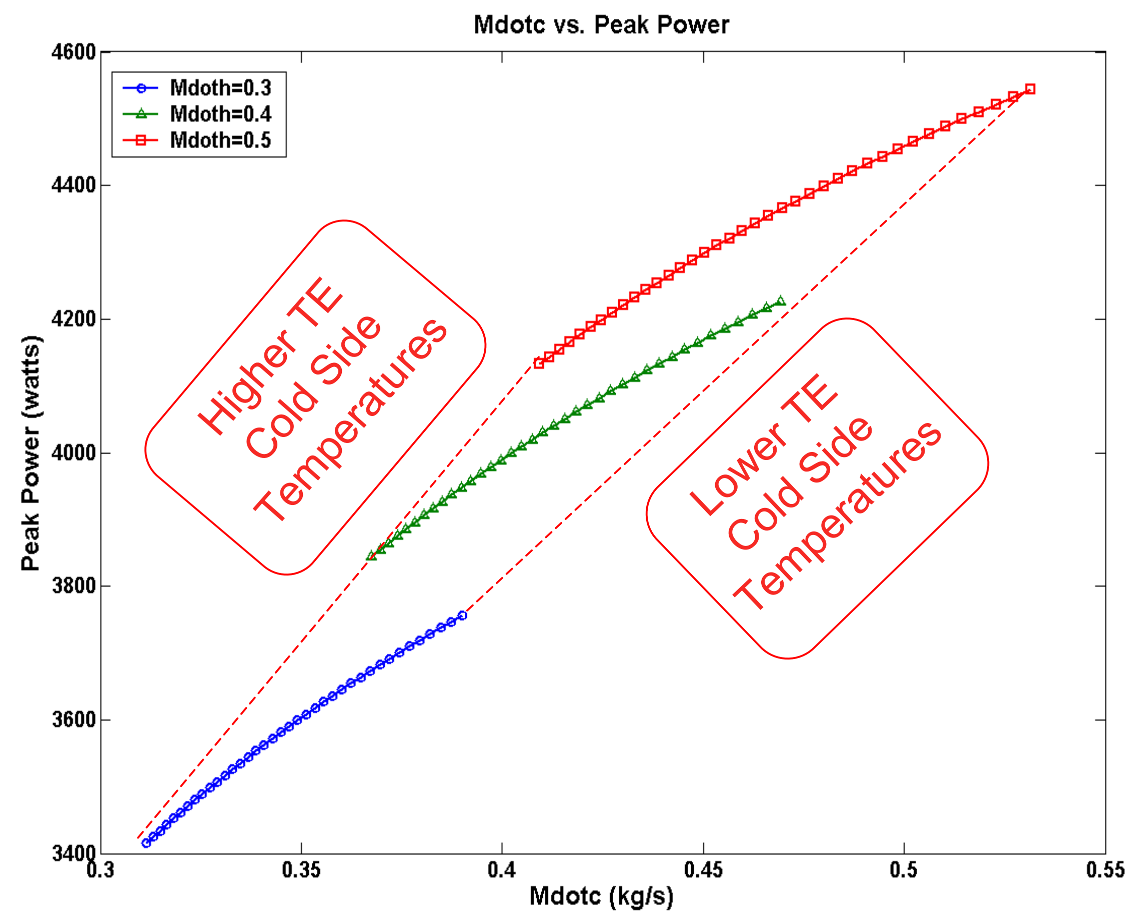
Cold Side Mass Flow Requirements

Preferred Temperature Regimes Due to Cold Side Cooling Requirements



Peak Power / Cooling Mass Flow Relationship

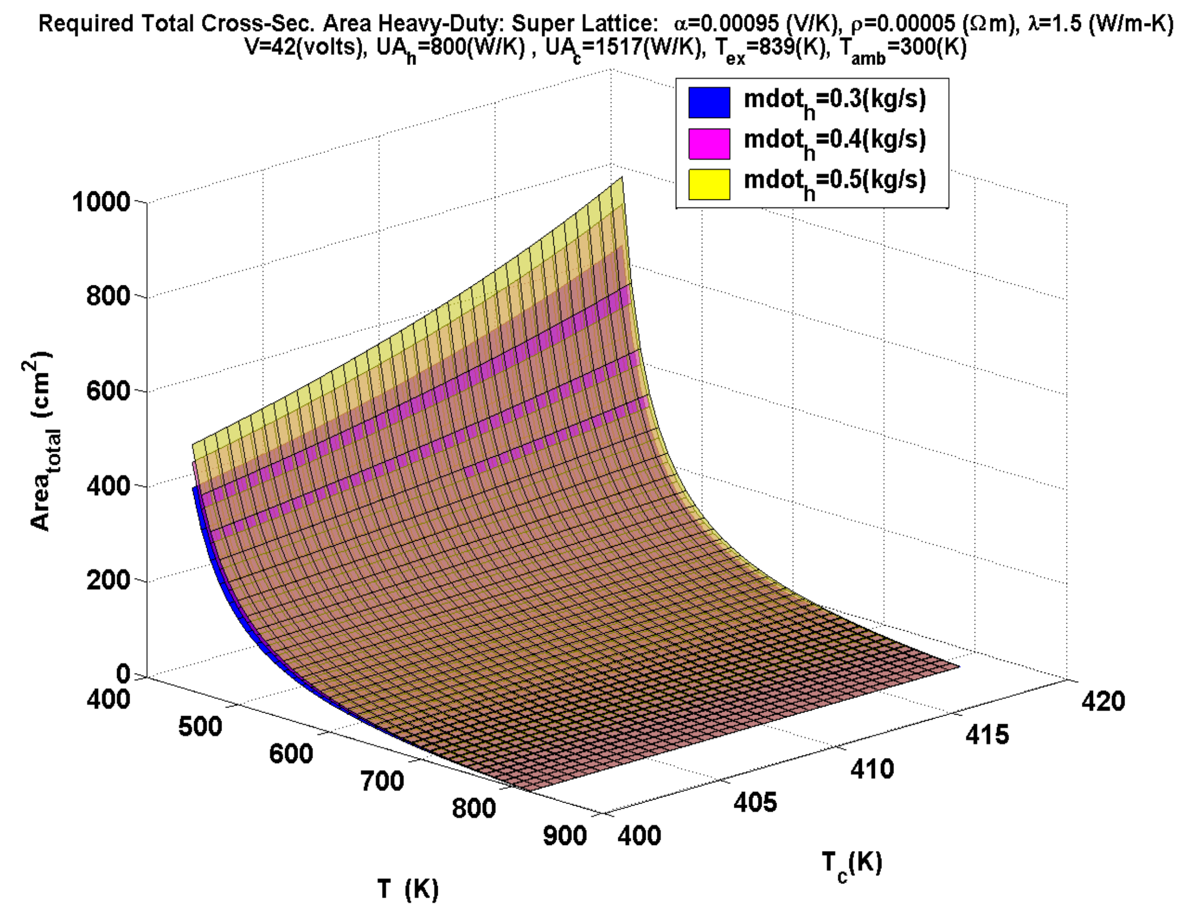
- Peak Power/Cooling Mass Flow Map Driven By TE Temperatures
- Increasing Exhaust Mass Flow Rate ⟹ Higher Power Output, But Diminishing Returns Are Evident (Application Specific)



Optimum TE Device Area Requirements

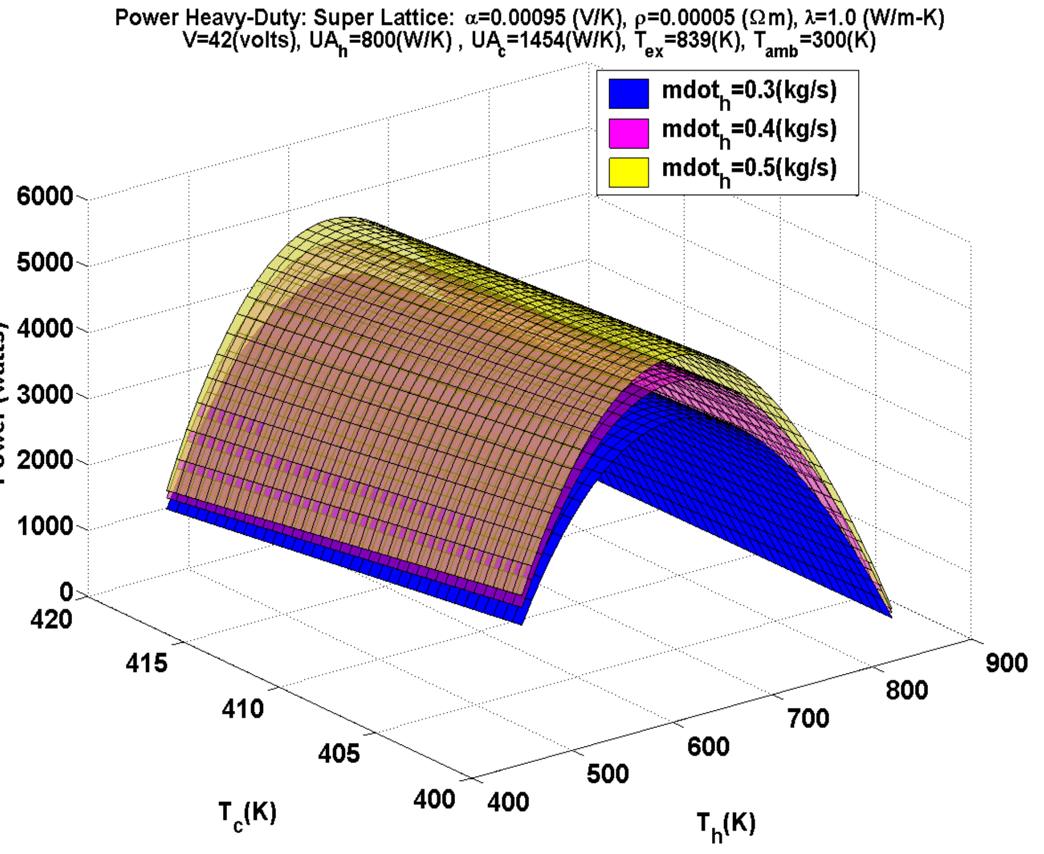
- Optimum TE Device Area: Depends on Final Element Lengths (Probably 50-600 cm^2 at Peak Power Points)
- Heat Exchangers Likely Much Bigger
- Thermal Funneling Effects in System Design

TE Element Length (µm)	Optimum Device Area (cm^2)
100	~50
1000	~500
1250	~625

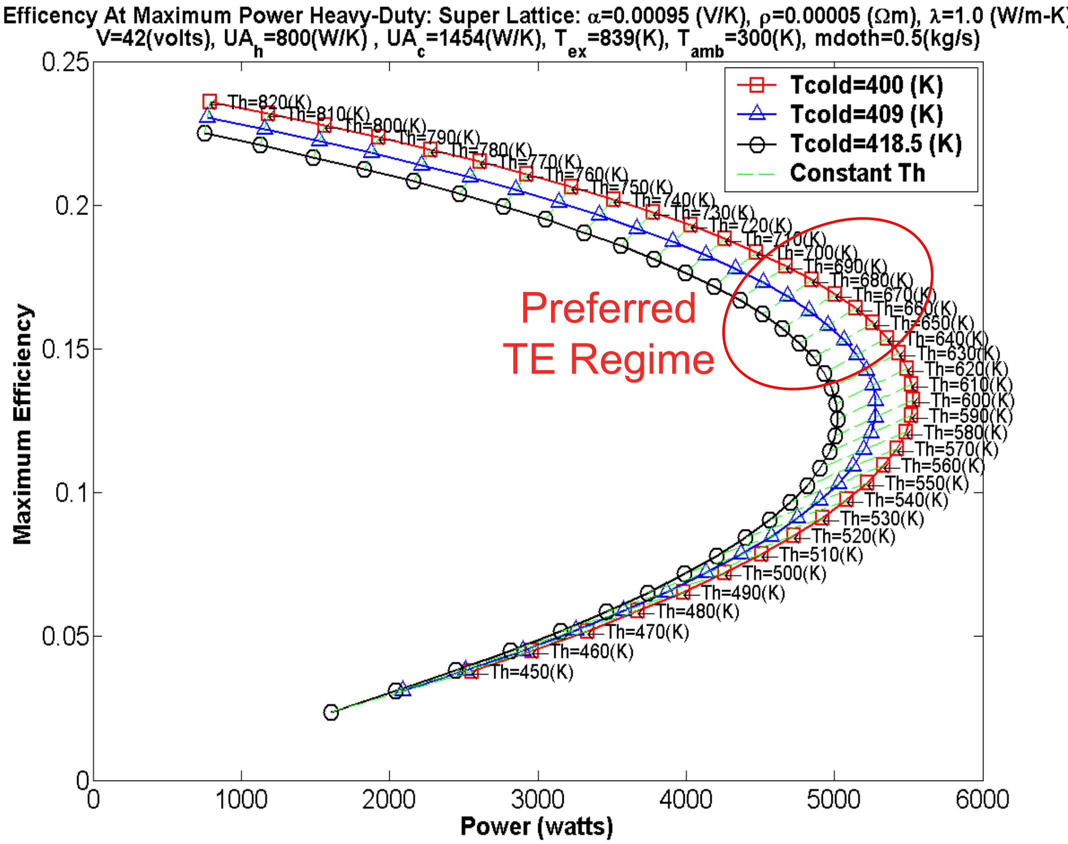

Required Total Cross-Sec. Area Heavy-Duty: Super Lattice: α=0.00095 (V/K), ρ=0.00005 (Ωm), λ=1.5 (W/m-K)
V=42(volts), UA_h=800(W/K) , UA_c=1517(W/K), T_{ex}=839(K), T_{amb}=300(K)

TE Material Thermal Conductivity Effects

- λ Reduced From 1.5 W/m-K ➡ 1.0 W/m-K
- Peak Powers for Optimized Systems: 5000-5500 W @ 14-15%
- Quantifies the Effect of Materials R&D Focus in this Area



Power Heavy-Duty: Super Lattice: $\alpha=0.00095$ (V/K), $\rho=0.00005$ (Ωm), $\lambda=1.0$ (W/m-K)
V=42(volts), $UA_h=800$(W/K) , $UA_c=1454$(W/K), $T_{ex}=839$(K), $T_{amb}=300$(K)

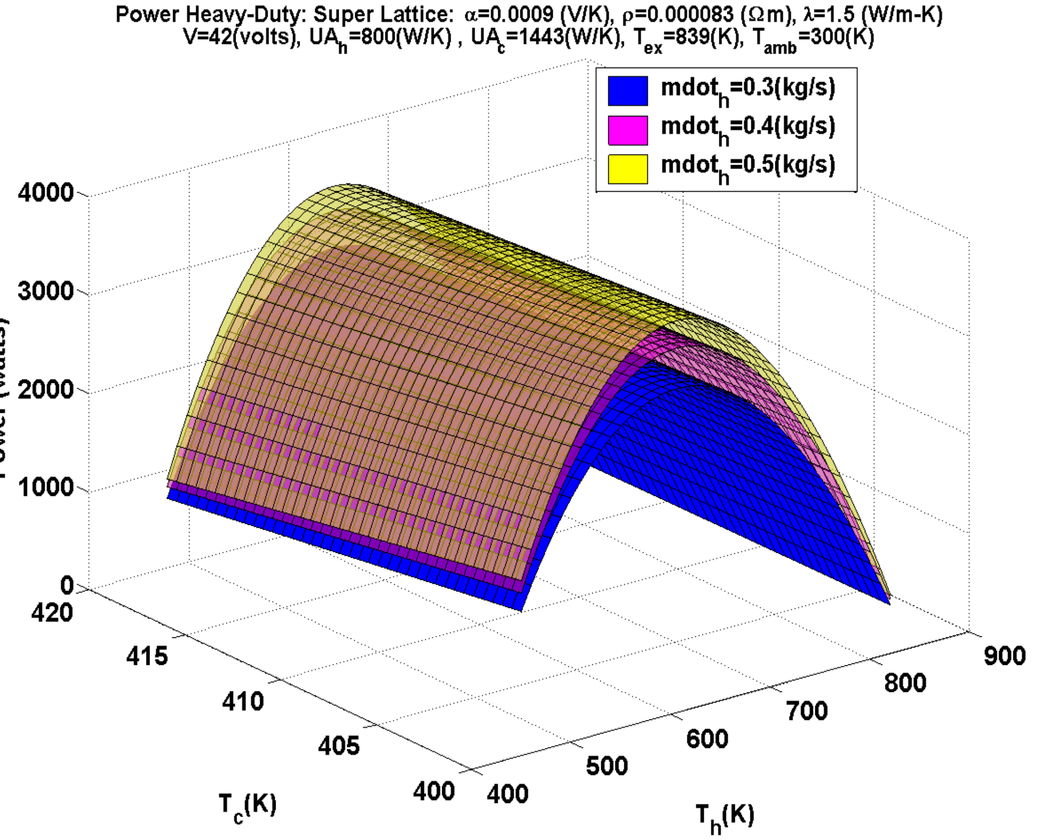


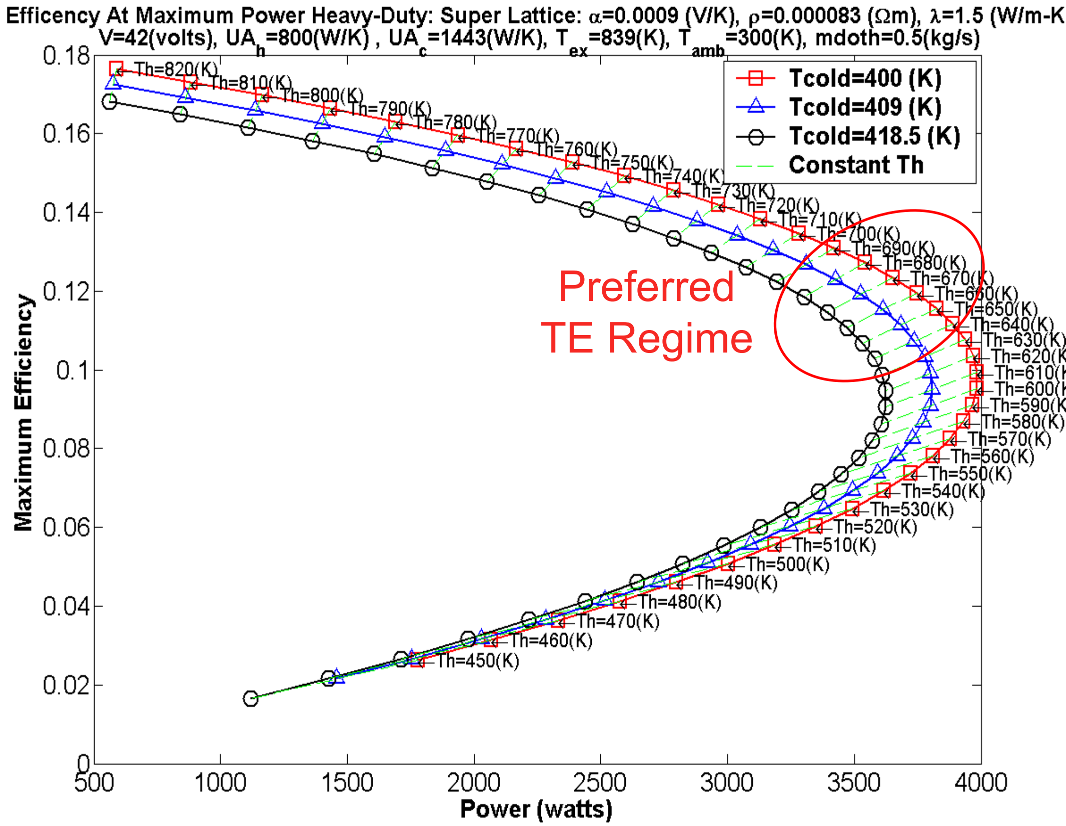
Efficency At Maximum Power Heavy-Duty: Super Lattice: $\alpha=0.00095$ (V/K), $\rho=0.00005$ (Ωm), $\lambda=1.0$ (W/m-K
V=42(volts), $UA_h=800$(W/K) , $UA_c=1454$(W/K), $T_{ex}=839$(K), $T_{amb}=300$(K), mdoth=0.5(kg/s)

Preferred TE Regime

Higher Electrical Resistivity Effects

- ρ Increased from 0.005 Ω-cm ➡ 0.0083 Ω-cm
- Peak Powers in Optimized Design: 3500-4000 W @ 10%
- Quantifies the Effect of Materials R&D Focus in this Area

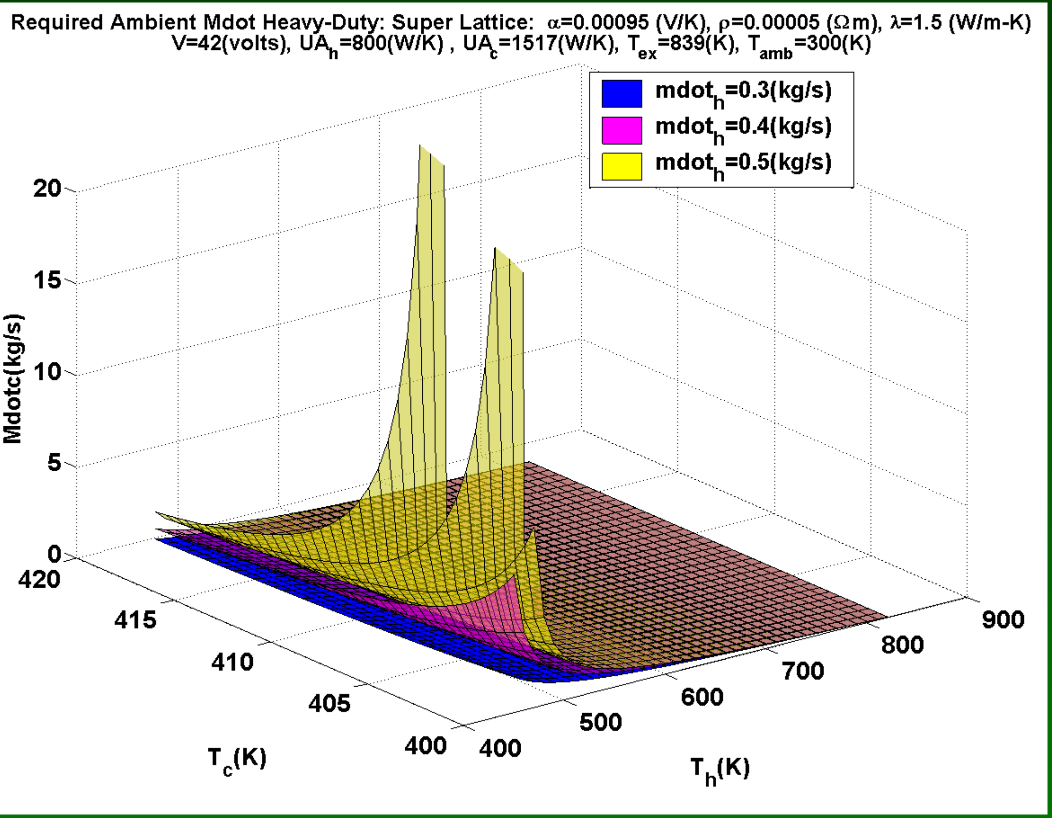

Power Heavy-Duty: Super Lattice: α=0.0009 (V/K), ρ=0.000083 (Ωm), λ=1.5 (W/m-K)
V=42(volts), UA_h=800(W/K) , UA_c=1443(W/K), T_{ex}=839(K), T_{amb}=300(K)


Efficency At Maximum Power Heavy-Duty: Super Lattice: α=0.0009 (V/K), ρ=0.000083 (Ωm), λ=1.5 (W/m-K
V=42(volts), UA_h=800(W/K) , UA_c=1443(W/K), T_{ex}=839(K), T_{amb}=300(K), mdoth=0.5(kg/s)

Resistivity Effect on Cold Side Mass Flow Requirements

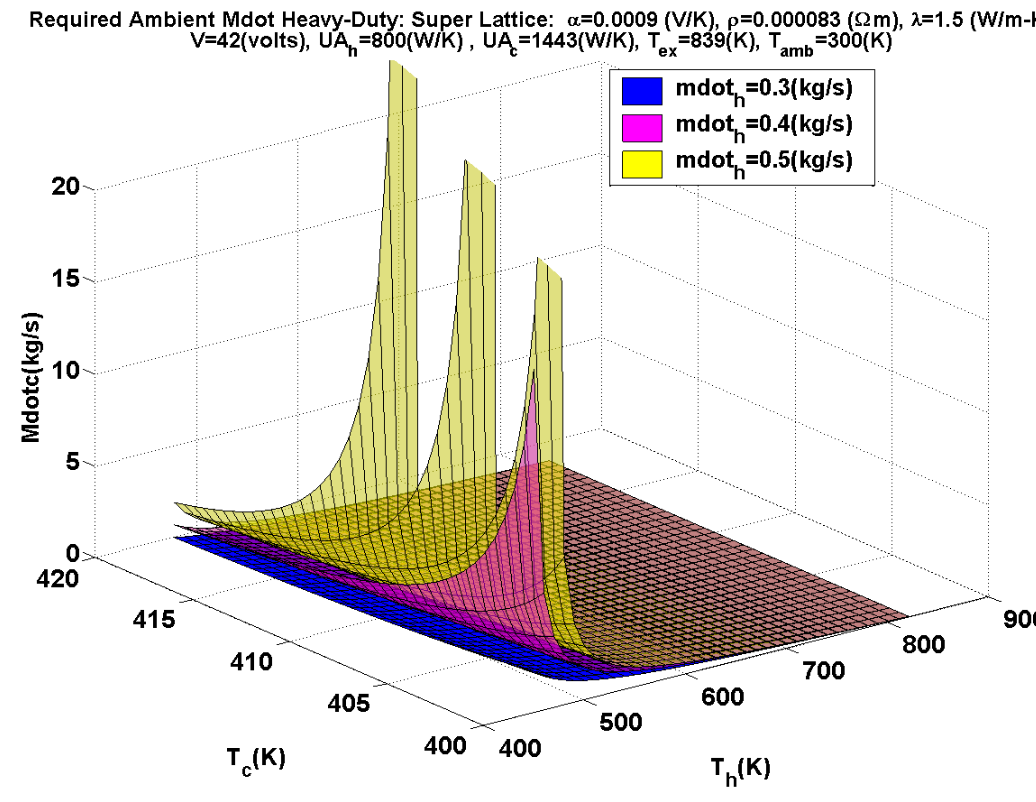
- And the Cold Side Mass Flow Requirements Get More Severe & Tenuous

Lower Resistivity Case



Required Ambient Mdot Heavy-Duty: Super Lattice: α=0.00095 (V/K), ρ=0.00005 (Ωm), λ=1.5 (W/m-K)
V=42(volts), UA_h=800(W/K) , UA_c=1517(W/K), T_{ex}=839(K), T_{amb}=300(K)

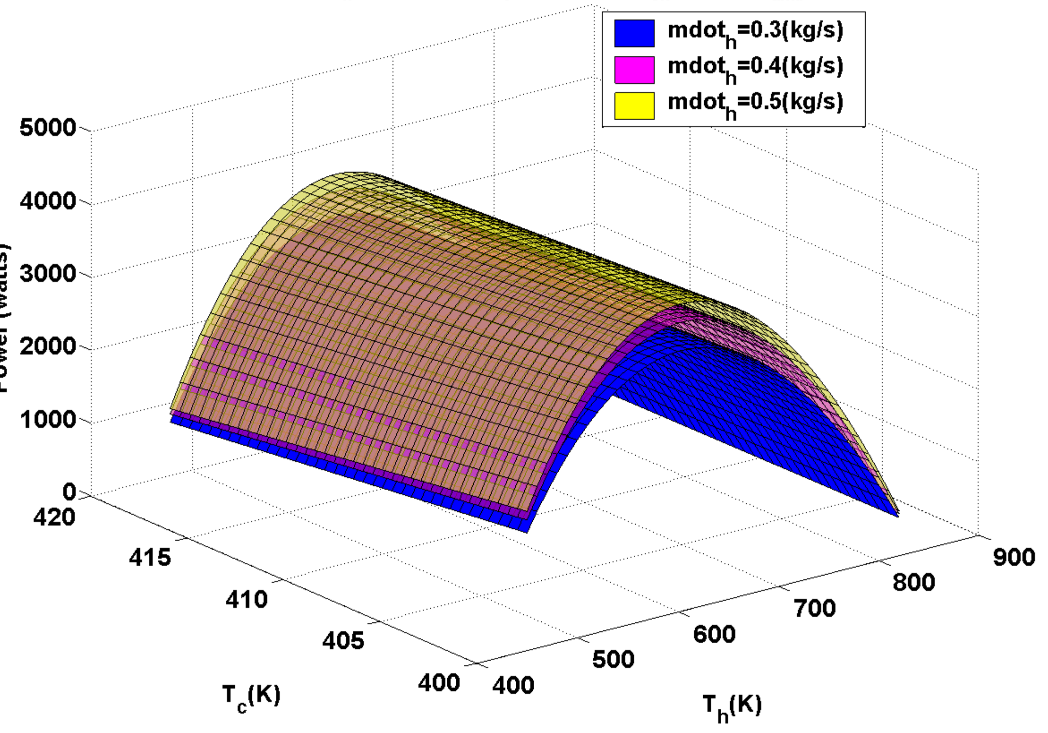
Higher Resistivity Case

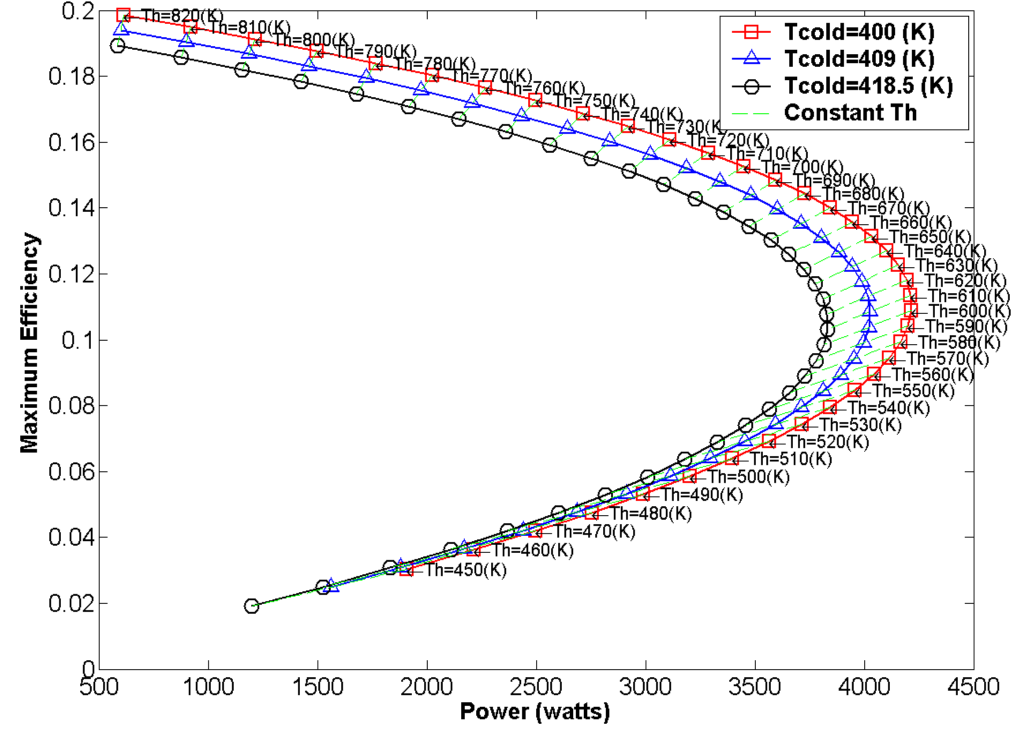


Required Ambient Mdot Heavy-Duty: Super Lattice: α=0.0009 (V/K), ρ=0.000083 (Ωm), λ=1.5 (W/m-
V=42(volts), UA_h=800(W/K) , UA_c=1443(W/K), T_{ex}=839(K), T_{amb}=300(K)

Hot Side Heat Exchanger UA Effects

- Hot Side UA Reduced From 800 W/K ➡ 600 W/K
- Peak Powers in Optimized Systems: 3700-4200 W @ 11-12 %
- Quantifies the Effect of Heat Exchanger R&D As Critical Enabling Technology

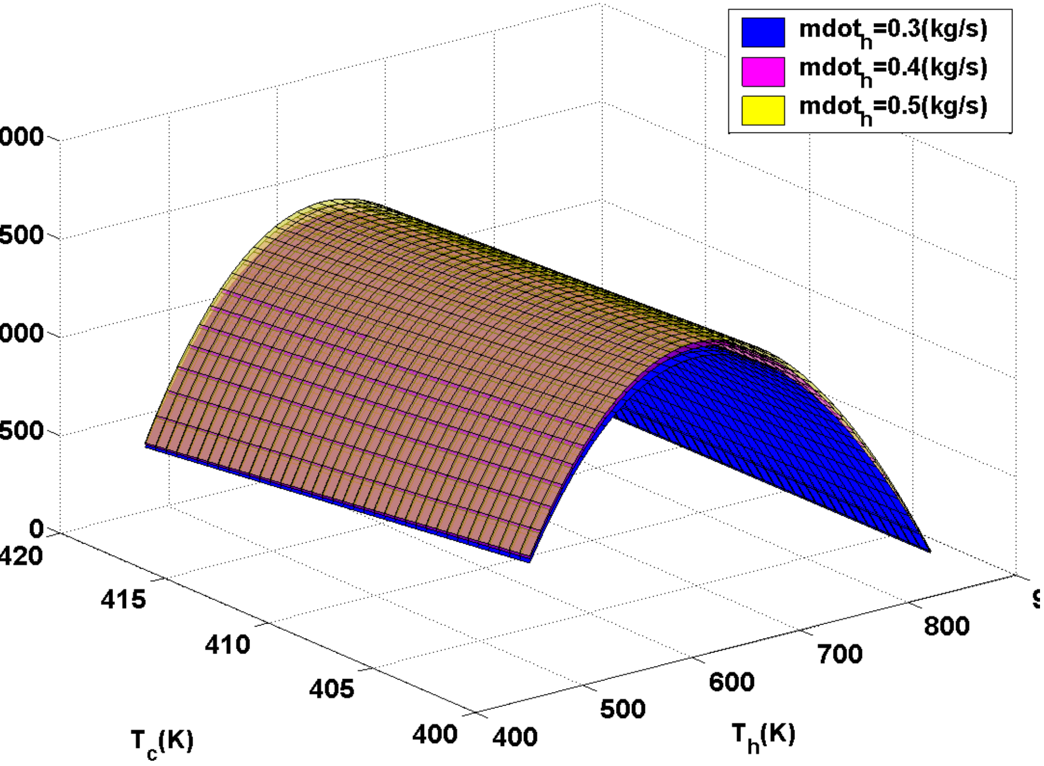

Power Heavy-Duty: Super Lattice: α=0.00095 (V/K), ρ=0.00005 (Ωm), λ=1.5 (W/m-K)
V=42(volts), UA_h=600(W/K), UA_c=1349(W/K), T_{ex}=839(K), T_{amb}=300(K)


Efficency At Maximum Power Heavy-Duty: Super Lattice: α=0.00095 (V/K), ρ=0.00005 (Ωm), λ=1.5 (W/m-K)
V=42(volts), UA_h=600(W/K), UA_c=1349(W/K), T_{ex}=839(K), T_{amb}=300(K), mdoth=0.5(kg/s)

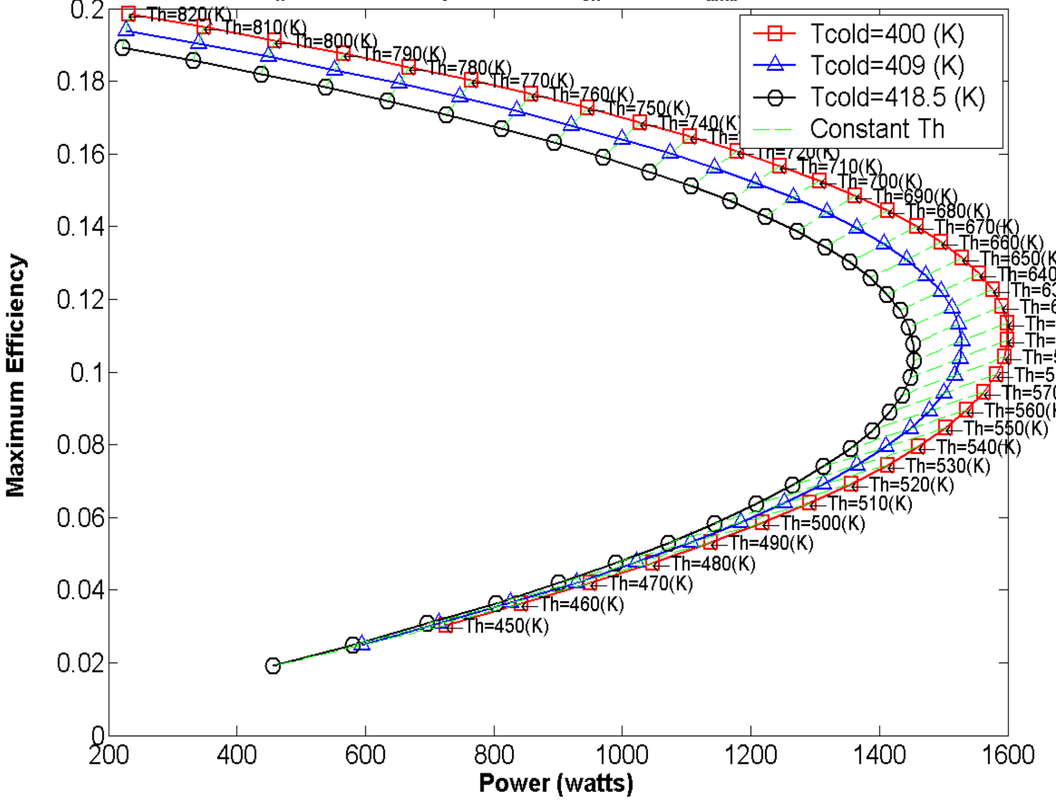
Hot Side Heat Exchanger UA Effects

- Hot Side UA Reduced From 800 W/K ➡ 100 W/K
- Devastating Impact on Power Output: 1400-1600 W @ 11-12%
- Optimum TE Device Area Drops to 250-300 cm^2 @ Peak Powers

Power Heavy-Duty: Super Lattice: α=0.00095 (V/K), ρ=0.00005 (Ωm), λ=1.5 (W/m-K)
V=42(volts), UA_h=100(W/K) , UA_c=386(W/K), T_{ex}=839(K), T_{amb}=300(K)

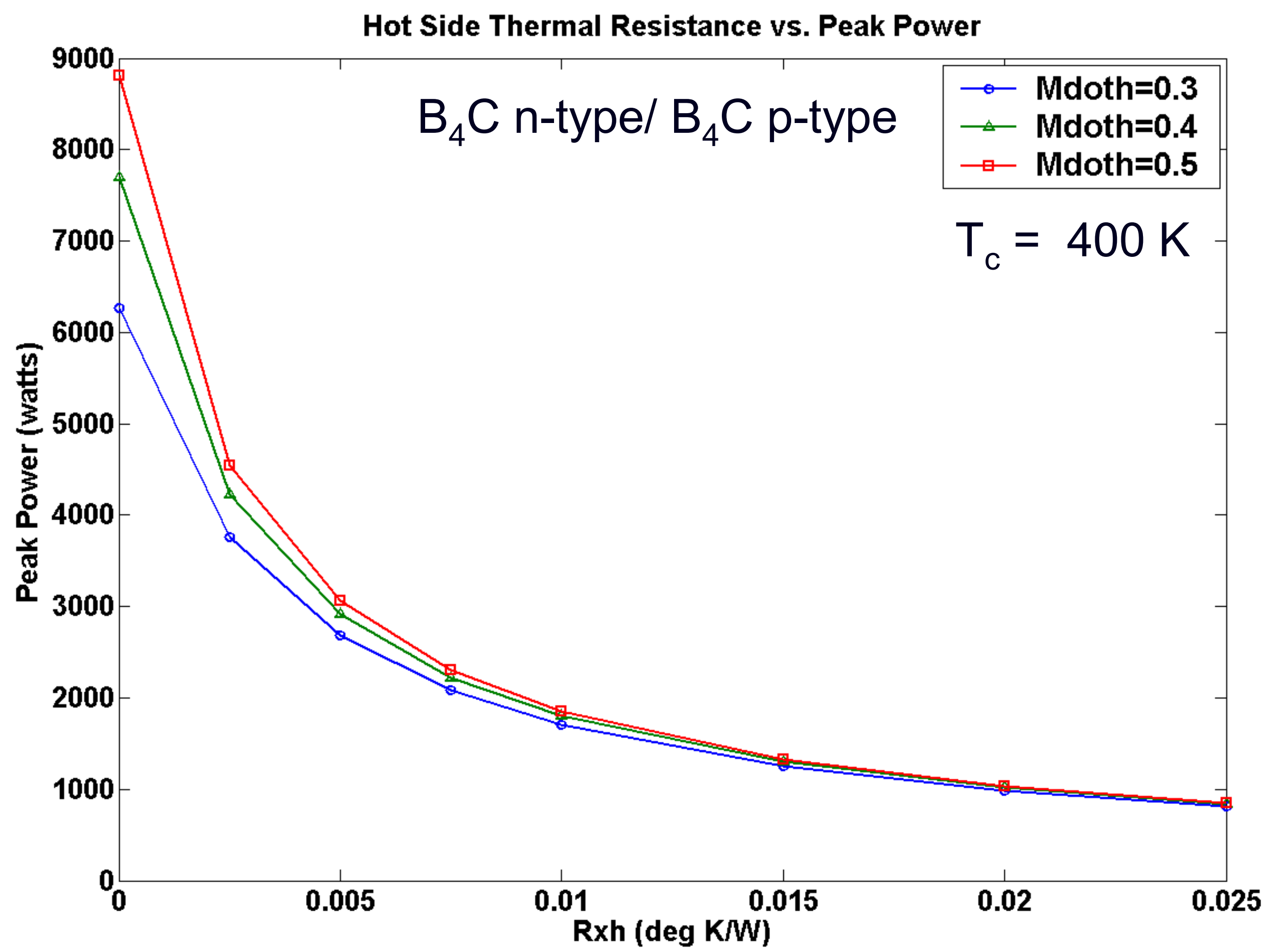


Efficency At Maximum Power Heavy-Duty: Super Lattice: α=0.00095 (V/K), ρ=0.00005 (Ωm), λ=1.5 (W/m
V=42(volts), UA_h=100(W/K) , UA_c=386(W/K), T_{ex}=839(K), T_{amb}=300(K), mdoth=0.5(kg/s)



Hot Side Thermal Resistance Effects

- Device-to-Heat Exchanger Thermal Resistance Will Have Large Effect on Peak Power Available
- $R_{thermal}$ Can Dominate If Interface Designed Poorly
- Mass Flow Rate Effect Large at Low $R_{thermal}$



Potential Heavy Hybrid Vocations/Markets

Marketing / Commercialization Thoughts

- Different Devices/Systems Than Previously Dealt With
  - TE Device Not That Big for 3.5 – 5.0 kW Powers
  - Thermal Funneling
  - Could Be Ultra-Thin TE Devices
- Advanced Heat Exchangers Key Enabler
- Preferred Temperature Regimes Definitely Exist
    - Maximum TE Power
    - System Cooling
- Coupled TE Materials <u>and</u> System-Level R&D Required
- Heavy-Duty Markets Present Larger Power Opportunity Than Light-Duty Markets
- Device/System Characterization, Verification, & Validation
- Heat Exchanger / TE System is the Key!

Technical Challenges in LD & HD Applications

- Cost
- Material Interface Contacts
  - Electrical Resistance
  - Structural Ruggedness - Shock & Vibration
  - Thermal Expansion
  - Thermal Diffusion
- Tailor TEG Systems to Vehicle Systems & Requirements
  - Design/Fabricate For New TE Materials
  - Thermal Funneling
  - Establish TE System Cost Basis
- Location for Optimal Heat Recovery
- Maintaining Relatively Constant Cold Side Temperatures
- Maximum Power Output is at Maximum Engine Output
  - Not Necessarily Synchronized With Times of Maximum Power Requirement
  - Requires Energy Storage (e.g., batteries)
- Establish Supplier Infrastructure
  - TE Materials, System Fabrication, System Testing

Conclusions

- WHR Applications Currently In Light-Duty & Heavy-Duty Vehicles
  - Automotive Exhaust Waste Heat Recovery
  - Heavy Hybrid Vehicle Program Applications - Truck Electrification & SOC Maintenance
- Heat Exchanger / Thermoelectric Device Design Must Be Analyzed & Optimized Simultaneously Within Vehicle-Level Studies (ADVISOR)
- Coupled TE Materials & System-Level R&D Required
- Heat Exchanger / TE Device Tradeoffs
  - Heavy Duty Power Potential Higher Than Light Duty Vehicle Power
  - Maximum Power Near $T_h = 625$ K
  - Cold Side Mass Flow Rates Could Be Challenging
  - Optimum Design Regimes Exist (TE Performance & Cold Mass Flow Reasons)
  - Thermal Funneling Will Be A Design Issue
  - TE Materials Strongly Impact Thermal System Design
  - Thermal Interfaces & Thermal Losses Could Limit Power Potential (Be Smart!)

Acknowledgements

Sincerest Thanks to:

- Dr. Peter Martin, PNNL, Richland, WA
- John Fairbanks, DOE OFCVT
- Susan Rogers, DOE OFCVT

References

- Hendricks, T.J. and Lustbader, J.A., "Advanced Thermoelectric Power System Investigations for Light-Duty and Heavy-Duty Applications: Part I," *Proceedings of the 21st International Conference on Thermoelectrics*, Long Beach, CA, IEEE Catalogue #02TH8657, p. 381, 2002.
- Hendricks, T.J. and Lustbader, J.A., "Advanced Thermoelectric Power System Investigations for Light-Duty and Heavy-Duty Applications: Part II," *Proceedings of the 21st International Conference on Thermoelectrics*, Long Beach, CA, IEEE Catalogue #02TH8657, p. 387, 2002.
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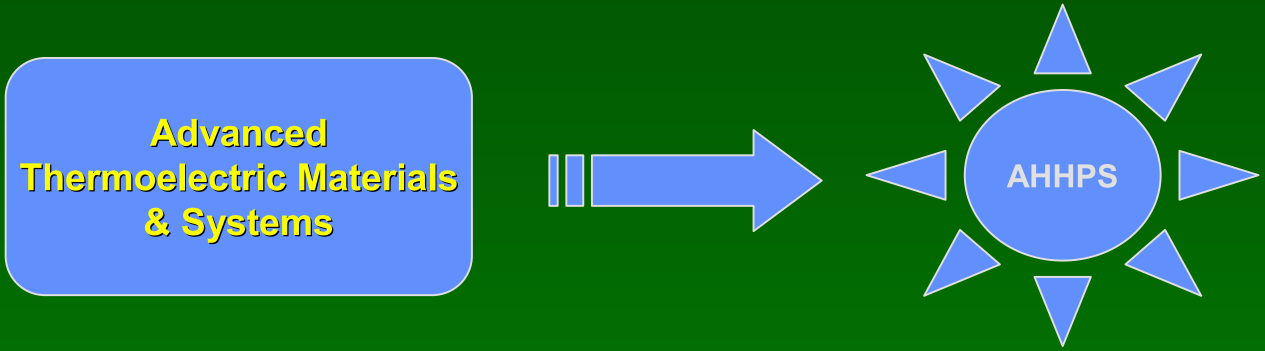
- Martin, P.M. and Olsen, L.C., "Scale-Up of $Si/Si_{0.8}Ge_{0.2}$ and B_4C/B_9C Superlattices for Harvesting of Waste Heat in Diesel Engines," Pacific Northwest National Laboratory, U.S. Department of Energy Office of FreedomCAR & Vehicle Technologies, *Proceedings of the 2003 Diesel Engine Emissions Reduction Conference*, Newport, RI, 2003.

NREL System-Level Investigations

Advanced TE System Analyses Required

- Knowing Material ZT is Critical & Necessary, but Not Sufficient
- TE System Performance & Benefits Dependent on System Temperatures Likely in Actual Operating Systems
- Accurately Quantifying Requires a Full System Analysis Approach
- Focus & Direct TE Material R&D to Most Beneficial Opportunities & Material Combinations



Advanced Thermoelectric Materials & Systems

AHHPS