Time for World Class Solutions

Advanced Thermoelectric Power System Investigations for Light-Duty / Heavy-Duty Vehicle Applications
21st International Conference On Thermoelectrics
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U.S. Department of Energy's National Renewable Energy Laboratory

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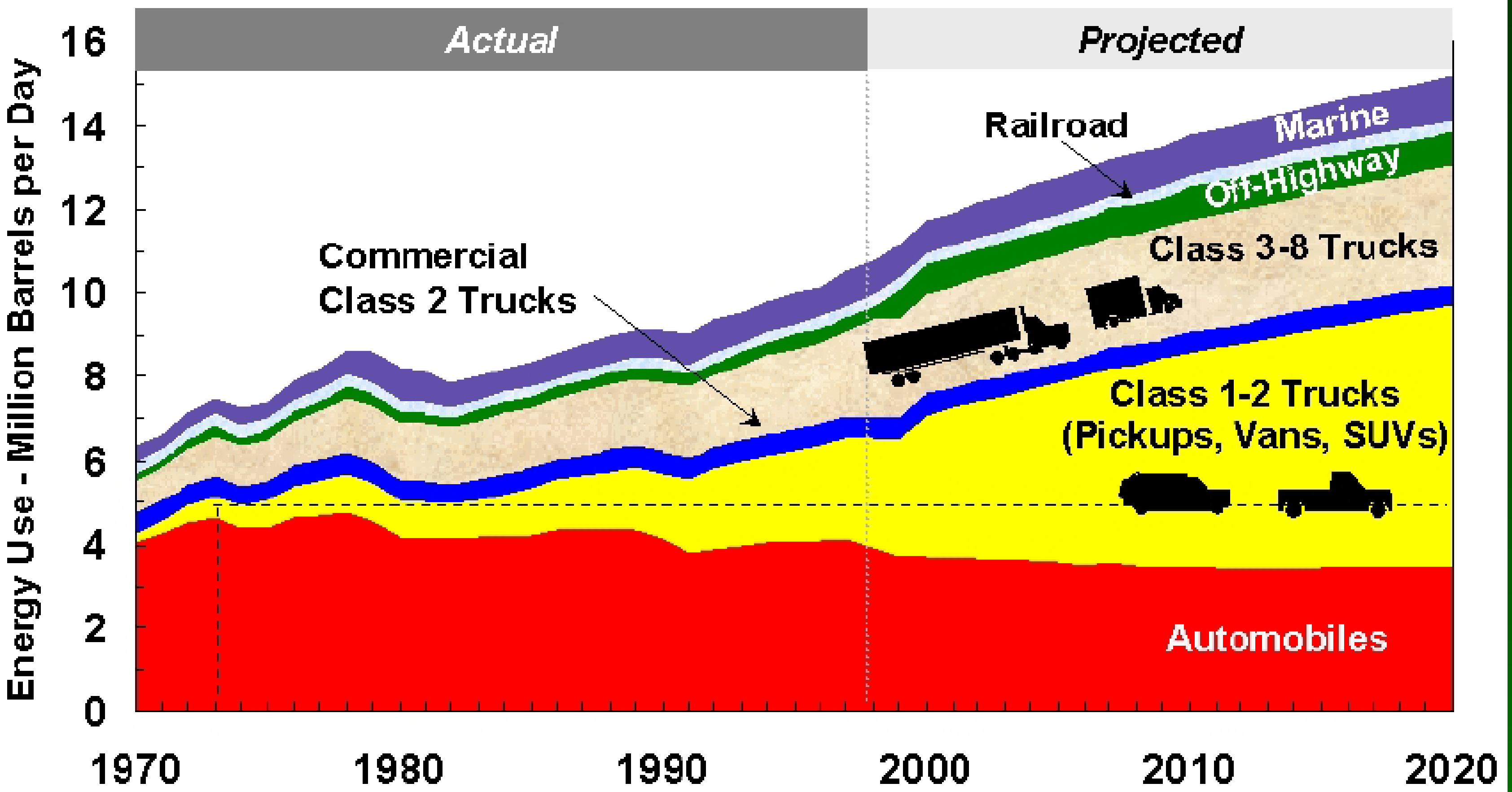
CENTER FOR TRANSPORTATION TECHNOLOGIES AND SYSTEMS

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

National Impacts

- Creates Serious National Economic Issues
- Complicates Almost Every Political Issue & Landscape
- And ……

Continuing National Security Issue

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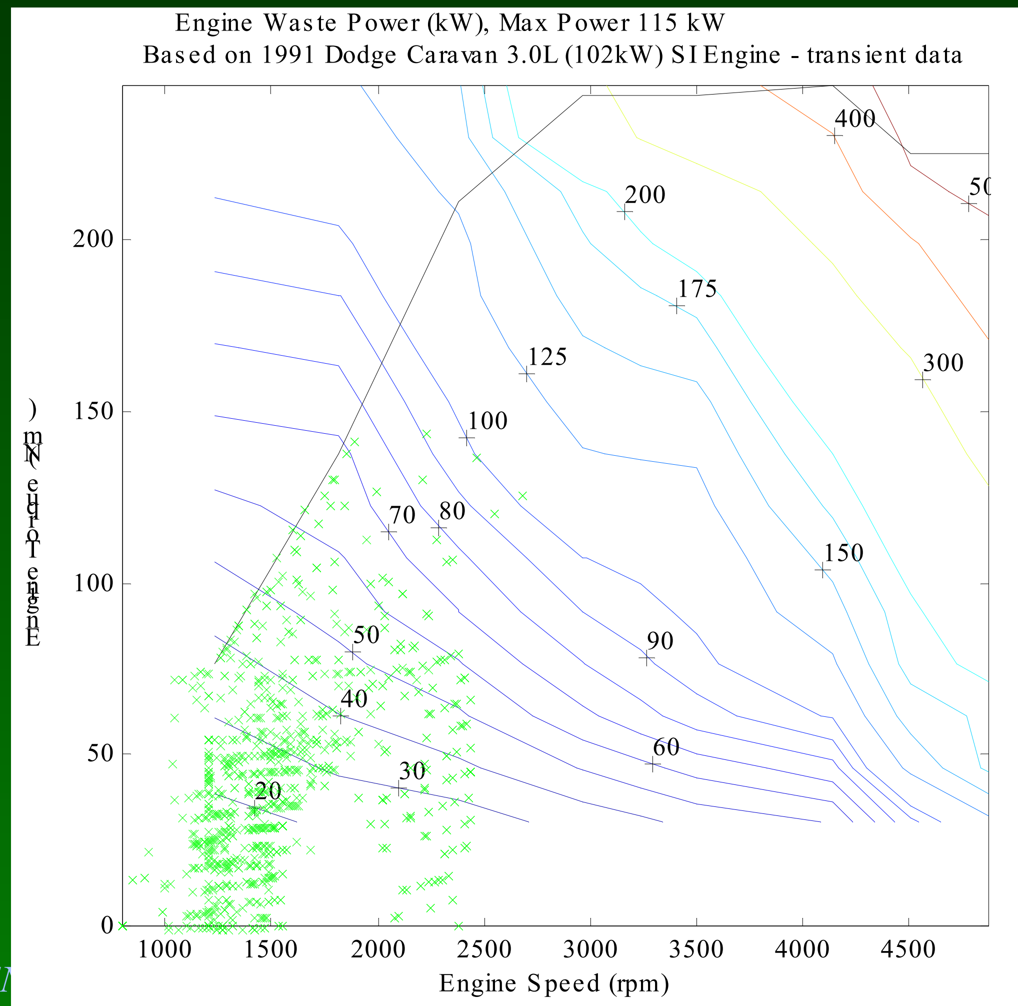
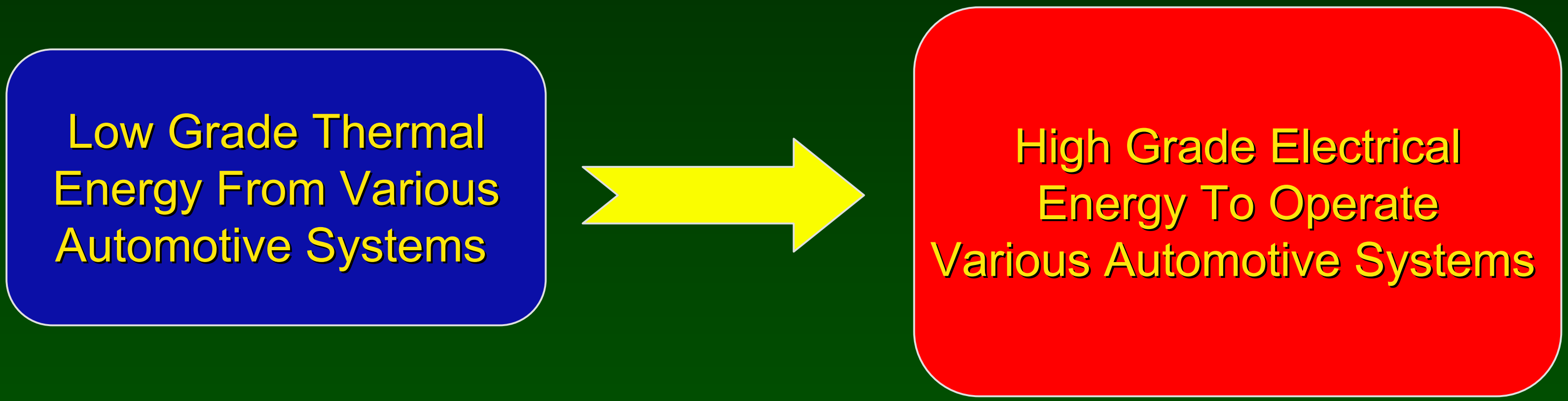
- We Do This to Ourselves & There Is No Need To

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



- 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
- **Automotive Exhaust Heat Temperatures 600-700 °C**
  - Interested in ~1000 W System
- **Heavy Vehicle Exhaust Heat Temperatures 500-550 °C**
  - APUs
  - Truck Electrification

Light-Duty Vehicle Applications

Continuing National Security Issue

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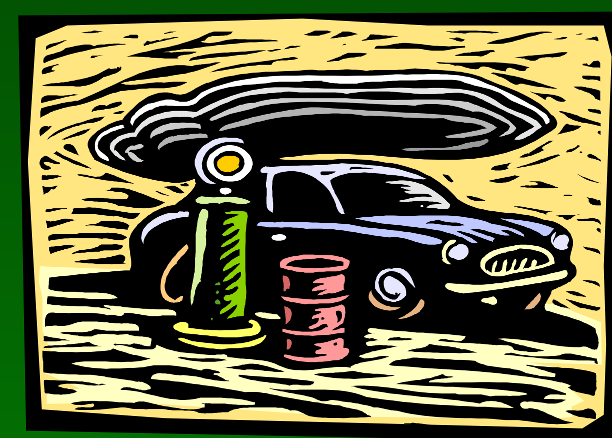
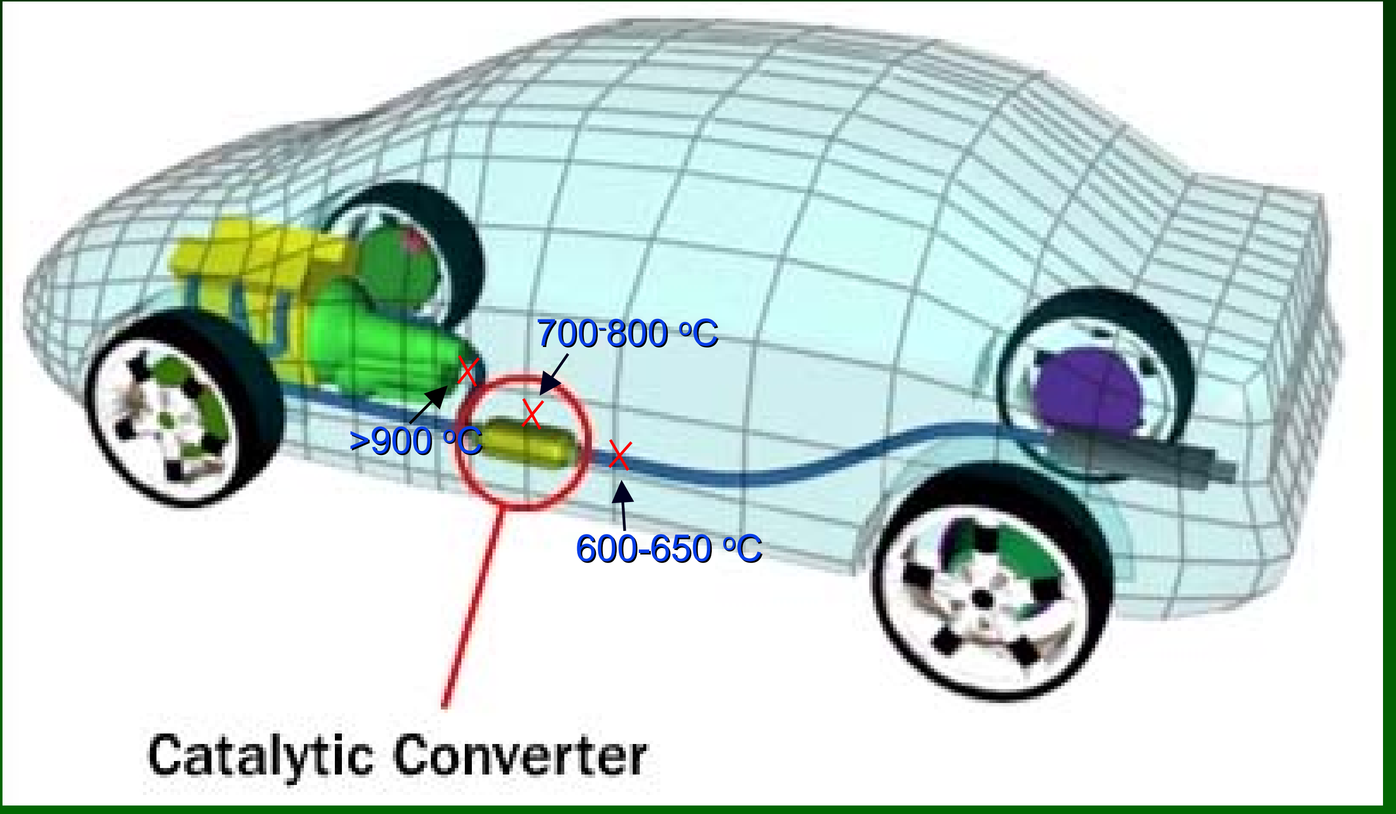


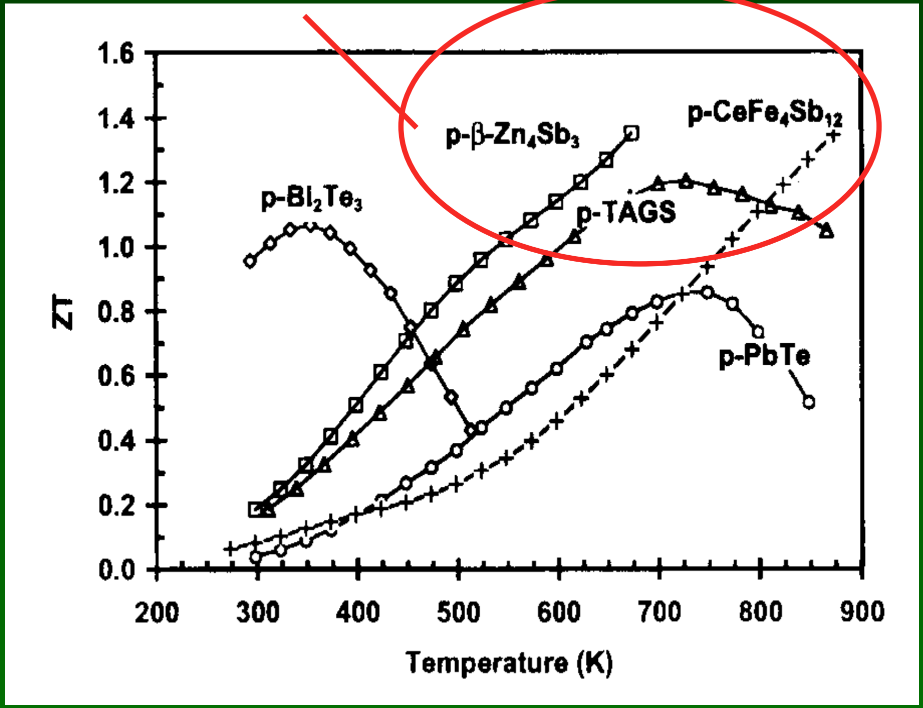
System Placement



New Thermoelectric Materials

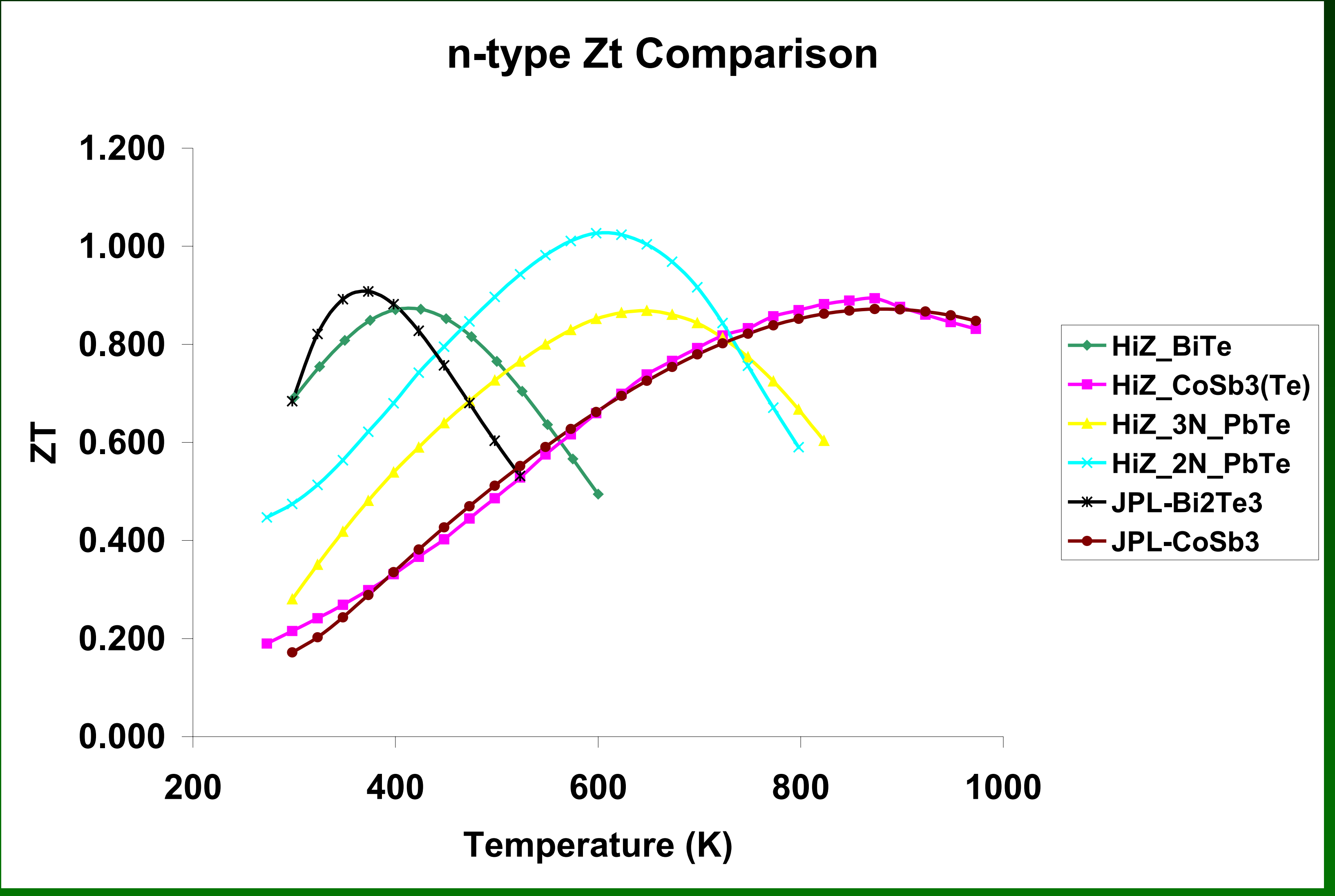
- New TE Materials Currently Being Studied
  - Skutterudites: $CeFe_4Sb_{12}$ & $CoSb_3$
  - Zn_4Sb_3 Alloys
  - Quantum Well Materials
  - Thin-Film Superlattice Materials
- TE Set #1: p-type $CeFe_4Sb_{12}$ – Bi_2Te_3: n-type $CoSb_3$ - Bi_2Te_3
- TE Set #2: p-type TAGS - Bi_2Te_3: n-type 2NPbTe - Bi_2Te_3
- TE Set #3: p-type $CeFe_4Sb_{12}$ – Zn_4Sb_3 - Bi_2Te_3: n-type $CoSb_3$ - Bi_2Te_3

New TE Materials

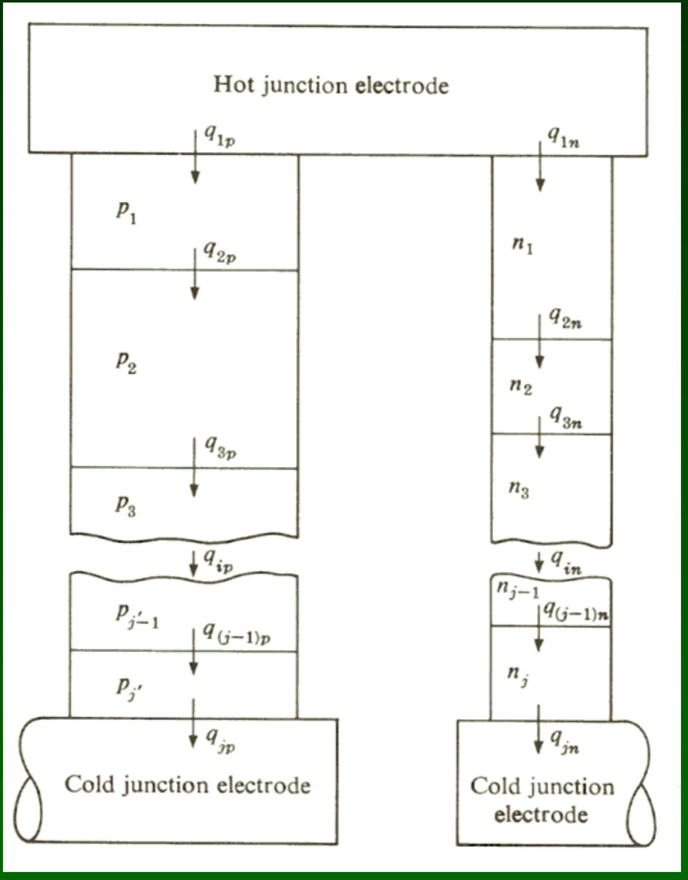


Caillat, T., Fleurial, J.-P., Snyder, G.J., Borshchevsky, A. Journal of Phys. Chem. Solids, 1997

New Thermoelectric Materials

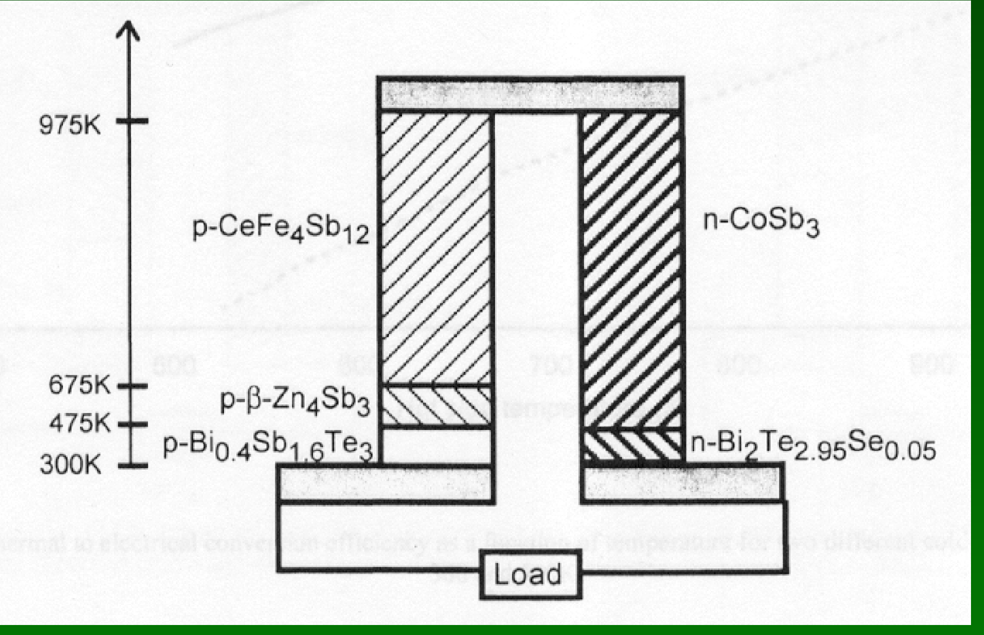


Segmented Unicouple Design Approach



Basic Segmented Leg Concept

Current Embodiment/Materials



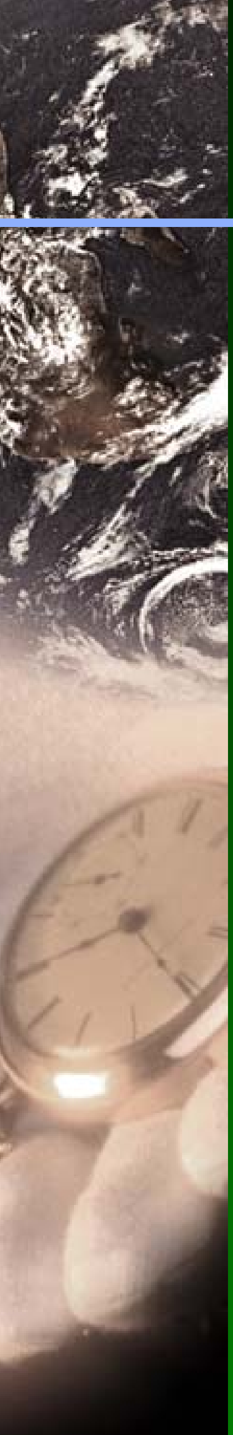
Modeling Goals

- System Approach
  - Simultaneous Modeling of Heat Exchangers and Thermoelectric Device
- Single Material Legs
- Multi-Material Legs
- Effects of System Placement
- Heat Exchanger Performance (UA) Effects
- System Thermal Resistance Effects
- Thermal Loss Effects

System Solution Method

(Single & Multiple Material Legs)

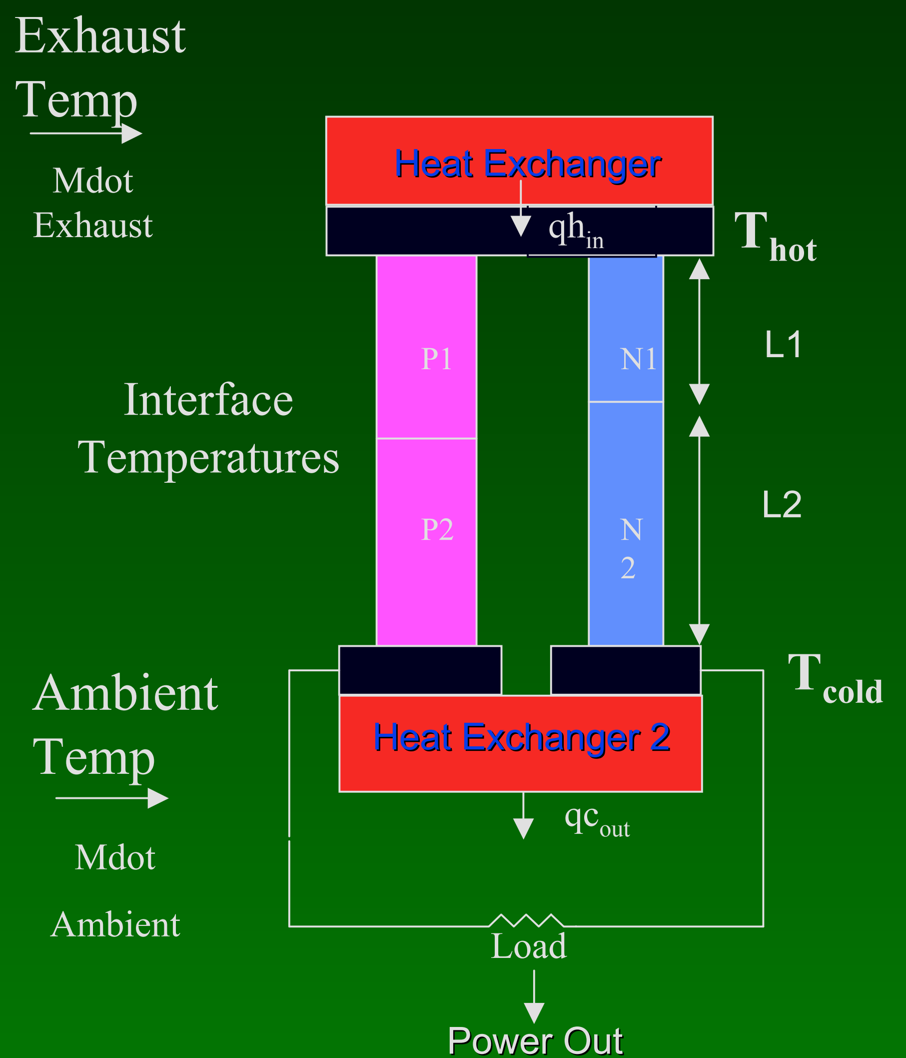
- Maximum Device Efficiency Analysis (This Paper)
- Maximum Device Power Density Analysis (Future Work)
- Challenges
  - Highly Non-linear equations (with respect to temp)
  - Temperature Dependent TE Properties
  - Mathematics Discussed in Paper
  - Needed:
    - 1 Thermoelectric Parameter
    - 1 Heat Exchanger Parameter
    - Thermoelectric Hot and Cold Sides (T_h & T_c)
- Solution
  - Iterative Solutions For Range of Thermoelectric Hot & Cold Side
  - Cases Done: $\dot{m}_c, V : \dot{m}_c, \gamma_n : \dot{m}_h, \gamma_n : \dot{m}_h, V : N, \gamma_n : q_h, \gamma_n : \dot{m}_h, I : \dot{m}_c, I$



Advanced Thermoelectric System Design

2-p/2-n Segmented-Leg TE Design Analysis

Advanced Thermoelectric System Design



P1=CeFeSb

P2=BiTe

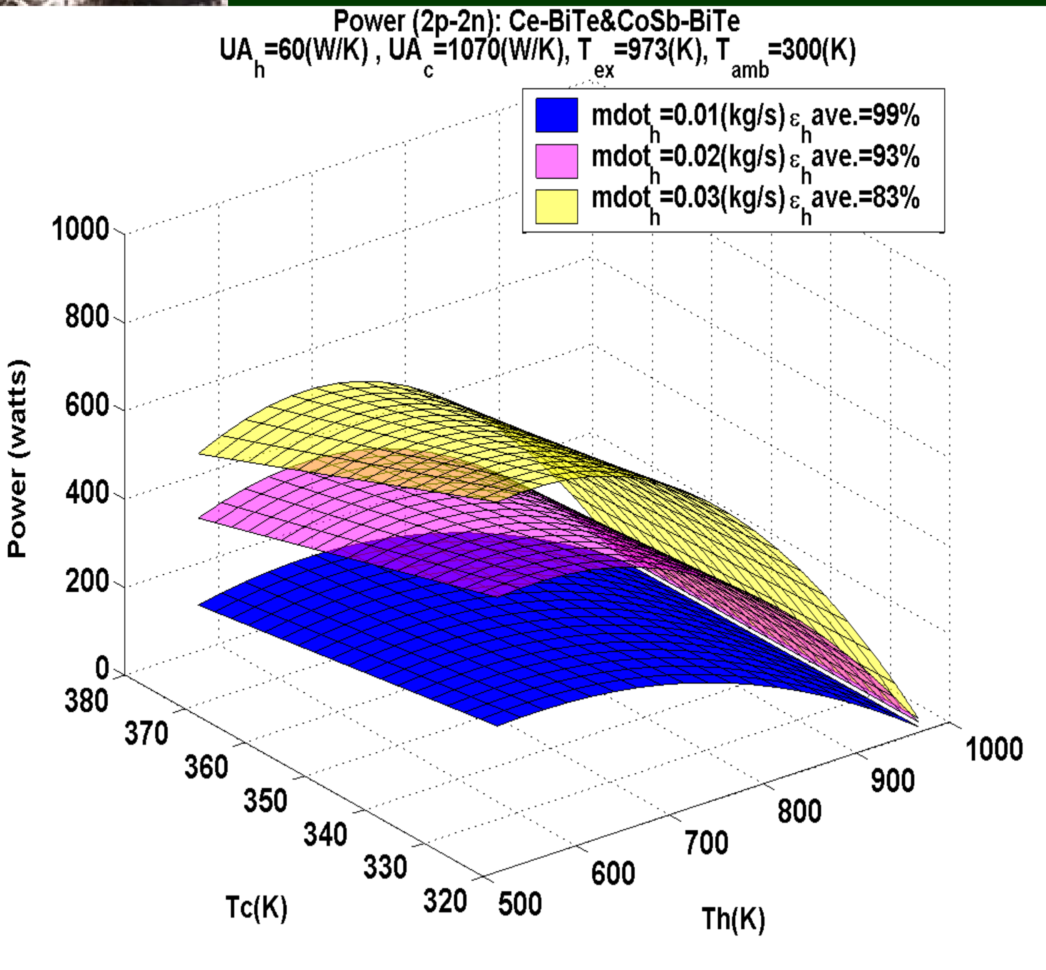
N1=CoSb

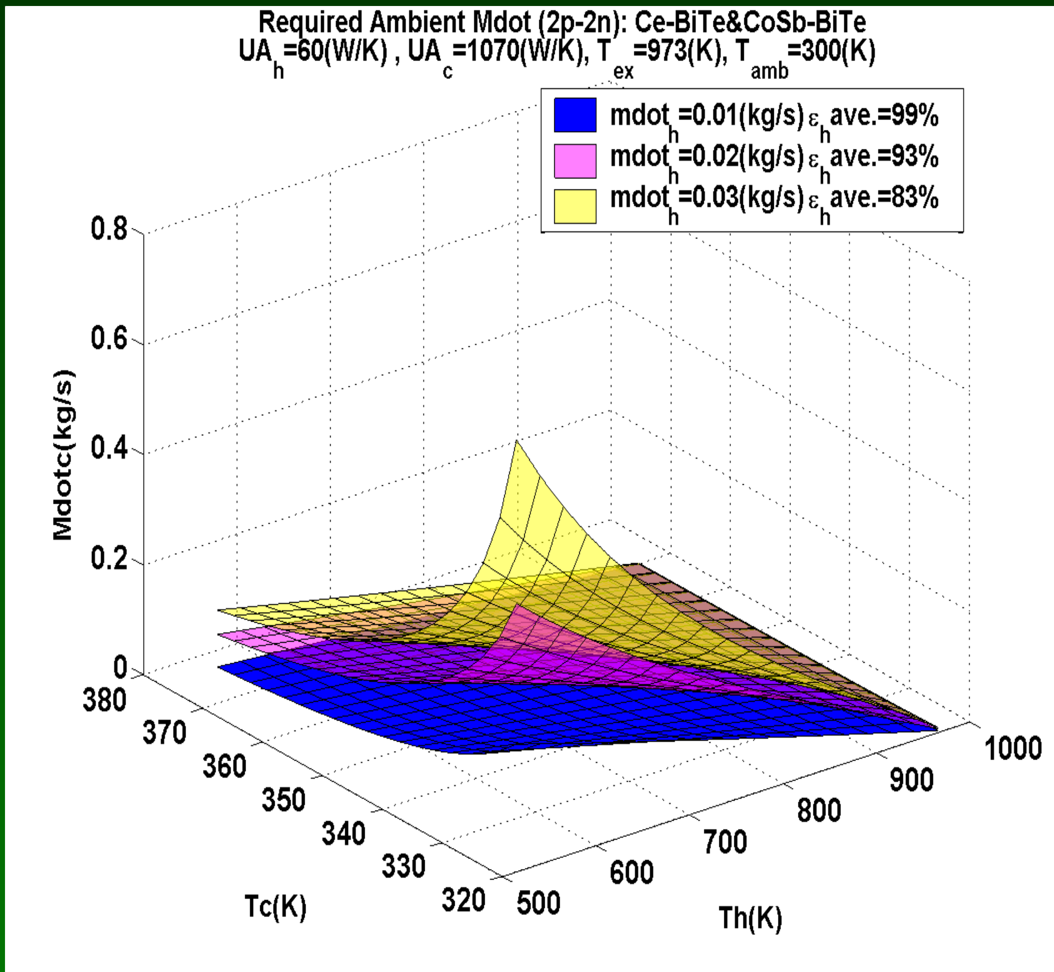
N2=BiTe

Results: Maximums Found

Peak Power: 333, 626, 843 (W)

At Peak P: 0.21, 0.41, 0.71 (kg/s)

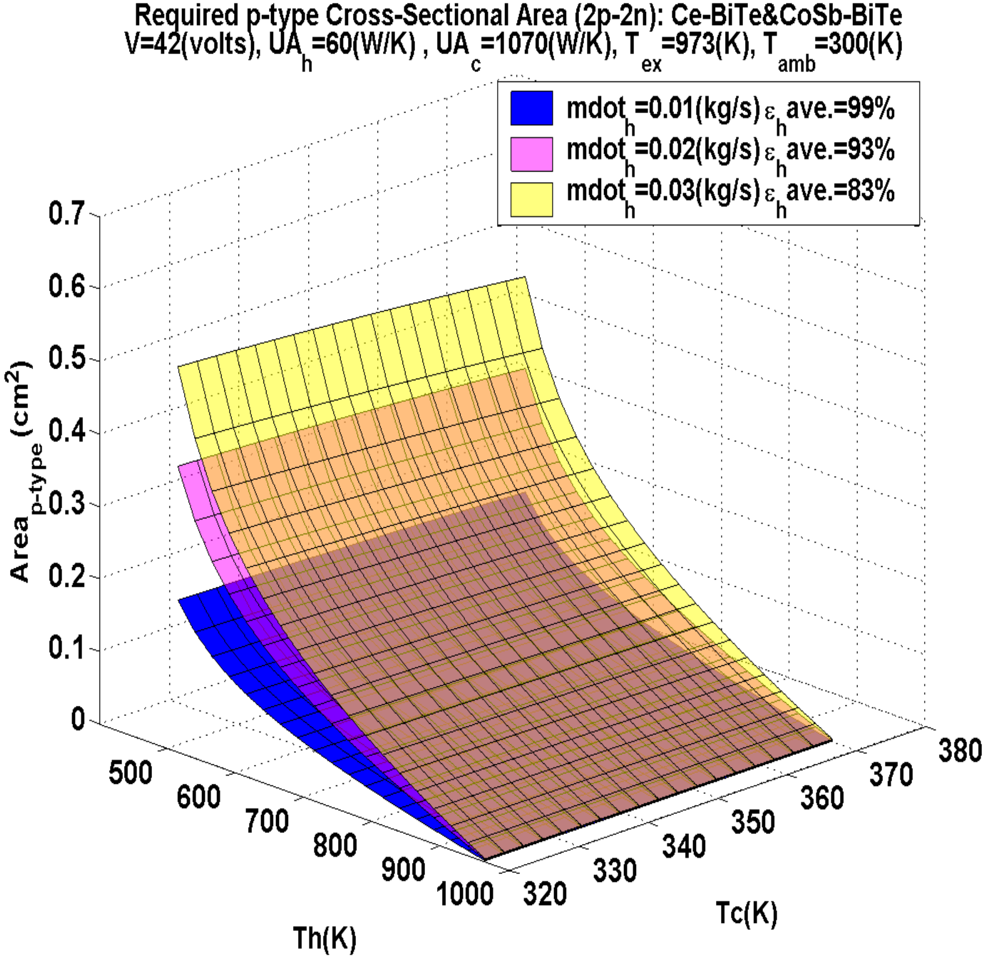


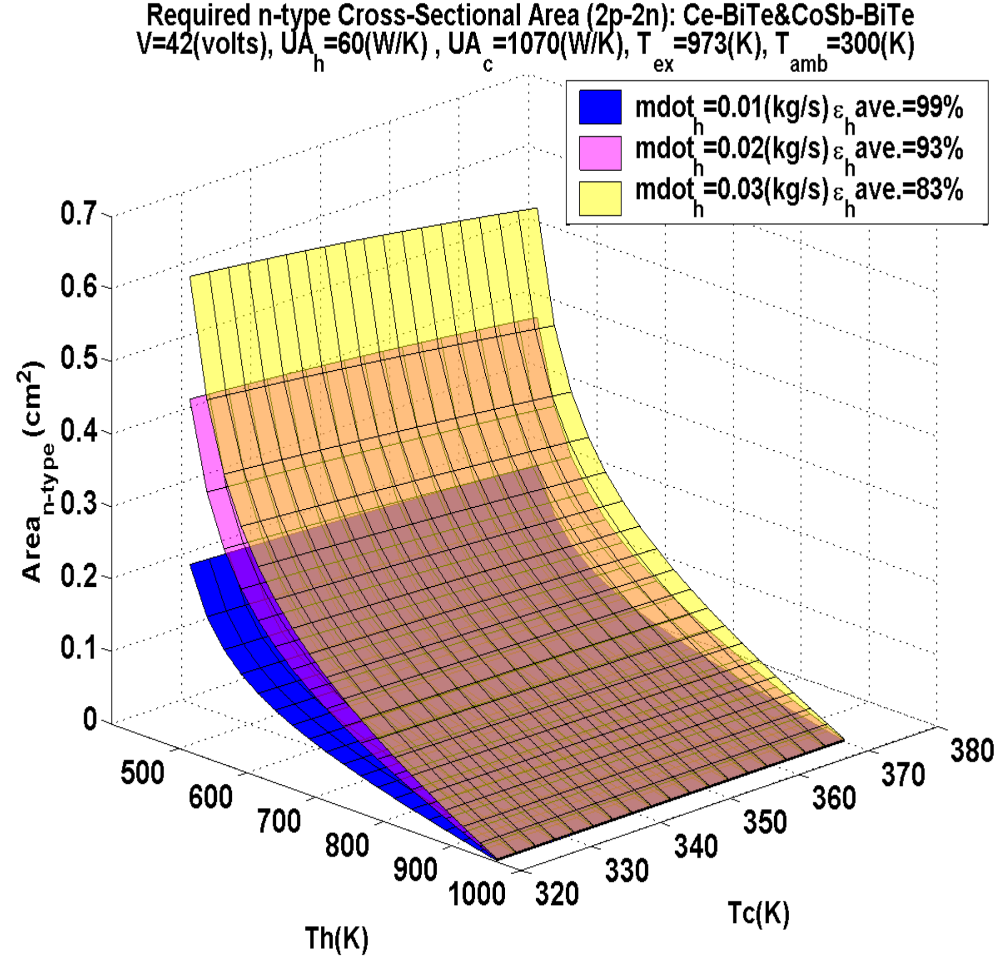


Results: TE Cross-Sectional Area Comparison

At Peak P: 0.15, 0.28, 0.44 (cm^2)
Decrease from 12V ~ 71%

At Peak P: 0.16, 0.29, 0.49 (cm^2)
Decrease from 12 V ~ 71%



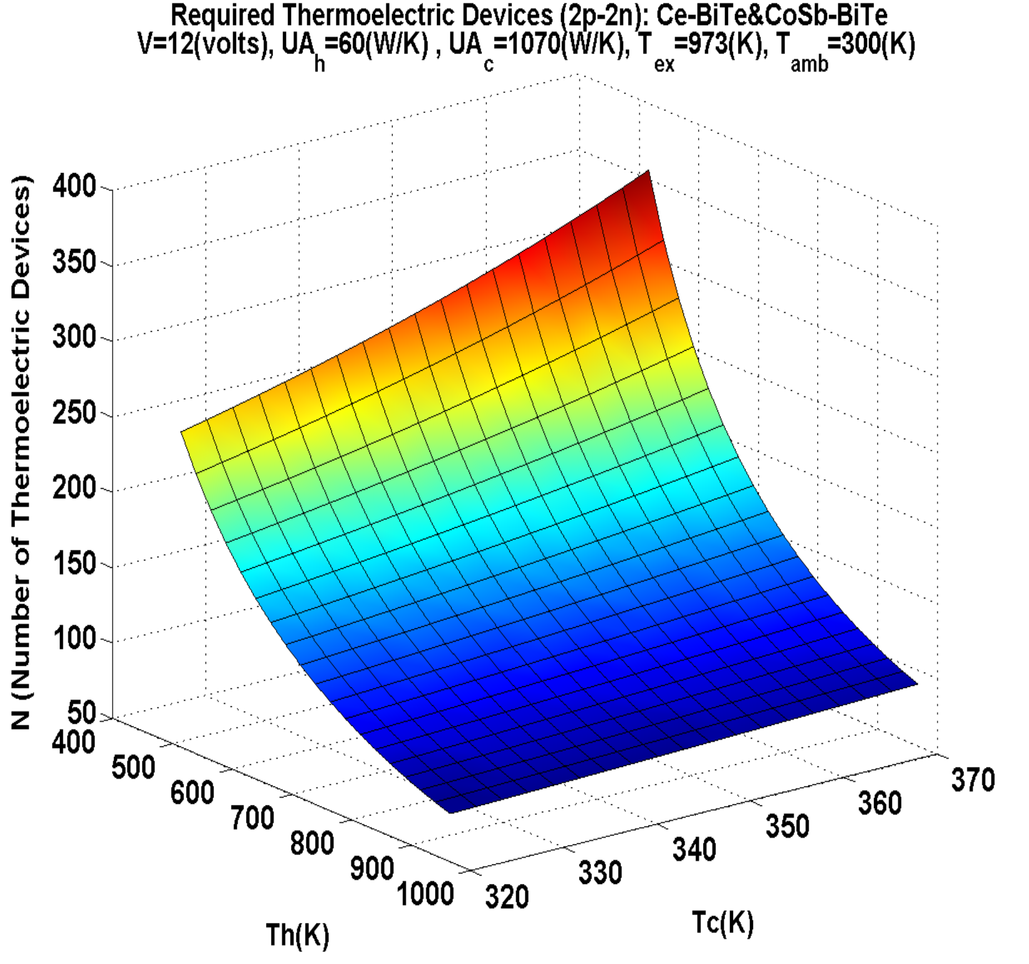


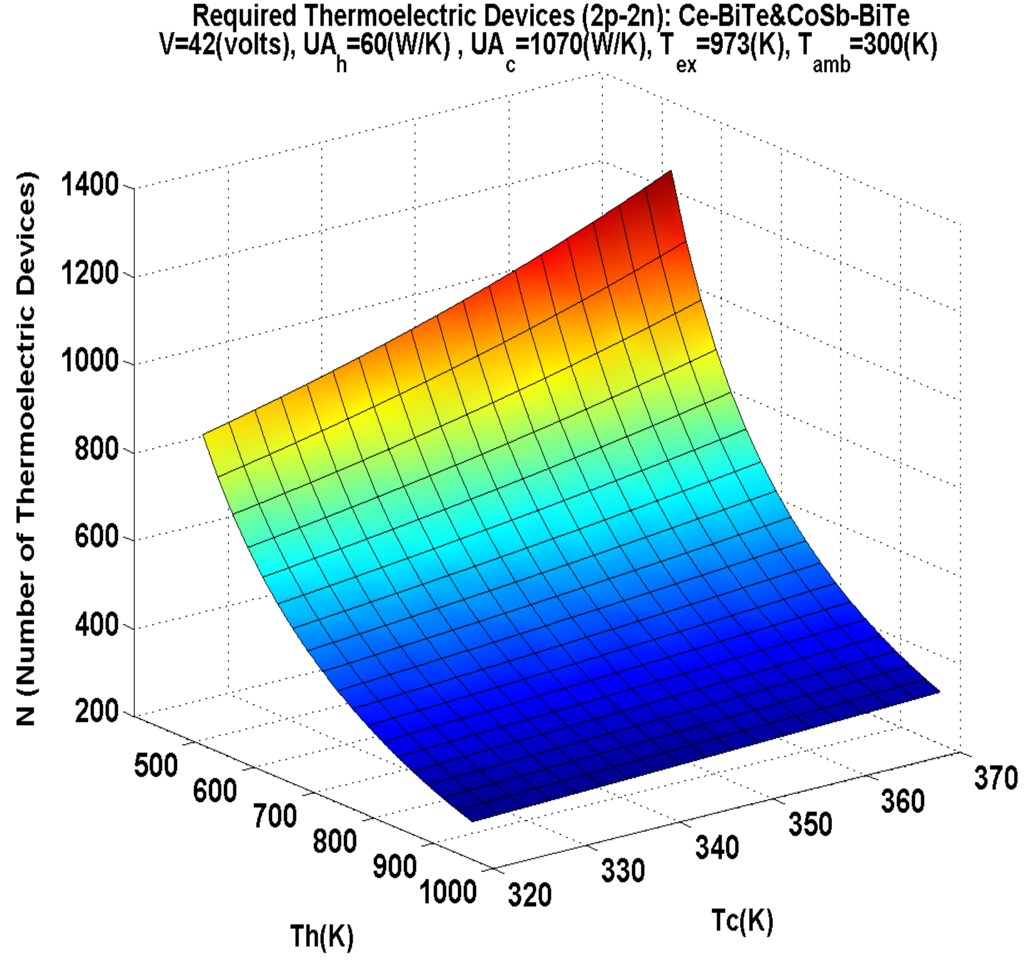
Results: Required TE Couples Comparison

42 V Larger by ~ 235%

At Peak P: 225 (devices)

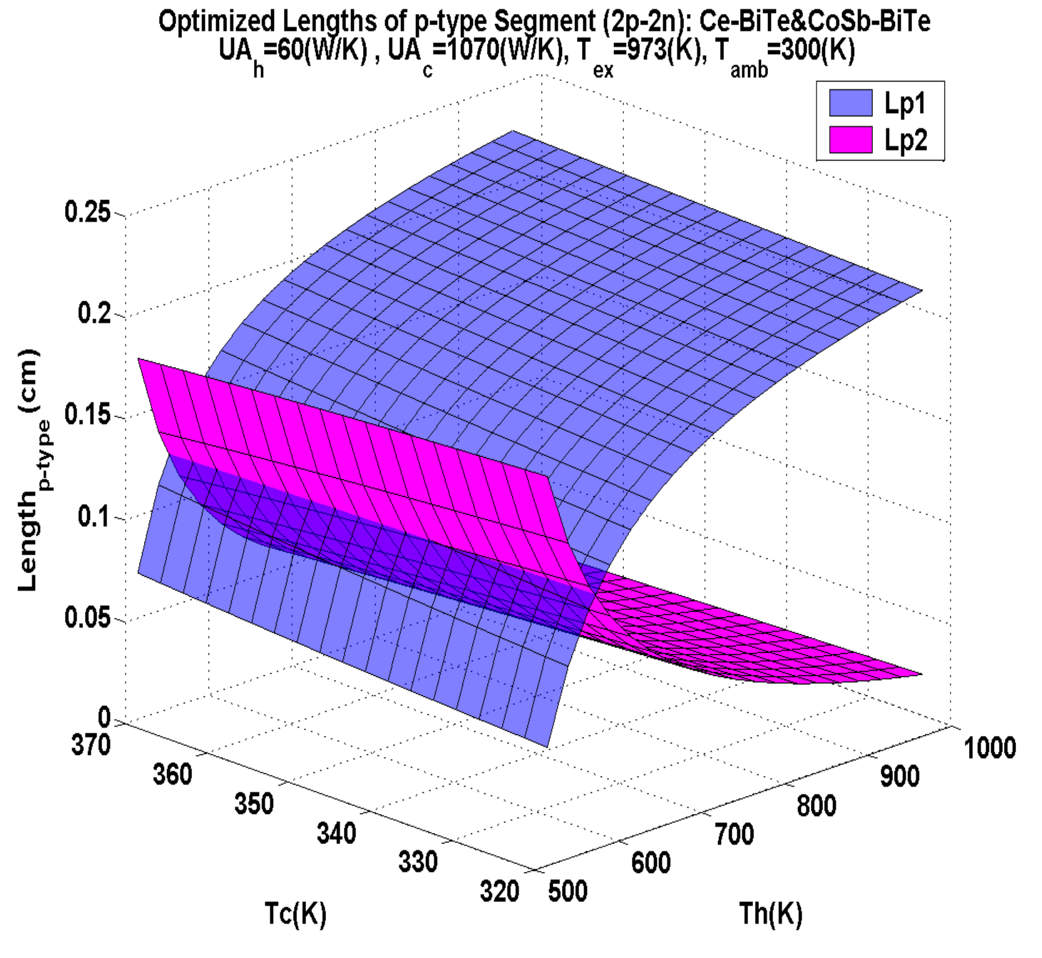
At Peak P: 754 (devices)



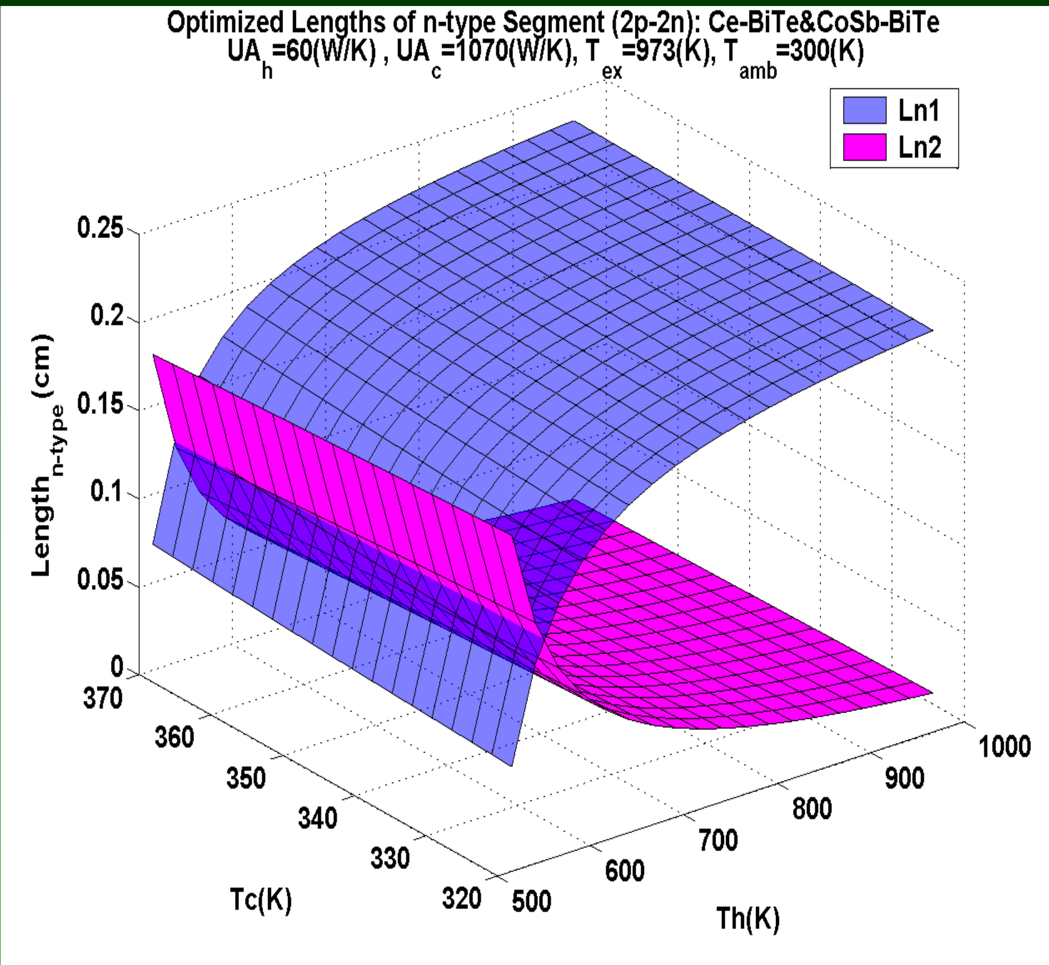


Results: TE Element Length Trends

p-Type



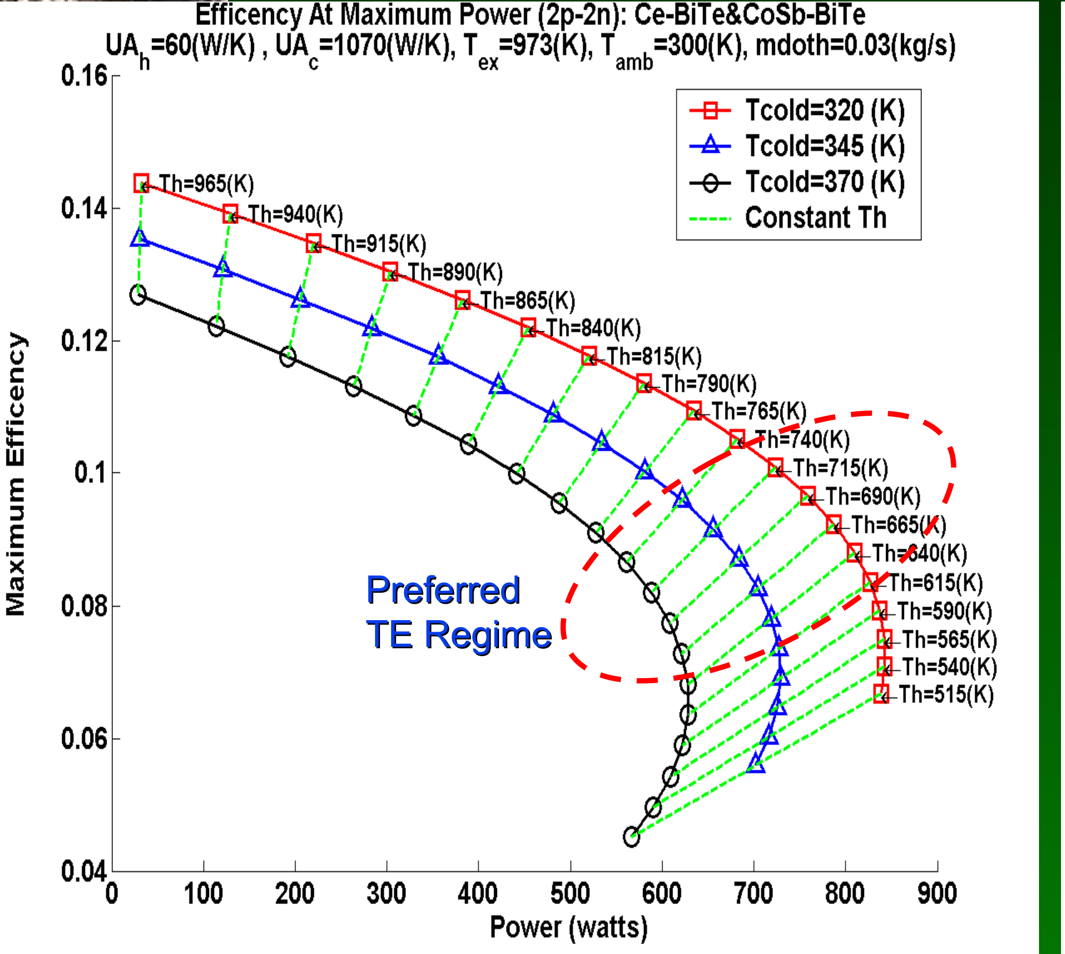
n-Type

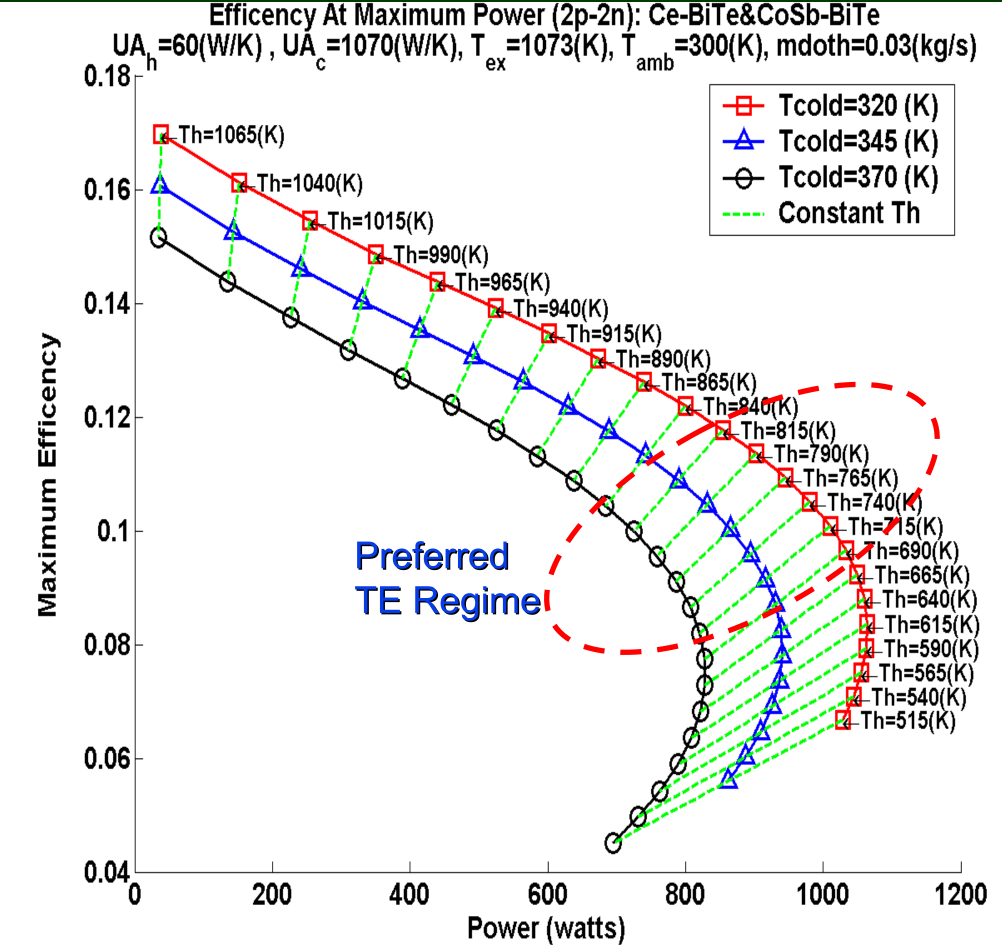


Results: Peak Power Not At Peak Eff.

Tex=973(K) $P_{,pk}$: 333, 626, 843 (W)

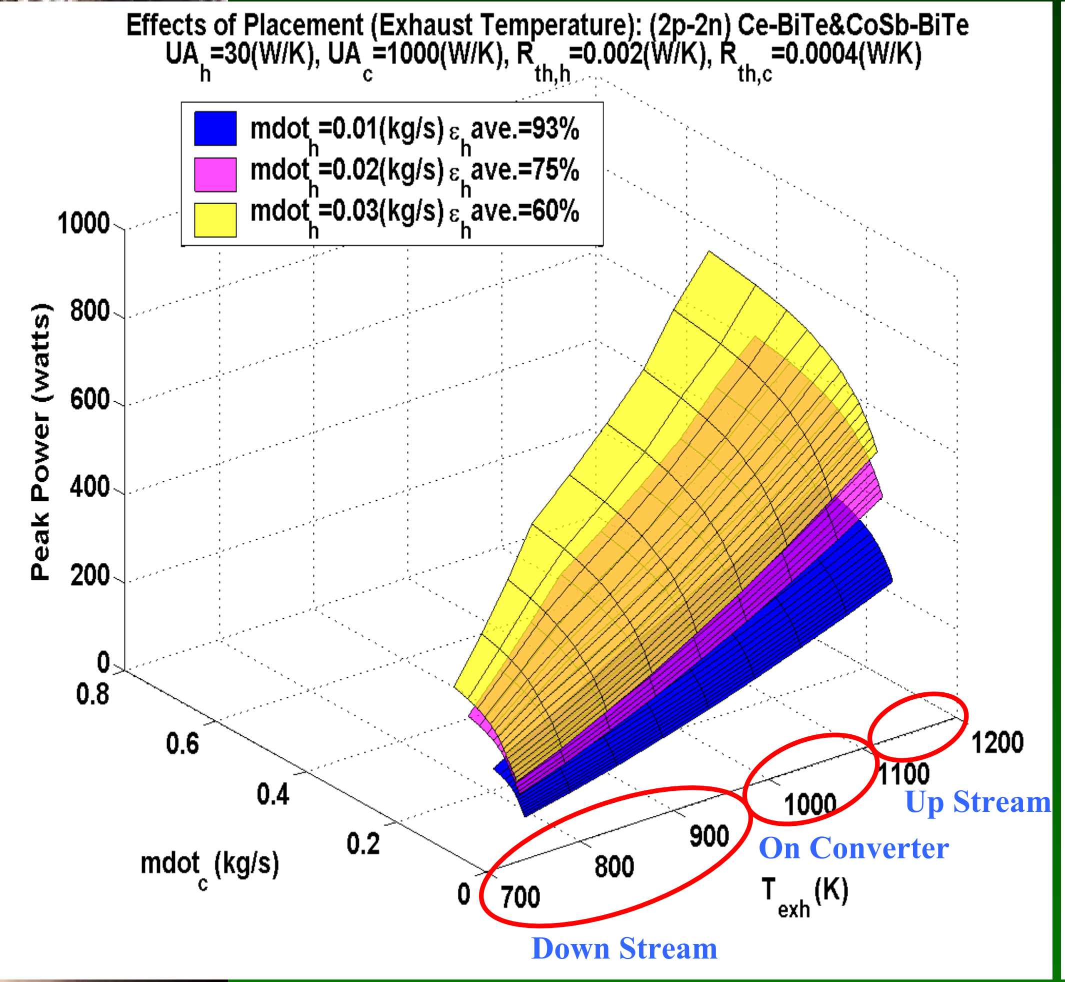
Tex=1073(K) $P_{,pk}$: 423, 793, 1064 (W)
Increased from 973(K) ~ 26%



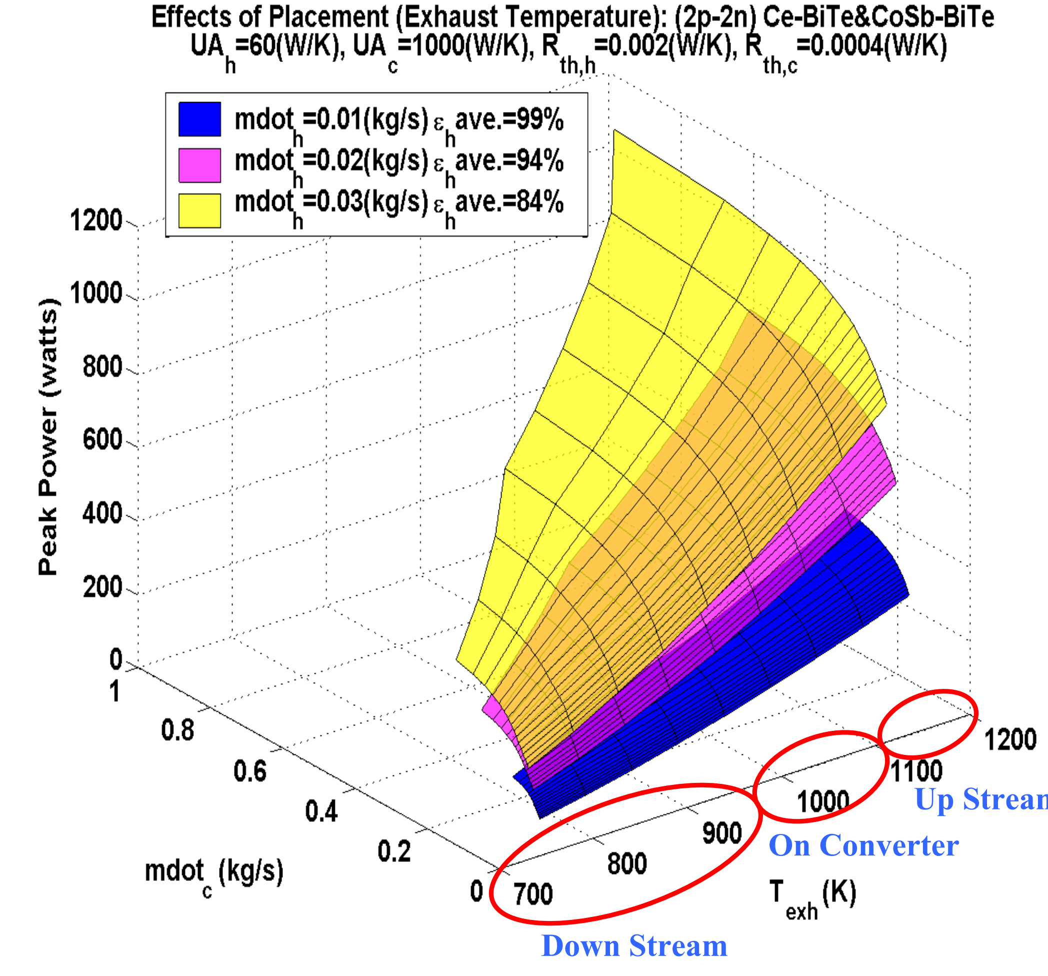


Results: Effects of Placement and UAh

UAh=30 (W/K)

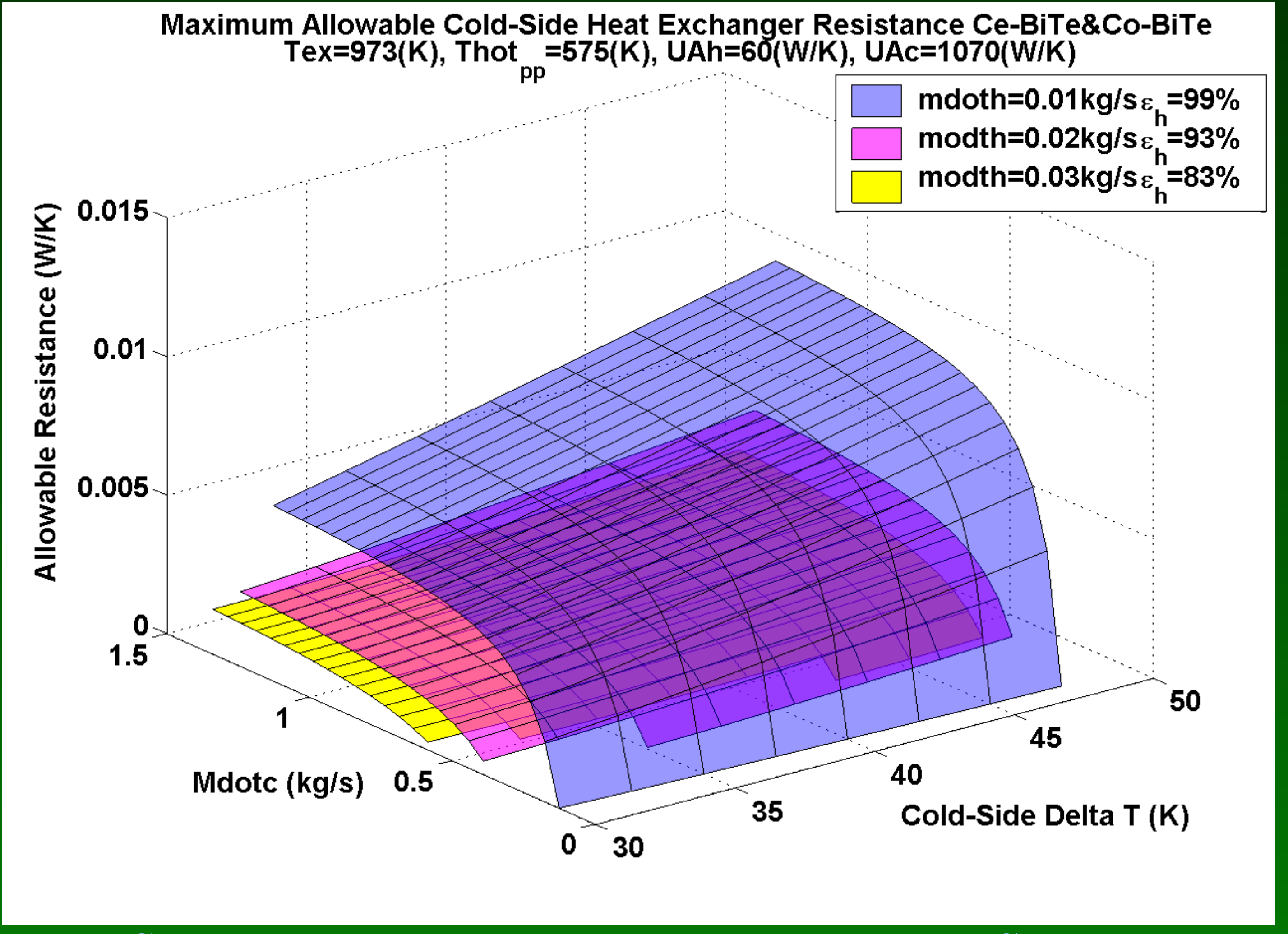


UAh=60 (W/K)

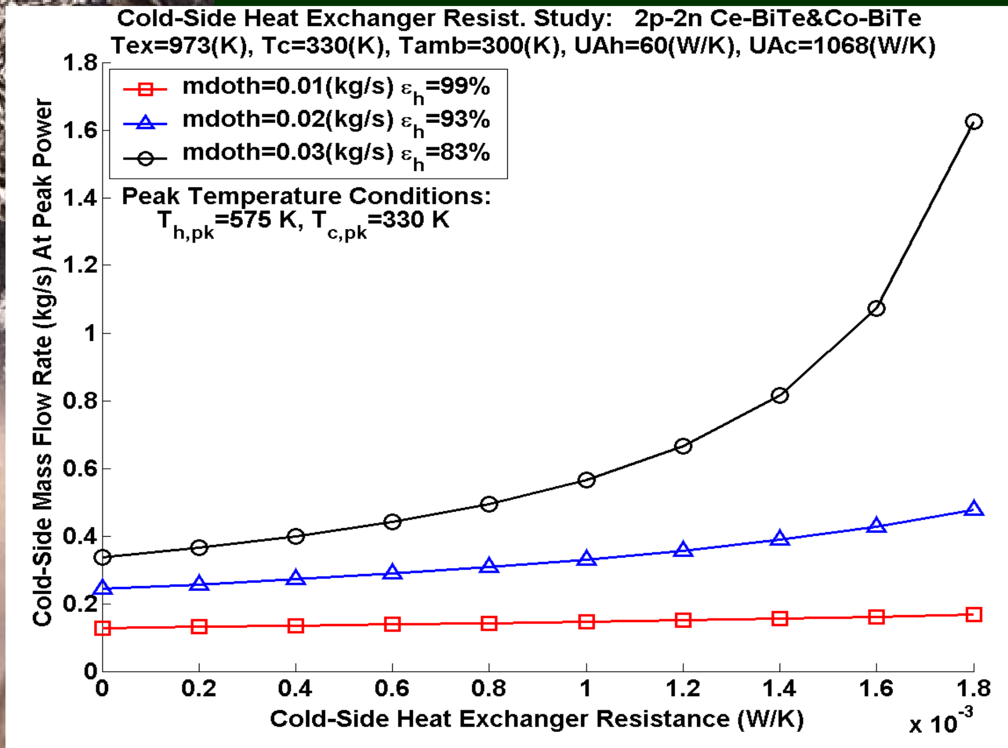


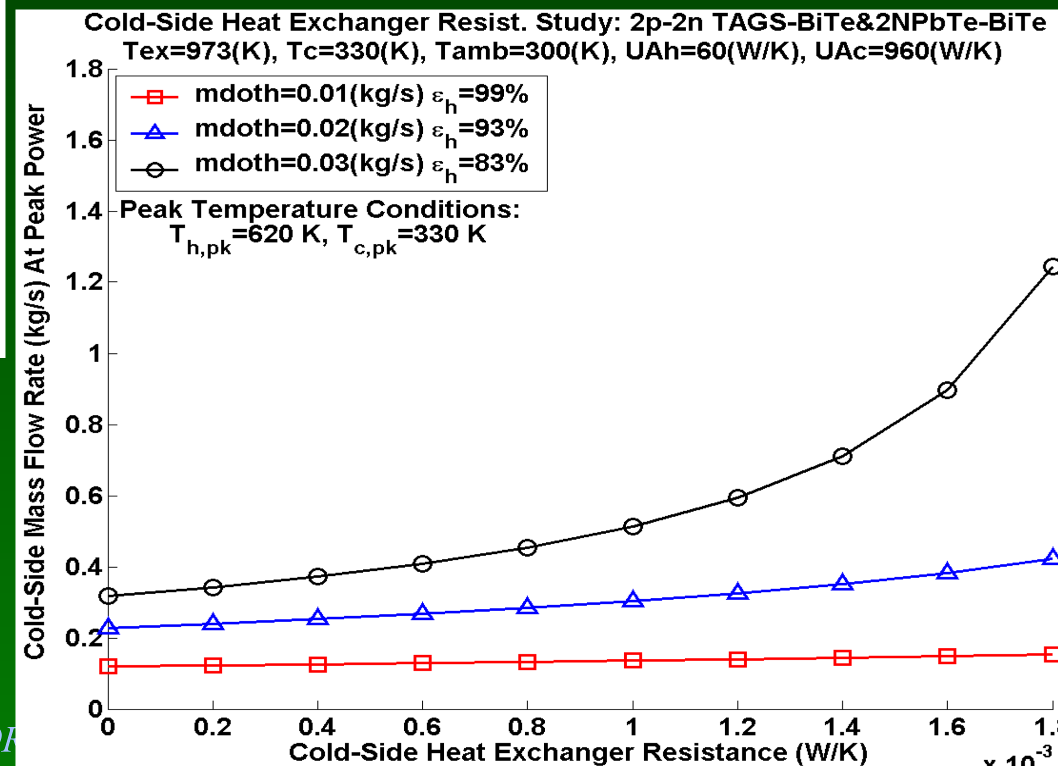
Results: Cold Side Thermal Resistance Study

Exhaust Temperature=973(K)

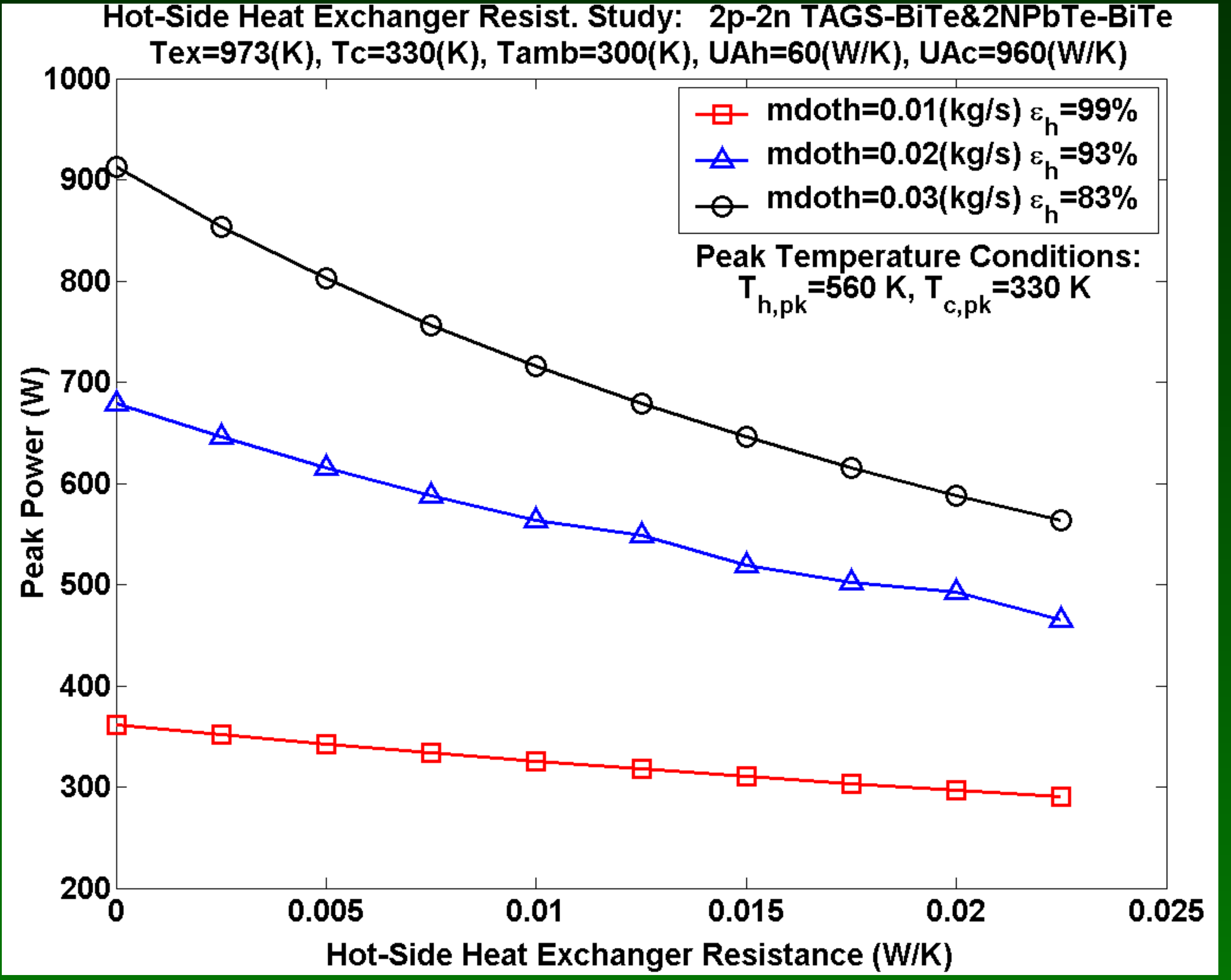


Results: Cold Side Thermal Resistance Study





Results: Hot SideThermal Resistance Study



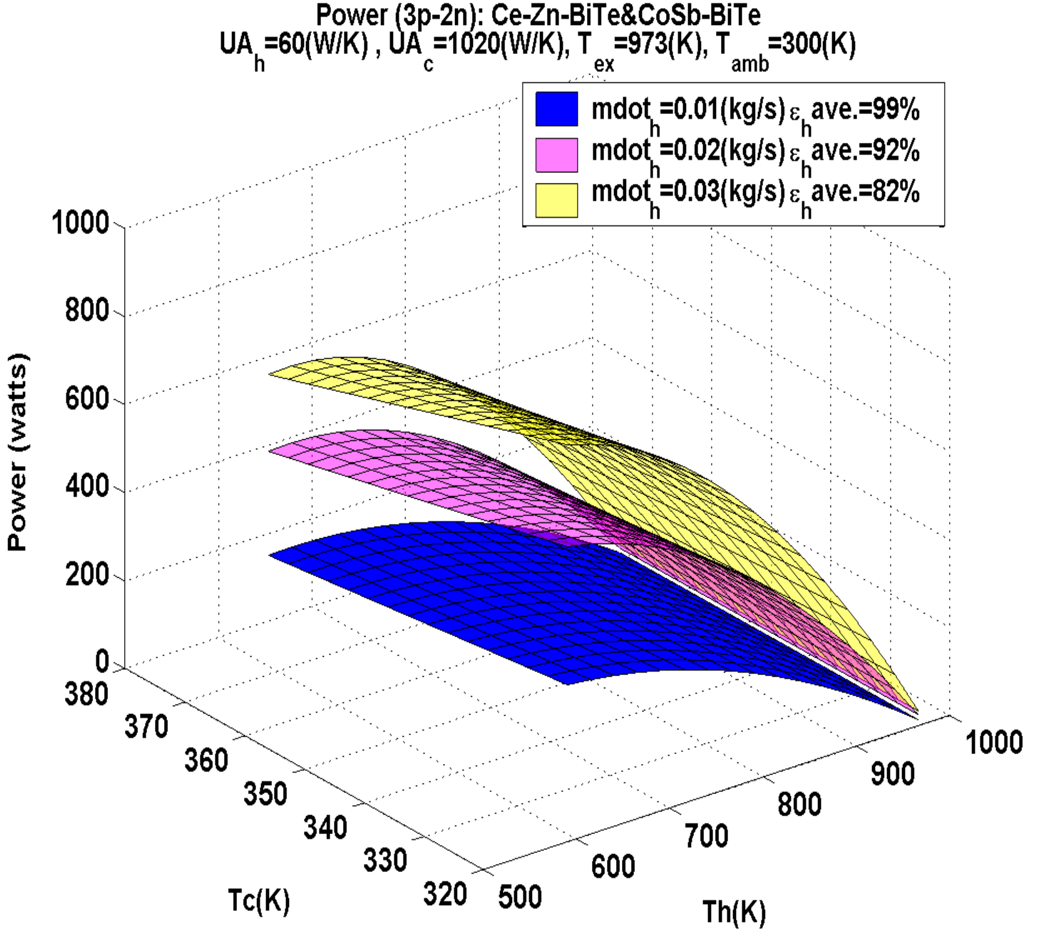
Advanced Thermoelectric System Design

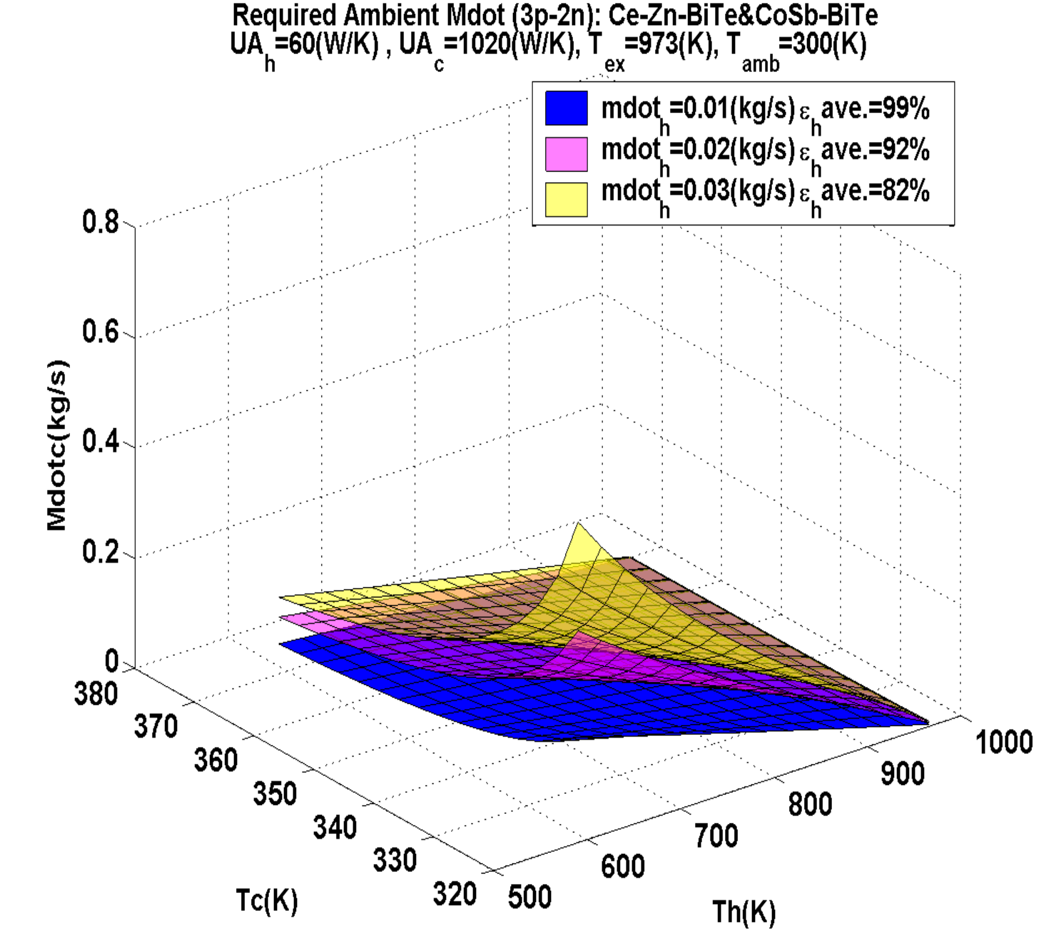
3-p/2-n Segmented-Leg TE Design Analysis

Results: Maximums Found

Peak Power: 360, 670, 900 (W)
Increase from 2p-2n ~7%

At Peak P: 0.19, 0.38, 0.58 (kg/s)
Decrease from 2p-2n ~ 7%

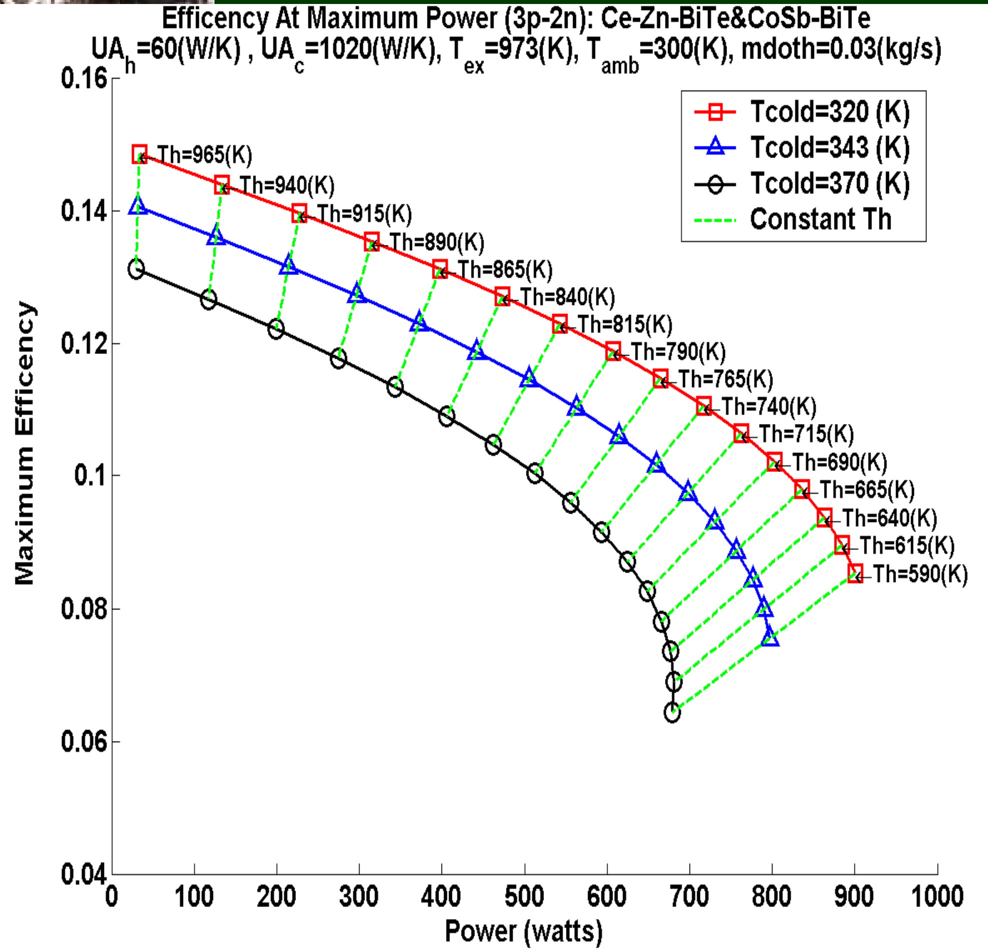


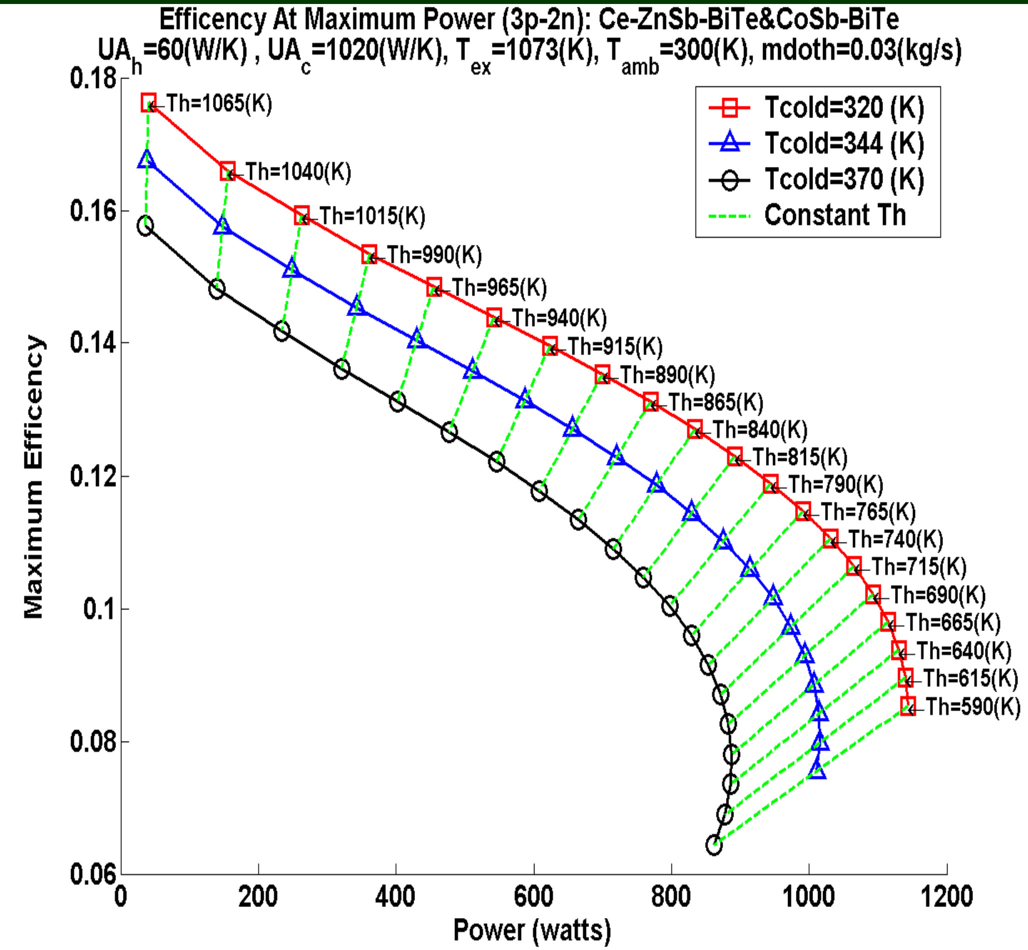


Results: Comparison To 2p-2n Segments

Peak Power: 356, 670, 901 (W)
Increase from 2p-2n ~ 7%

Peak Power: 454, 852, 1144 (W)
Increase from 973(K) ~ 27%

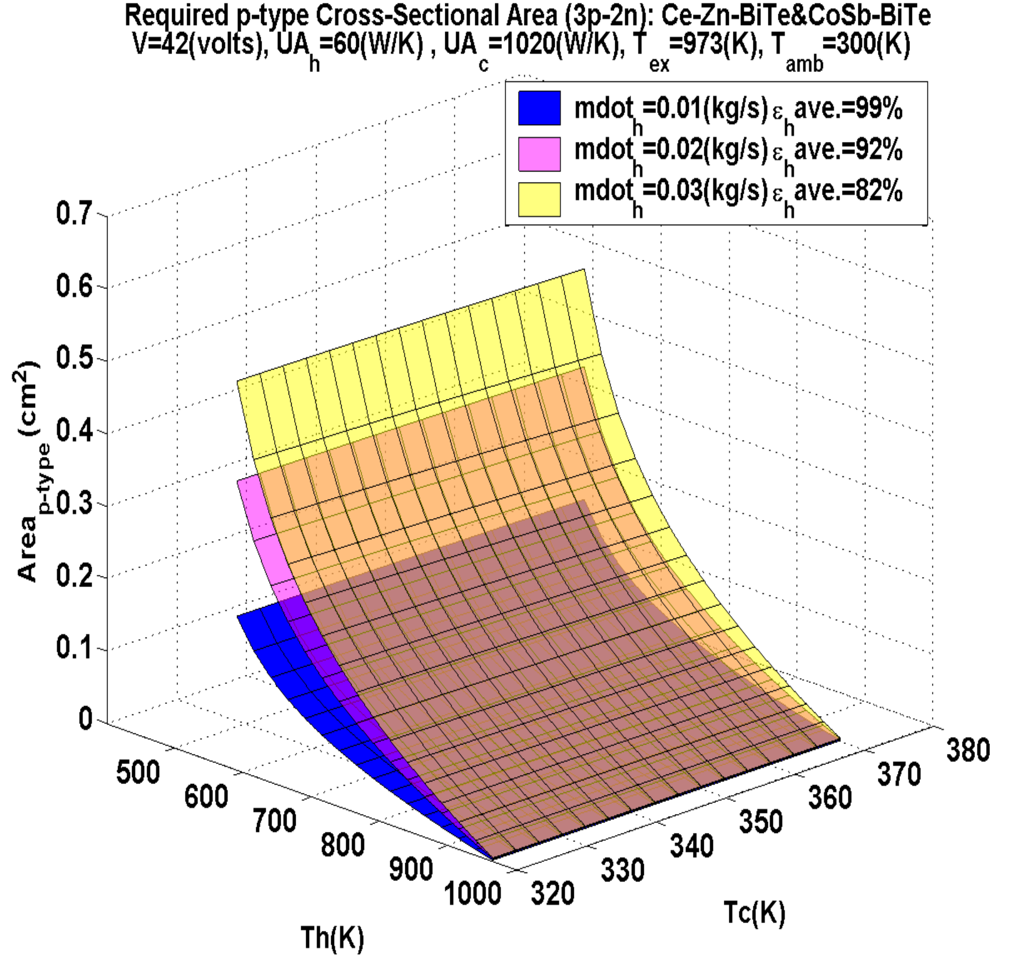


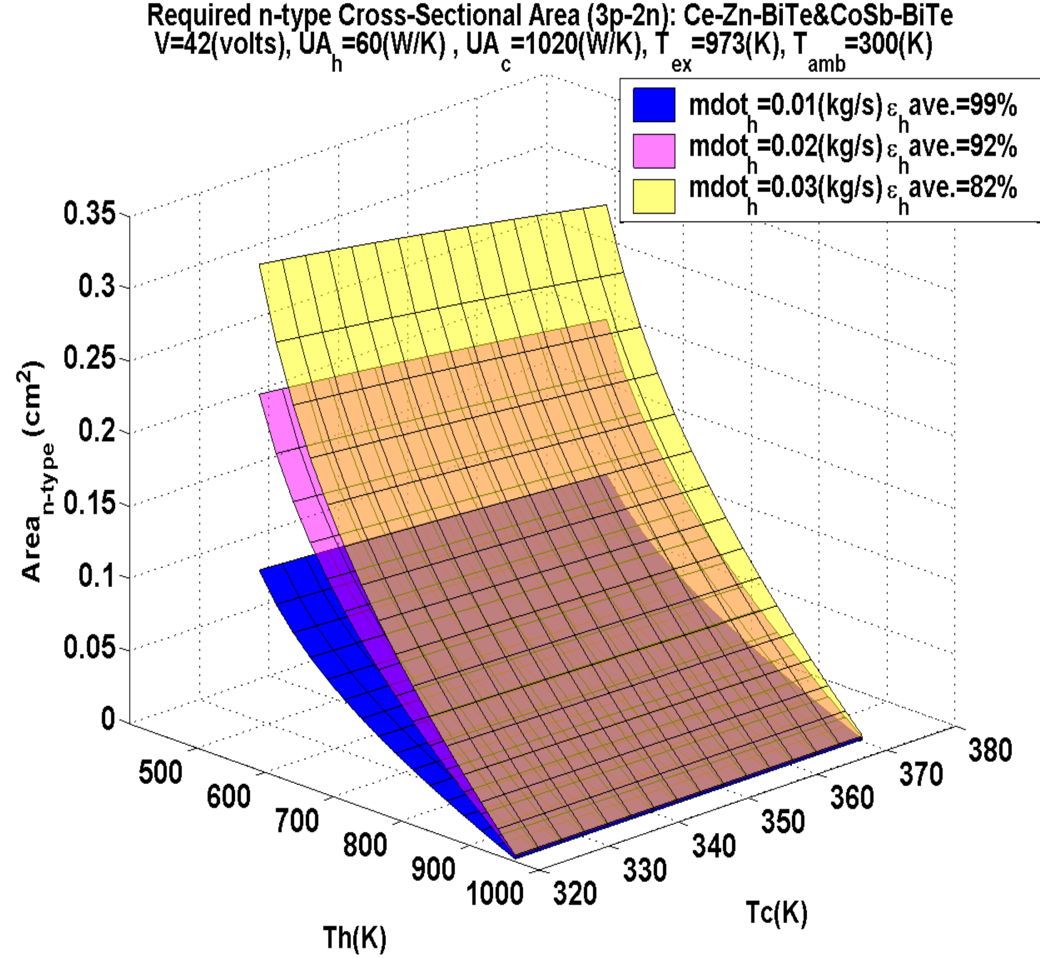


Results: TE Cross-Sectional Area Comparison

At Peak P: 0.21, 0.40, 0.54 (cm^2)
Increased from 2p-2n

At Peak P: 0.14, 0.26, 0.35 (cm^2)
Increased from 2p-2n

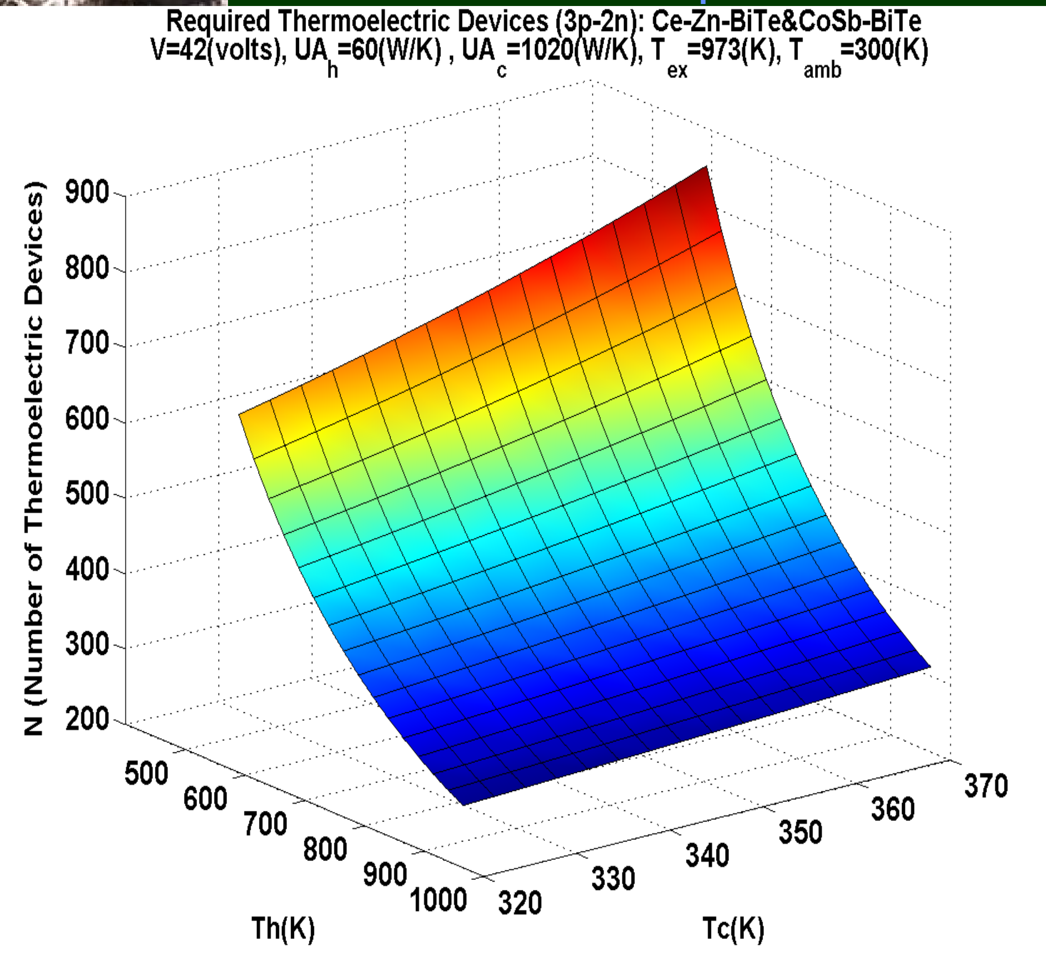


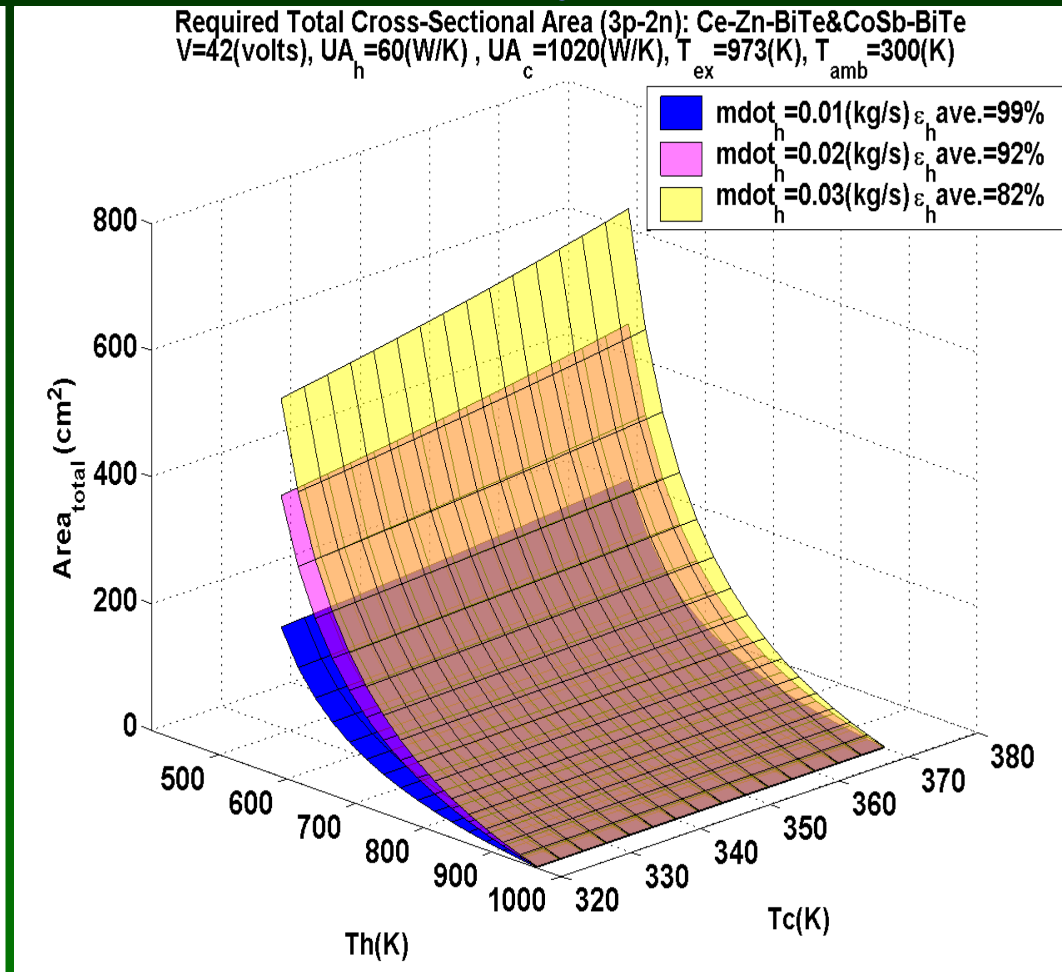


Results: Required TE Couples & Total Area

At Peak P: 674 (devices)
Decrease from 2p-2n

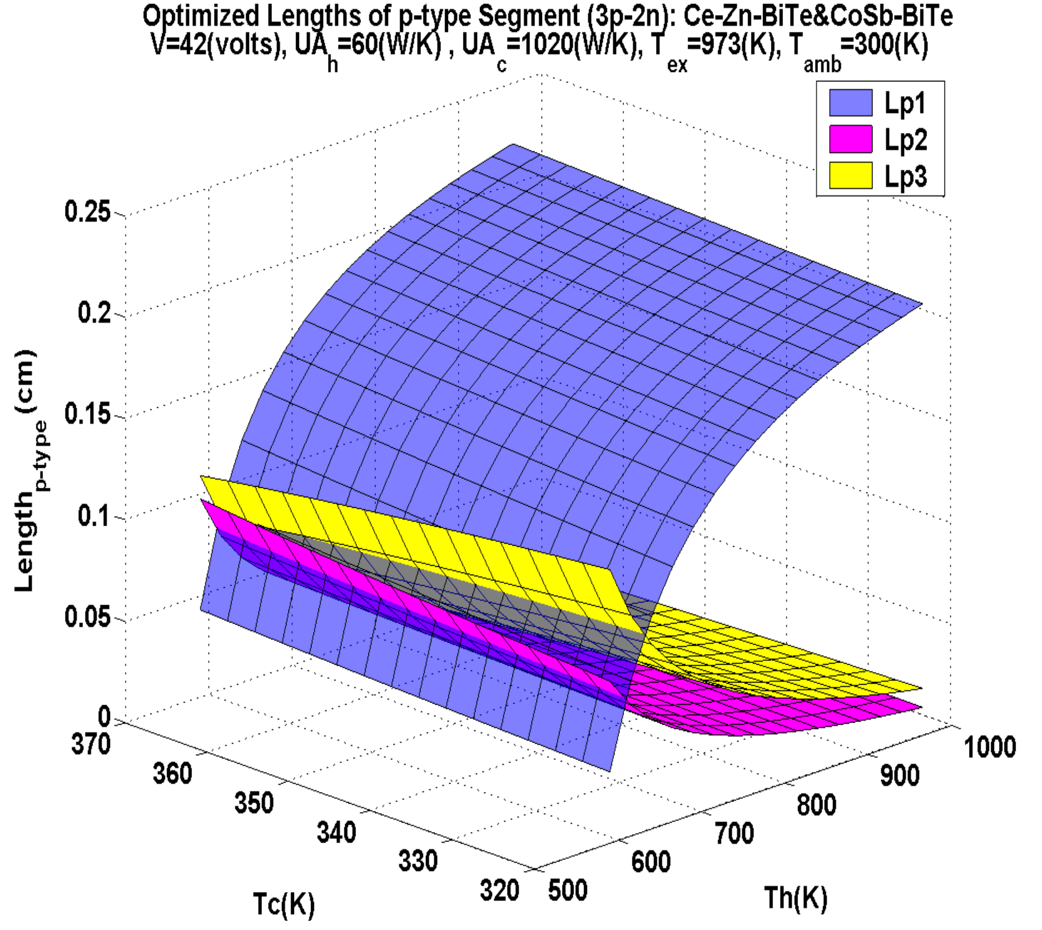
At Peak P: 236, 444, 597 (cm^2)
Approximately Equal to 2_2



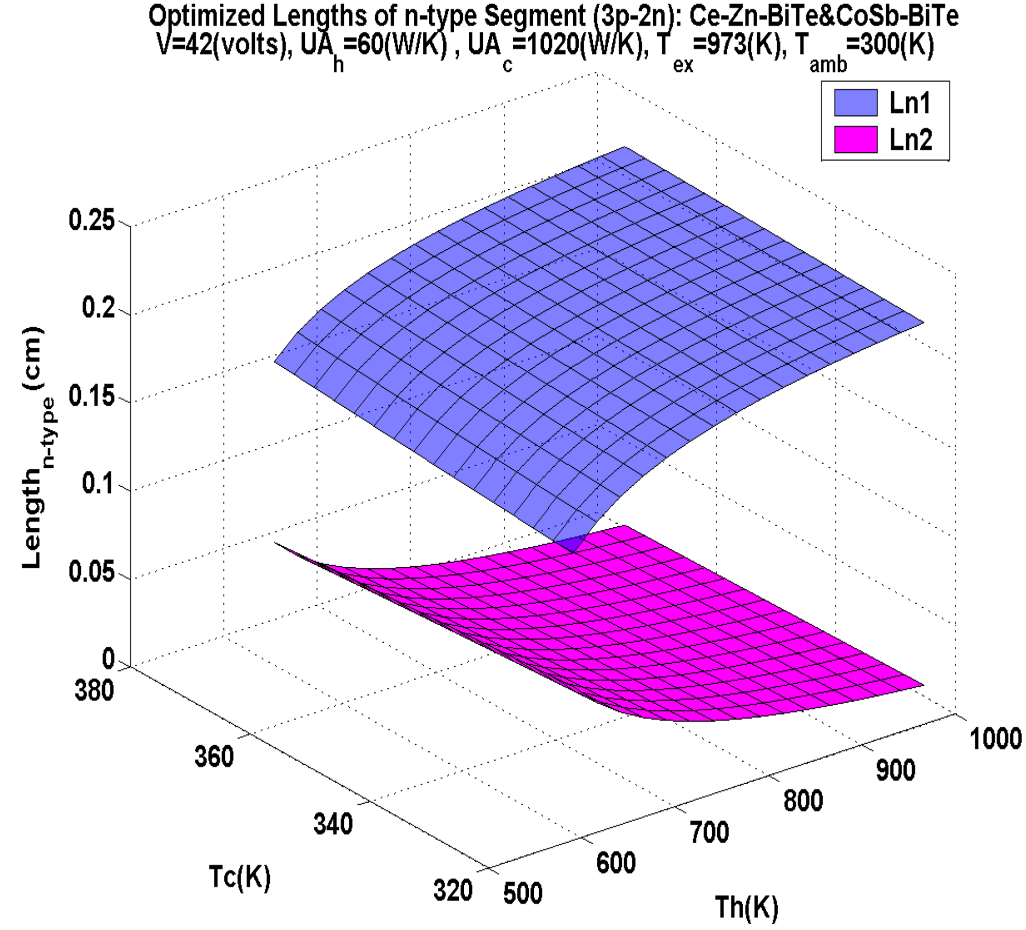


Results: TE Element Length Trends

p-Type



n-Type



Automotive Vehicle Definitions

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)

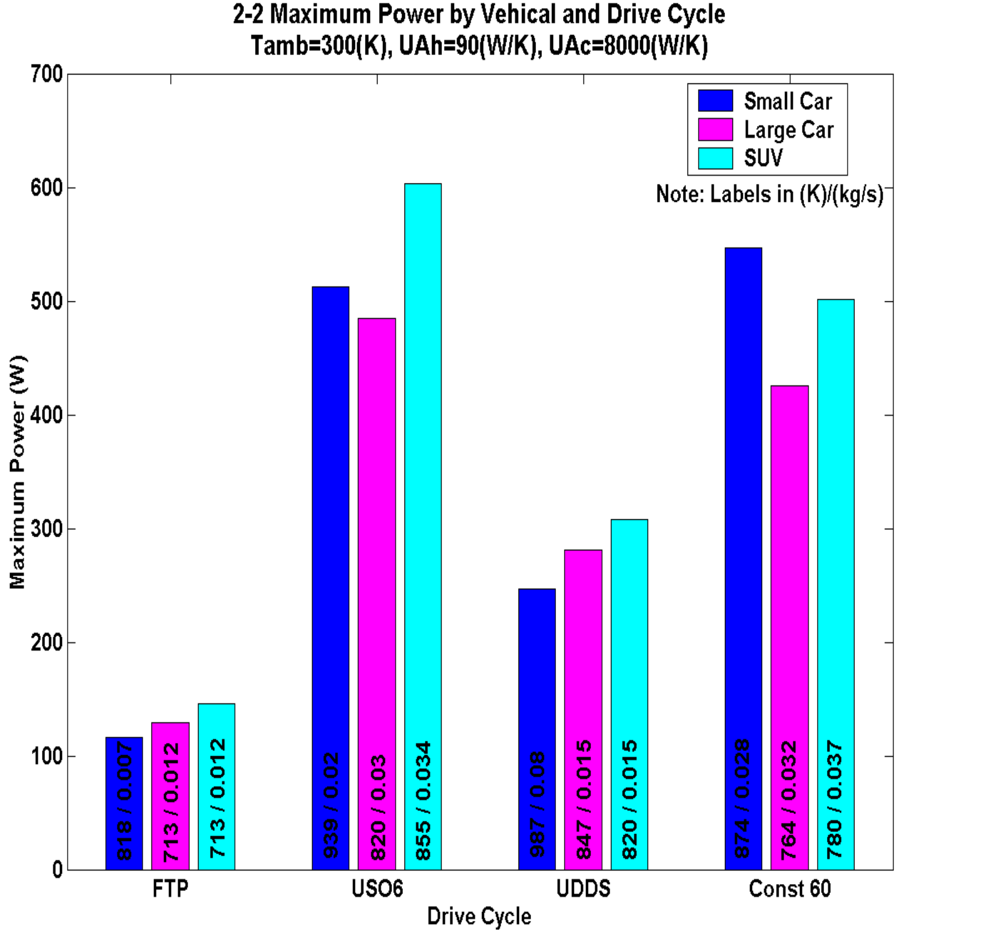
Ford Explorer
Toyota 4 Runner
GMC Envoy
Land Rover Discovery

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

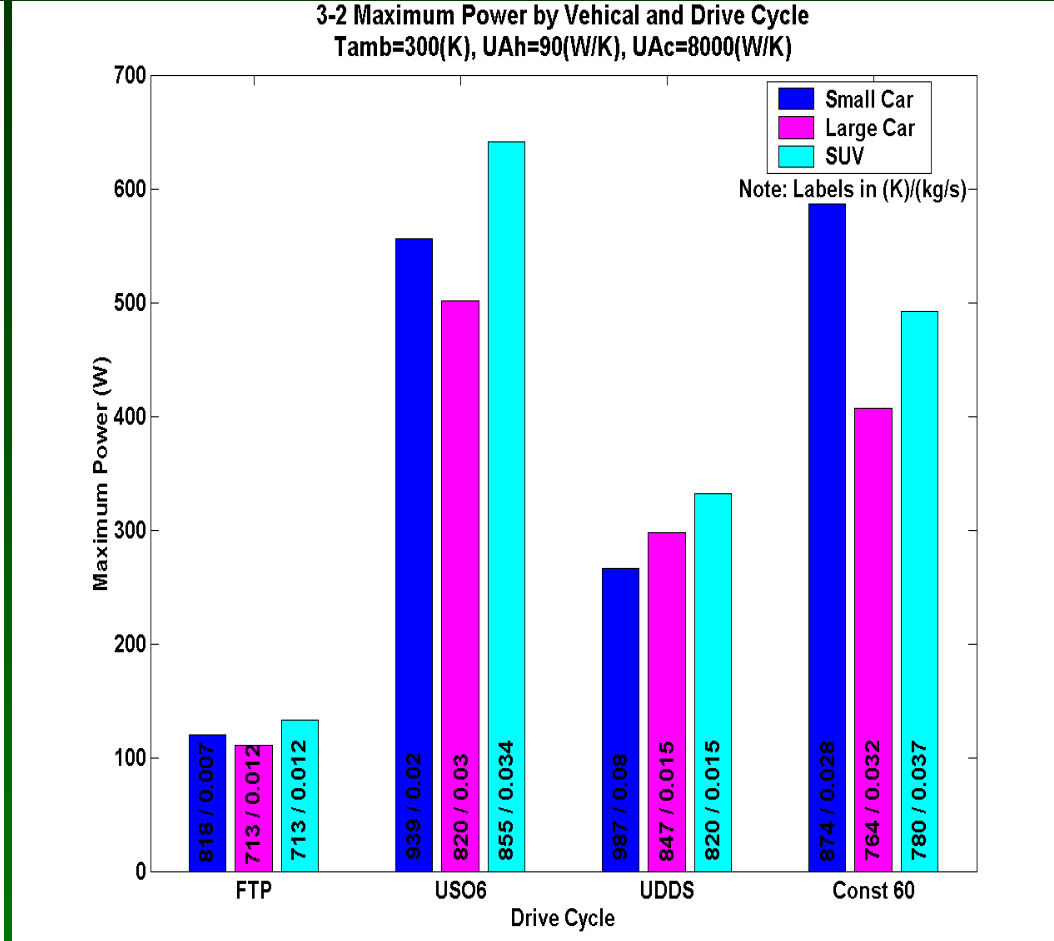
Advisor Interface

Drive Cycle Summary

2-2 Drive Cycle Summary



3-2 Drive Cycle Summary



Heavy-Duty Vehicle Applications

Continuing National Security Issue

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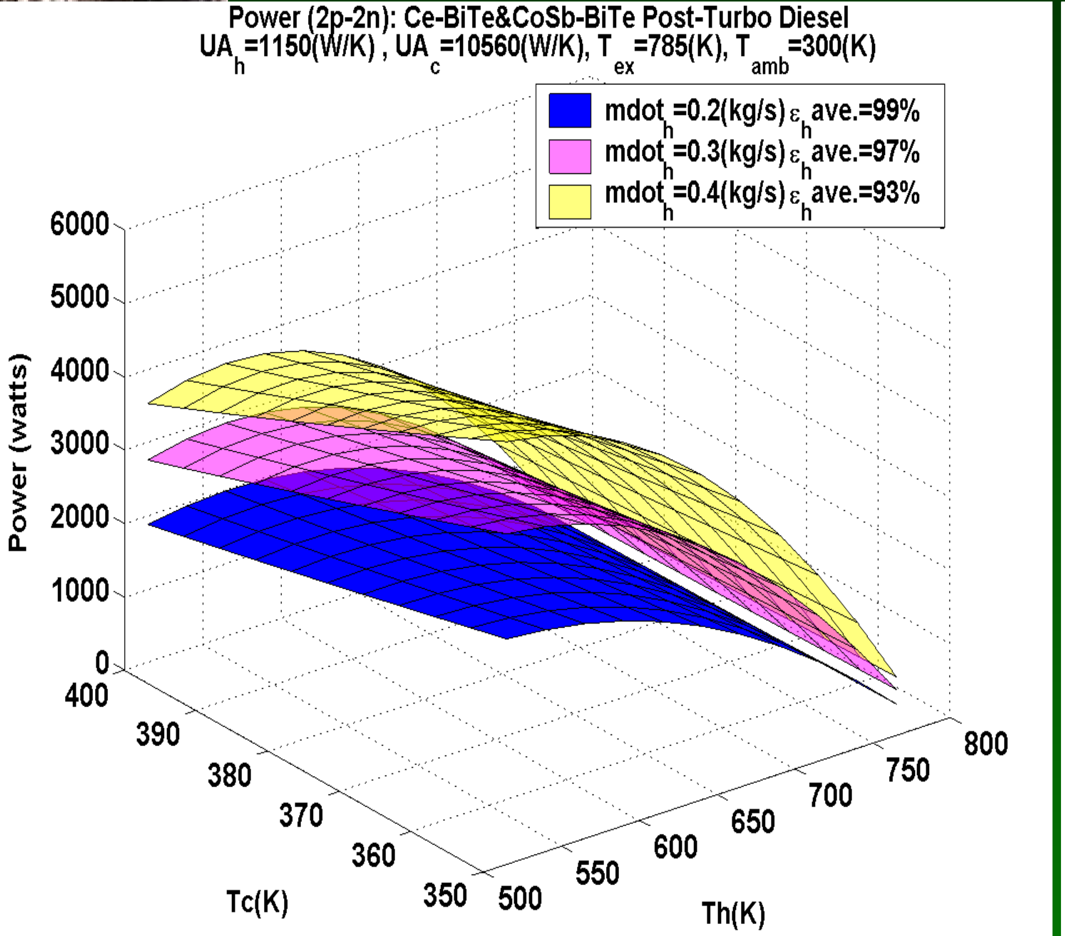
Heavy Duty Diesel Characterization

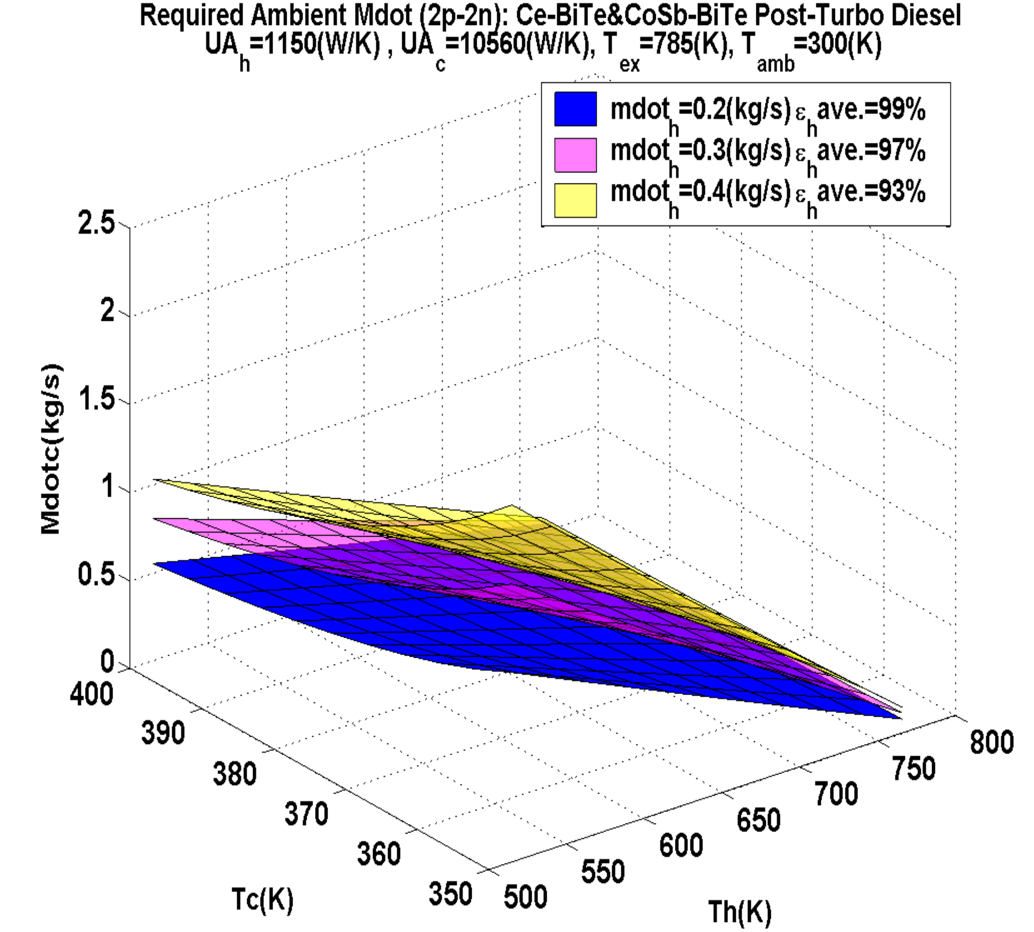
2p-2n Diesel (WAVE): Maximums Found

Skutterudite-Bi_2Te_3 & $CoSb_3$-Bi_2Te_3

Peak At: 3.1, 4.5, 5.8 (kW)

At Peak P: 1.1, 1.6, 2.0 (kg/s)



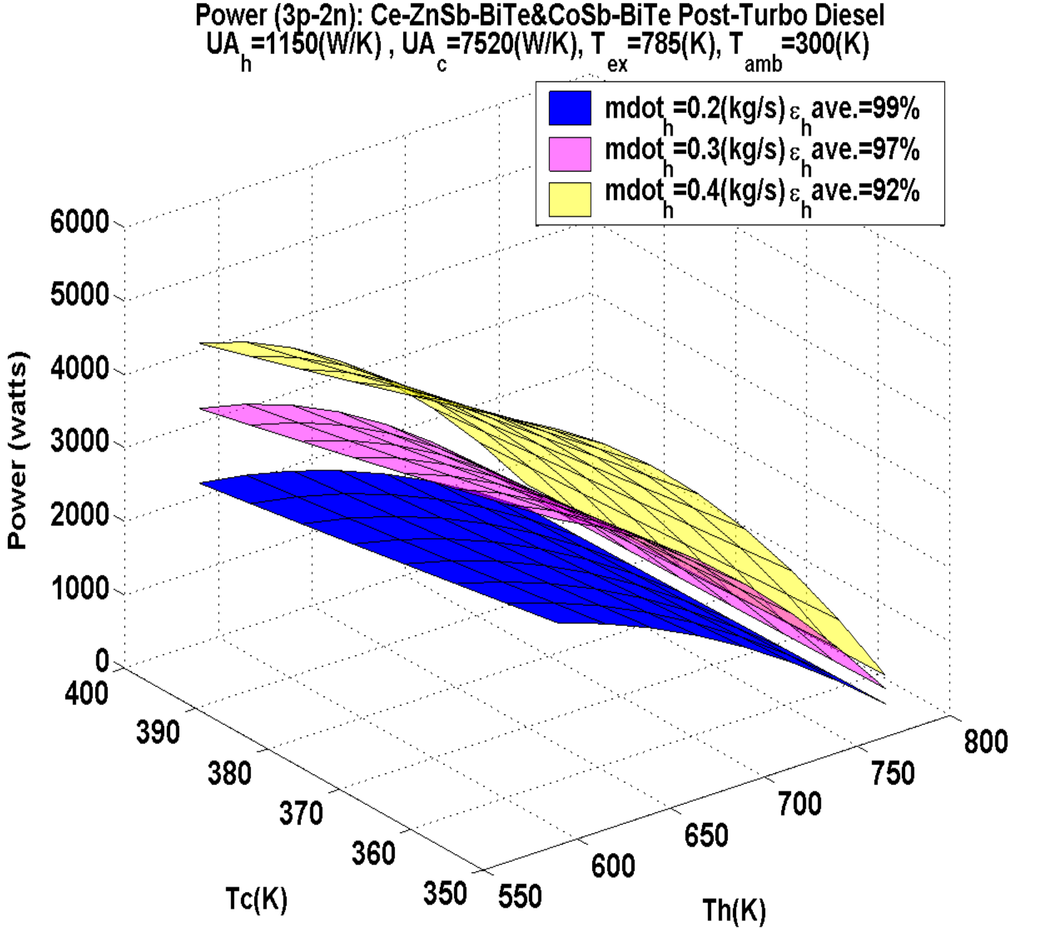


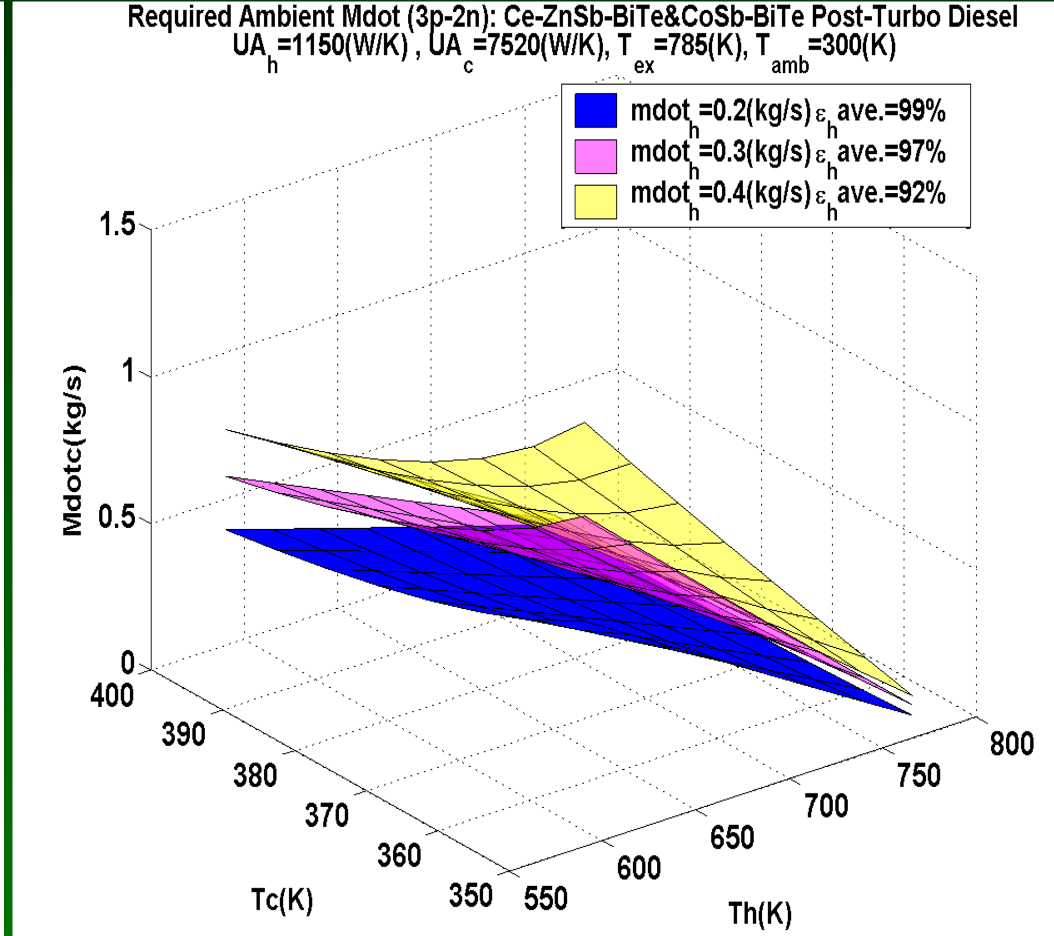
3p-2n Diesel (WAVE): Maximums Found

Skutterudite-Zn_4Sb_3-Bi_2Te_3 & $CoSb_3$-Bi_2Te_3

Peak Power: 3.0, 4.4, 5.7 (kW)
Decrease from 2p-2n ~ 2-3%

At Peak P: 0.77, 1.1, 1.4 (kg/s)
Decrease from 2p-2n ~ 30%

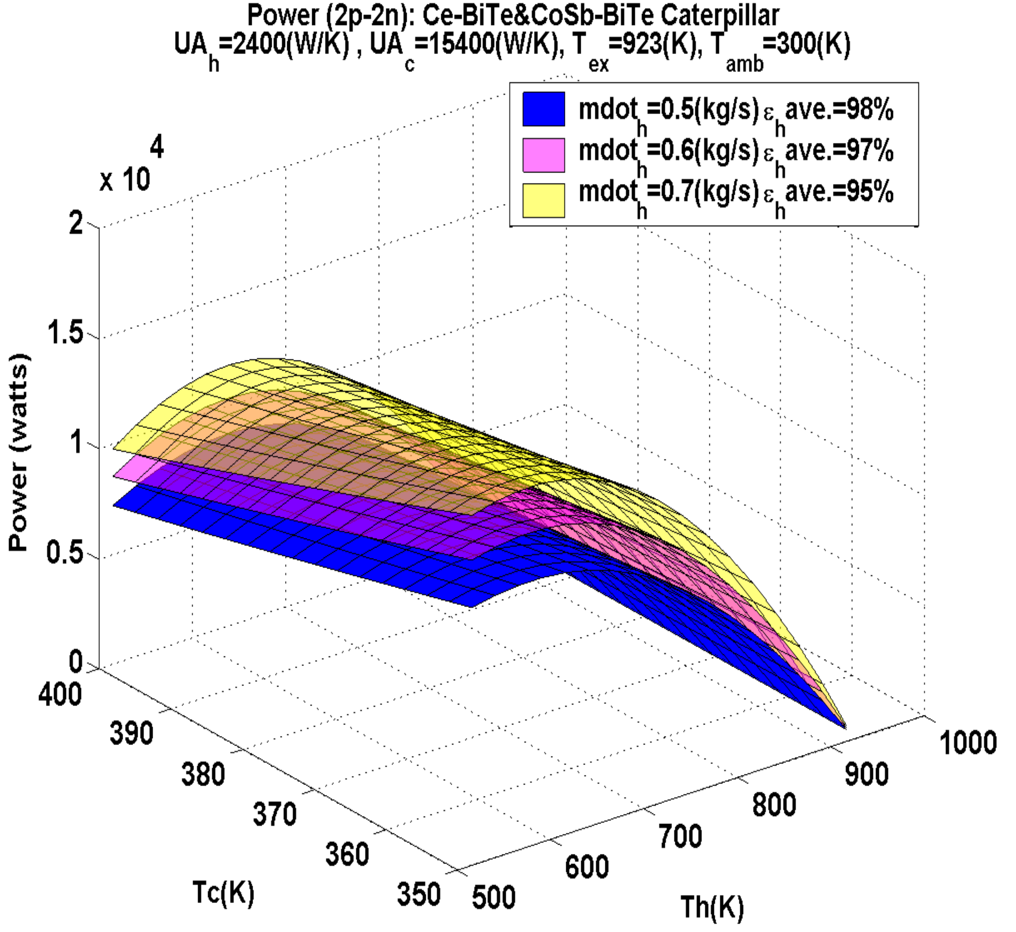




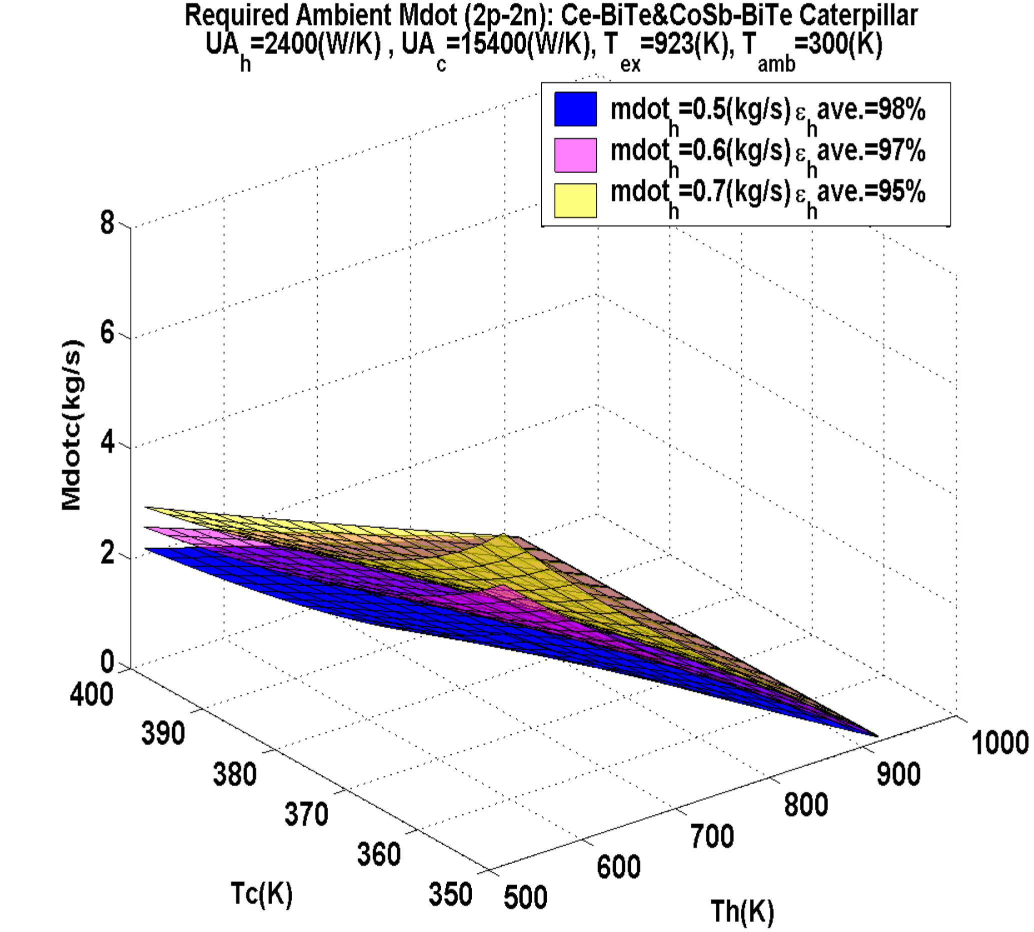
2p-2n Diesel (Cat): Maximums Found

Skutterudite-Bi_2Te_3 & $CoSb_3$-Bi_2Te_3

Peak At: 12.0, 14.2, 16.3 (kW)



At Peak P: 3.6, 4.2, 4.8 (kg/s)

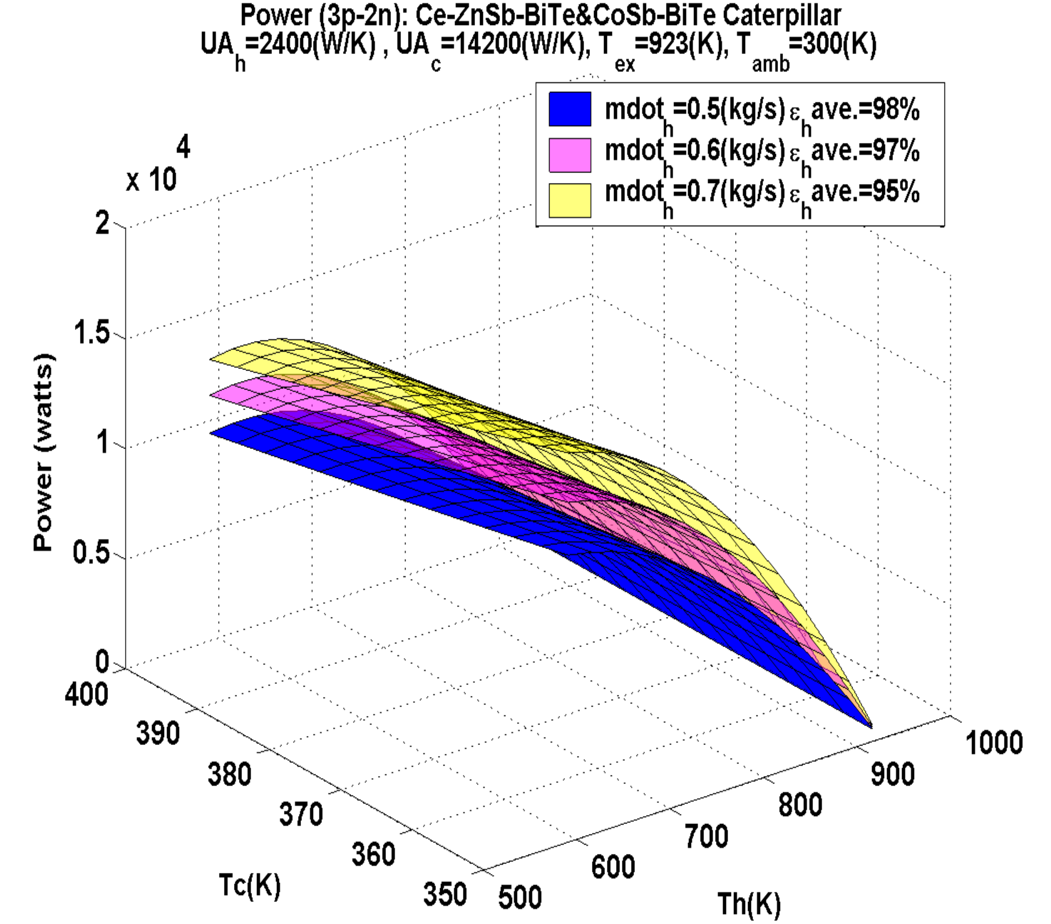


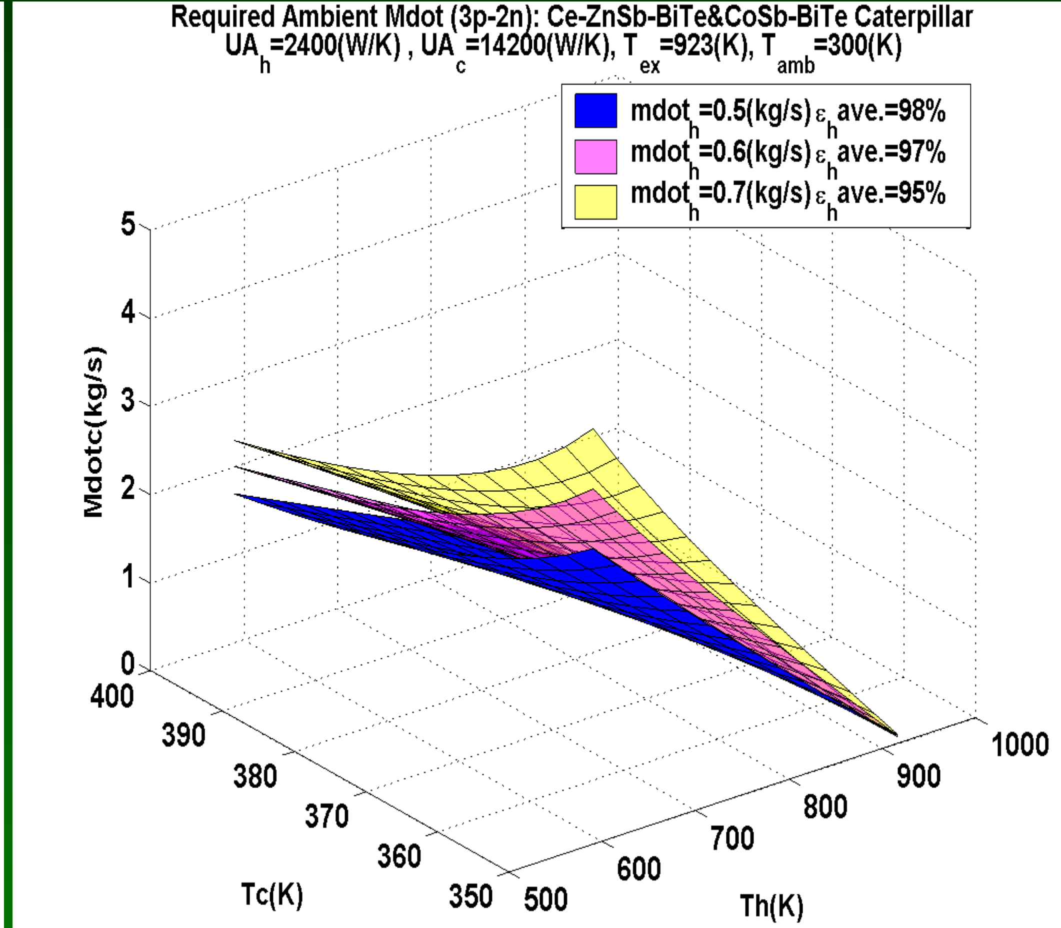
3p-2n Diesel (Cat): Maximums Found

Skutterudite-Zn_4Sb_3-Bi_2Te_3 & $CoSb_3$-Bi_2Te_3

Peak At: 13.0, 15.4, 17.6 (kW)
Increase from 2p-2n ~ 8%

At Peak P: 3.3, 3.9, 4.5 (kg/s)
Decrease from 2p-2n ~ 6-8%

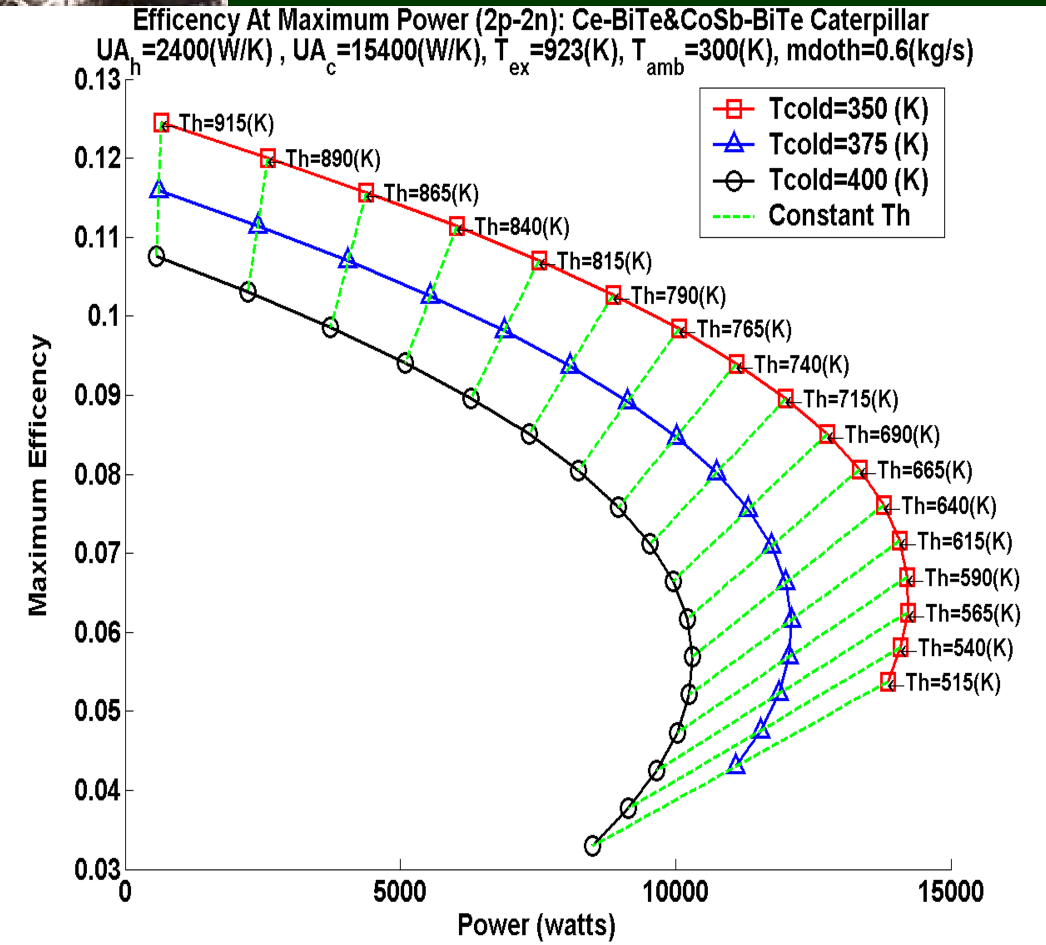




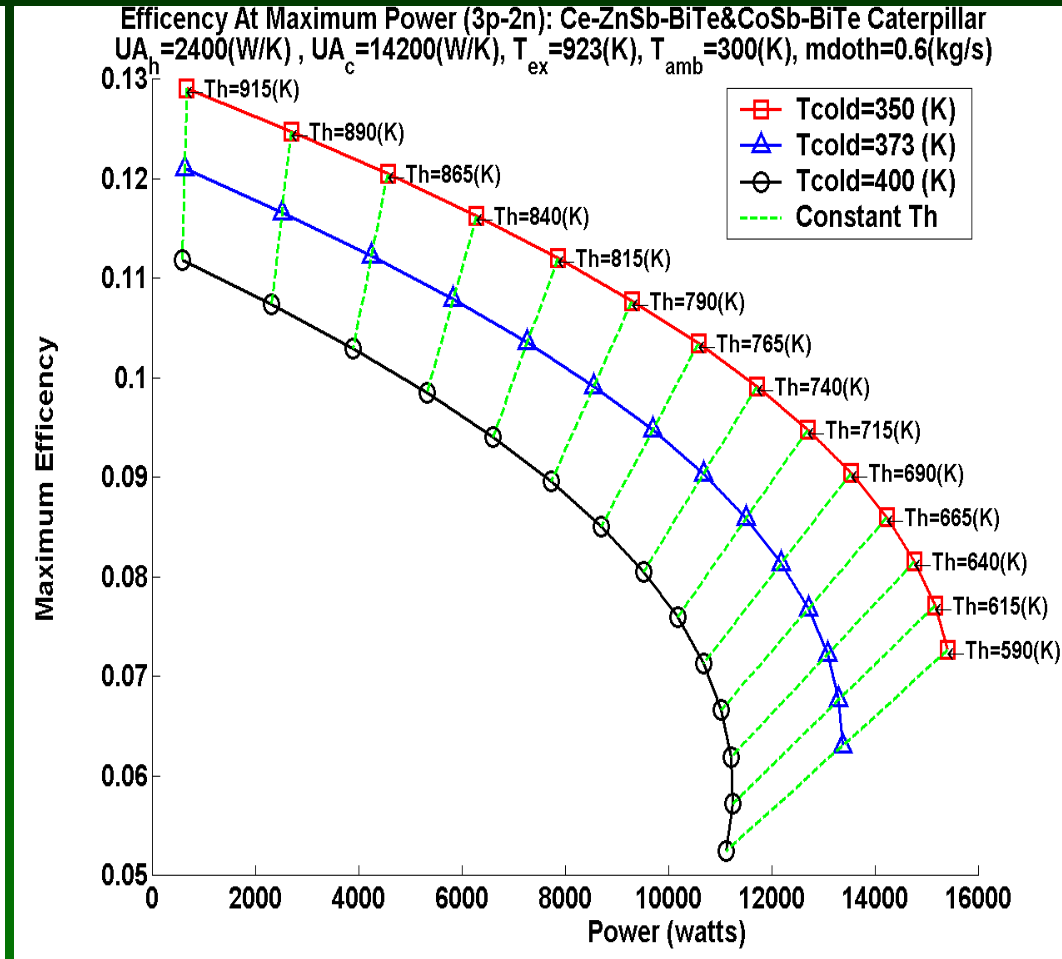
Diesel (Cat): Peak Power Not At Peak Eff.

Skutterudite-(Zn_4Sb_3)-Bi_2Te_3 & $CoSb_3$-Bi_2Te_3

Middle Mdoth (0.3 kg/s)



Higher Efficiency & Higher Power

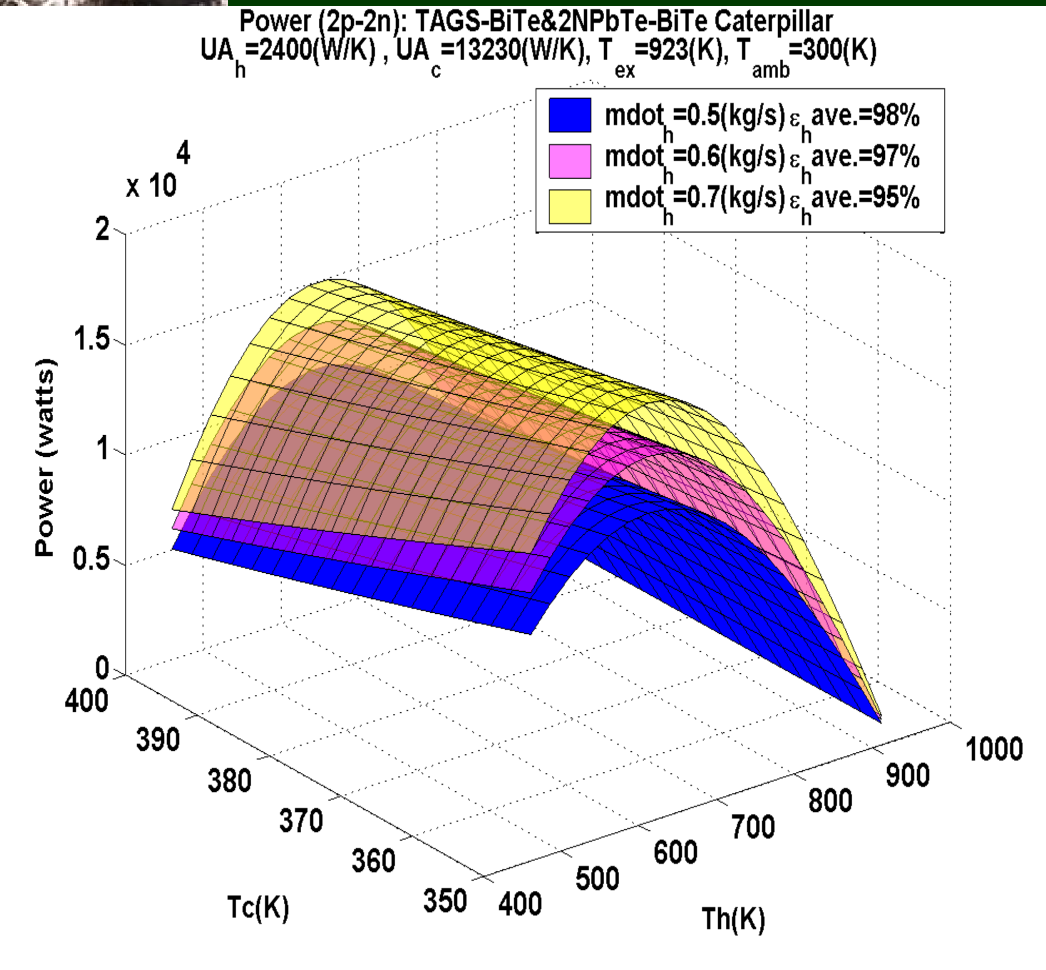


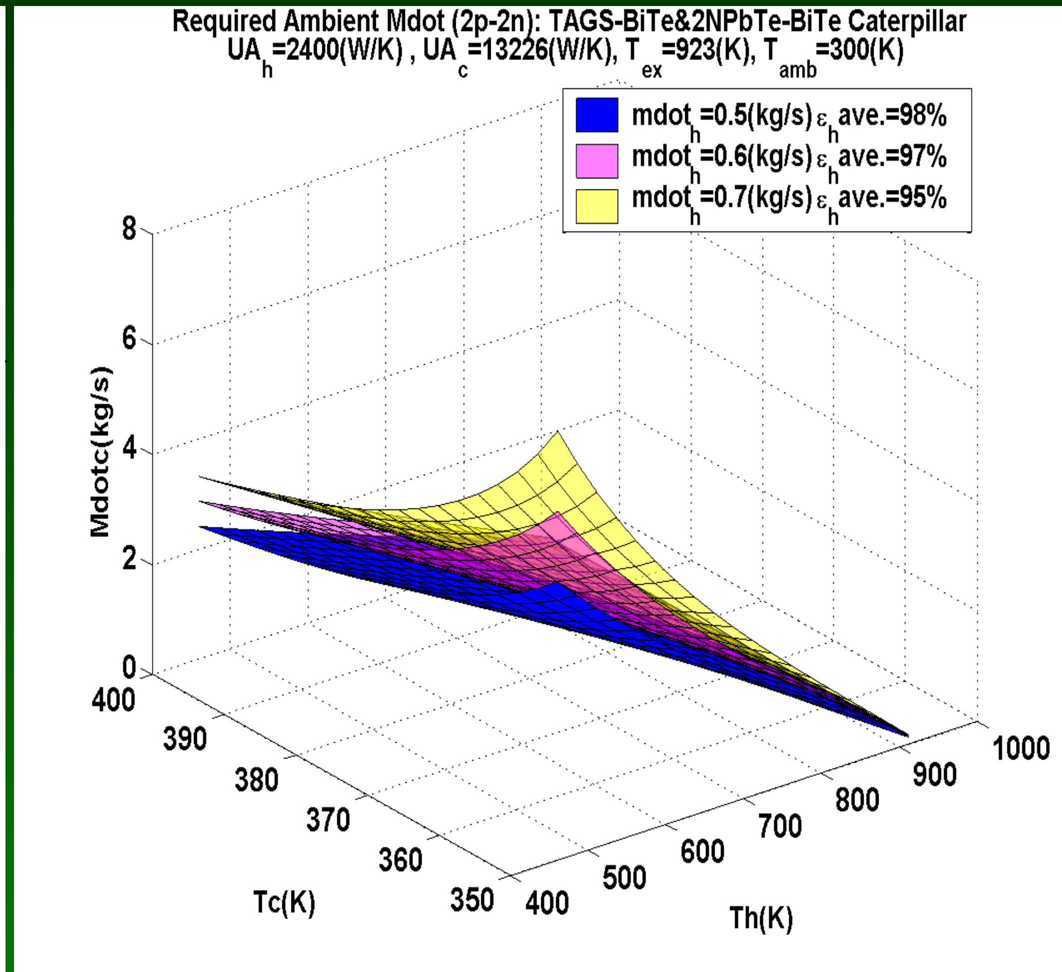
2p-2n Diesel (Cat): Maximums Found

TAGS-Bi_2Te_3 & 2NPbTe-Bi_2Te_3

Peak At: 14.0, 16.6, 19.0 (kW)
Increase from 1st Material Set ~ 17%

At Peak P: 3.1, 3.6, 4.2 (kg/s)
Decrease from 1st Material Set ~13-14%





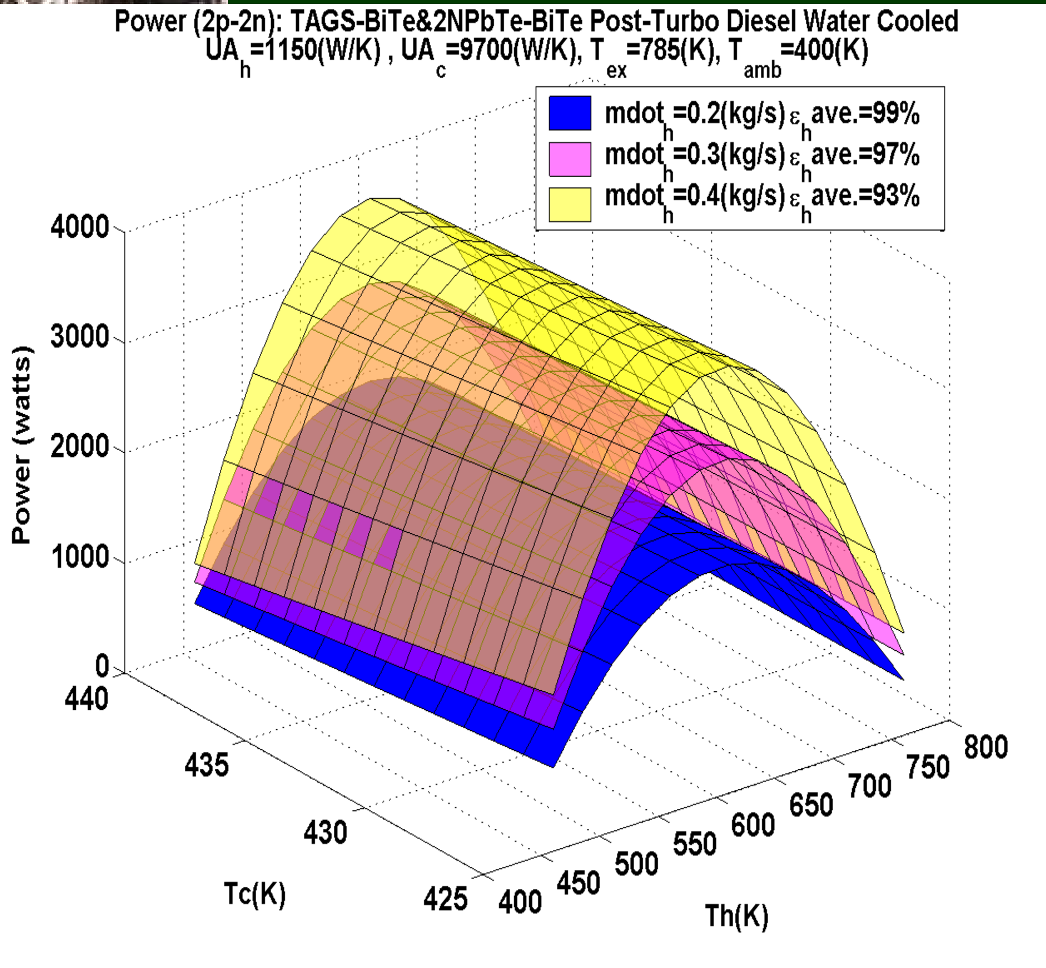
2p-2n (Diesel WAVE): Maximums Found

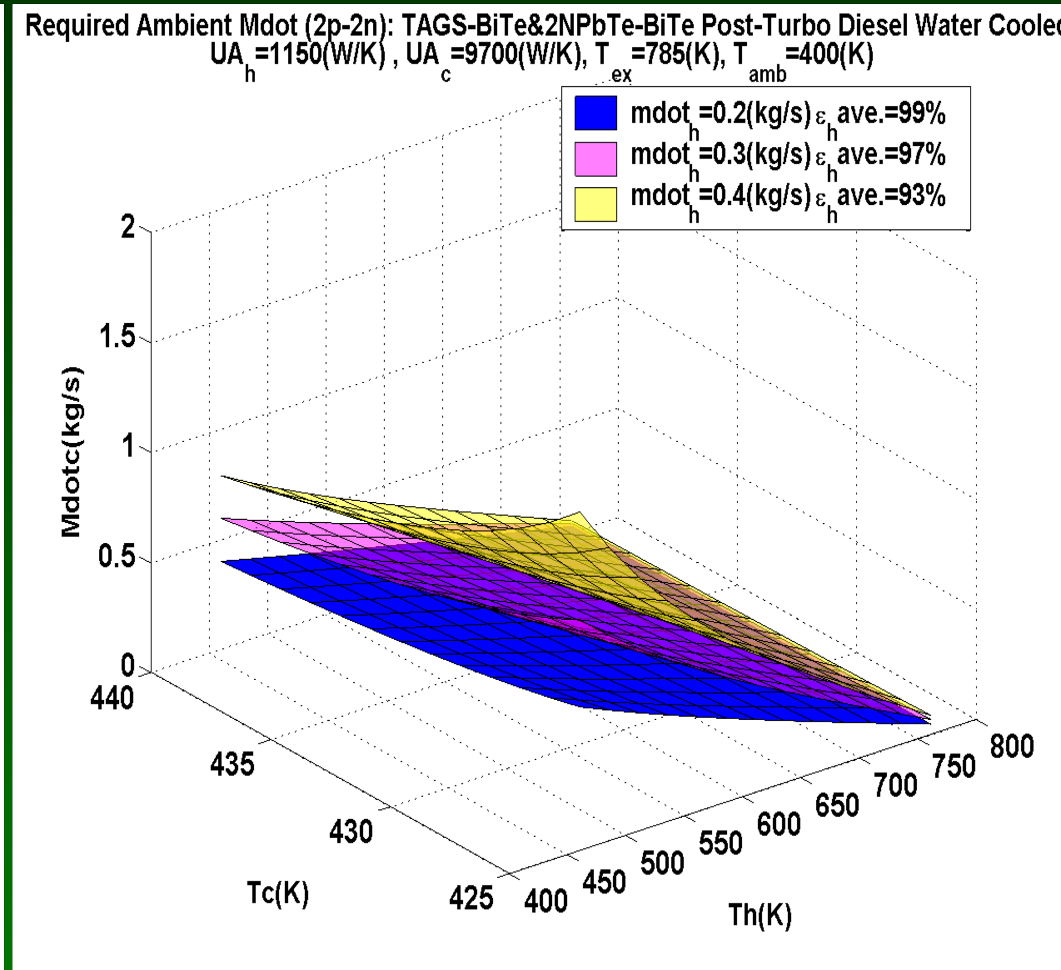
TAGS-Bi_2Te_3 & 2NPbTe-Bi_2Te_3 ***Water Cooled***

Peak At: 2.1, 3.0, 3.9 (kW)

Decrease from Air Cooled ~ 37 %

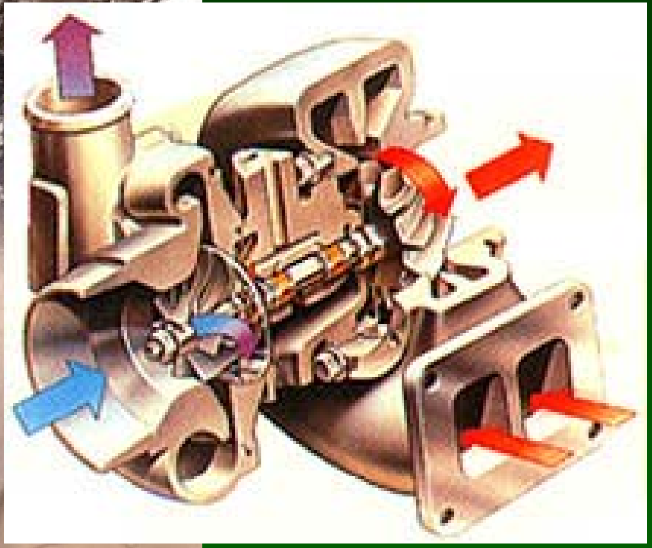
At Peak P: 0.33, 0.49, 0.64 (kg/s)





Turbocharger Configuration

High Pressure Loop Exhaust Gas Recirculation



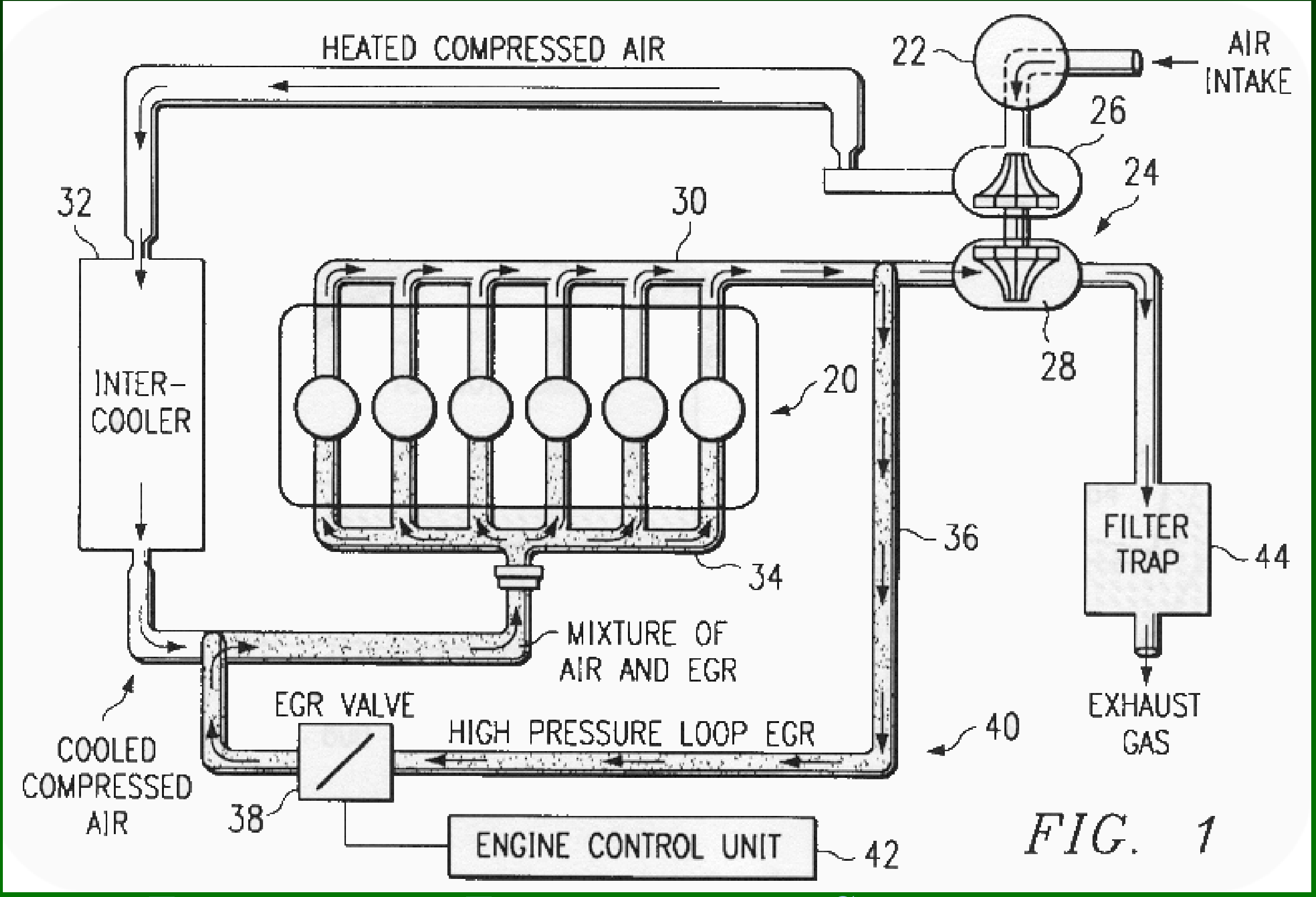


FIG. 1

Power Available

~ 500-600 Watts

How Much Fuel Can Be Saved?

- Potential to Recover 8-10%
  - Light Duty
    - 45 Billion Gallons Out the Exhaust
    - Save 30 Billion Gallons/Year
  - Heavy Duty
    - Save 1.3 Billion Gallons/Year
    - 5 kW TE System

Technical Challenges in Automotive 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
  - 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-Duty Vehicle APUs, Truck Electrification, & Anti-Idling
- Heat Exchanger / Thermoelectric Device Design Analyzed & Optimized Simultaneously Within ADVISOR for Vehicle-Level Studies
  - Design Issues Identified Simultaneously
  - Design Requirements Identified Simultaneously
- Heat Exchanger / TE Device Tradeoffs
  - 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)
  - TE Materials Strongly Impact Thermal System Design
  - Heavy Duty Power Potential Higher Than Light Duty Vehicle Power
  - Exhaust Temperature Constraints May Limit Need for 3p-2n Elements
  - Thermal Interfaces & Thermal Losses Could Limit Power Potential (Be Smart!)

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- Test:

Continuing National Security Issue

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