Micro- & Nano-Technologies Enabling More Compact, Lightweight Thermoelectric Power Generation & Cooling Systems

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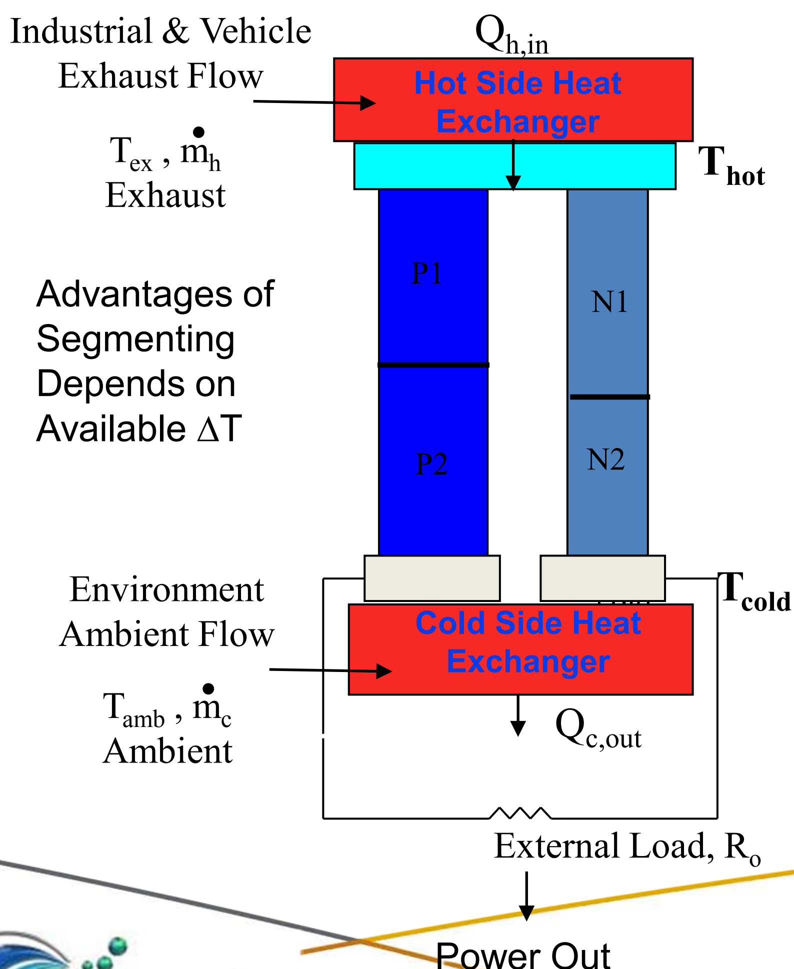
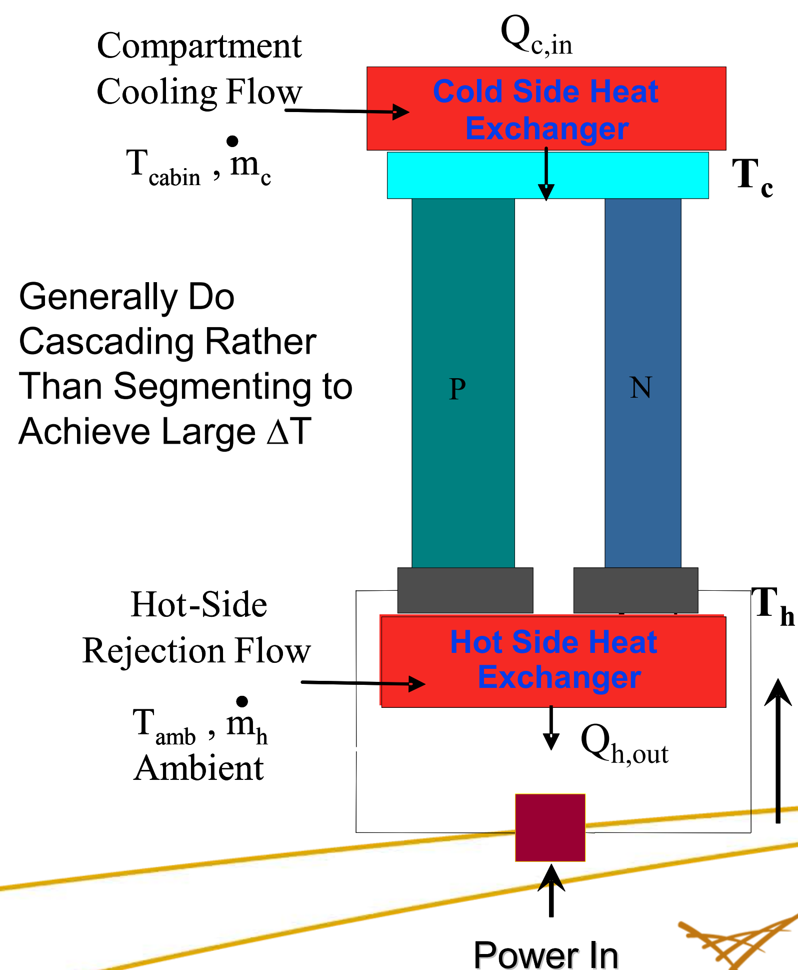
Advanced Thermoelectric System Design

Single & Segmented Material TE Legs

Thermoelectric Power Generation High-Temperature Systems



Thermoelectric Heating/Cooling Low-Temperature Systems



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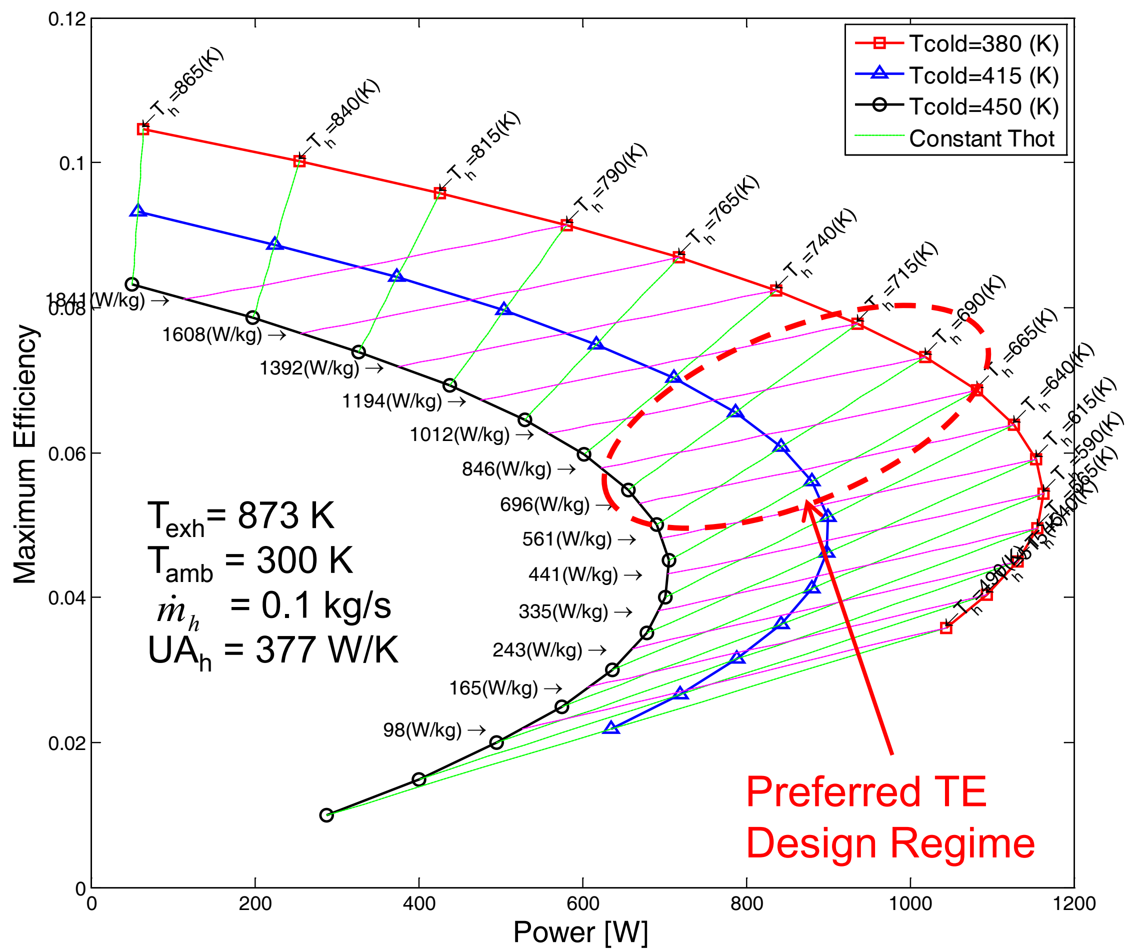
TE Power Generation
Heat Exchanger / TE Device Integration Requirements

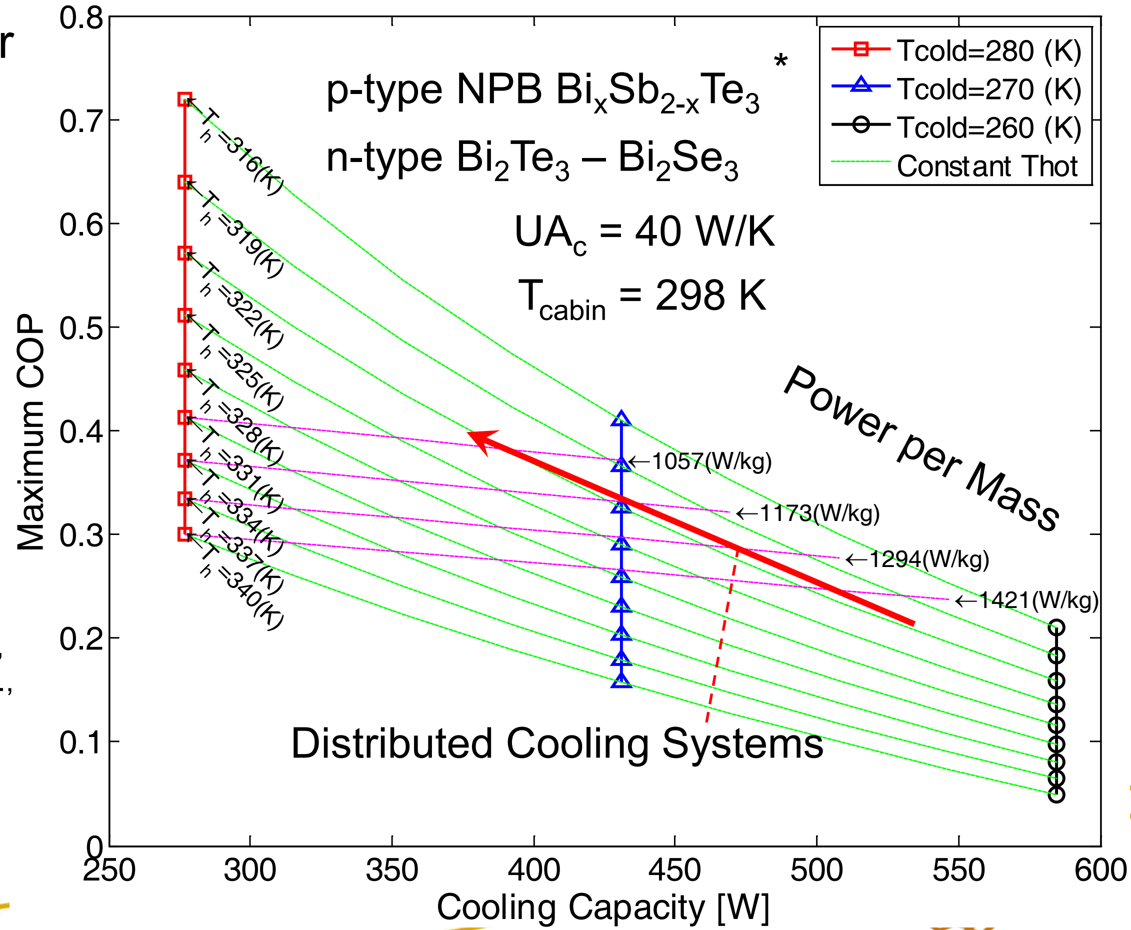
- Regions of Higher Specific Power Also Associated with Higher Heat Flux Regions
- Hot Side Heat Exchanger Dictates:
  - TE Specific Power
  - TE Power Flux
  - TE Volumetric Specific Power
- Heat Fluxes > 15 W/cm^2 in Preferred Design Regimes
  - Hot-side
  - Cold-side

Segmented Skutterudite /Bi_2Te_3 Materials



TE Cooling
Heat Exchanger / TE Device Integration Requirements

- Typical COP – Cooling Capacity – Power / Mass Relationship Shown
- Distributed TE Cooling Systems
  - Create Lower Heat Flows per Unit
  - Higher COP's
  - Lower Power / Mass
- Generally Right Directions for Automotive Distributed Cooling



* Poudel, B., Hao, Q.H., Ma, Y., Lan, Y., Minnich, A. Yu, B., Yan, X., Wang, D., Muto, A., Vashaee, D., Chen, X., Liu, J., Dresselhaus, M.S., Chen, G., Ren, Z., 2008, "High-Thermoelectric Performance of Nanostructured Bismuth Antimony Telluride Bulk Alloys," *Sciencexpress*, 10.1126, science.1156446.

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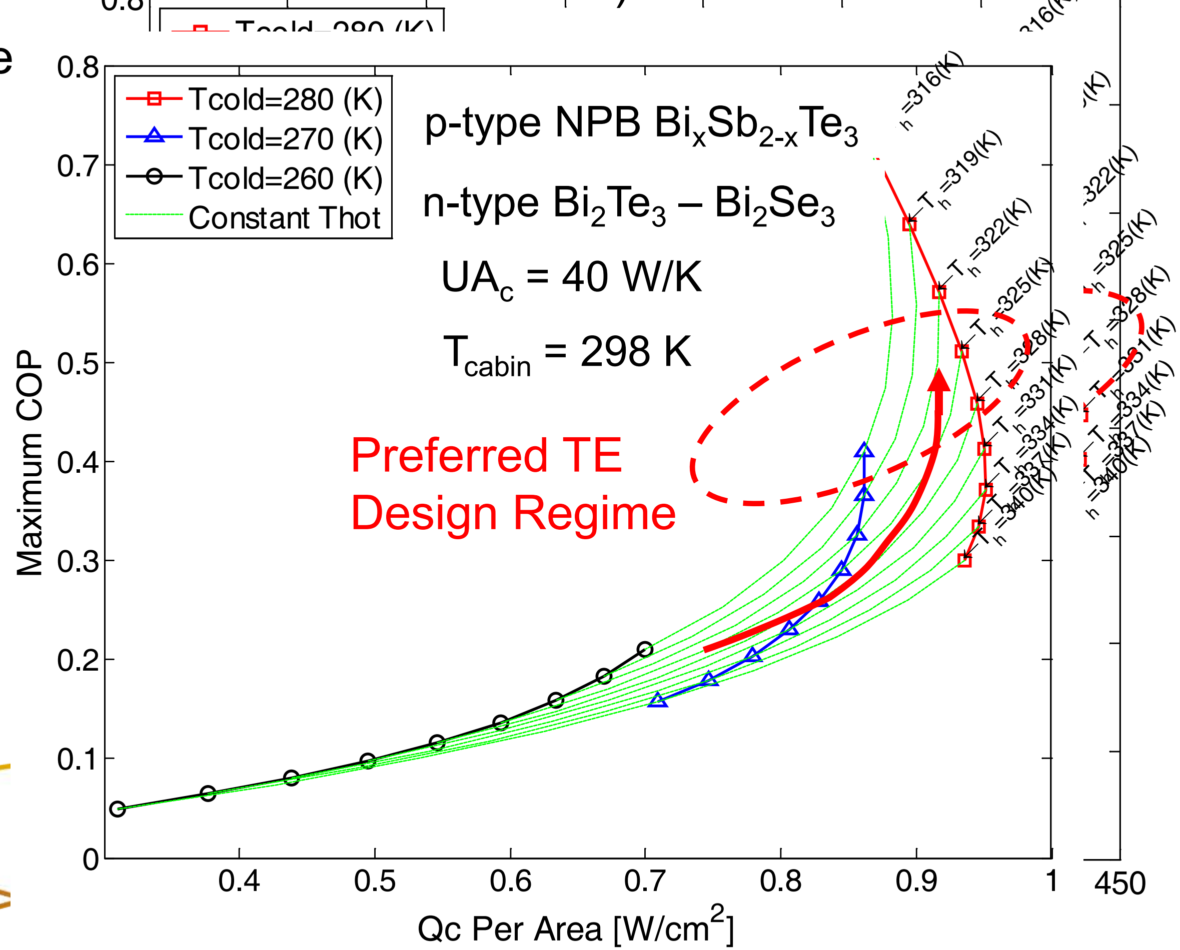
TE Cooling
Heat Exchanger / TE Device Integration Requirements

- Distributed TE Cooling Systems Generally Move Into Regions of:
  - Higher COP's
  - Higher Specific Cooling Capacity (Compact, Lightweight Systems)
  - Higher Heat Fluxes (Higher Heat Transfer Coefficients)
- Generally Higher Performance Heat Exchanger Systems Required



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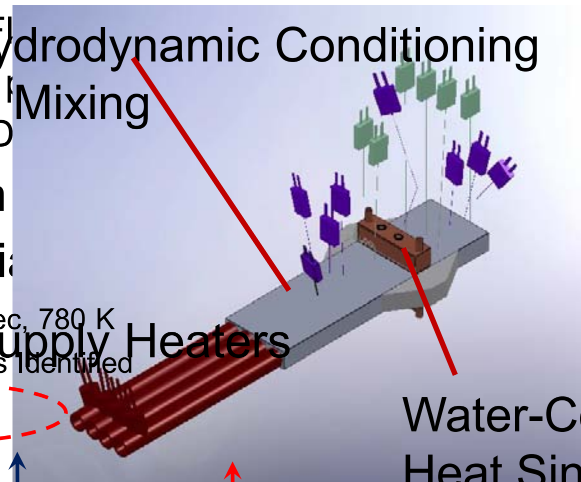
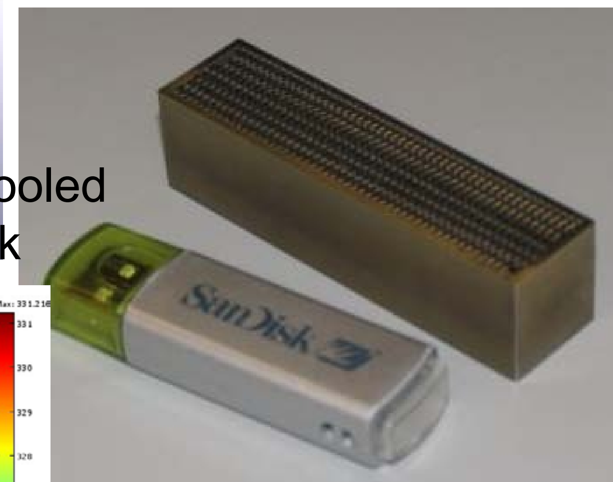
PNNL Developing High-Performance Microtechnology Heat Transfer Technologies

- TE Power Generation From TQG Exhaust Energy Recovery
  - Hot-Side Heat Exchanger Designs Being Developed & Refined
  - CFD Analyses & Experimental Testing Helping to Refine Designs
  - Design Performance Goals:
    - High Thermal Transfer Fl... at Exchanger
    - Low Pressure Drop (< 1 ...
    - Heat Flux vs. Pressure D... ifferent Design Approaches
  - Different Materials Can ... Inconel, Haynes Materi...

60 kW TQG Design Conditions: 0.158 kg/sec, 780 K

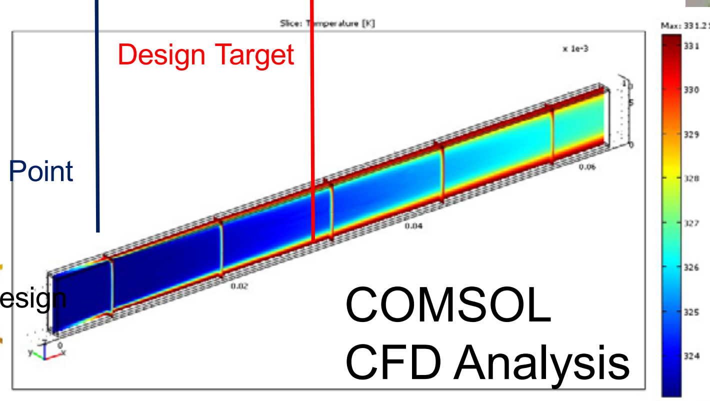
Several Workable Design Points Identified





Design Target

Design Point



COMSOL CFD Analysis

Rectangular Honeycomb Design

ε = 0.93

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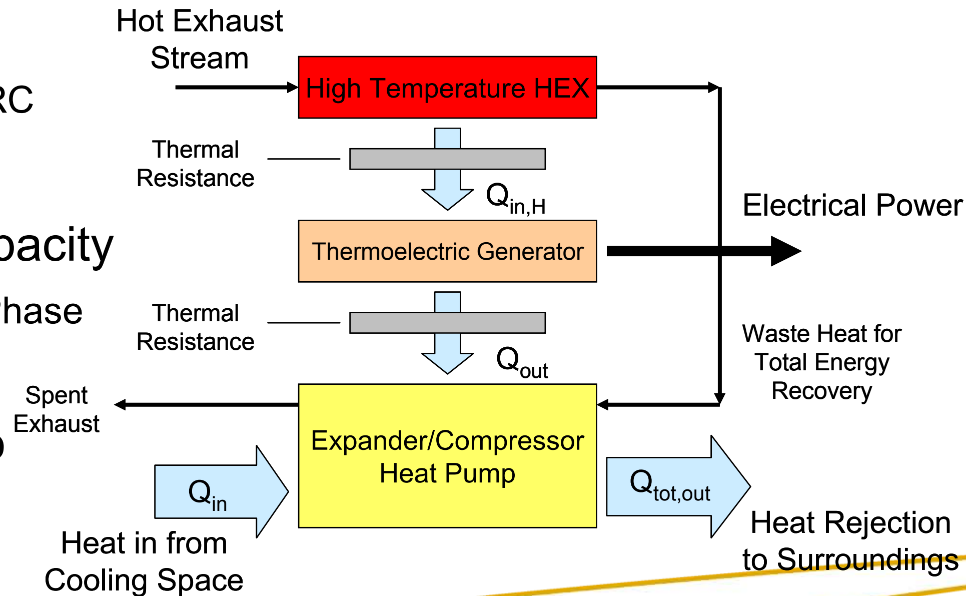
Co-Functional Power / Cooling Systems

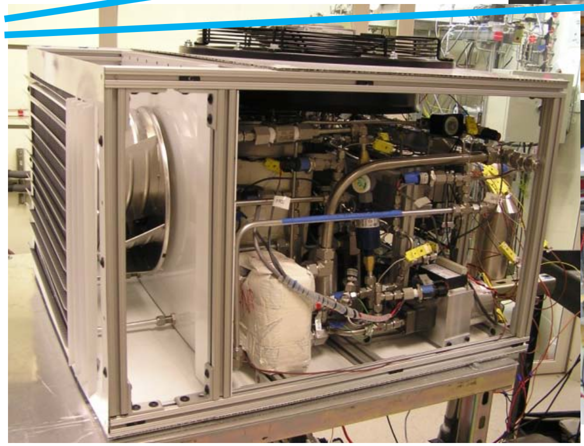
- Co-Functional Integration of 3 Power & Cooling Technologies
  - Organic Rankine Cycle Based Cooling
  - Thermoelectric Power Generation
  - Micro/Nano Heat Transfer Technologies (Microchannel Heat Exchangers)
- System Designed, Fabricated & Tested at PNNL MBI
- TE Topping Cycle
  - Step-Down (Lower) Input Temperatures to ORC
  - Simultaneously Produce Useful Power
- E/C ORC to Provide Useful Cooling Capacity
  - Known & Demonstrated Components in this Phase
  - Reduce Cost & Risk & Development Time
- Microchannel Heat Exchangers Used to Dramatically Reduce Volume & Weight
- Funded by U.S. Army RDECOM

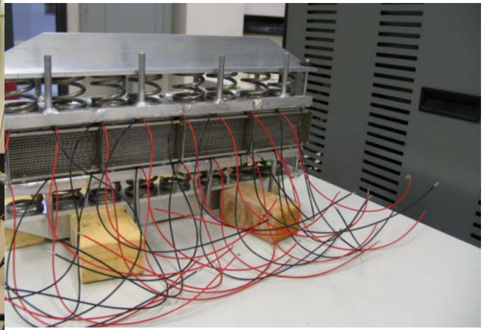


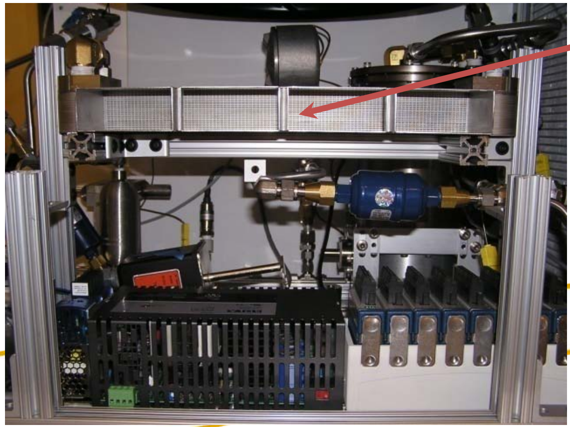
CFPC – Fabrication & Test

- First-in-Class, Pioneering System
- TEG Power System Uses MicroChannel Heat Exchangers
  - Stainless Steel Air HX On Hot-Side
  - Aluminum R245fa HX on Cold-Side
- High-Temperature Bi_2Te_3 Modules
  - First-Ever 320° C Bi_2Te_3 Modules
- System Size
  - Dimensions: 30” X 30” X 19”
  - Weight: ~100 kgs
- System Fabrication Completed
- System Testing Completed
  - Exhaust Heat Simulated with Electrical Heater / Blower System
  - Stable System Operation
  - Many Performance Metrics Satisfied

TEG Power System





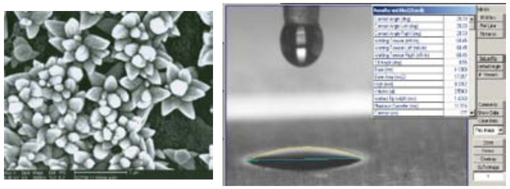


Co-Functional System Build-up

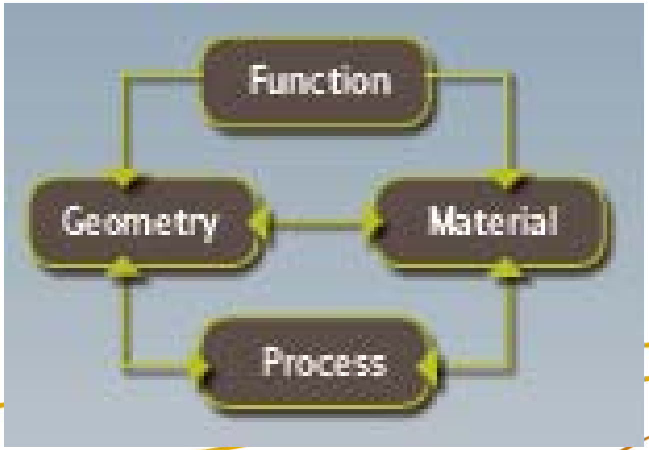
MicroTechnology in Distributed TE HVAC Systems

- DOE Project in Advanced TE HVAC Systems for Automobiles
  - Zonal Climate Control for Thermal Comfort
  - Compact Microtechnology Heat Exchangers
    - Reduce Weight & Volume
    - Low Cost Manufacturing
  - Coupled with Compact TE HVAC Systems
  - Wicking Systems for Water Management
    - Leveraging Nano-Scale Coating Technology
  - Significant Microtechnology Cost Modeling
    - Cost Sensitivities Identified
    - Low-Cost Manufacturing Avenues Being Developed
    - Sensitivities to Production Volumes
    - Material and Process Cost Drivers

Hybrid / PHEV Vehicles



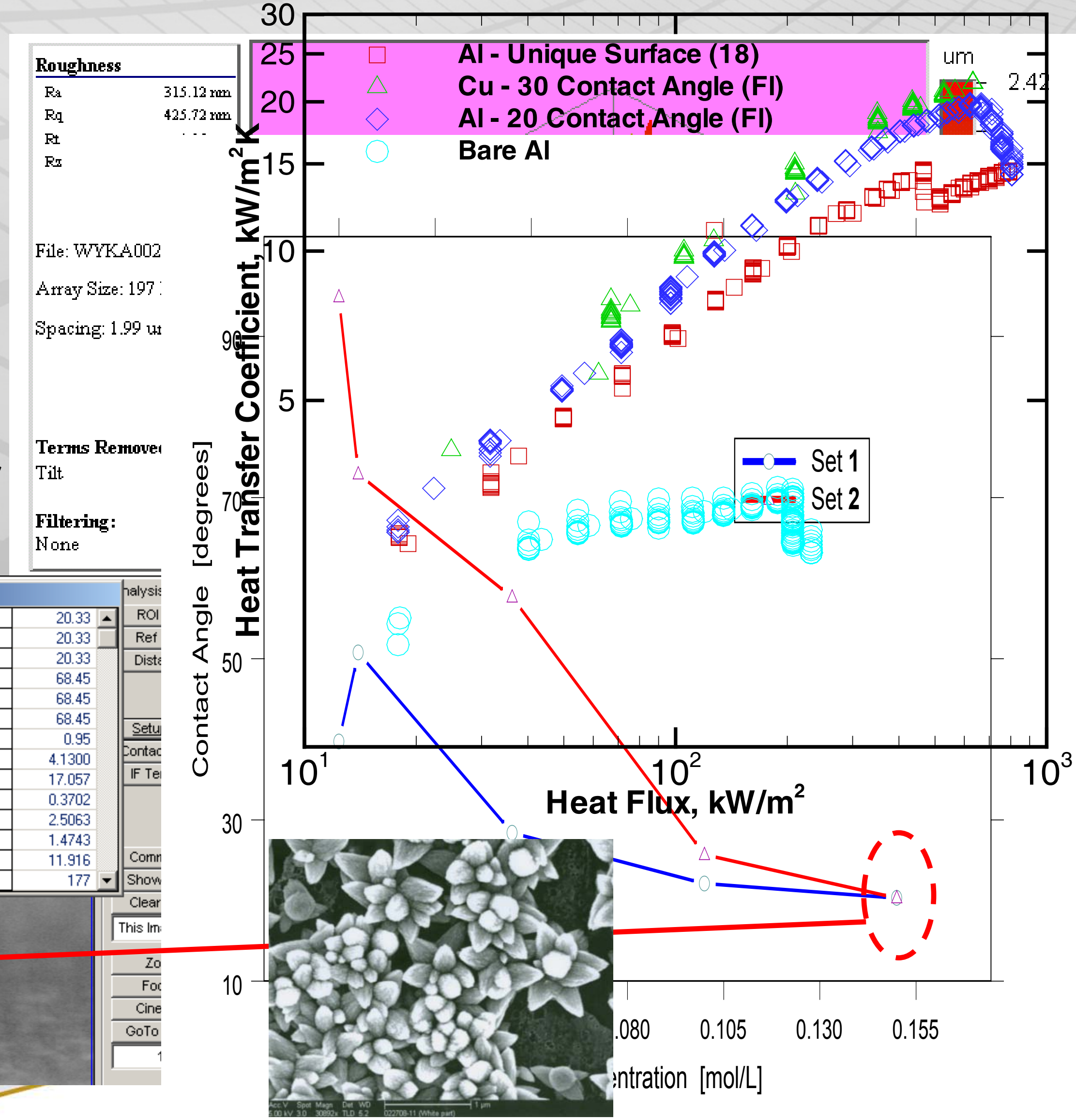
Nano-Scale Coatings

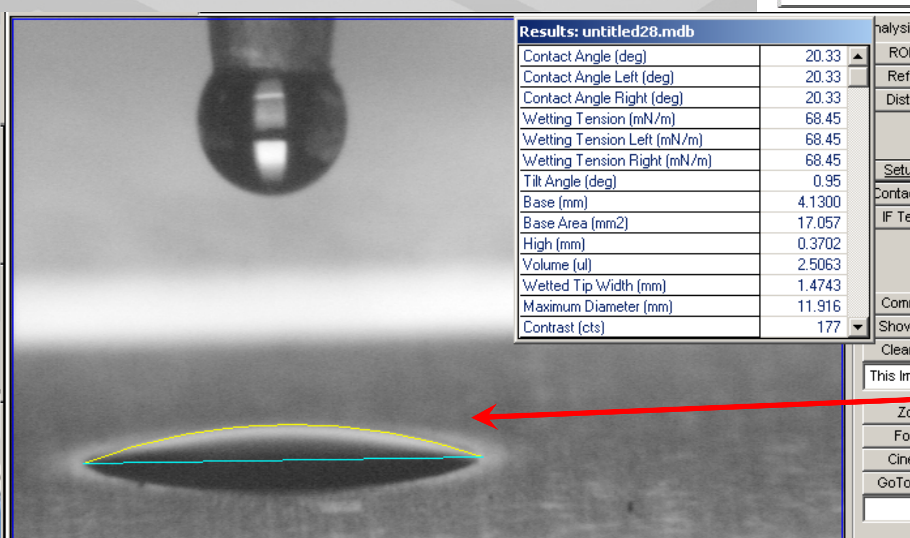


Cost Modeling Approach

PNNL Nano-Scale Coatings Impact Surface Hydrophobicity and Surface Boiling Heat Transfer

- ZnO on Al Substrate
- R_{ave} = 315 nm
- θ = 20.3°
- Can Make Super-Hydrophilic Surfaces θ= 0°
- Bare Aluminum Substrate θ=104°
- Huge Ramifications on Water Management / Transport





Results: untitled28.mdb

Contact Angle (deg)	20.33
Contact Angle Left (deg)	20.33
Contact Angle Right (deg)	20.33
Wetting Tension (mN/m)	68.45
Wetting Tension Left (mN/m)	68.45
Wetting Tension Right (mN/m)	68.45
Tilt Angle (deg)	0.95
Base (mm)	4.1300
Base Area (mm2)	17.057
High (mm)	0.3702
Volume (ul)	2.5063
Wetted Tip Width (mm)	1.4743
Maximum Diameter (mm)	11.916
Contrast (cts)	177

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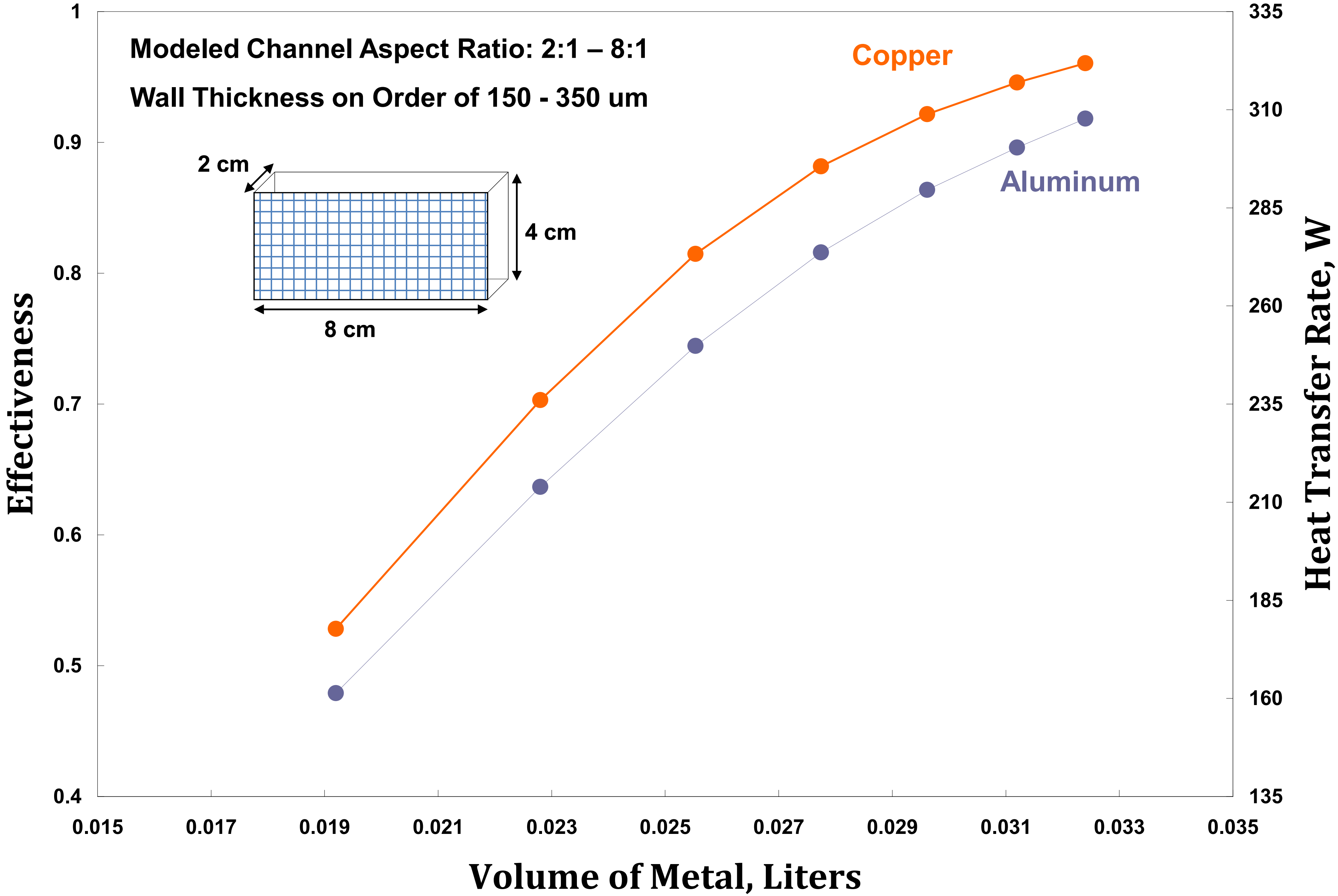
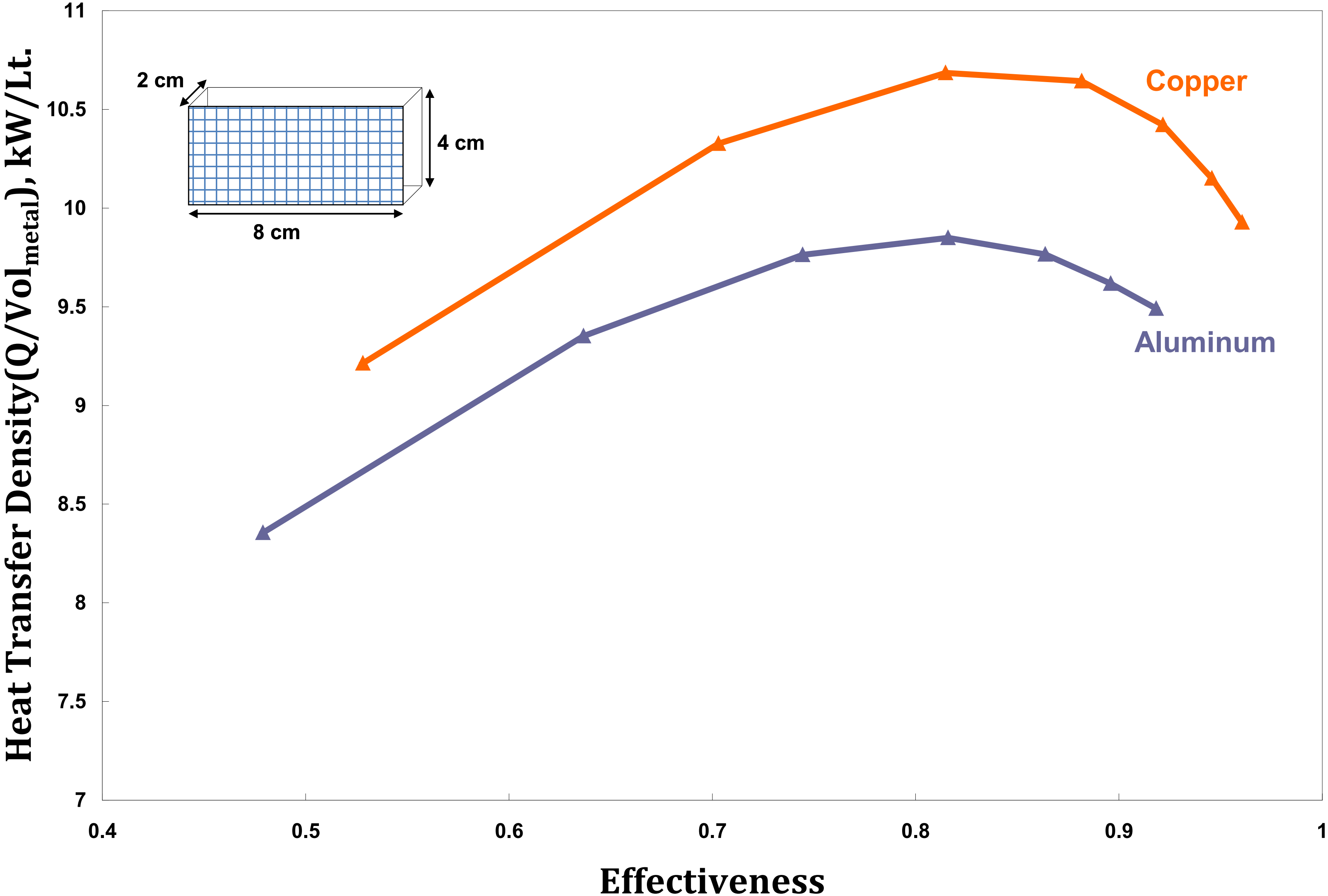
PNNL Developing High-Performance Microtechnology Heat Transfer Technologies

- TE Cooling / Heating
  - Automotive Distributed HVAC Systems
  - A Number of Microtechnology Designs Are Being Investigated
  - An Example of One Such Design Is Presented Here
- Heat Transfer vs. Pressure Drop Characteristics Quantified

Effect of Channel Aspect Ratio on Effectiveness



Effect of Channel Aspect Ratio on Flux Density



Process-Based Microtechnology Cost Modeling

- Microtechnology Manufacturing Cost is Key to Automotive Applications
- Process-Based Cost Modeling
  - Cost Sensitivities Identified
  - Low-Cost Manufacturing Avenues Being Developed
  - Sensitivities to Production Volumes
  - Material and Process Cost Drivers
- System Performance Modeling Integrated with Cost Modeling to Identify Low-Cost, Manufacturable Microtechnology Designs
- Cost Modeling Incorporates Critical Process & Cost Elements
- Prioritizes R&D Investment Plans & Enables Business Decisions
- Compared 3 Process Approaches for Microtechnology Heat Exchanger Design Discussed Above
  - Cost Modeling for High-Temperature Exhaust Recovery Applications
  - Cost Modeling for Low-Temperature Advanced Cooling Applications

Process Based Cost Modeling

Bottom-Up Approach to Estimating Cost of Goods Sold (COGS)
Based on Operation of Virtual Manufacturing Line – Breaks Down Cost by Unit Process

Model Inputs

Process Flow

Unit Process 1
Unit Process 2
Unit Process 3
Etc.

Cost Elements

Capital Equipment
Labor
Materials
Energy
Facilities
Maintenance

Process-Based Cost Model Algorithm

Not Included
Overhead & Profit
Insurance
Taxes
Inventory Management
Accounting
Marketing
Sales

Model Outputs

Cost of Goods Sold (COGS)

Fixed Costs
Capital Equipment
Maintenance
Facilities/Buildings

Variable Costs
Direct Labor
Direct Materials
Indirect Materials
Utilities

Process COGS vs. Volume and Pareto
Cost Sensitivity
ID Cost Drivers
Process to Process Comparisons
Define Fabrication Toolbox
Inform R&D Agenda

Start with Process Flow and Associated Equipment Set

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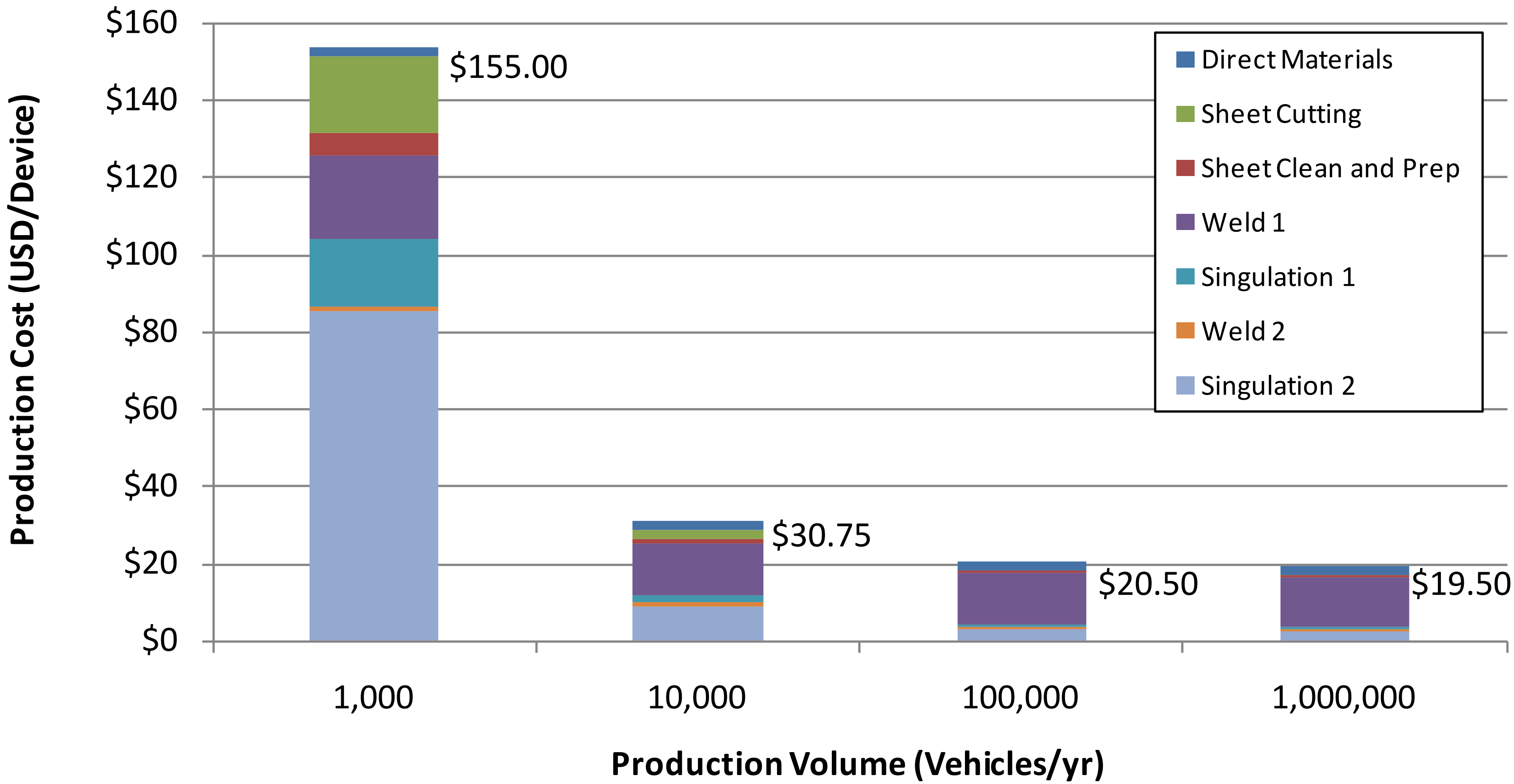
Integrated HTX COGS Estimation and Pareto : Process "A"

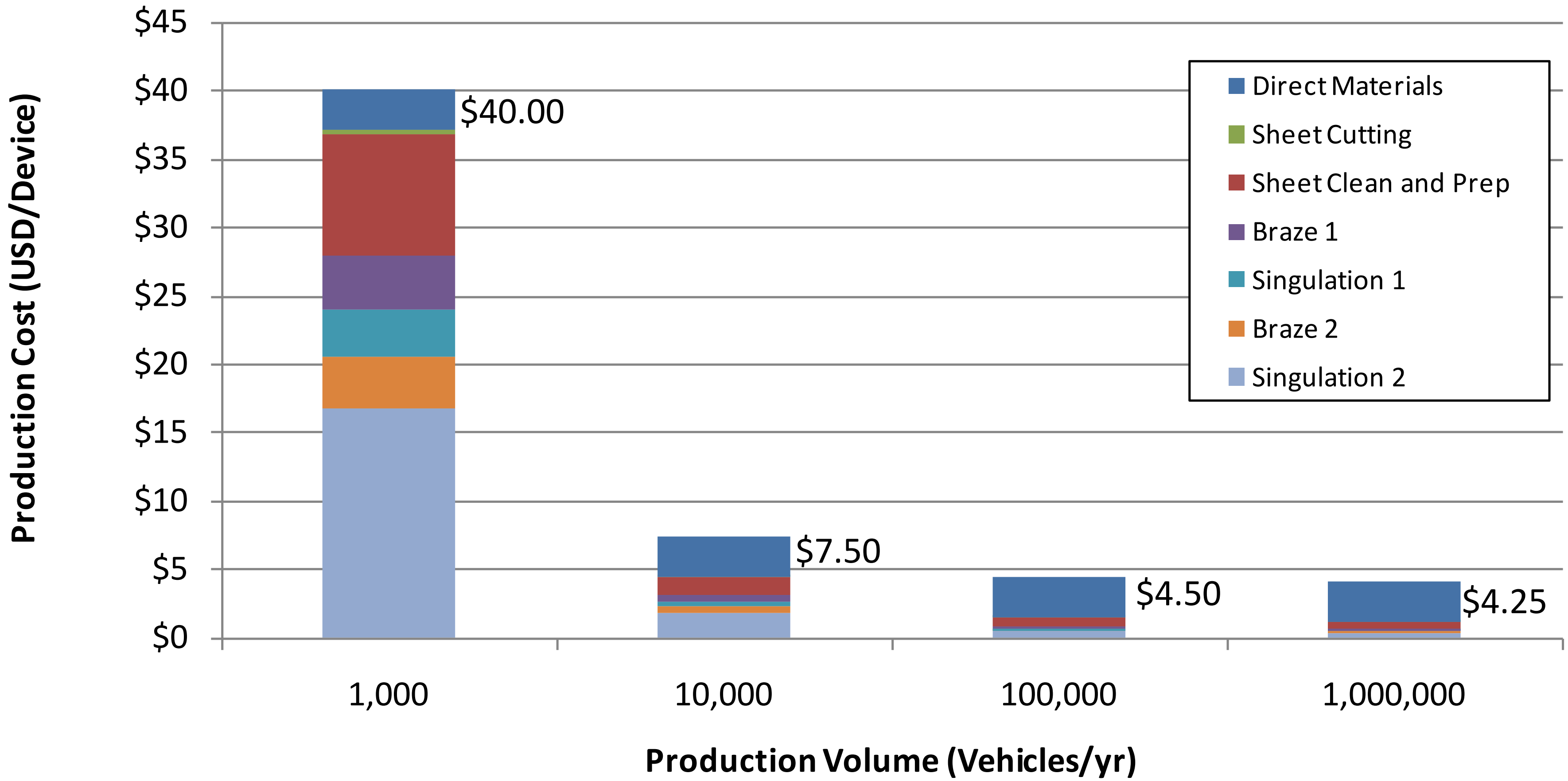
8 HTX per Vehicle / Aluminum HTX / 2 cm x 4 cm x 8 cm HTX Dimensions



Process Relies on Significant Laser Use → Not a Good Design + Process Match
Existing, Scalable Fabrication Processes and OTS Production Equipment

Integrated HTX COGS Estimation and Pareto : Process "B"

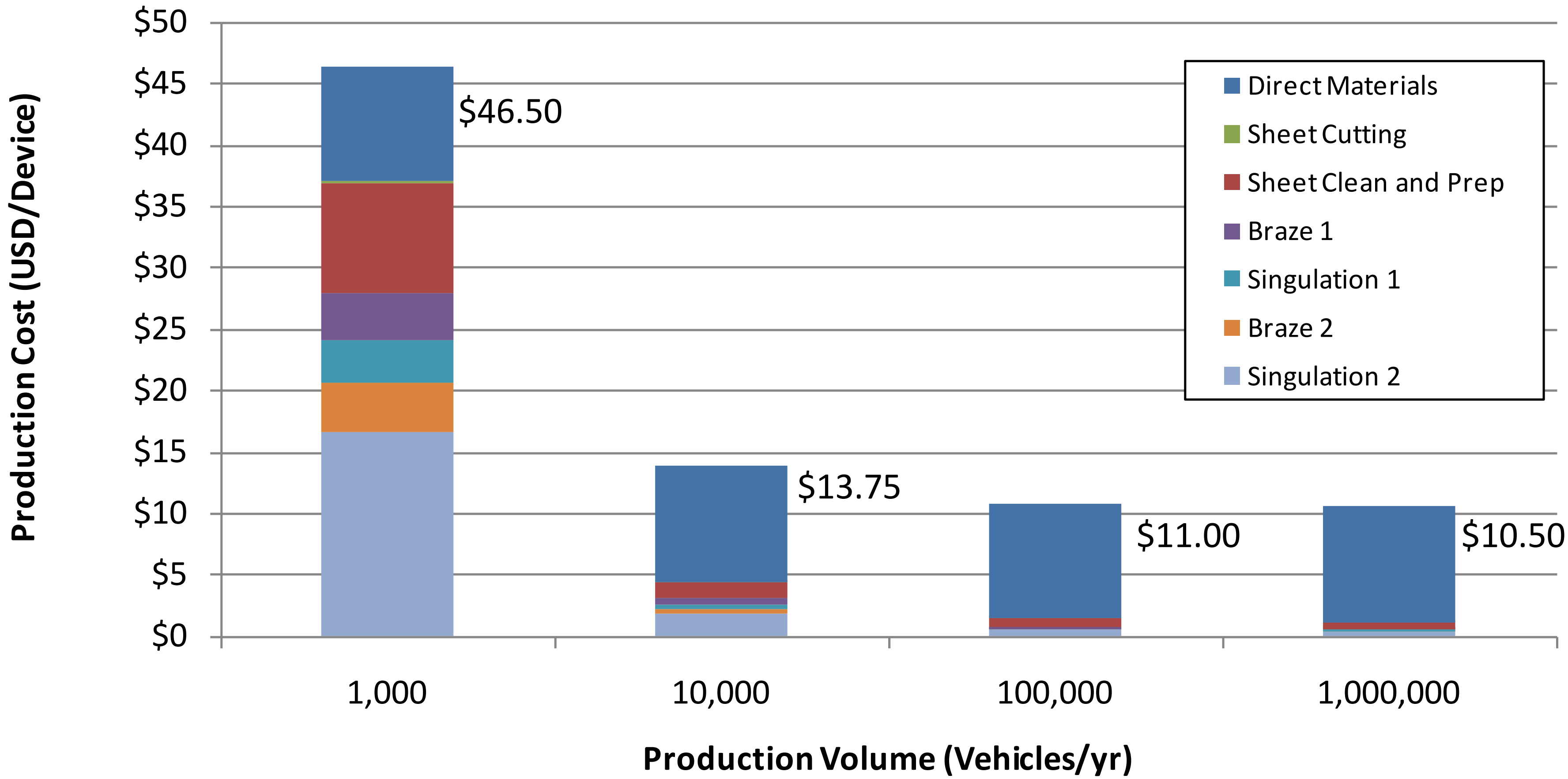
8 HTX per Vehicle / Aluminum HTX / 2 cm x 4 cm x 8 cm HTX Dimensions



Direct Materials Primary Cost Driver at Production Volumes
Existing, Scalable Fabrication Processes and OTS Production Equipment

Integrated HTX COGS Estimation and Pareto : Process "C"

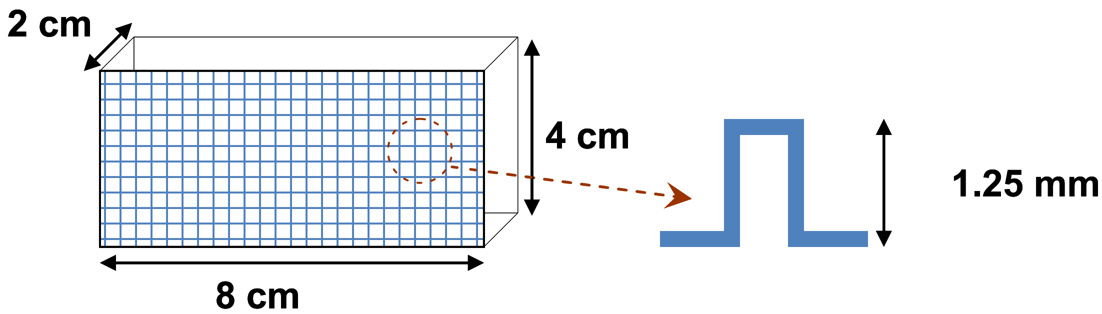
8 HTX per Vehicle / Copper HTX / 2 cm x 4 cm x 8 cm HTX Dimensions



Direct Materials Cost for Copper is 4x that for Aluminum → Drives Cost
Improved Yield and Cycle Times in Copper Braze vs. Aluminum Braze

Summary - Process Comparisons

Annual Volume		Aluminum				Copper	
		Process A		Process B		Process C	
Vehicles	HTX Units	$/Unit	Capital Equipment ($k)	$/Unit	Capital Equipment ($k)	$/Unit	Capital Equipment ($k)
1,000	8,000	$153.90	$1,705	$40.09	$1,400	$46.48	$1,400
10,000	80,000	$30.85	$5,455	$7.44	$1,400	$13.87	$1,400
100,000	800,000	$20.54	$43,830	$4.55	$2,550	$10.91	$2,050
1,000,000	8,000,000	$19.55	$459,300	$4.19	$17,750	$10.61	$14,750



Summary

- Microtechnology Thermal Systems Required to Enable Compact, Light weight TE Systems
  - TE Power Generation
  - TE Cooling / Heating
- Microtechnology Thermal Systems Successfully Integrating into TE Systems
- Process-Based Cost Modeling is Critical to Developing Low Cost Manufacturing Pathways, Processes, and Materials
  - Cost Modeling Incorporates Critical Process & Cost Elements
  - Cost Sensitivities Identified
  - Low-Cost Manufacturing Avenues Being Developed
  - Sensitivities to Production Volumes
  - Material and Process Cost Drivers Identified
- System Performance Modeling Integrated with Cost Modeling to Identify Low-Cost, Manufacturable Microtechnology Designs
- Prioritizes R&D Investment Plans & Enables Business Decisions

Thank you for your time and interest

We are What We Repeatedly do. Excellence, Then, is not an Act, But a Habit.

Aristotle

Questions & Discussion