Heat Exchanger Performance Impacts on Optimum Cost Conditions in Thermoelectric Energy Recovery Designs

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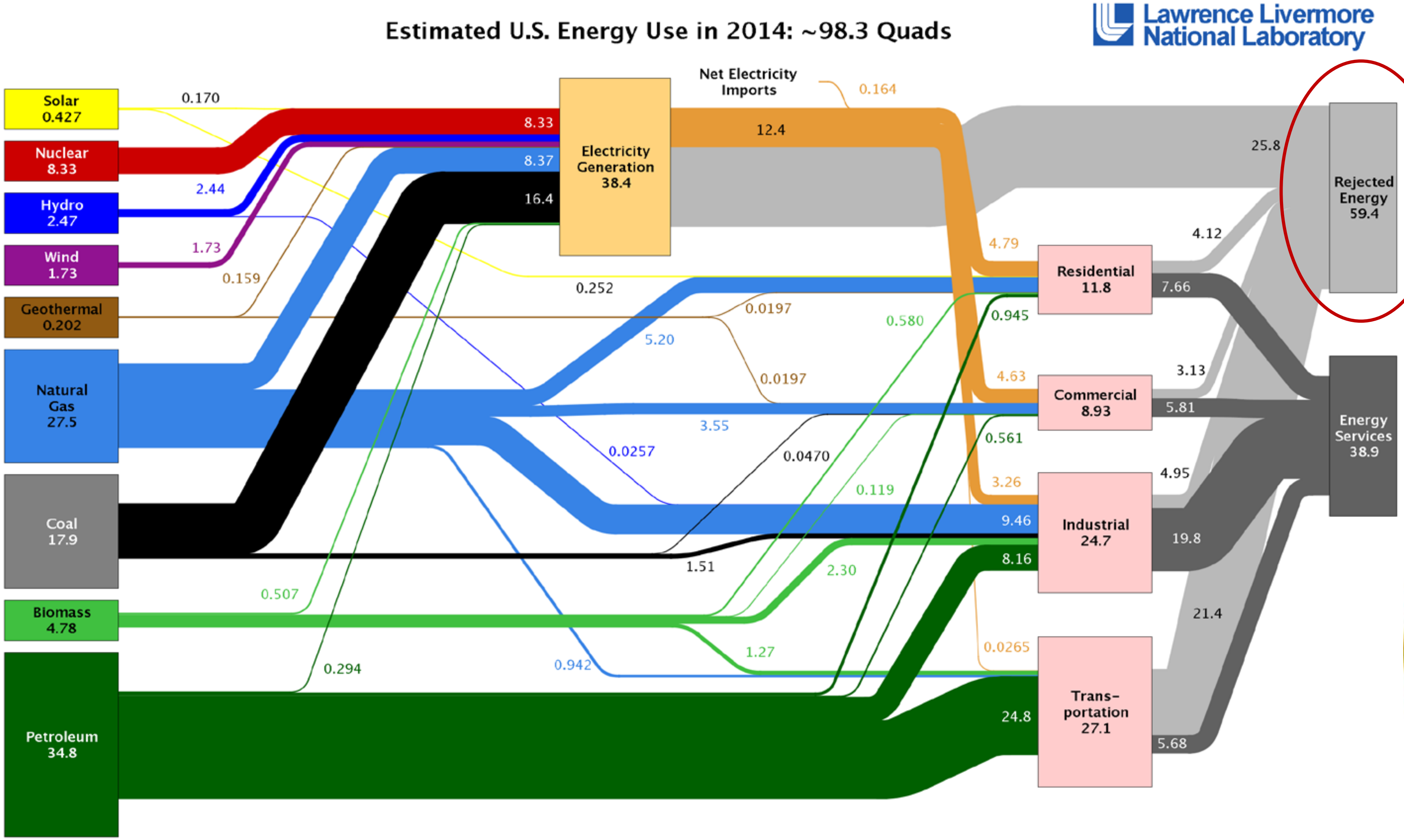
AGENDA

- Motivations
- System Cost Modeling & Integration with System-Level Analysis
- Characteristics of Maximizing Specific Power & Cost Minimization When HEX Rigorously Included
- Effects on Optimum Fill Factor
- Conclusions

United States Energy Flow



Source: LLNL 2015. Data is based on DOE/EIA-0035(2015-03), March, 2014. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential and commercial sectors 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

- Waste Heat To Be “Harvested”

59.4 Quads

- Up ~ 5Quads From 2009

U.S. National Waste Energy Recovery

- **Transportation Sector**
  - 12.5 Quads
  - Light-Duty Passenger Vehicles + Light-Duty Vans/Trucks (SUVs)[1]
  - Medium & Heavy-Duty Vehicles[1]

- **Industrial Process Sector is Another Opportunity**
  - 10 Quads of Waste Energy Flows in Industrial Processes
    - Aluminum, Glass
    - Paper
    - Petroleum
    - Chemical
  - 1.8 Quads Recoverable, Potentially 1.56 GW[2]
  - Wide Range of Temperatures & Heat Sources

- **Europe and Asia Have Similar Challenges**

Waste Energy All Around Us

[1] *Transportation Energy Data Book*, 2010, Edition 29, U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Vehicles Technology Program. ORNL-6985, Oak Ridge National Laboratory, Oak Ridge, Tennessee. http://cta.ornl.gov/data/index.shtml.

[2] U.S. Energy Information Agency, 2007 Annual Energy Outlook

Terrestrial Waste Energy Recovery

- Thermoelectric Systems Considered a Prime Energy Recovery Technology Candidate / Option in Many Terrestrial Applications
- Terrestrial Energy Recovery Goals are Often Tied to:
  - Energy Savings
  - Environmental Savings and Impacts
  - Maximizing Conversion Efficiency
  - Maximum Power Output
- However, JPL is Currently Working on System Designs Where the Critical Design Metric is Maximizing Specific Power (W/kg)
  - Knowing Its Relationship to Maximum Power or Efficiency Points is Key
  - T_{exh} = 823 K; T_{amb} = 273 K
- In Additional, Key Barriers Are is Not So Much Performance Anymore as It is System-Level Cost (As Discussed in 2015 ICT, Dresden, Germany)

Cost Modeling and Integrating Cost Modeling With System-Level Performance Modeling is Critical

Must Develop Technologies / Methods to Recover Energy Economically

- Leverage Cost Modeling Work of LeBlanc et al. [1] and Yee et al. [2]
- Combine with System-Level Analysis Work of Hendricks et al. [3]
- Include the Effects of Real-World Heat Exchangers in More Rigorous Methodology
  - Cost & Performance (Heat Exchanger UA_h)
  - Heat Exchanger Interfacial Heat Flux
  - Rigorously Account for Different Operational Areas
- Hendricks et al. [3] Analysis Modified to Add in Fill Factor, F, and Heat Exchanger Area, A_{HEX}, into System Analysis Techniques
- Fill Factor and Heat Exchanger Area Are No Long "Arbitrarily Selected" Design Parameters – Part of Design Optimization Process

$$F = \frac{A_{TE}}{A_{HEX}}$$

$$\left(\frac{V}{N}\right)^{*} = f_v(T_h, T_c)$$

$$\left(I \cdot \frac{L}{F \cdot A_{HEX}}\right)^{*} = f_I(T_h, T_c)$$

$$\eta_{TE}^{*} = \frac{P}{Q_{h,TE}} = f_{eff}(T_h, T_c)$$

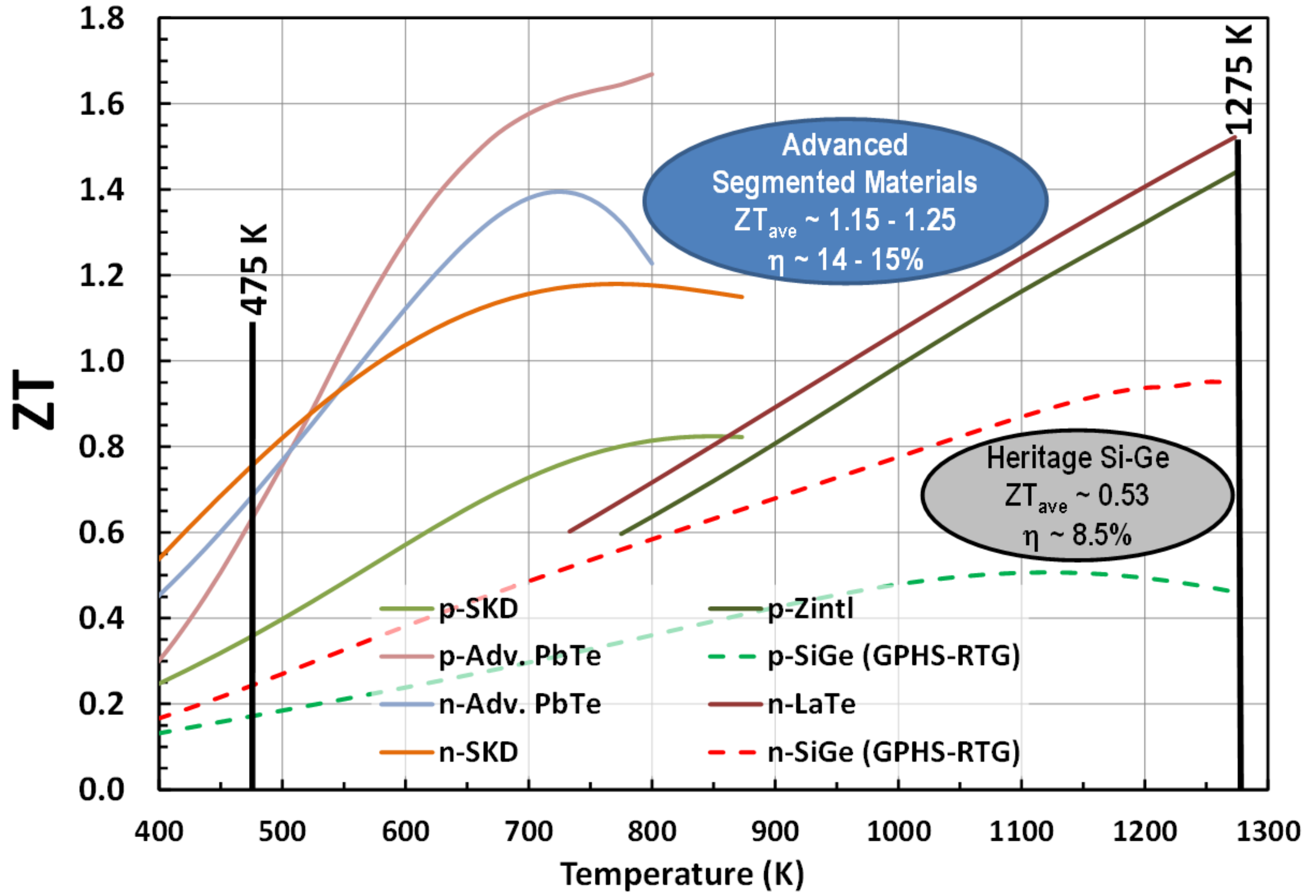
$$\left(\frac{Q_{h,TE} \cdot L}{N \cdot F \cdot A_{HEX}}\right)^{*} = f_{qh}(T_h, T_c)$$

$$\dot{q}''_{h,HEX} = F \cdot \dot{q}''_{h,TE} = \frac{Q_{h,TE} + Q_{loss}}{A_{HEX}} = f_Q(T_{exh}, T_h, T_c)$$

1. S. LeBlanc, S. K. Yee, M. L. Scullin, C. Dames and K. E. Goodson, *Renewable and Sustainable Energy Reviews*, **32**, 313-327, 2014.
2. S. K. Yee, S. LeBlanc, K. E. Goodson and C. Dames, *Energy & Environmental Science*, **6**, 2561-2571, 2013.
3. Hendricks, T.J. and Crane, D. "Thermoelectric Energy Recovery Systems: Thermal, Thermoelectric and Structural Considerations", **CRC Press Handbook of Thermoelectrics & Its Energy Harvesting: Modules, Systems, and Applications in Energy Harvesting**, Book 2, Section 3, Chapter 22, Taylor and Francis Group, Boca Raton, FL, 2012.

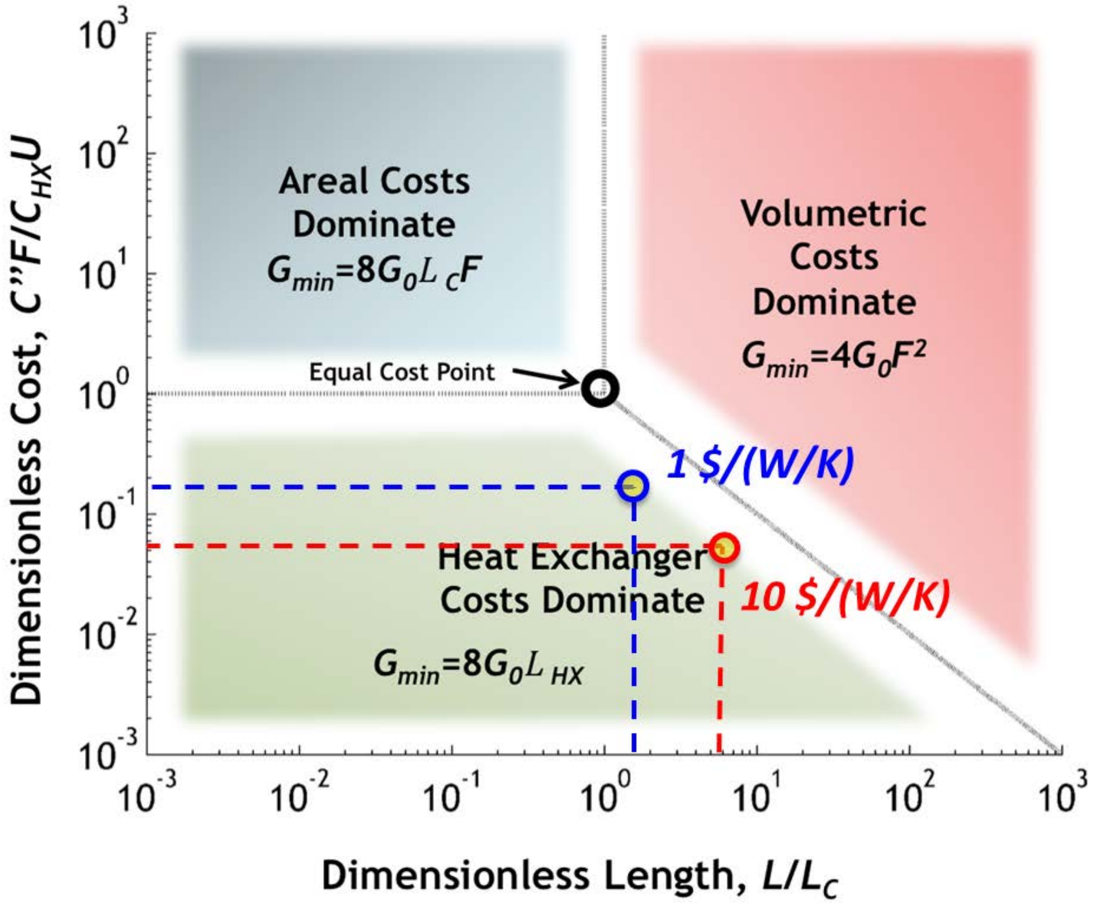
TE Materials Investigated

- Focused on JPL Skutterudites Shown Here In This Initial Work
- Currently Developing and Commercializing These Materials
- We Used JPL Raw Cost Data in This Work



Heat Exchanger Cost

- Considered One Heat Exchanger Cost Conditions In the Cost Domain Map Identified by Yee et al.
  - $1/(W/K) - Aggressive, Highly Challenging Condition That Will Require R&D Investment
- The $1/(W/K) Condition Still Does Not Escape the Heat Exchanger Cost-Dominated Regime

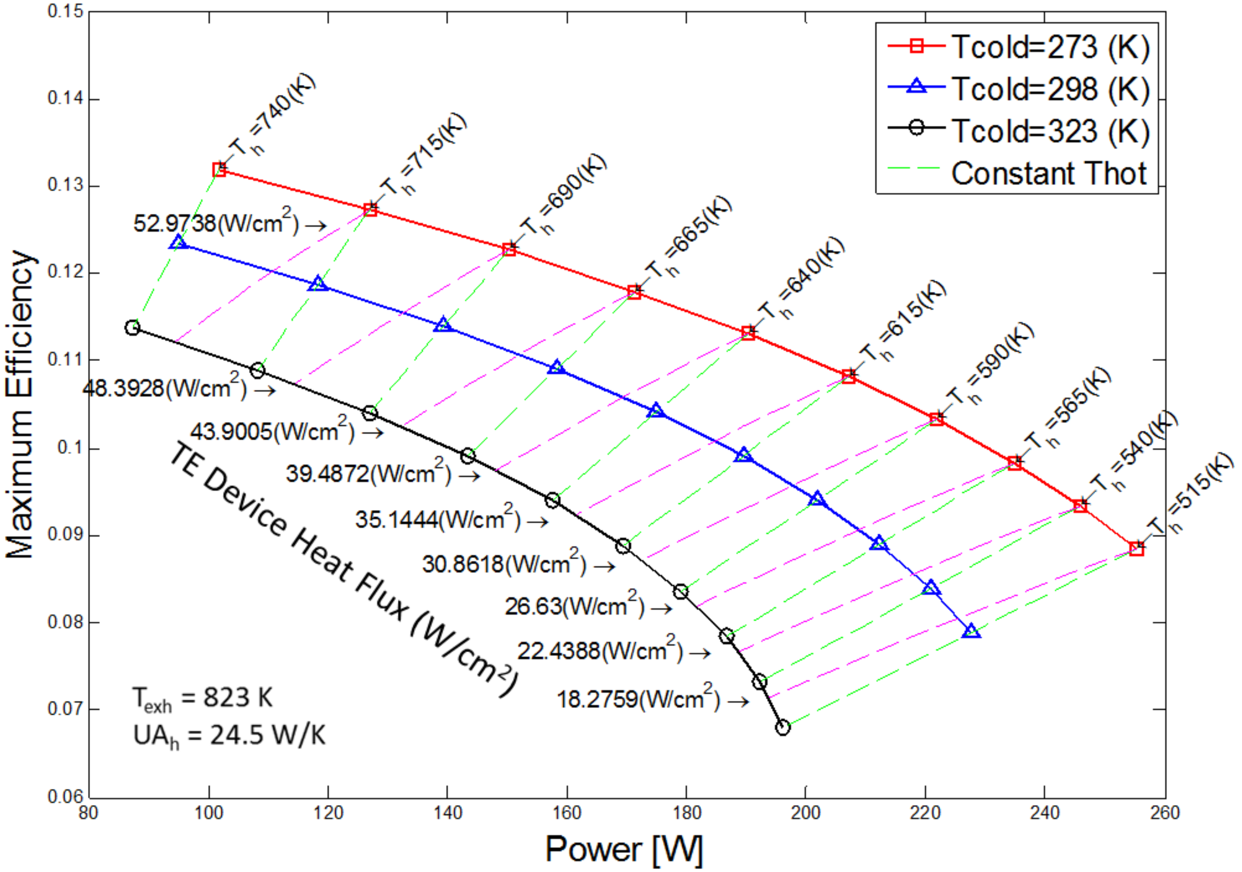


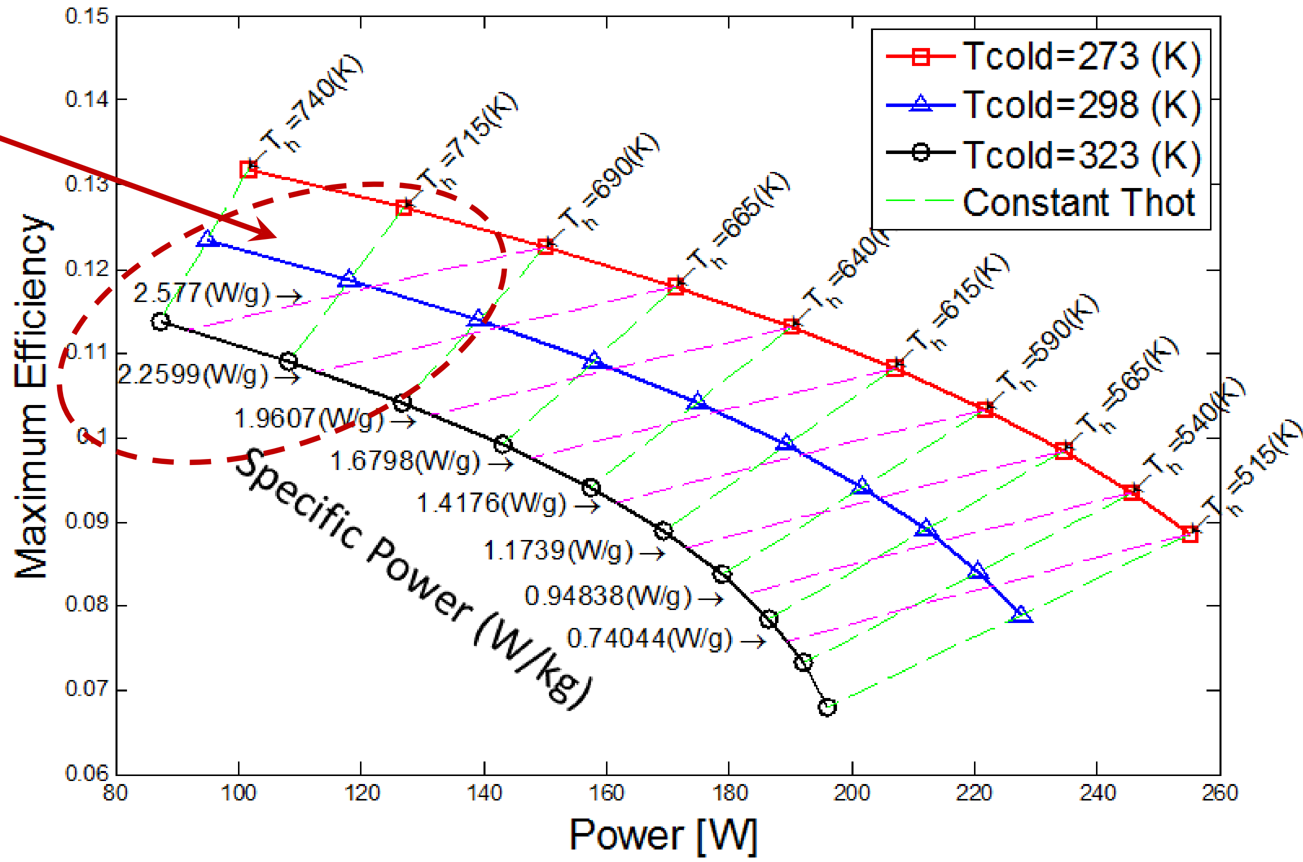
Heat Exchangers Dominate The Costs, Even at Low Cost Levels and It is Extremely Difficult to Escape this Regime

Hendricks, T.J., Yee, S., LeBlanc, S., “Cost Scaling of a Real-World Exhaust Waste Heat Recovery Thermoelectric Generator: A Deeper Dive,” *Journal of Electronic Materials*, **45**, Issue 3, 1751-1761, DOI 10.1007/s11664-015-4201-y, Springer, New York, 2015.

TE System Design Regime Results
T_{exh} = 823 K, Heat Exchanger Costs \$1/(W/K)

- High TE Device Specific Power Regime Identified
  - Coincides with High Efficiency Regimes
  - But Coincides With Low Power Regions

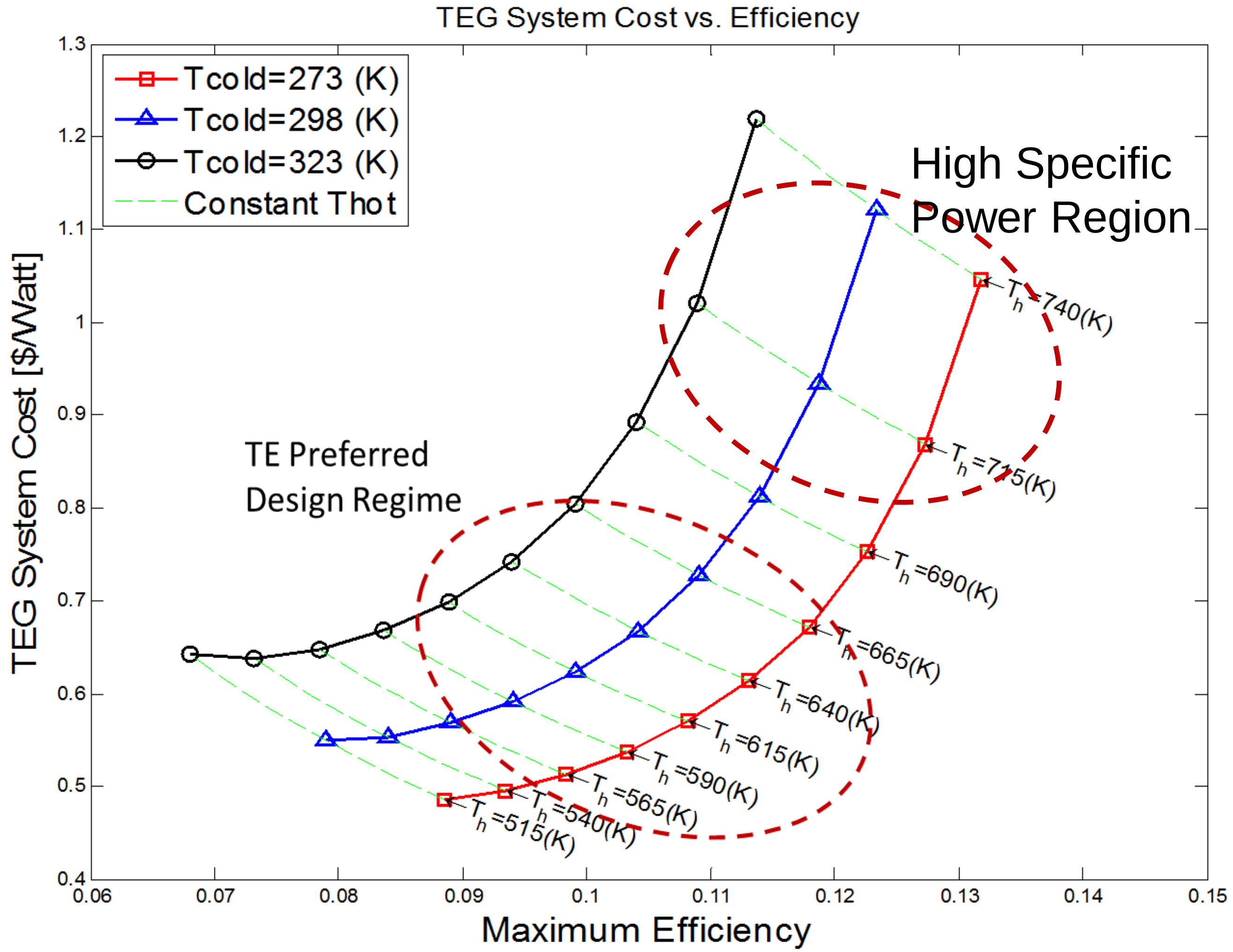




- Also Critical to Identify and Map the Constant TE Device Heat Flux Lines (Regions)
- High TE Device Regions Correspond with High Specific Power Regions
- Design Challenge Associated with High S.P.

Results – T_{exh} = 823 K, Heat Exchanger Costs $1/(W/K)

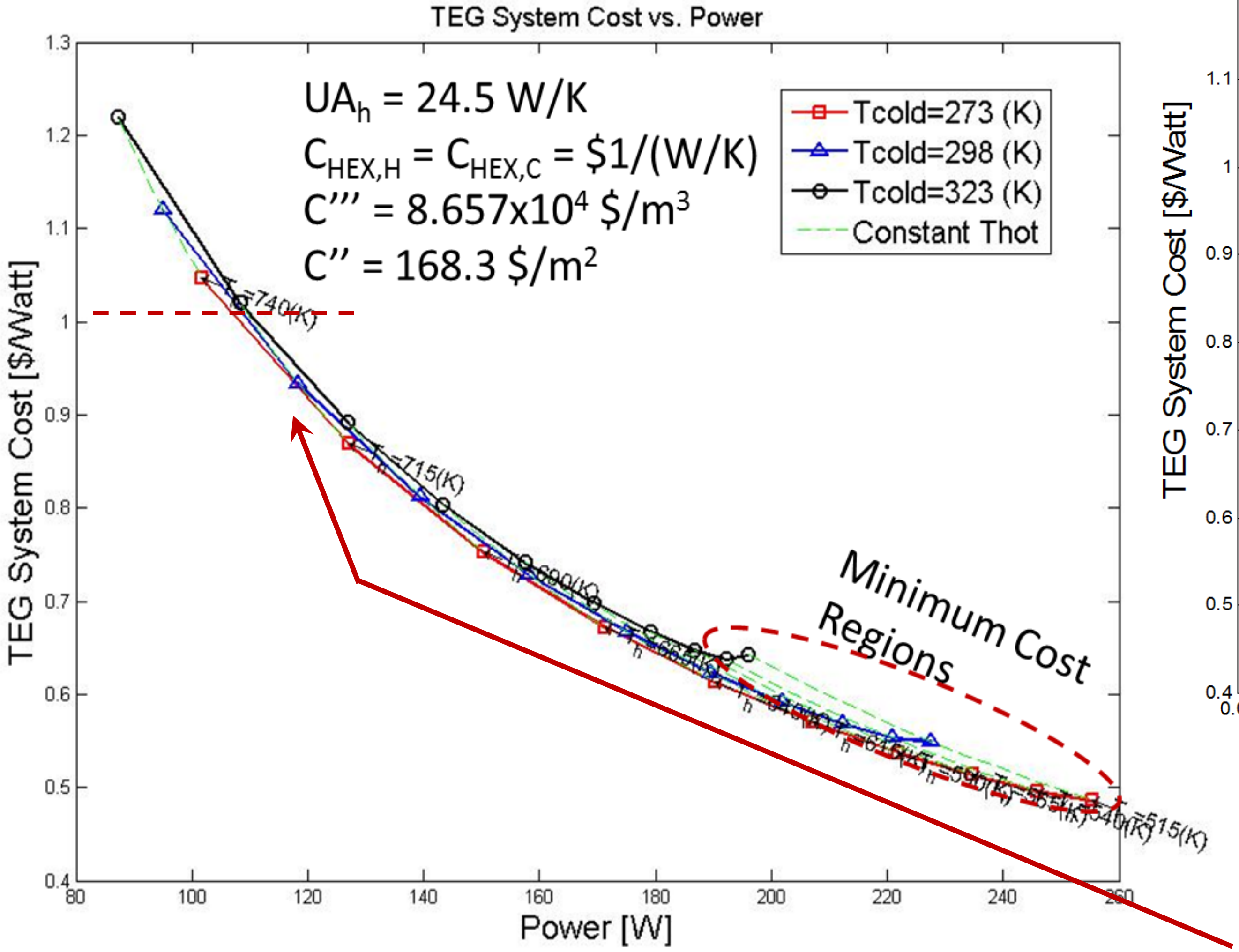
- Preferred TE Design Regimes Allow us to Move into Higher Efficiency, Higher Power Densities and Fluxes With Very Little Cost and Power Penalties – "PRETE (Pretty)" Design Regime
- High Specific Power Regions Even Higher in Efficiency Than PRETE Design Regime

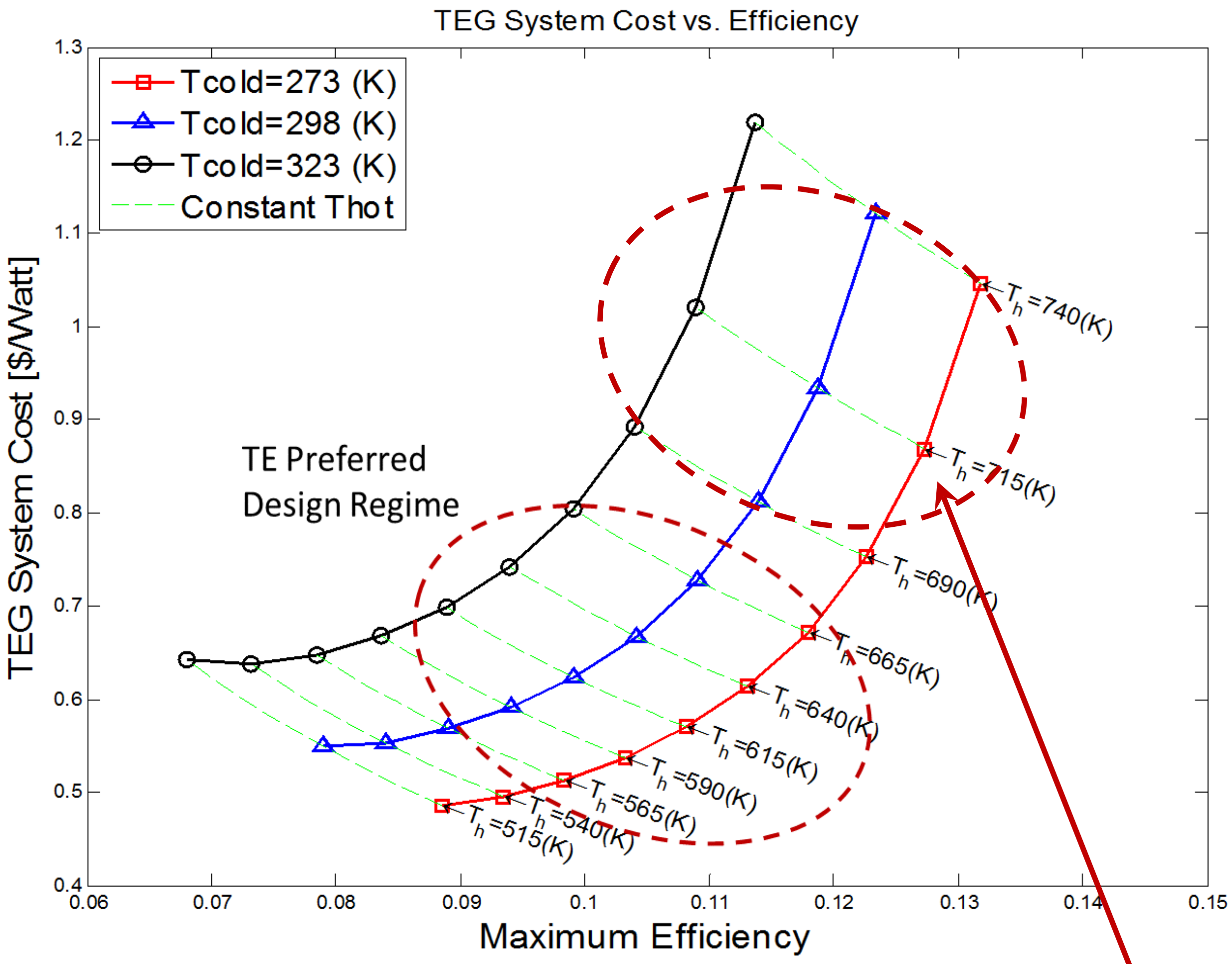


TE System Design Results

T_{exh} = 823 K, Heat Exchanger Costs ~$1/(W/K)

- System Cost is Our Dilemma at the Moment
- But We Now Have the Tools to Work Out of This





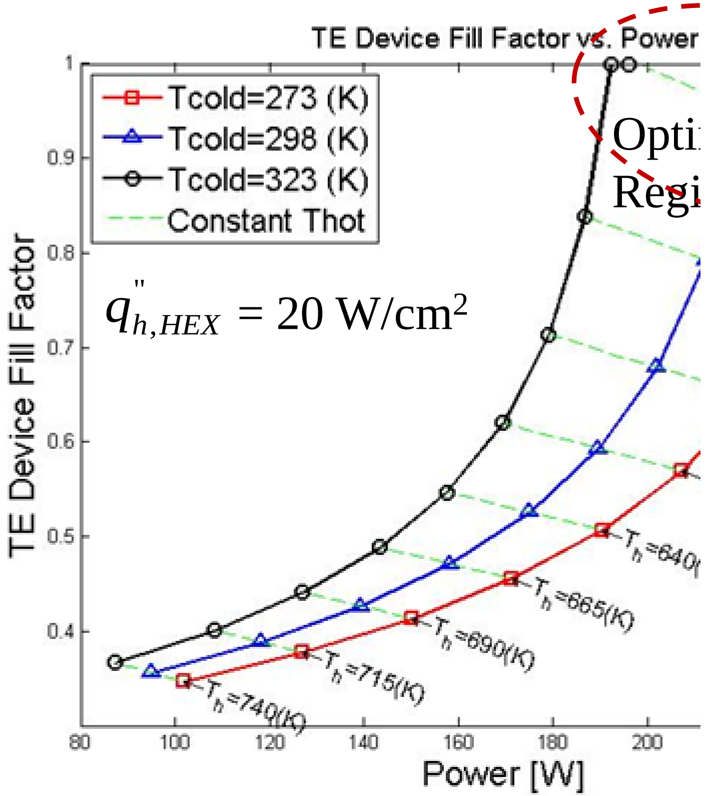
- Cost per Watt is ~1/P – Indicative of System Costs Being Dominated by Heat Exchanger Costs
- Higher Cost per Watt Regions Associated with High S.P. Regimes – Penalty Appears Small

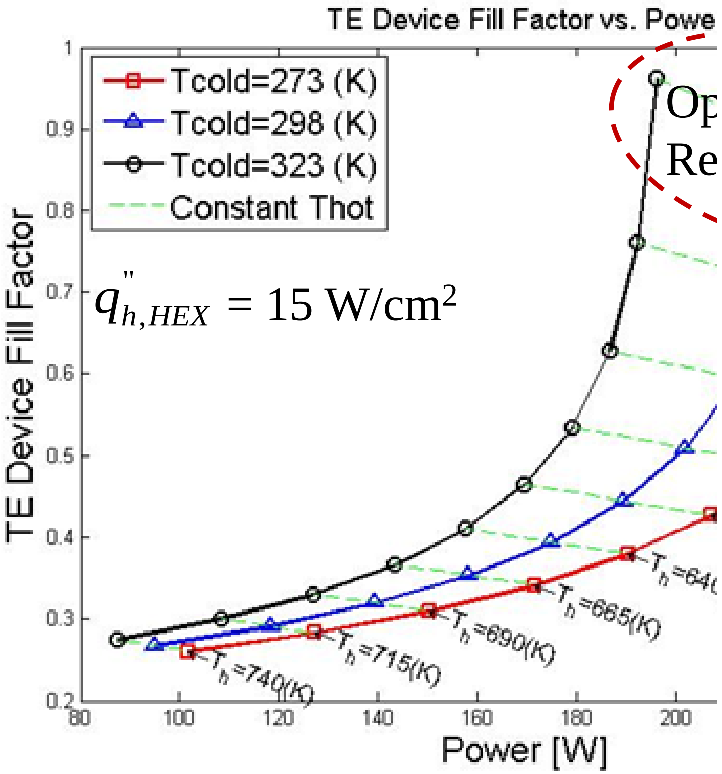
Fill Factor In Various Design Regions

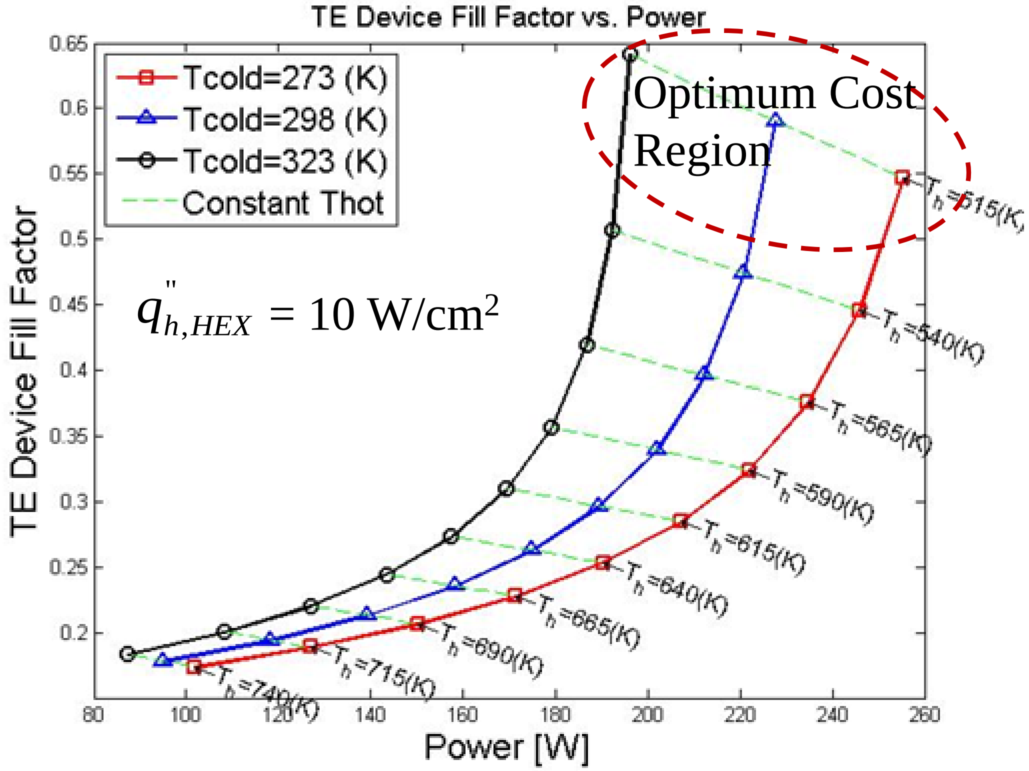
- Required Fill Factor Dependent on TE Device Heat Flux AND Heat Exchanger Heat Flux

$$F = \frac{A_{TE}}{A_{HEX}} \qquad q''_{h,HEX} = F \cdot q''_{h,TE} = \frac{Q_{h,TE} + Q_{loss}}{A_{HEX}} = f_Q(T_{exh}, T_h, T_c)$$

- High Required Heat Exchanger Heat Fluxes Can “Saturate” the Available Heat Exchanger Area (F=1)
- For Constant UA_h = 24.5 W/K Characteristic F-Behavior Shown Below - F = f ($q''_{h,HEX}$ &)







Optimum Cost Fill Factor Analysis

- Yee et al.* Originally Looked at this in 2013
- Optimum Cost Fill Factor of Yee et al.* Is Different Type of Analysis
  - Did Not Account for Heat Exchanger Heat Flux Conditions
  - Thermal Matching of the Hot-Side and Cold-Side Heat Exchangers (Very Bad Assumption)
  - $A_u = A_{HEX}$ (Very Bad Assumption)
  - $K_H = UA_{HEX}$ (Very Bad Assumption)
- TE Module Optimum Fill Factor, F_{opt} , Impacted by:
  - Heat Exchanger Interfacial Heat Flux, $q''_{h,HEX}$
  - Heat Exchanger Effectiveness, UA_h
  - Parasitic Thermal Losses, σ
- Latest Results Indicate This Relation* is Not Really Accurate and Was Only Intended to Identify Key Dependences

$$F_{opt} \approx \frac{1}{2} \cdot \sqrt{\frac{C_{HEX,H} + C_{HEX,C}}{C''' \cdot \kappa}} \cdot \left(\frac{U}{} \right)$$

*Yee, S. K., LeBlanc, S., Goodson, K. E., and Dames, C. *Energy & Environmental Science*, 2013, **6**, 2561-2571.

Cost Modeling Approach

- Costs-per-Watt Relationships Become More Complex When Heat Exchanger Performance, UA_h, Heat Exchanger Heat Flux, $q''_{h,HEX}$, and Different System Areas Accounted For
  - A_{TE}, A_{HEX} , and A_u Are Considered in Rigorous Detail; A_{HEX} and A_u Can Be Very Different in Magnitude
- Yee et al. and LeBlanc et al. Have Shown that Heat Exchanger Costs Can Be Characterized by $C_{HEX,H}$ & $C_{HEX,C}$
  - \$/(W/K) – Basically Cost per UA of the Heat Exchangers
  - Here We Include the Hot-Side and Cold-Side Heat Exchangers Individually
- Started Over With Fundamental Cost and G Relationships of Yee et al.
  - Did NOT Invoke Simplifying Assumptions of Yee et al.

$$C_{TEG}[\$] = \left(C''' \cdot L + C''\right) \cdot F \cdot A_{HEX} + \left(C_{HEX,h} \cdot K_H + C_{HEX,c} \cdot K_C\right)$$

$$G\,[\$/W] = \frac{\text{Total TEG Costs}}{P} = \frac{\text{Total TEG Cost}}{\eta_{TE} \cdot Q_H} = \frac{\text{Total TEG Cost}}{\eta_{TE} \cdot (1-\sigma)Q}$$

$$G = \frac{4}{S_{pn}^{\ 2}\sigma(T_1 - T_2)^2}\left(\frac{(m+1)^2}{m}\right)\left(C'''L^2 + C''L + \frac{C_{HX}UL}{F}\right)$$

$K_C / K_H > 10$ to 20 Incorporated this Added Relationship for Maximum Power**

T. J. Hendricks, “Integrated Thermoelectric–Thermal System Resistance Optimization to Maximize Power Output in Thermoelectric Energy Recovery Systems, Mater. Res. Soc. Symp. Proceedings, **1642, Materials Research Society, mrsf13-1642-bb02-04 doi:10.1557/opl.2014.443, 2014.

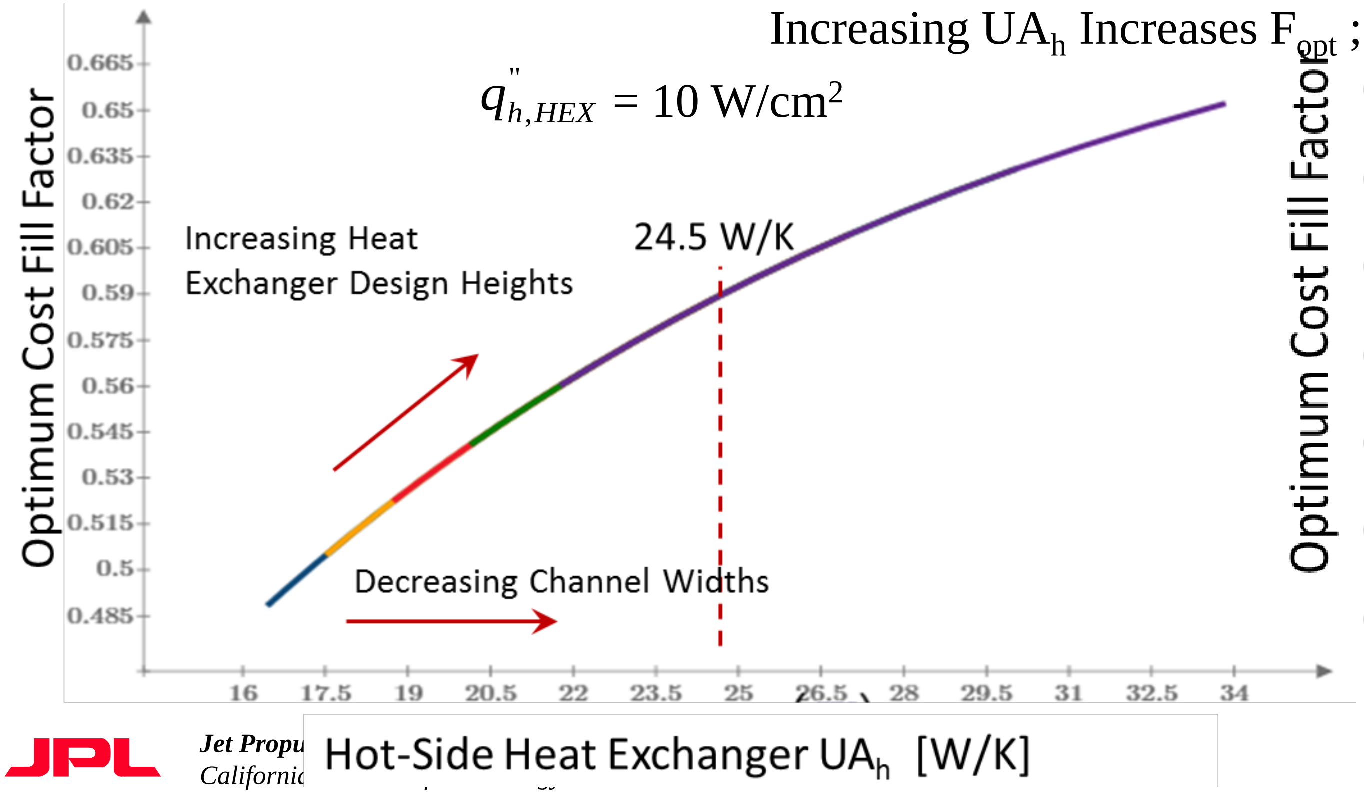
Critical F_{opt} Sensitivities

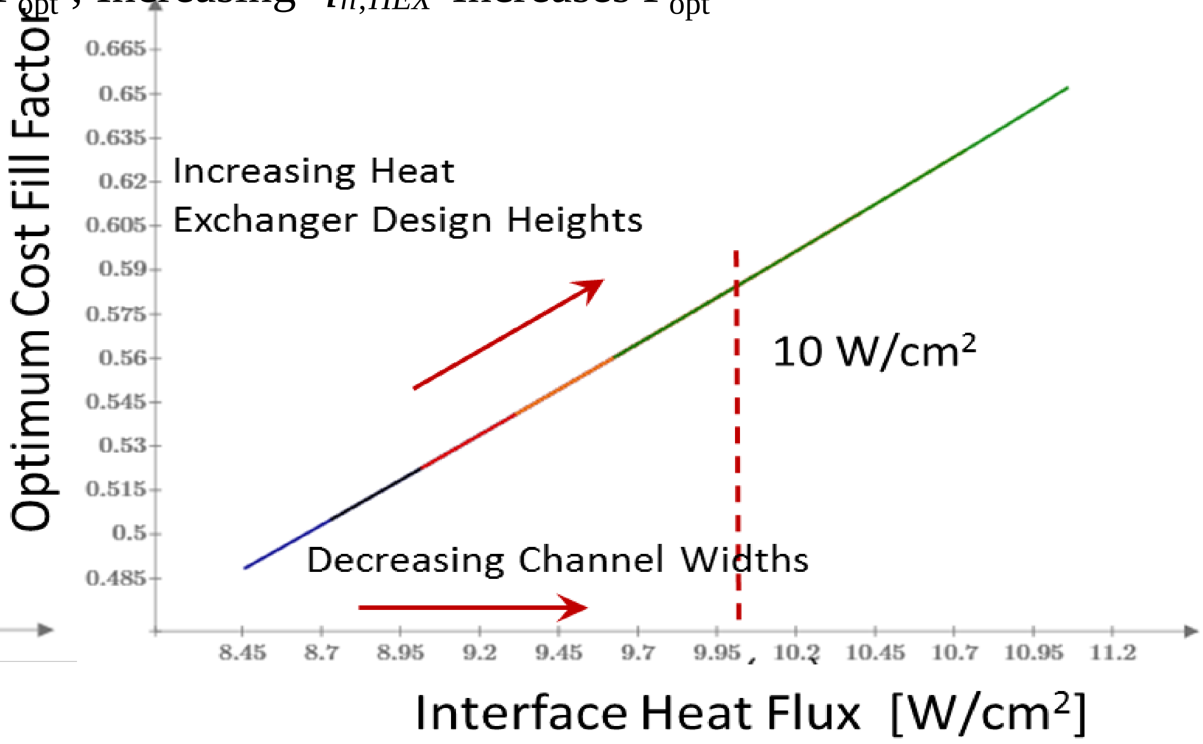
- $\partial G/\partial F=0$ Condition Creates a New, More Accurate, but More Complicated Relationship

$$F_{opt}=\frac{-\left(\frac{\left(C_{HEX,H}+C_{HEX,C}\right)\cdot UA_h}{L_{TE}}\right)\cdot\left(\frac{1.1\cdot\kappa_{TE}}{K_H}\right)+\sqrt{\left(\frac{\left(C_{HEX,H}+C_{HEX,C}\right)\cdot UA_h}{L_{TE}}\right)^2\cdot\left(\frac{1.1\cdot\kappa_{TE}}{K_H}\right)^2+8.8\cdot\left(C''+C'/L_{TE}\right)\cdot\left(\frac{\kappa_{TE}}{K_H}\right)\left(C_{HEX,H}+C_{HEX,C}\right)\cdot UA_h}}{4.4\cdot\left(C''+C'/L_{TE}\right)\cdot\left(\frac{\kappa_{TE}\cdot A_{HEX}}{K_H}\right)}$$

- More Accurately Predicts the Optimum Cost Fill Factors Seen Above and Heat Flux Dependency
- Demonstrates Dependencies on Heat Exchanger Design and Heat Exchanger Heat Flux

Increasing UA_h Increases F_{opt} ; Increasing $q''_{h,HEX}$ Increases F_{opt}





Final Thoughts & Conclusions

- Investigated and Characterized Maximum Specific Power Regimes and Relationships with Maximum Efficiency, Maximum Power, and Low Cost per Watt Regions - Highly Relevant Terrestrial Power System Application
- Leveraged Cost Modeling Methodology of Yee and LeBlanc Combined with TE System-Level Analyses of Hendricks to Develop More Comprehensive Optimum Cost Fill Factor Analysis
- Hot-Side and Cold-Side Heat Exchanger Performance and Costs More Rigorously & Directly Included
  - Heat Exchanger UA
  - Heat Exchanger Heat Flux, $q''_{h,HEX}$
  - All Relevant Areas (A_{TE}, A_{HEX}, and A_u) Accounted For Separately

Expanding Our Energy Toolbox

- New F_{opt} Relationship Developed – More Comprehensive Relationship that More Accurately Accounts for UA and $q''_{h,HEX}$ Effects
- Optimum TE Module Fill Factor, F_{opt}, Inextricably Governed by Heat Exchanger Design Parameters and Heat Flux
  - Increasing Heat Exchanger UA → Increases F_{opt}
  - Increasing Heat Exchanger Heat Flux → Increases F_{opt}
  - Characterized Detailed Heat Exchanger Design Parameter Effects (i.e., Channel Widths and Design Heights)
- Goal is to Transition Terrestrial Power Advances Back into NASA Missions & Systems

Terrestrial Power Advances ↔ NASA Mission Requirements

ACKNOWLEDGMENTS

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Cost Disclaimer:

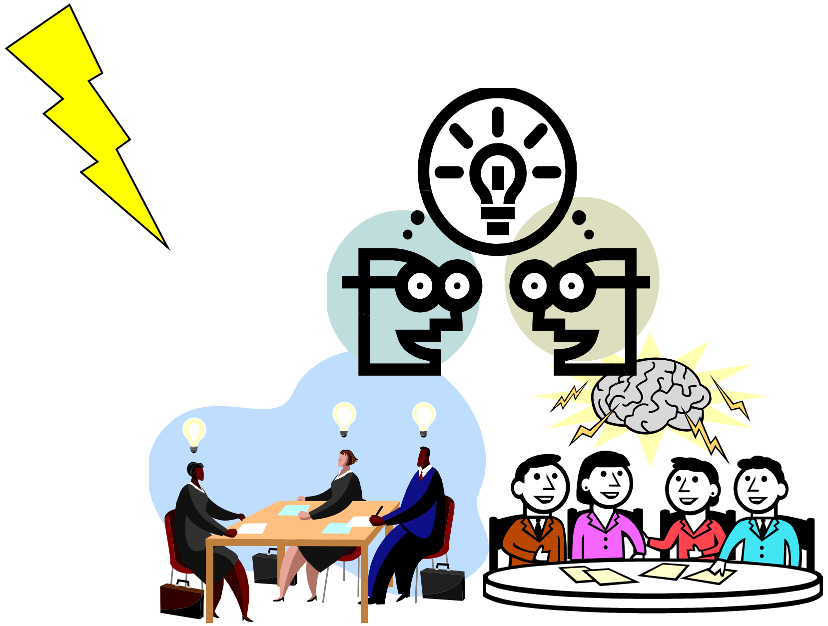
The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

Thank you for your interest and attention

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

Aristotle

Questions & Discussion



Heat Exchanger Cost Characterization

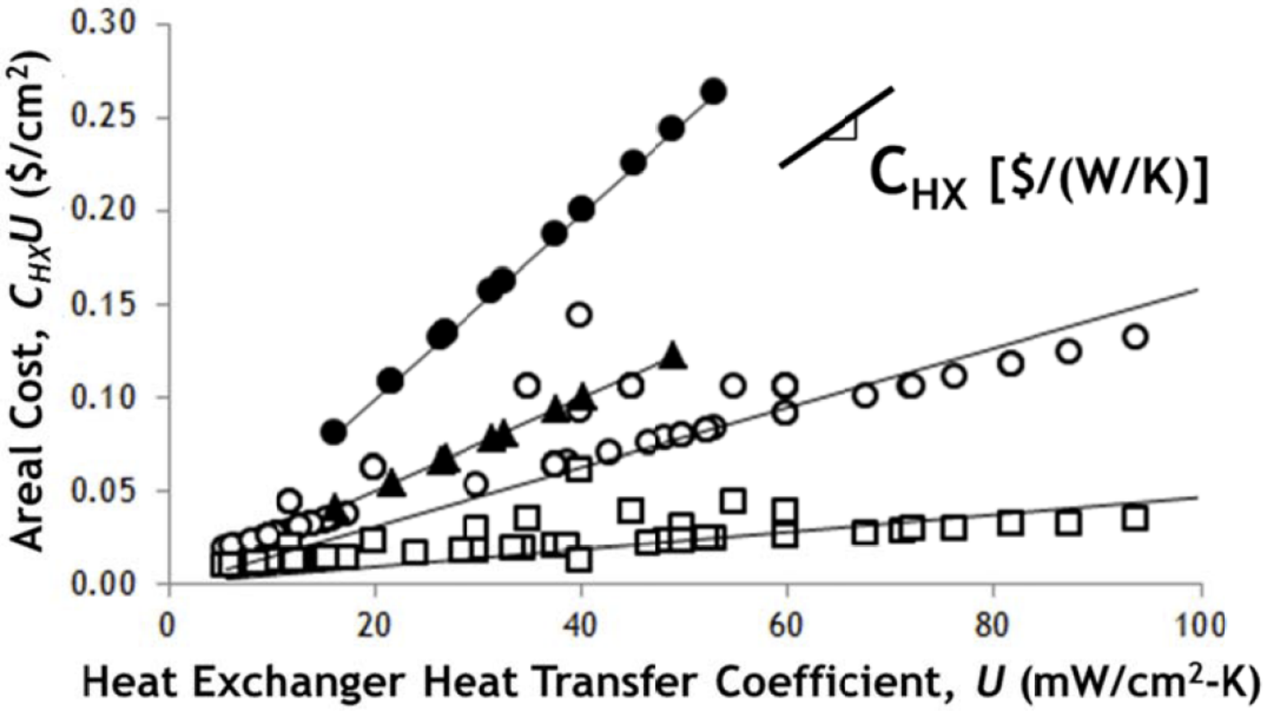
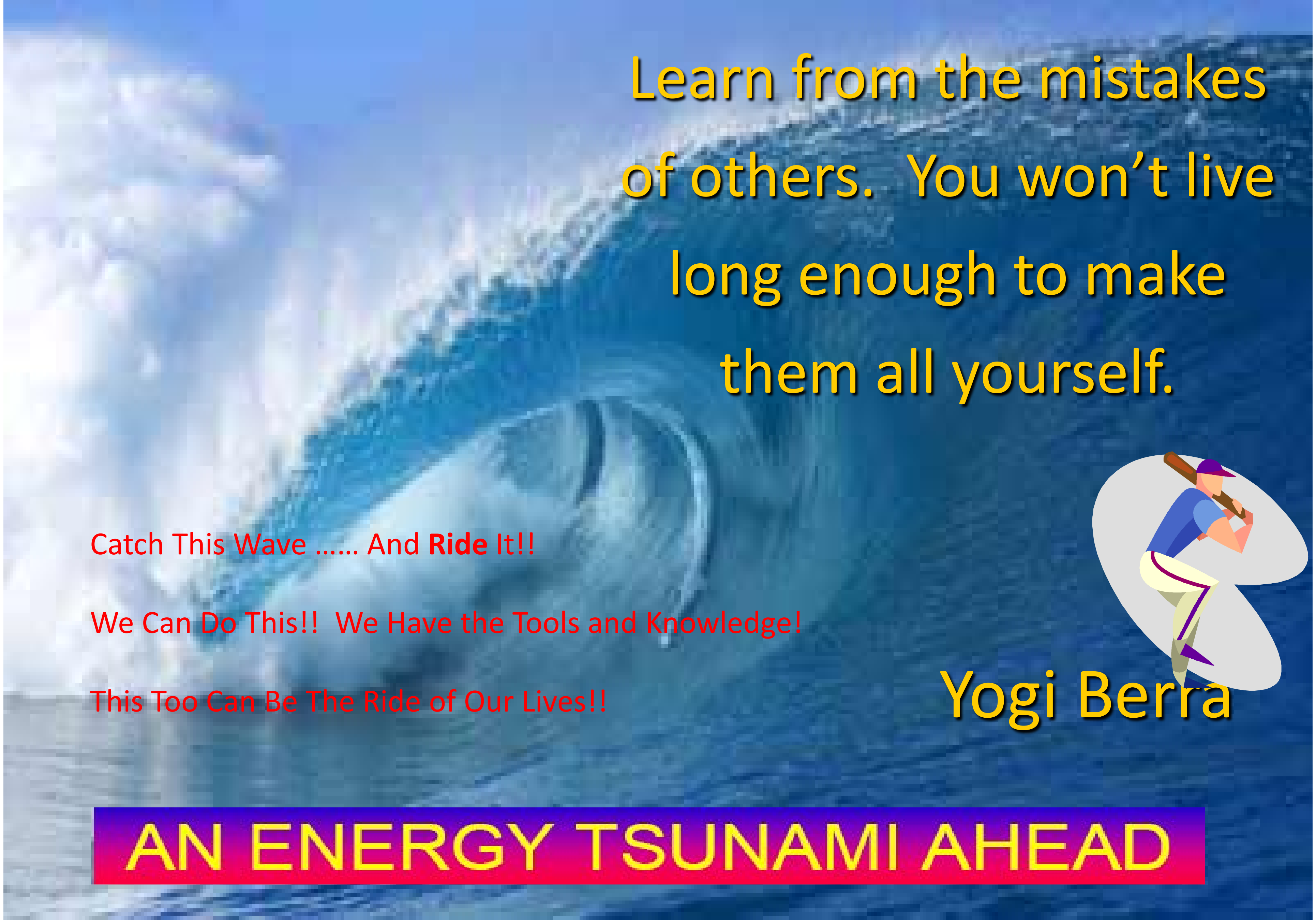


Figure S1: Heat exchanger costs. Typical areal cost as a function of heat transfer coefficient for tube and shell (open points) and plate and fin heat exchangers (solid points). The cost depends on the heat flow Q_H and temperature difference (T_H-T_1). For K_H= Q_H/(T_H-T_1)= 5 kW/K (circles), 10 kW/K (triangles), and 30 kW/K (squares). Data extracted from Ref. 17.

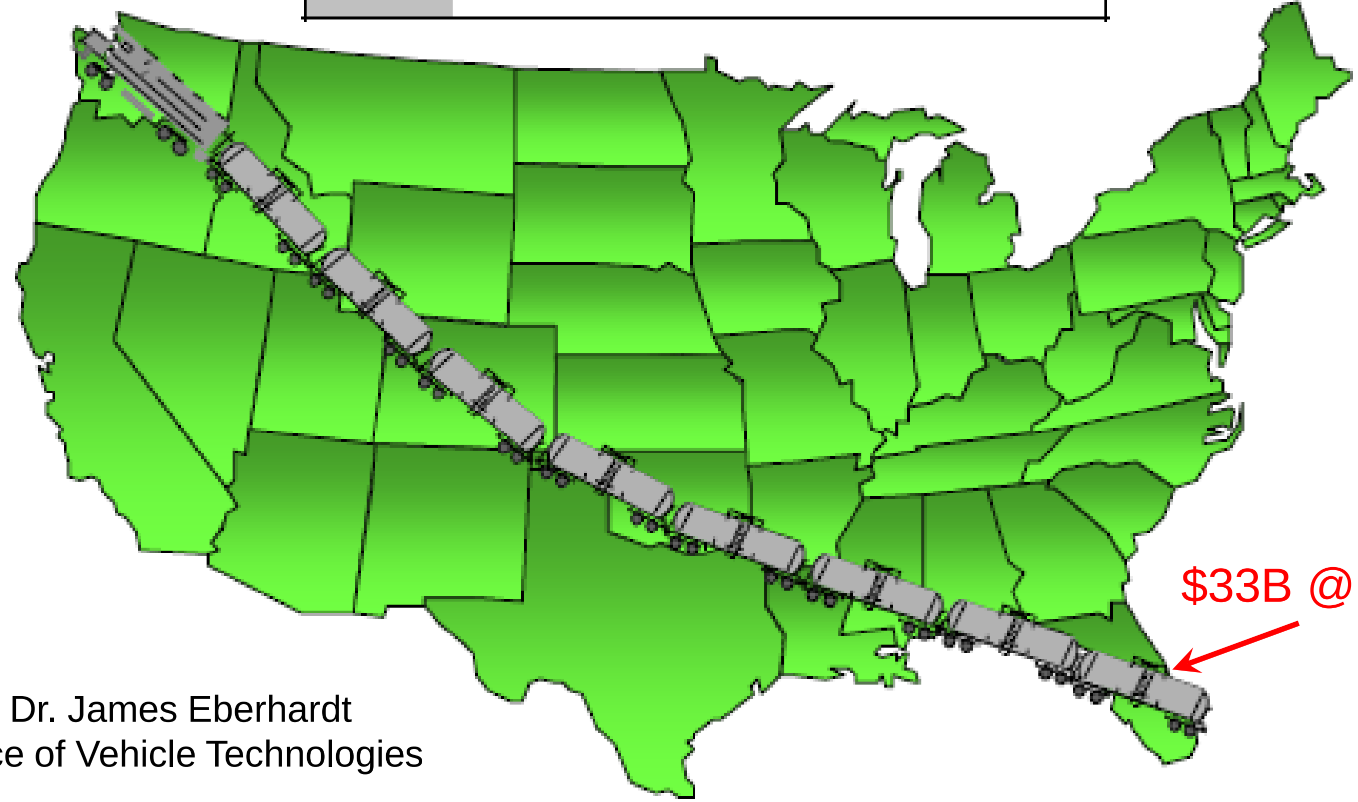

Learn from the mistakes of others. You won't live long enough to make them all yourself.
Yogi Berra
Catch This Wave …… And Ride It!!
We Can Do This!! We Have the Tools and Knowledge!
This Too Can Be The Ride of Our Lives!!
AN ENERGY TSUNAMI AHEAD

The Magnitude of Our Energy Problem

Office of Heavy Vehicle Technologies

	1973	1997
U.S.	74 Quads	91 Quads
World	225 Quads	365 Quads

2009
~94.6 Quads



$33B @ $100/Barrel

Reference - Dr. James Eberhardt
DOE – Office of Vehicle Technologies

1 Quad of energy is equivalent to 340,000 tank cars
of crude oil stretched from Miami to Seattle (3,300 miles).