Design and Testing of High-Performance Mini-Channel Graphite Heat Exchangers in Thermoelectric Energy Recovery Systems

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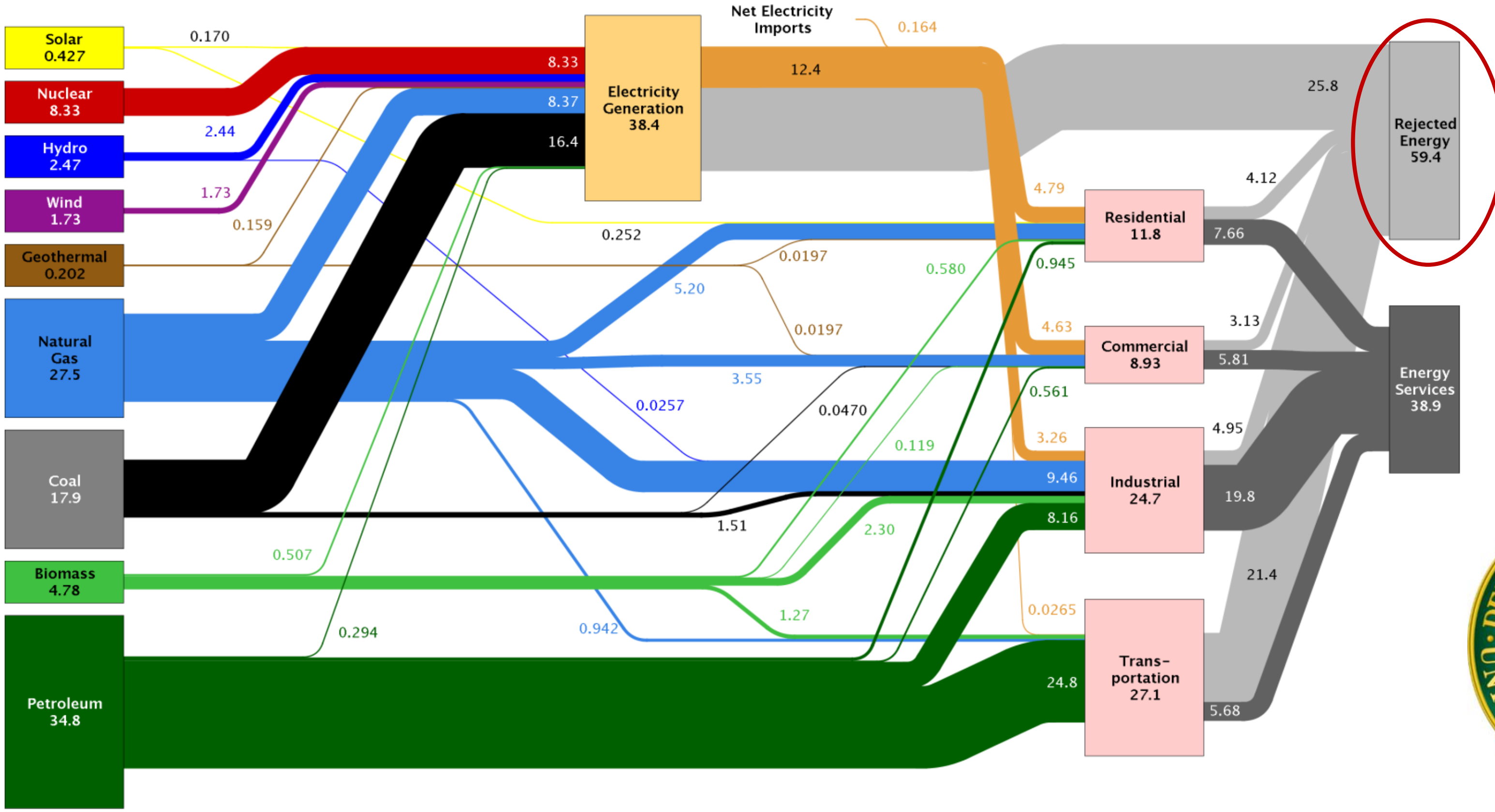
AGENDA

- Terrestrial Energy Recovery Applications
- JPL's System-Level Requirements Development
- JPL Graphite Heat Exchanger Development
- Graphite Heat Exchanger Testing Results & Analysis
- Conclusions

United States Energy Flow

Estimated U.S. Energy Use in 2014: ~98.3 Quads

Lawrence Livermore National Laboratory



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

Terrestrial Industrial Process Waste Heat Recovery

- System Solutions Needed to Recover Energy Throughout the Industrial Processing Complex
  - Produce Power
  - Residential & Commercial Space Heating
  - Radiant Collectors, Rankine cycles, Stirling cycles, & Thermoelectric Conversion
  - High-Temperature TE & Structural Materials and Systems; High Temperature Thermal Energy Storage
- Steel Industry
  - Electric Arc & Blast Furnaces, Steel Slabs, Slag By-Products
  - 10's of Megawatts of Thermal Energy Available in Each Potential Location in Steel Processing
  - Process Temperatures Available: 200-1000°C
  - 13 GW Total Potential Power Production in U.S. Alone
- Various Other Industrial Processes
  - Glass Furnaces, Aluminum Processes, Petro-chemical All Have Common Requirements
  - Process Temperatures Available: 760 – 1400°C
  - Another >39 GW Potential Power Production in These Industries in U.S.
  - Large International Interest in WHR Systems
    - Latest International Conferences on Thermoelectrics 2016, Wuhan, China & 2015, Dresden, Germany
    - Energy Harvesting - 2014 U.S. Emerging Technology Conference & Exhibition, Santa Clara, CA

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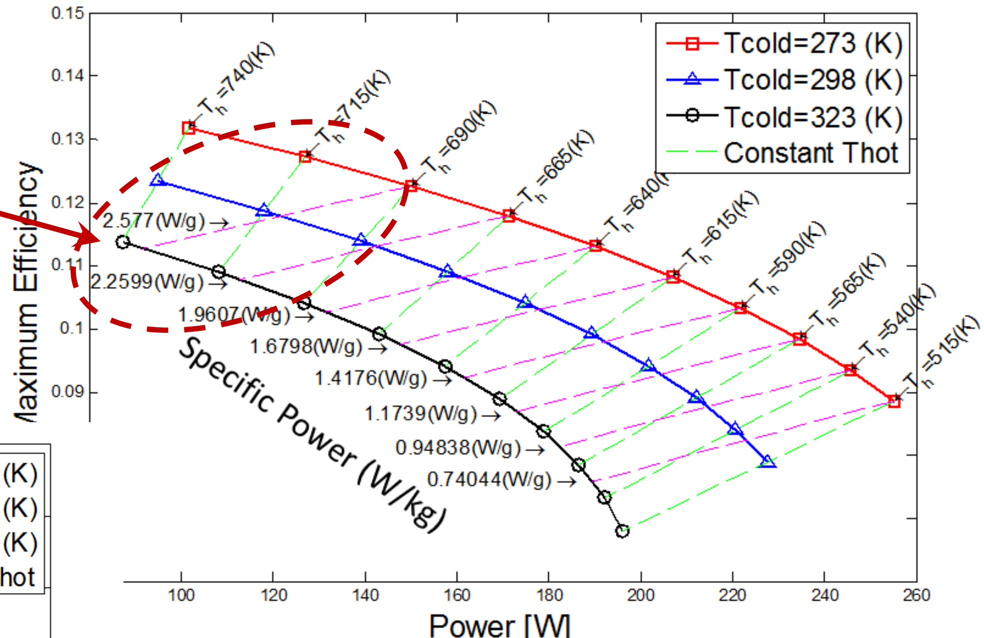
Terrestrial Waste Energy Recovery

- 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
- System Analysis Shows This Design Metric Requires High Power Flux and High Heat Flux TE Modules
- Cost-Effectiveness and Performance Are Constant Requirements

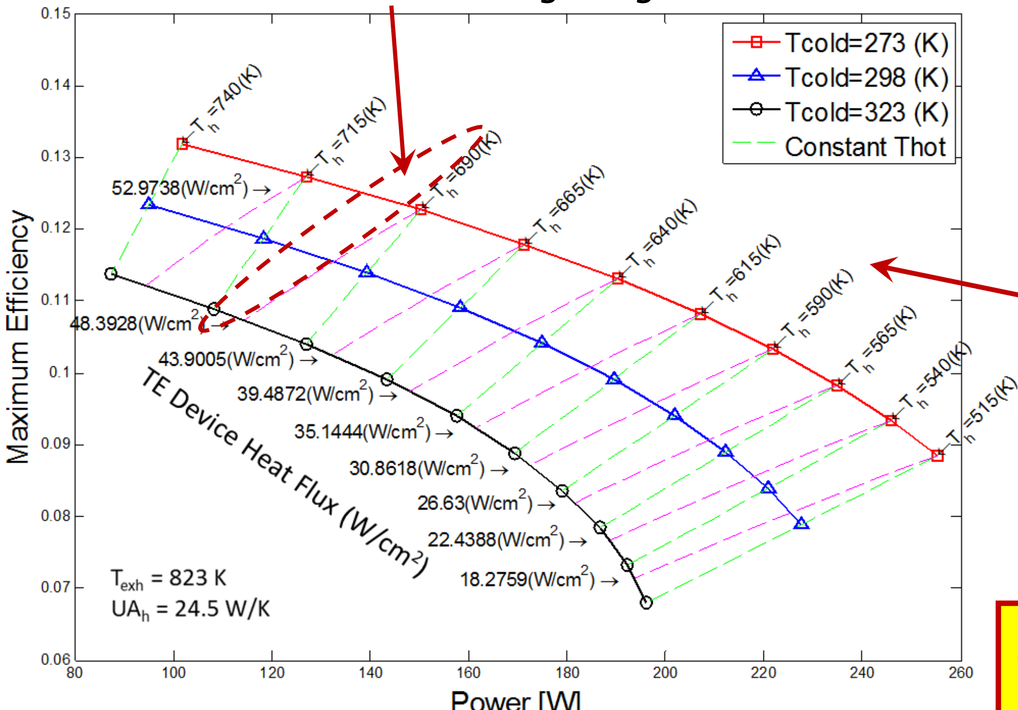
TE System Design Regime Results

T_{exh} = 823 K, T_{cold} = 273 – 323 K

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



Current Design Region



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

JPL developing high performance heat exchangers to meet these heat flux and heat transfer requirements

Relating System-Level Metrics to Heat Exchanger Metrics

- Heat exchanger and TE module heat fluxes also readily quantified and interrelated

$$q''_{HEX} = q''_{TE} \cdot F$$

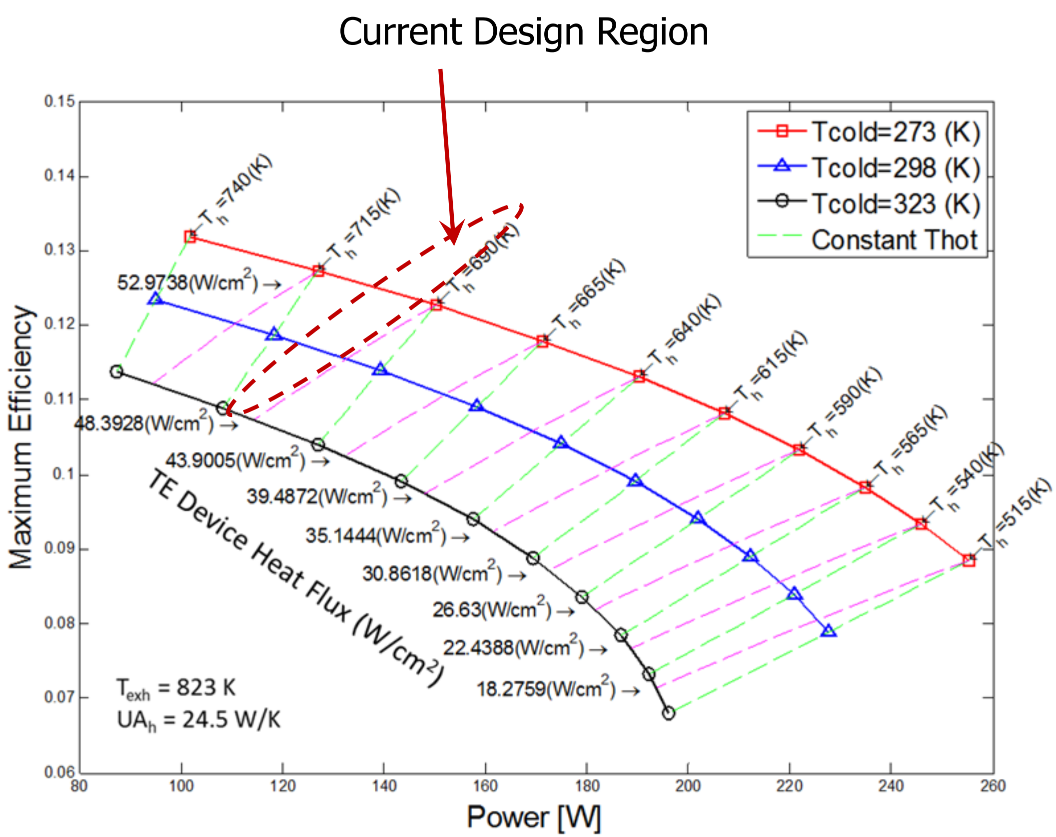
(F = Module Fill Factor; η = Module Conversion Efficiency; P′′ = Power Flux)

- Module level and TE element level information are readily quantified an interrelated

$$P''_{TE} = q''_{TE} \cdot \eta$$

$$P''_{MODULE} = P''_{TE} \cdot F$$

- TE module and TE element conditio are then strongly coupled to this ma



Critical Heat Exchanger Metrics & Requirements

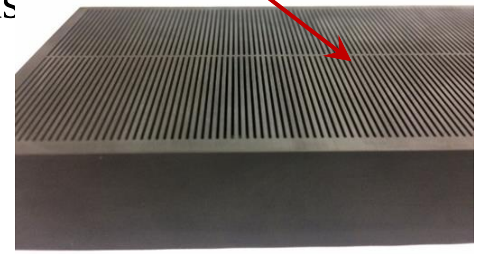
Table 1 – Light-Weight Hot-Side HEX Materials and Other Common Heat Exchanger Materials Compromises in TEG Systems - Engineering Properties.

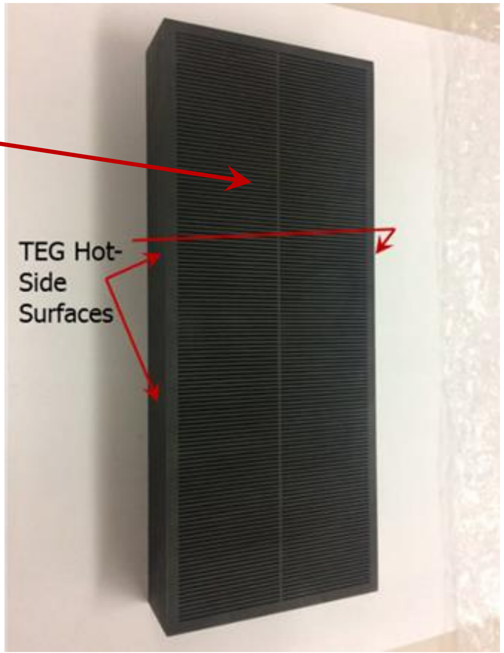
Hot Side HEX Materials	κ, Thermal Conductivity (W/m-K)	ρ, Density (gm/cm^3)	κ/ρ [(W/m-K)/(g/cm^3)]	CTE (10^{-6}/°C)	Fabrication Process	Coating Required	Government Funding
Ti_3Al	22-50 from high to low T	4.0	~5.5-12.5	11.0-15.0	EBM (Vacuum)	No	DARPA
SiC	70-80 @ 750 K	3.2	25	3.5-4.0	MI	No	Unknown
AlN	85 @ 600 K [6]	3.26	26.1	4.5	Sintering	No	Unknown
C-C Fiber	6-32 @ 873 K	1.8-2.2	2.7-14.5	0.54 [16]	CVD, PIP	Yes	Unknown
Graphite	40-70@973 K	1.3-1.8	22.2-38.9	7.5 [14]	Various	Yes	Unknown
Stainless Steel (Austenitic)	24.2-25.4 @800 K	7.9-8.2	~3.0-3.1	16-18	Various Standard Commercial	No	SERDP (2010)
Inconels & Other Nickel-Based Metals	21 @ 873 K [15]	8.4	2.4	15.7 [15]	Various Standard Commercial	No	No

Graphite Heat Exchanger Technology

Challenge: High Performance Heat Exchange Technology for Terrestrial and Planetary Energy Recovery and Thermal Management

- Demonstrated Minichannel Graphite Heat Exchange Technology @ JPL
  - Minichannels shown to right
  - Could be gas or liquid HEX
- High Temperature Heat Exchange
  - 500 µm channel widths
  - 4.8 W_{th}/cm^3
  - Low Density, Light weight - 128 grams
  - High Thermal Conductivity
  - Low CTE
  - Reasonably good strength
  - Good manufacturability



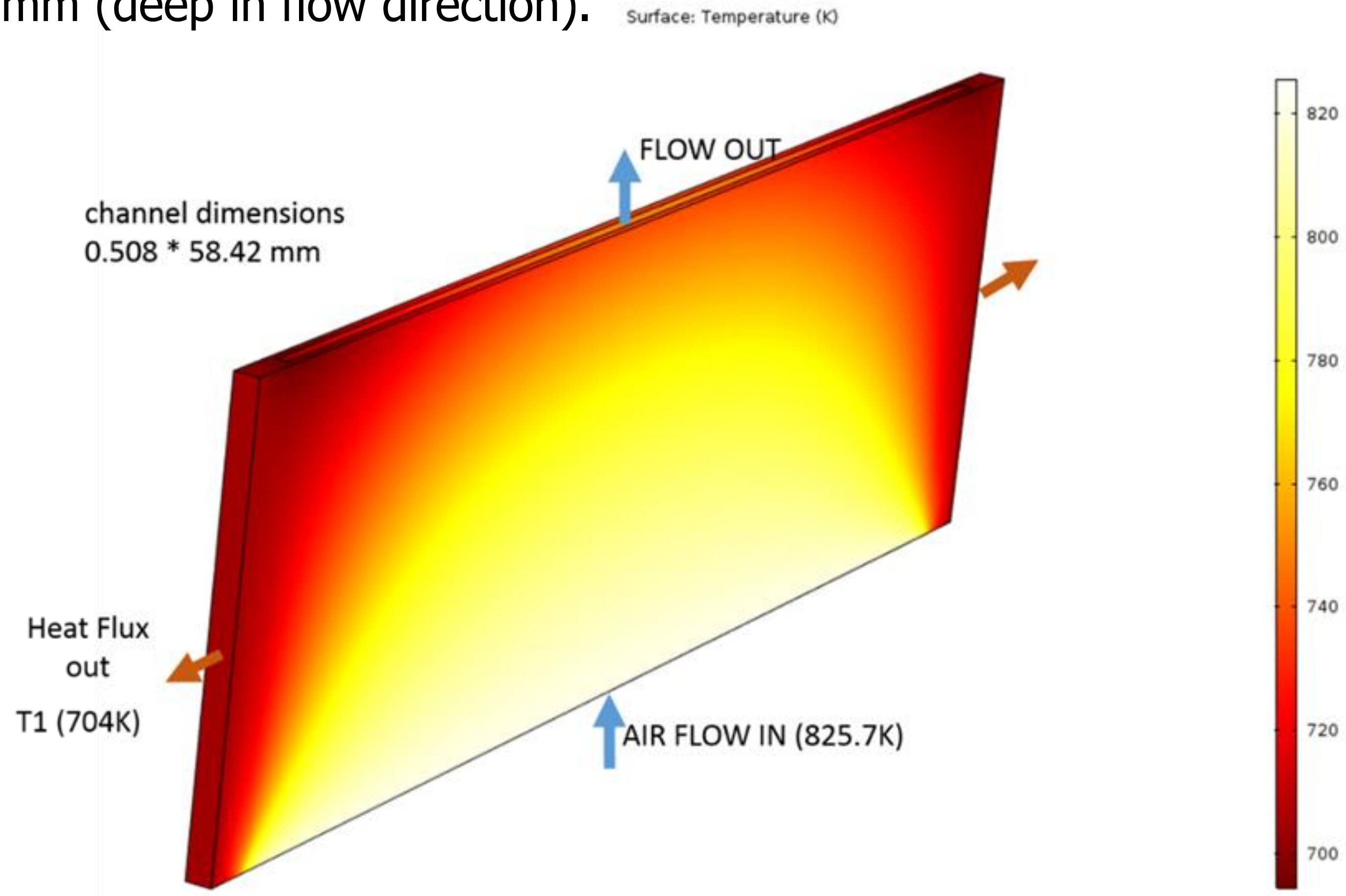


Looking to additively manufacture this unique structure
Lightweight, High Temperature, High-Performance Heat Exchange Structure

COMSOL™ Fluid Flow / Thermal Analysis

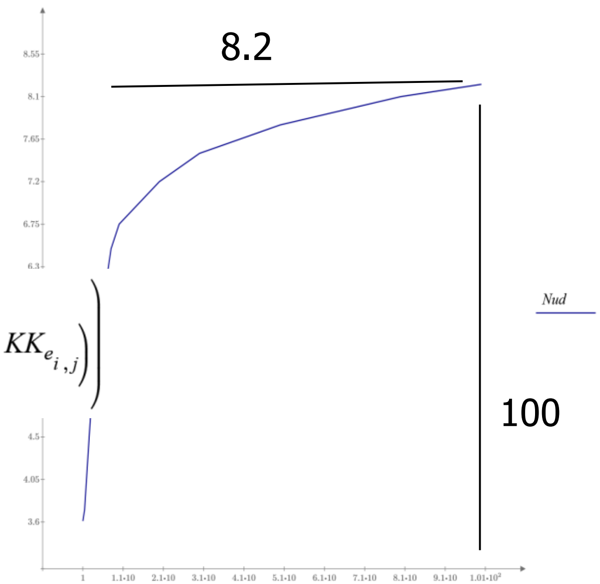
- COMSOL™ Thermal Analysis on One Channel of the Graphite Heat Exchanger Design (Channel Symmetry Assumed)

- Channel dimensions shown above 0.508 mm (wide) x 58.42mm (long dimension) x 20.3 mm (deep in flow direction).



Empirical Model vs. COMSOL Model Comparison

- Empirical Correlation Model also used in HEX Design
- Based on Heat Transfer and Pressure Drop Correlations Found in Kays and London, Incropera and Dewitt, and White
  - Laminar Flow (Re < 500)
  - Nu_d = function (aspect ratio - b/a)
  - f*Re = function (aspect ratio – b/a)



$$DP_{i,j} := \left(\frac{\left(G_{i,j}\right)^2}{2.0\cdot\rho_{air}}\right)\cdot\left(\left(KK_{c_{i,j}}+1.0-\left(\sigma_{ff_{i,j}}\right)^2\right)+2.0\cdot\left(\frac{T_2}{T_1}-1.0\right)+f_{i,j}\cdot\frac{A_{tot_{i,j}}}{N_j\cdot A_{c_{i,j}}}-\left(1.0-\left(\sigma_{ff_{i,j}}\right)^2-KK_{e_{i,j}}\right)\right)$$

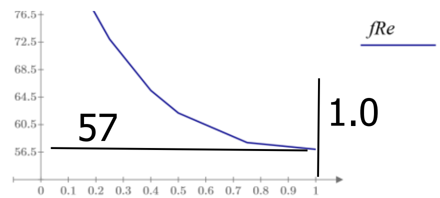
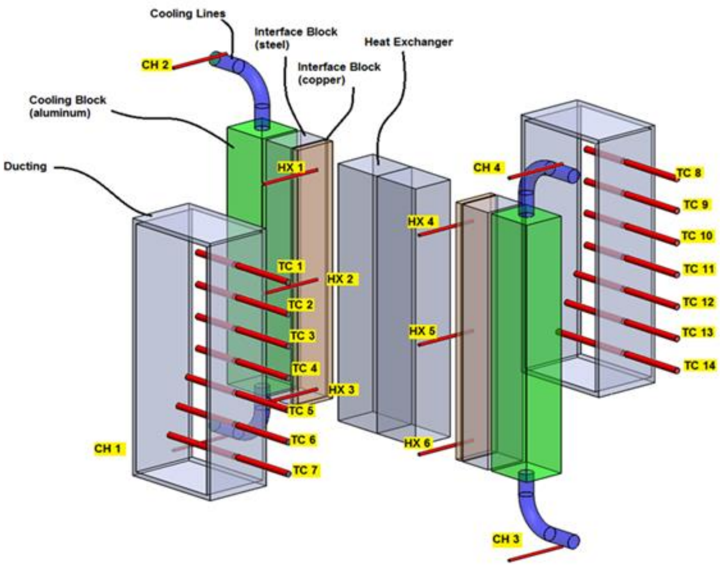


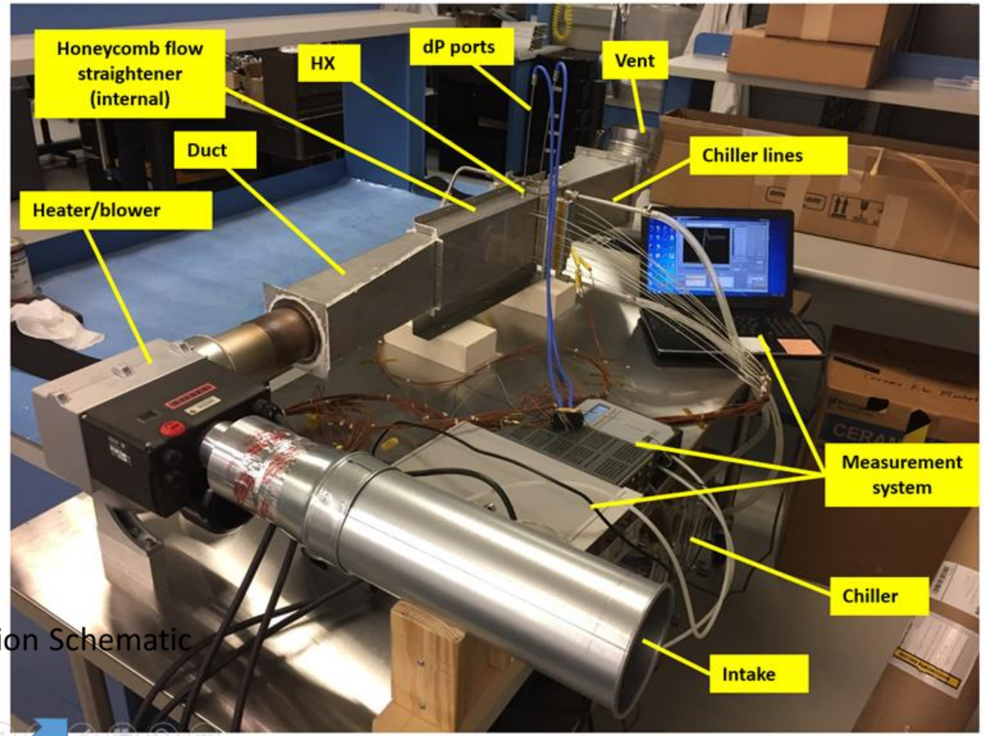
Table 2 – Heat Flux and Outlet Temperature Comparison Between COMSOL™ Model and Empirical Model

	COMSOL™ Model (version 5.2a)	Empirical Model
Surface Average Heat Flux [W/cm²]	20.06	20.36
Outlet temperature [K]	729.8	723.2
Pressure Drop [psi]	0.03	0.042

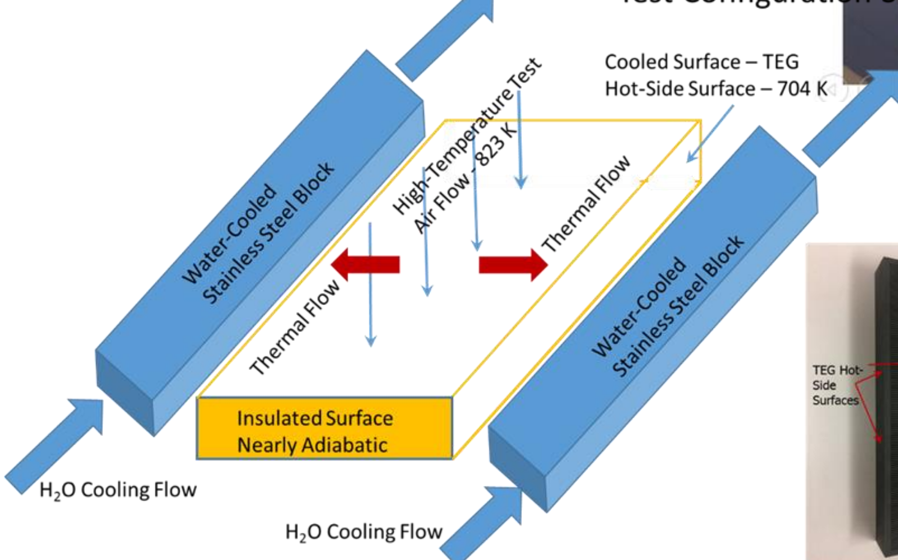
Surface Average Heat Flux is at the TEG Hot Side Surfaces in Figure 3

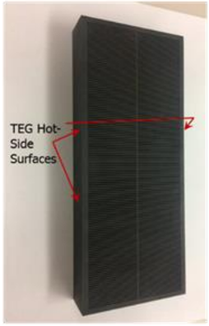
Graphite Heat Exchanger Test System





Test Configuration Schematic

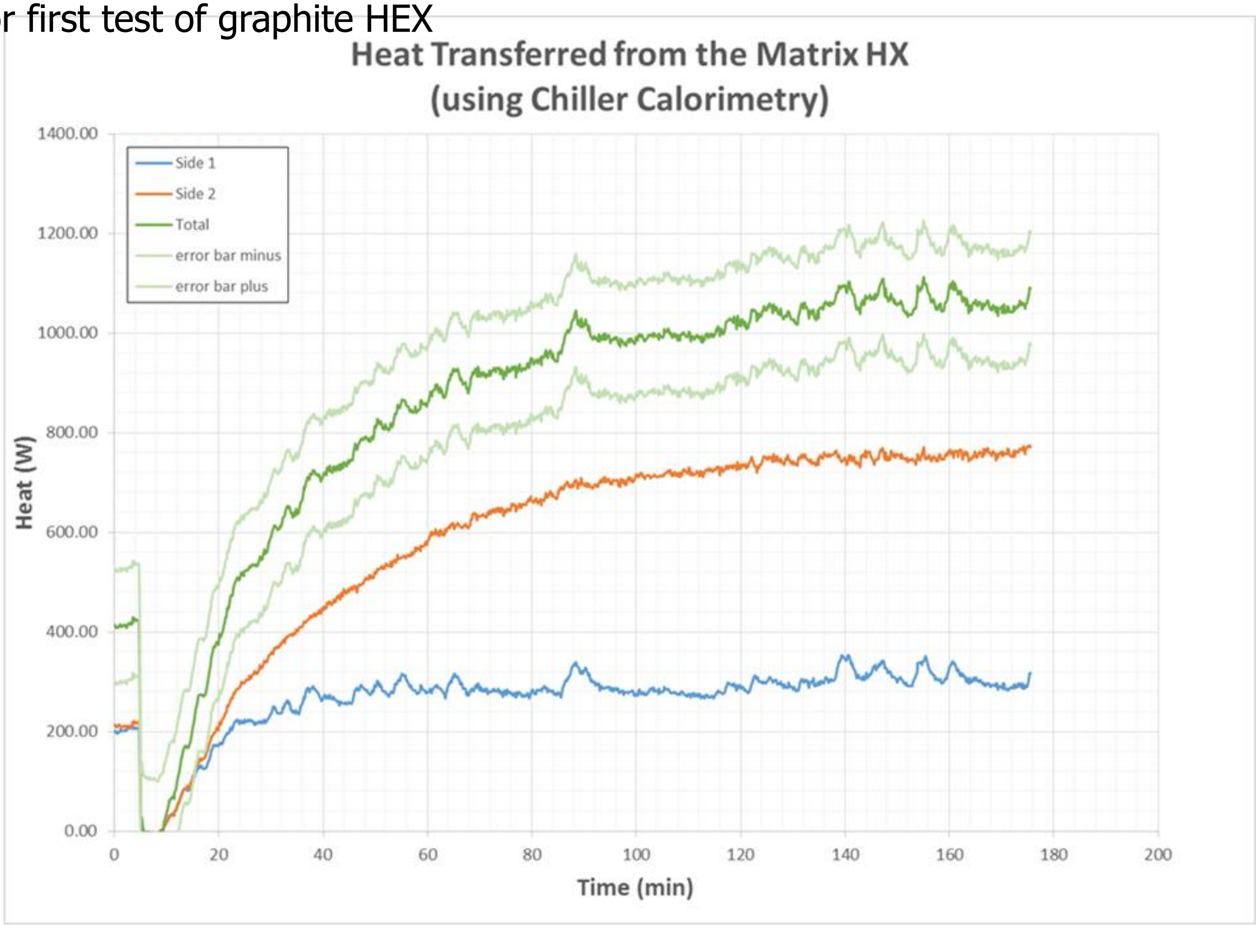




- Open Flow System
- Air Flow Rate = 0.012 kg/second
- High temperature air at 550°C

Heat Transfer Test Results

- Graphite HEX transferred about 1050 W (±110 W) thermal energy between the two-sides of the dual-side heat exchanger at near design operating conditions.
- The pressure drop across HEX measured 0.066 psi (±0.002 psi) at the targeted design flowrate.
- The average heat exchanger interface heat flux across our dual-sided cold interfaces was estimated at ~16.9 W/cm^2, and could be as high as 24.5 W/cm^2 on one side (Target: 20 W/cm^2)
- This HEX is capable of about 1120 W as cold-side temperature condition is brought closer to design condition (9 °C cooler cold surface)
- Very good performance for first test of graphite HEX



Conclusions

- Advanced graphite heat exchanger successfully designed and fabricated at JPL
- Lightweight minichannel design performed very close to design expectations
  - High heat transfer
  - Low Pressure drop
- Design confirmed for high temperature application in Thermoelectric Energy Recovery System
- Demonstrated coupling between TE Energy Recovery system metrics and heat exchanger design metrics
- Demonstrates high performance heat transfer with:
  - High thermal conductivity structure
  - Low coefficient of thermal expansion structure
  - Lightweight, low density structure
  - Good structural properties

ACKNOWLEDGMENTS

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