Demonstrated High-Performance, High-Power Skutterudite Thermoelectric Modules for Space and Terrestrial Applications

presented at

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Modules Technology and Development (Track 1)

Caen, France

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AGENDA

- Terrestrial Energy Recovery Applications
- JPL's System-Level Requirements Development
- JPL Skutterudite TE Module Description
- Skutterudite TE Module Testing Results & Analysis
- Conclusions & Next Steps

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

www.dpp-Europe.com

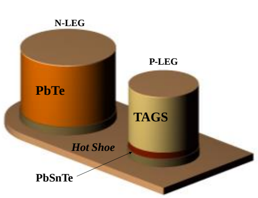
High Temperature TE Couple Technologies

Couple Configuration	P-leg	N-leg	Heat Source Coupling	Program
Segmented	Bi_2Te_3/TAGS/PbSnTe	Bi_2Te_3/PbTe	Conductive	Terrestrial RTGs
Segmented	TAGS/PbSnTe	PbTe	Conductive	SNAP-19, MMRTG
Segmented	$Si_{0.63}Ge_{0.37}$/$Si_{0.8}Ge_{0.2}$	$Si_{0.63}Ge_{0.37}$/$Si_{0.8}Ge_{0.2}$	Radiative	MHW-, GPHS-RTG
Segmented	Bi_2Te_3/SKD*	Bi_2Te_3/SKD	Conductive	Segmented TE Couple (2002)
Unsegmented	Zintl	Nano $Si_{0.8}Ge_{0.2}$	Radiative	2008
Unsegmented	Zintl	$La_{3-x}Te_4$	Conductive or radiative	2009 ATEC
Segmented	SKD/Zintl	SKD/$La_{3-x}Te_4$	Conductive or radiative	2011
Segmented	Adv. PbTe/Zintl	Adv. PbTe/$La_{3-x}Te_4$	Conductive	2012
Unsegmented	Filled SKD	Filled SKD	Conductive	2013 ATEC/eMMRTG

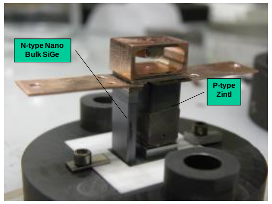
Skutterudites research as far back at early 1990's

~ 9.3 to 15 % efficiency with T_{cold} ~ 473 K

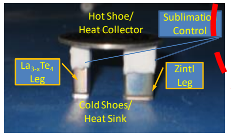
MMRTG



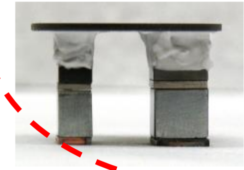
ATEC



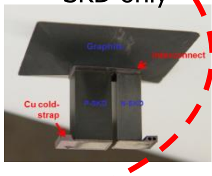
ATEC
Zintl/$La_{3-x}Te_4$



ATEC
SKD/Zintl/$La_{3-x}Te_4$



ATEC
SKD only



Arrays of discrete multicouples typically used for RTGs

Filled skutterudites currently being transitioned for use in enhanced MMRTG

Terrestrial Waste Energy Recovery

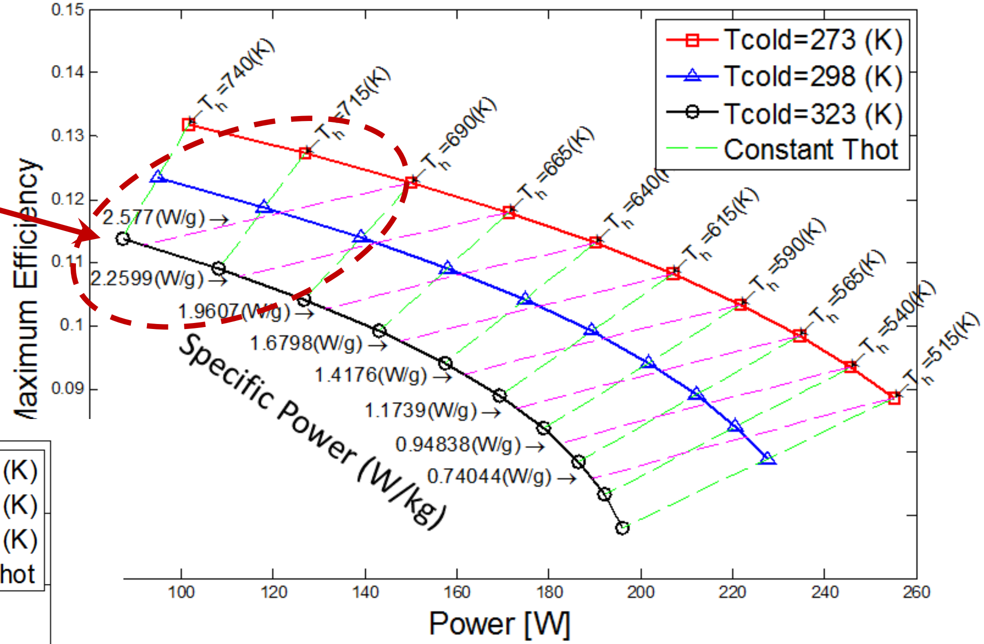
- Thermoelectric Systems Considered a Prime Energy Recovery Technology Candidate / Option in Many Terrestrial Applications
- Terrestrial Energy Recovery Goals are Often Tied to:

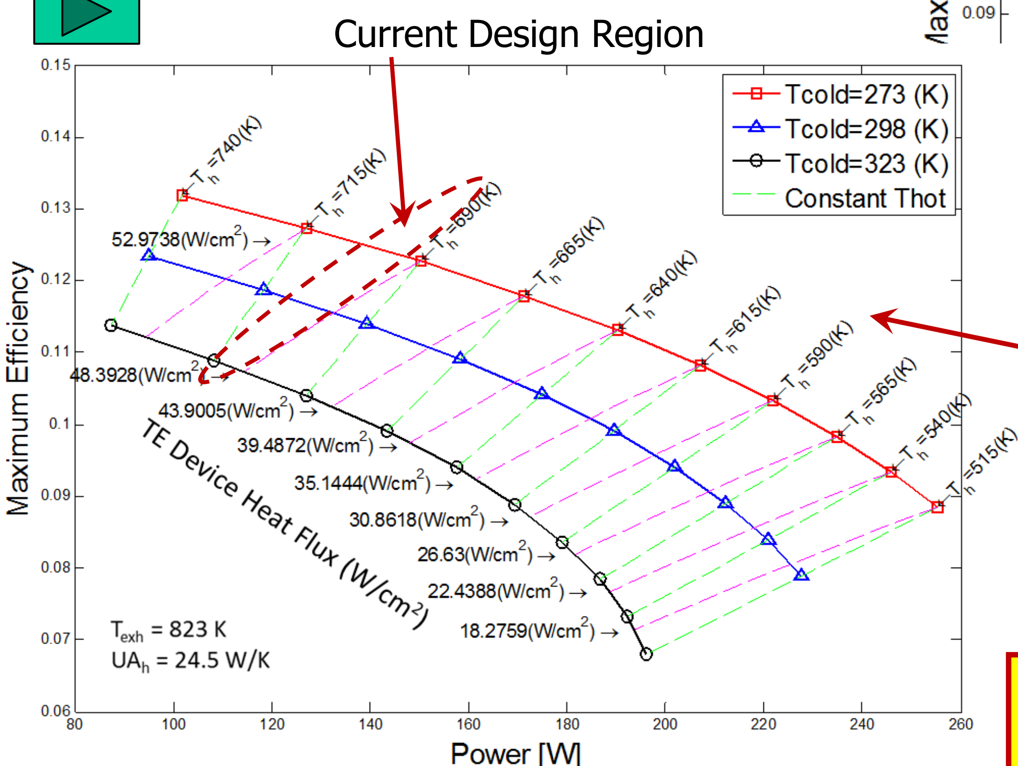
Energy Savings	Environmental Savings & Impacts
• Maximize Conversion Efficiency • Maximize Power	• Maximize Conversion Efficiency • Maximize Power

- 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} = 823-923 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





- 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 skutterudite-based TE modules to meet these requirements

Relating System-Level Metrics to Module Metrics

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

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

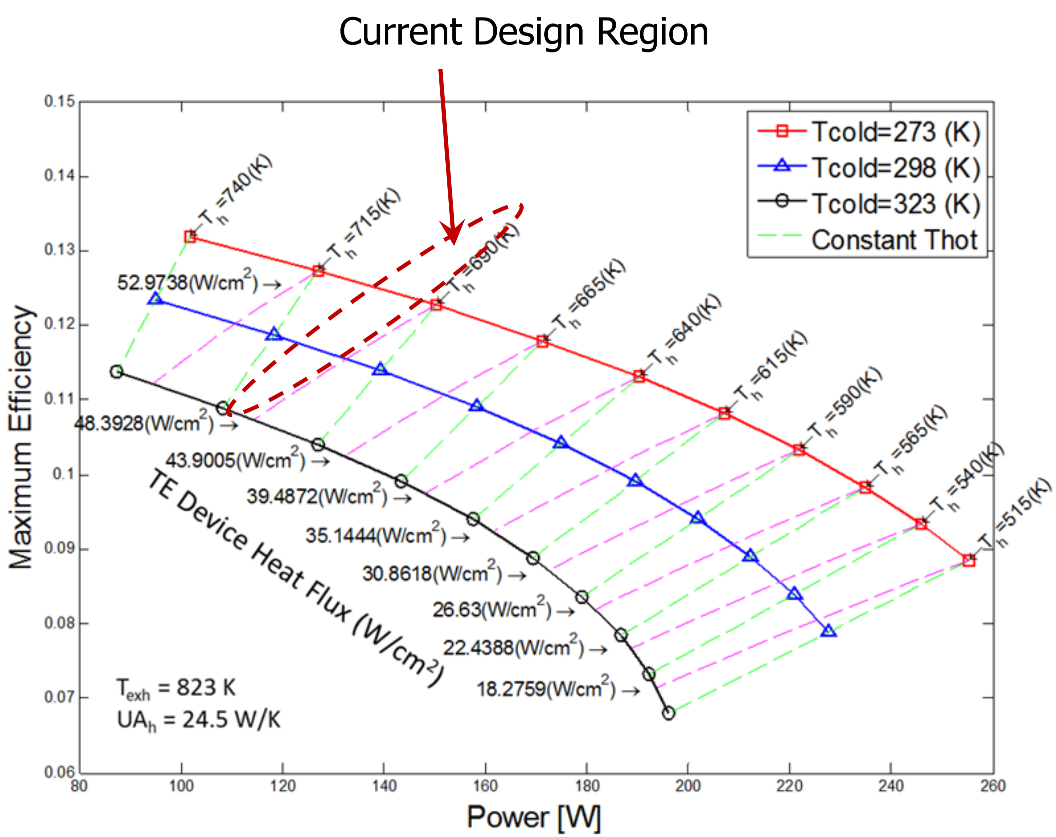
$$P''_{MODULE} = P''_{TE} \cdot F$$

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

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

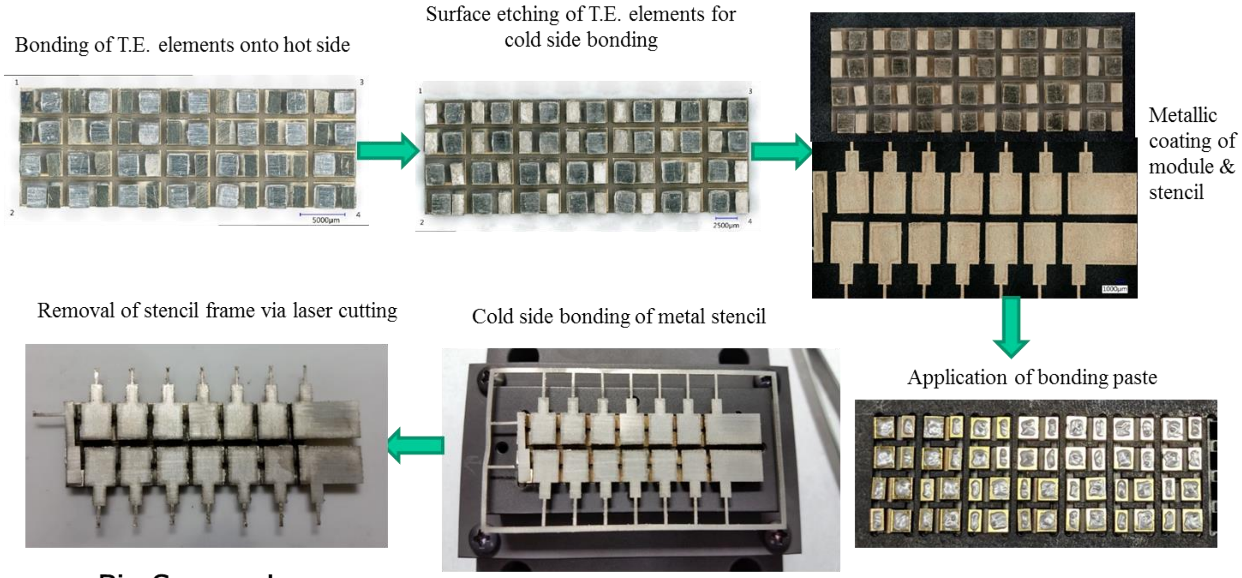
$$q''_{HEX} = q''_{TE} \cdot F$$

- TE module and TE element conditions are then strongly coupled to this map



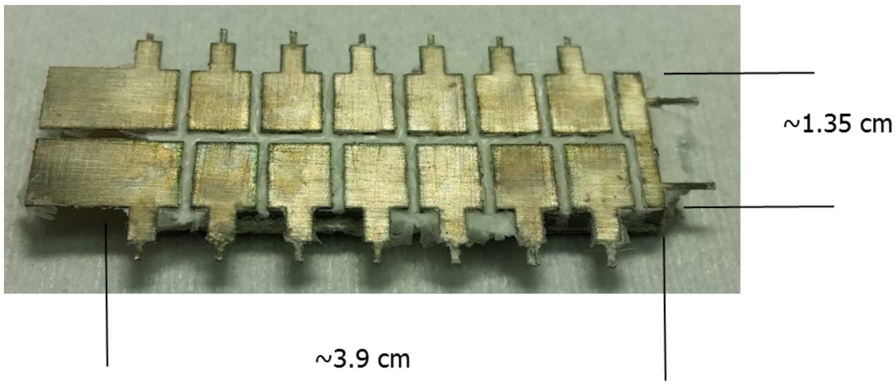
Module Fabrication Demonstrated & Module Completed for Testing

- Complete Module fabrication process defined and developed - (All Skutterudite Module)



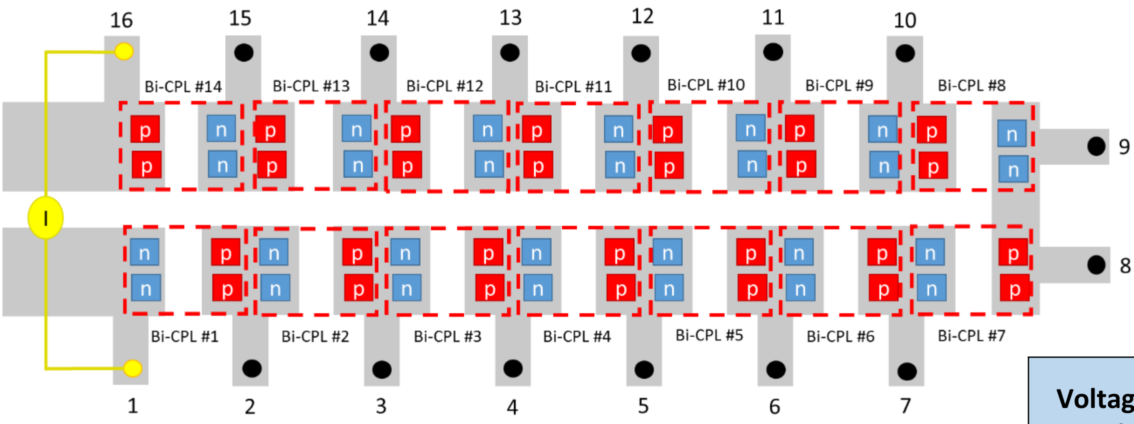
Big Success!

- Module after refined aerogel processing (removed excess aerogel)
- TE module the goes to testing:
  - Voc
  - I-V curve
  - Thermal interfaces



TE Module Testing

Resistance measurements for quarter module 6



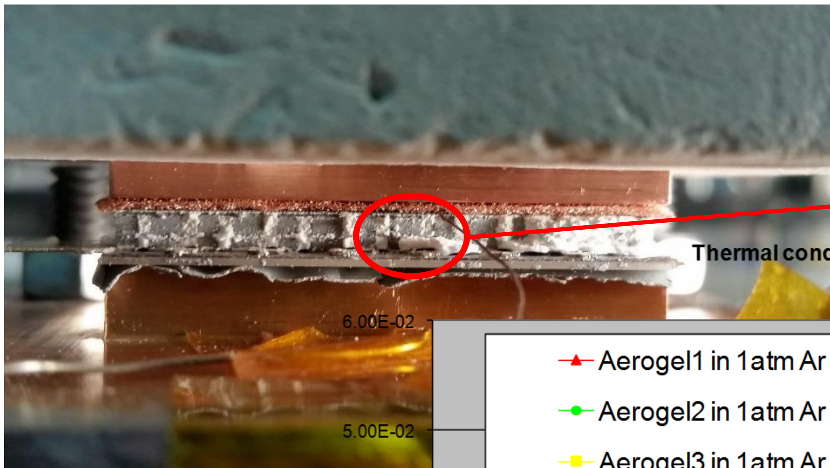
$R_{\text{Bi-CPL Calculated}}$ (mΩ):	3.14
½ $R_{\text{total device calculated}}$ (mΩ):	21.99
$R_{\text{total device calculated}}$ (mΩ):	43.98

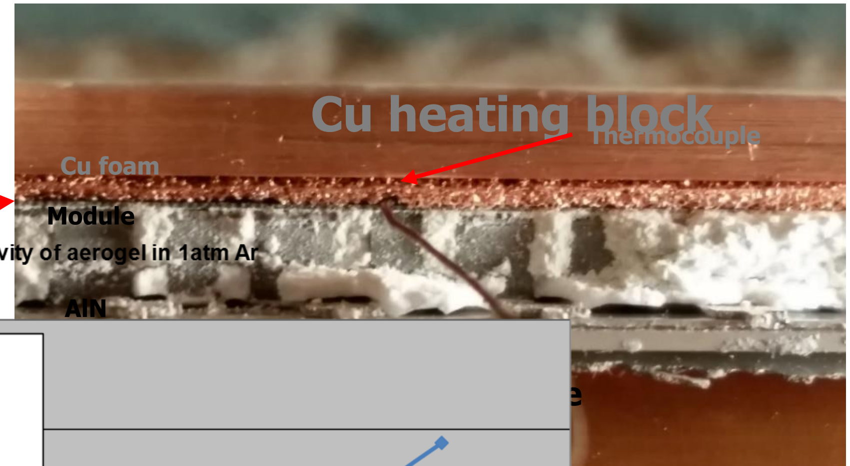
- Current leads were attached to nodes 1 and 16 and an AC current of **0.943 A** was applied to the module
- Voltages were then measured between nodes (e.g 2→3, 3→4, 4→5, etc.)
- All resistances were in accordance with the calculated values shown at the top right
  - **Percent differences were all ≤8 % (better than Module 5)**

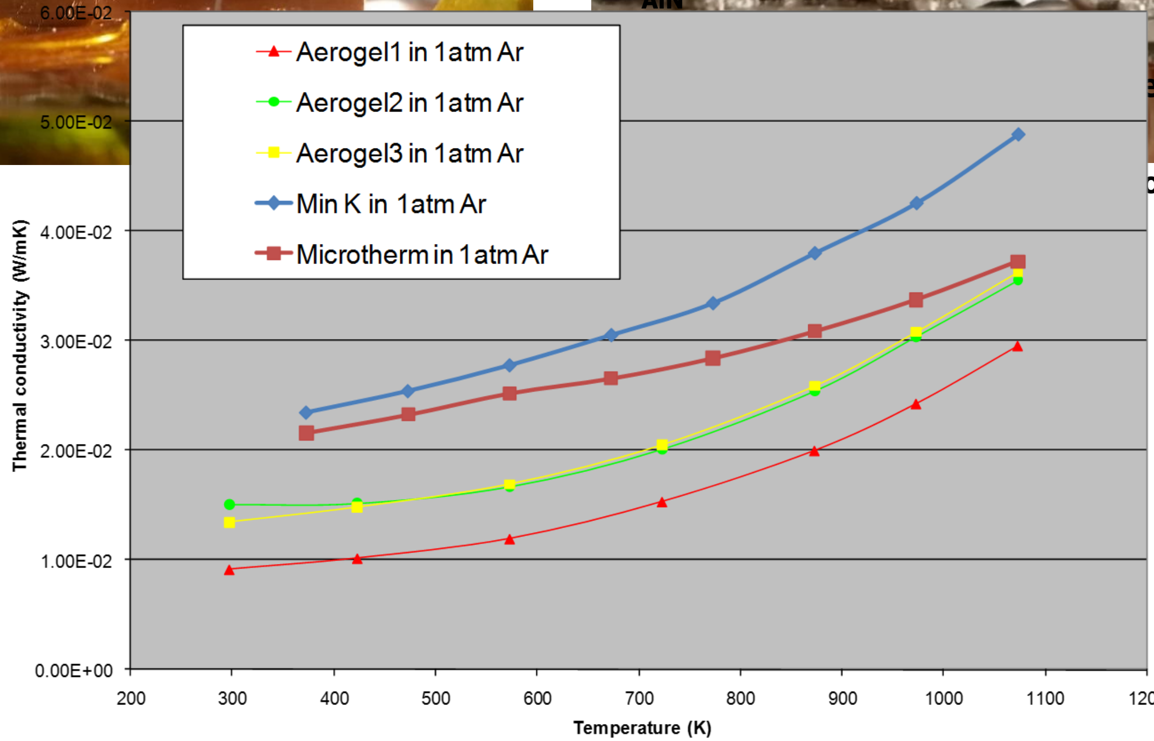
Voltage Probe Location Along Device	Measured Voltage AC (mV)	Measured R (mΩ) Calculated from measured V and measured I	Percent Difference (%)
$V_{1\text{-}16\ (\text{total})}$	41.65	44.17	0.43
$V_{1\text{-}9\ (\text{half})}$	19.88	21.08	4.13
$V_{9\text{-}16\ (\text{half})}$	20.67	21.92	0.32
$V_{1\text{-}2}$	3.02	3.20	1.99
$V_{2\text{-}3}$	3.11	3.30	5.03
$V_{3\text{-}4}$	2.79	2.96	5.78
$V_{4\text{-}5}$	2.81	2.98	5.10
$V_{5\text{-}6}$	2.75	2.92	7.13
$V_{6\text{-}7}$	2.76	2.93	6.79
$V_{7\text{-}8}$	2.93	3.11	1.05
$V_{9\text{-}10}$	2.84	3.01	4.09
$V_{10\text{-}11}$	2.94	3.12	0.71
$V_{11\text{-}12}$	3.15	3.34	6.38
$V_{12\text{-}13}$	2.74	2.91	7.46
$V_{13\text{-}14}$	2.95	3.13	0.37
$V_{14\text{-}15}$	3.16	3.35	6.72
$V_{15\text{-}16}$	3.07	3.26	3.68
$V_{1\text{-}16\ (\text{after all measurements})}$	41.41	43.91	0.15

Images of module and thermocouple placement inside test fixture

- Temperature sensor locations were critical to establish internal ΔT's
- Aerogel insulation around TE elements quite apparent
- Aerogel is certainly a key design feature

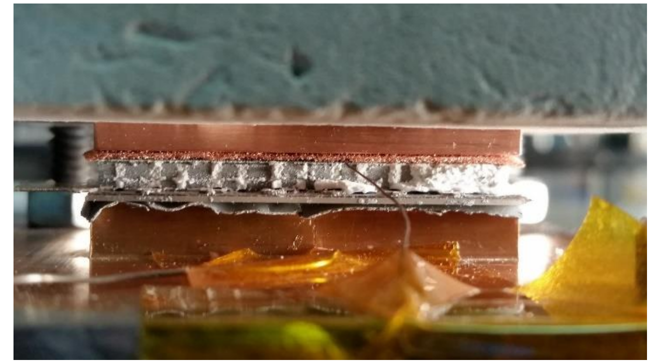




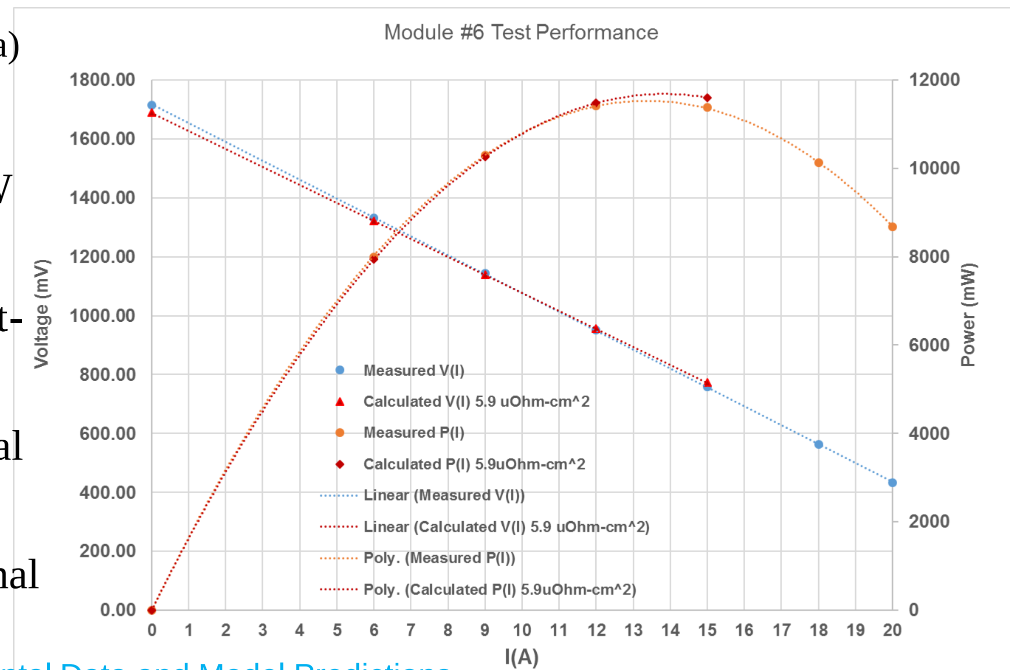


TE Module Testing (2017)

- Latest TE module test data looking better than ever
- Full I-V curve with comparison to model predicts
- Module measured resistance via I-V curve = 64.1 mΩ at temperature - Good compared to expected 60 mΩ
- Power output was 11.5 W at T_h ~425°C and T_c ~ 35°C
    - Best Ever for JPL All-SKD TE Module
    - Power flux > 2.1 W/cm^2 (Module Footprint Area)
    - Power flux ~5.1 W/cm^2 (TE Element Area)
- Hot-side thermal input is approximately 120 W
- Hot-side thermal resistances have now been analyzed with the aid of specific testing for hot-side ΔT's
- Working to get T_c lower now and lower thermal contact resistances at hot- and cold-sides.
- Even exposed to some thermal cycling – Internal resistances stayed constant



Module Mounted in Test System



- Excellent Agreement Between Experimental Data and Model Predictions
- Electrical Contact Resistance Between Components ~ 5.9 mOhm-cm^2 - This is quite reasonable

U.S. ARMY RDECOM®

TE Efficiency Testing Verification

ARL

- Device zT = 0.95 is the best value ever measured at ARL for non-bismuth-telluride materials.

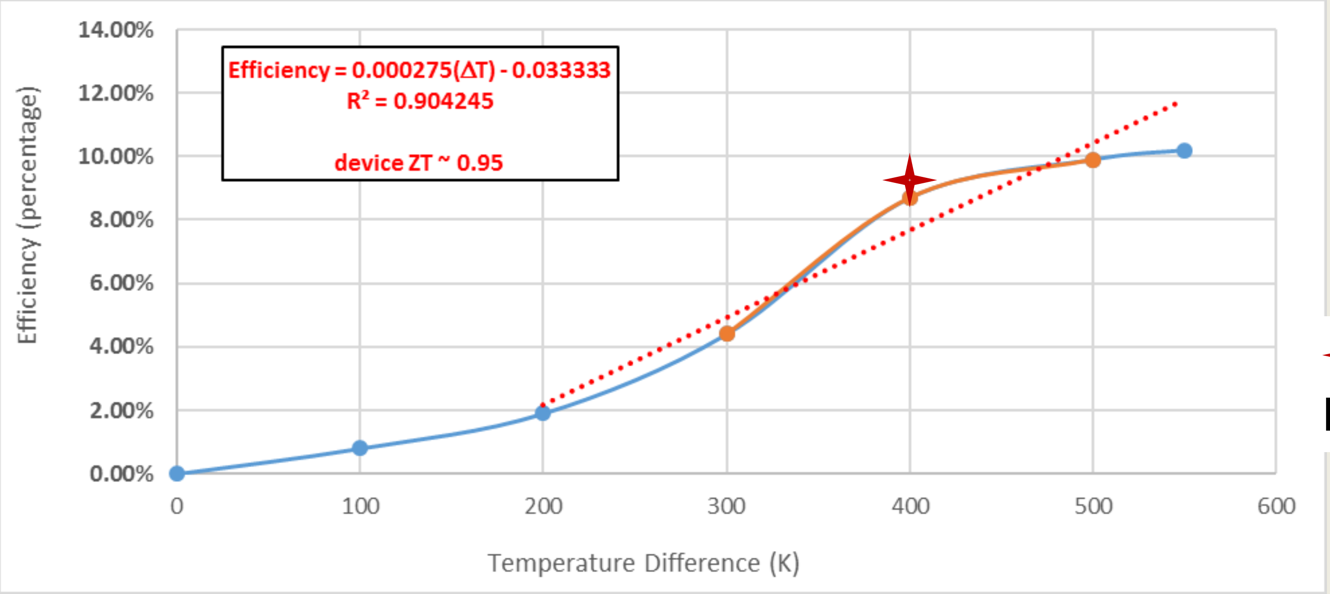
Good Thermal Conductance comparison

ARL (q-meter) K = 0.29 W/K

JPL (calorimetry) K ~ 0.31 W/K

- **Bottom-Line: <u>Module #6 exceeded 9% at high temperatures</u>**

ARL direct measurement



ARL thermal conductance

JPL Estimate

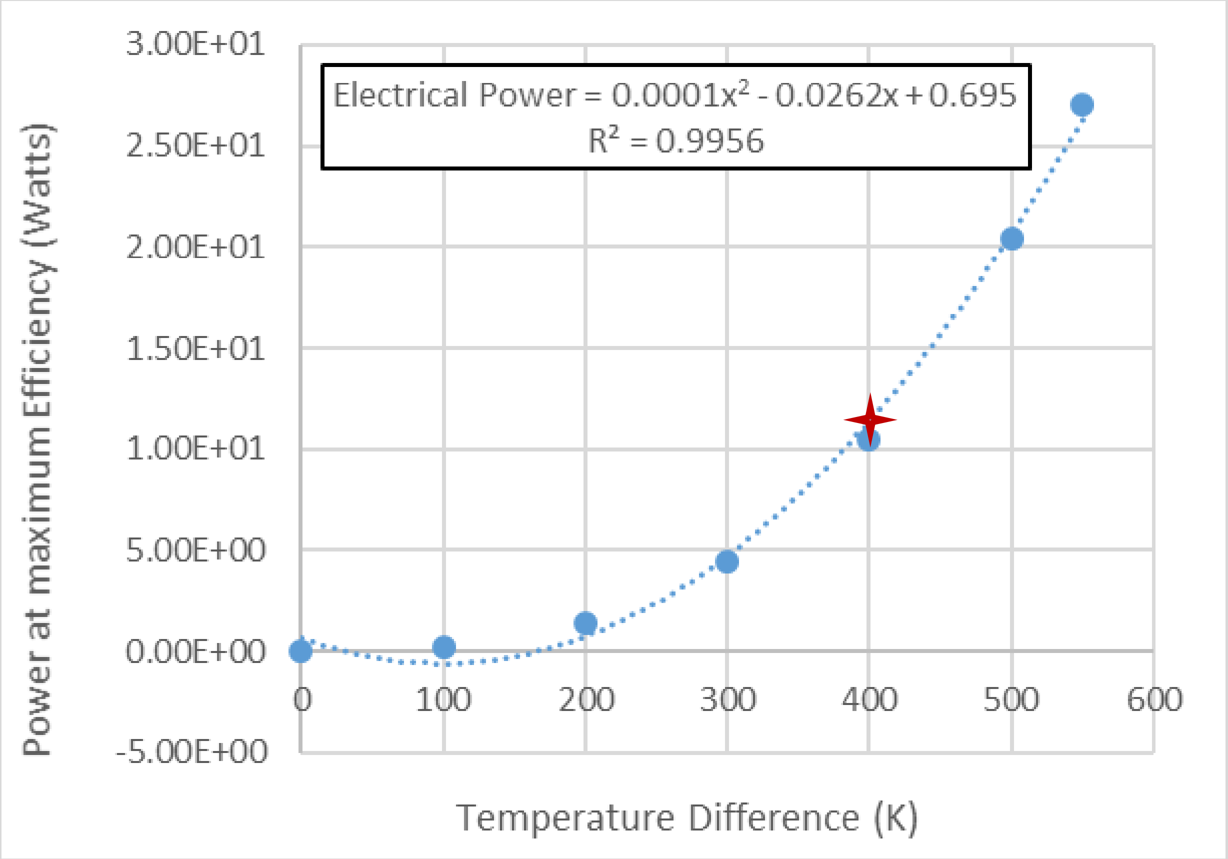
- **High power and high power density module**

JPL

- **Bottom-Line: <u>Module #6 exceeded 20 W power generation at high temperatures</u>**
- **Power density ~2.1 to 3.8 W/cm²** - Highest power density ever seen

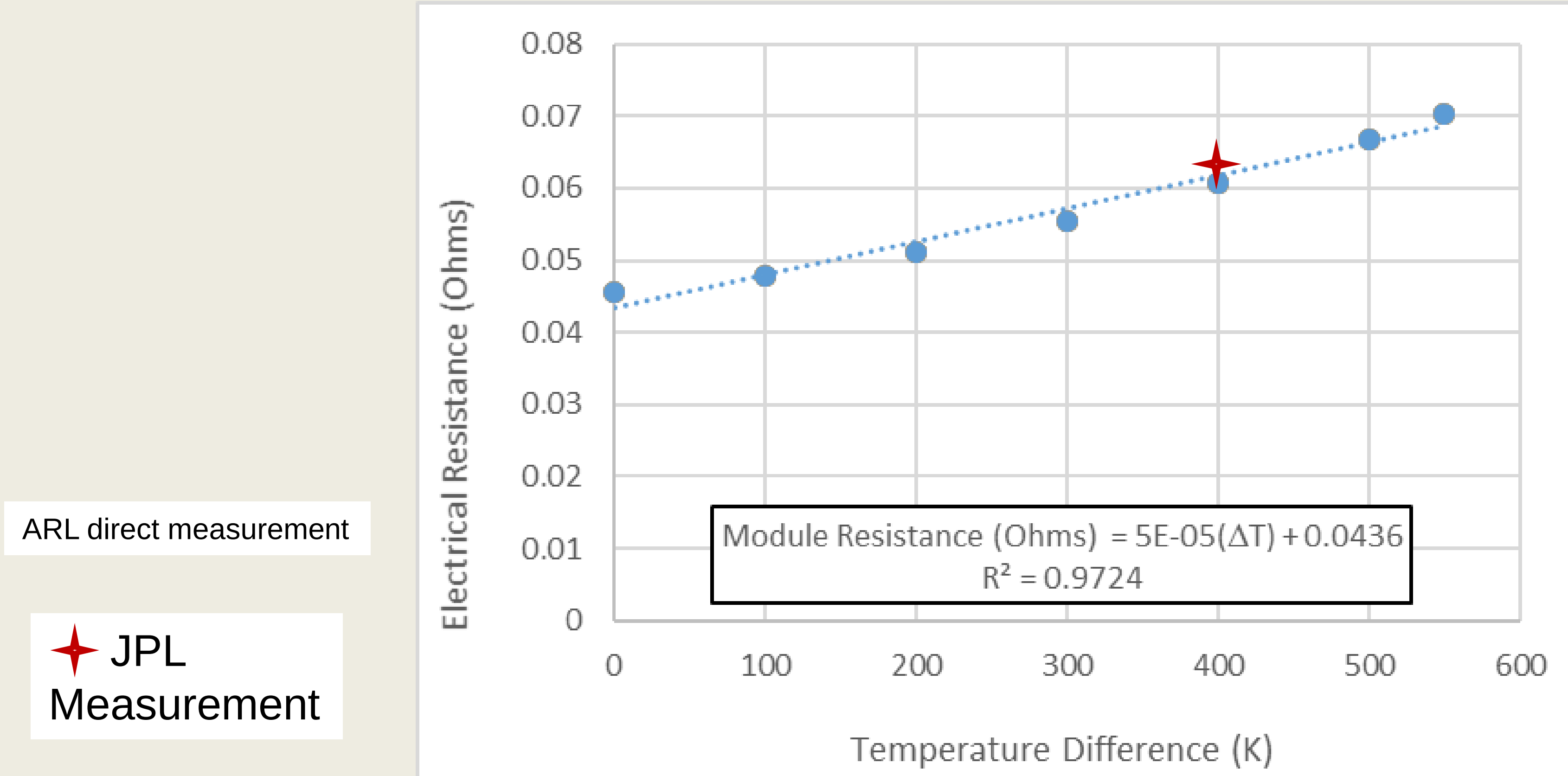
ARL direct measurement

JPL Measurement



TE Efficiency Testing Verification

- **Module electrical resistance very stable and consistent over time several heating / cooling cycles**
- **ARL and JPL resistance measurements in very good agreement**



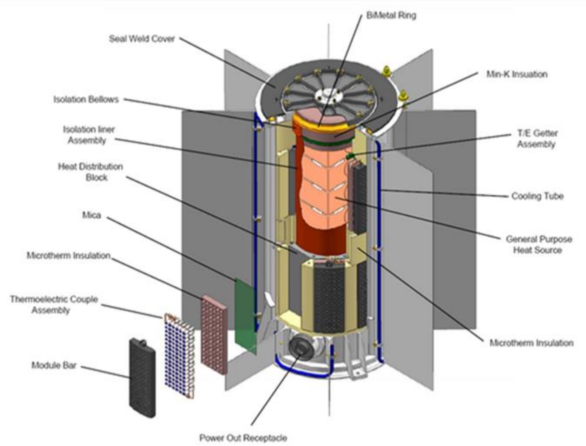
Skutterudite TE Module Technology

https://www1.eere.energy.gov/vehiclesandfuels/

- Skutterudite TE modules have been developed and demonstrated now
  - Demonstrated on U.S. DOE Waste Heat Recovery & Utilization Program - Automotive applications with T_h ~ 500°C
  - Now Demonstrated in High-Power-Density designs applicable to terrestrial power generation with T_h ~ 450-500°C
    - Industrial Processing energy recovery
    - Aircraft energy recovery
    - Oil and Gas system energy recovery
  - They are robust, high performance, structurally stable, and capable of handling thermal cycling
  - Interface designs are being refined and optimized

Skutterudite TE modules are here
They are now being refined for different applications

- Skutterudite TE module technology also being extended to higher temperature (T_h ~ 600°C) spacecraft power applications
  - Potential eMMRTG spacecraft power systems to Mars, Ocean Worlds, Icy Moons, and outer regions of our solar system (Saturn, Uranus, Neptune, and beyond)
  - Interface designs are being refined and optimized



Summary & Conclusions

- High power density all-skutterudite TE modules under development and demonstration at JPL
- Module requirement driven from high specific power system-level requirement in current terrestrial application
- Requirements for TE module design driven by efficiency-power-specific power-heat flux map
- High power density all-skutterudite modules showing excellent power density
  - Power flux > 3.8 W/cm^2 (Module Footprint Area)
  - Power flux ~9.2 W/cm^2 (TE Element Area)
  - T_h ~525°C and T_c ~ 20°C
  - Highest Power – Highest Power Flux All-SKD TE Module ever at JPL
- Excellent agreement between experimental data and model predictions
- Module fabrication and testing on-going to improve performance even further
- Next Step is high-power-density segmented TE module & Transition to Industry

ACKNOWLEDGMENTS

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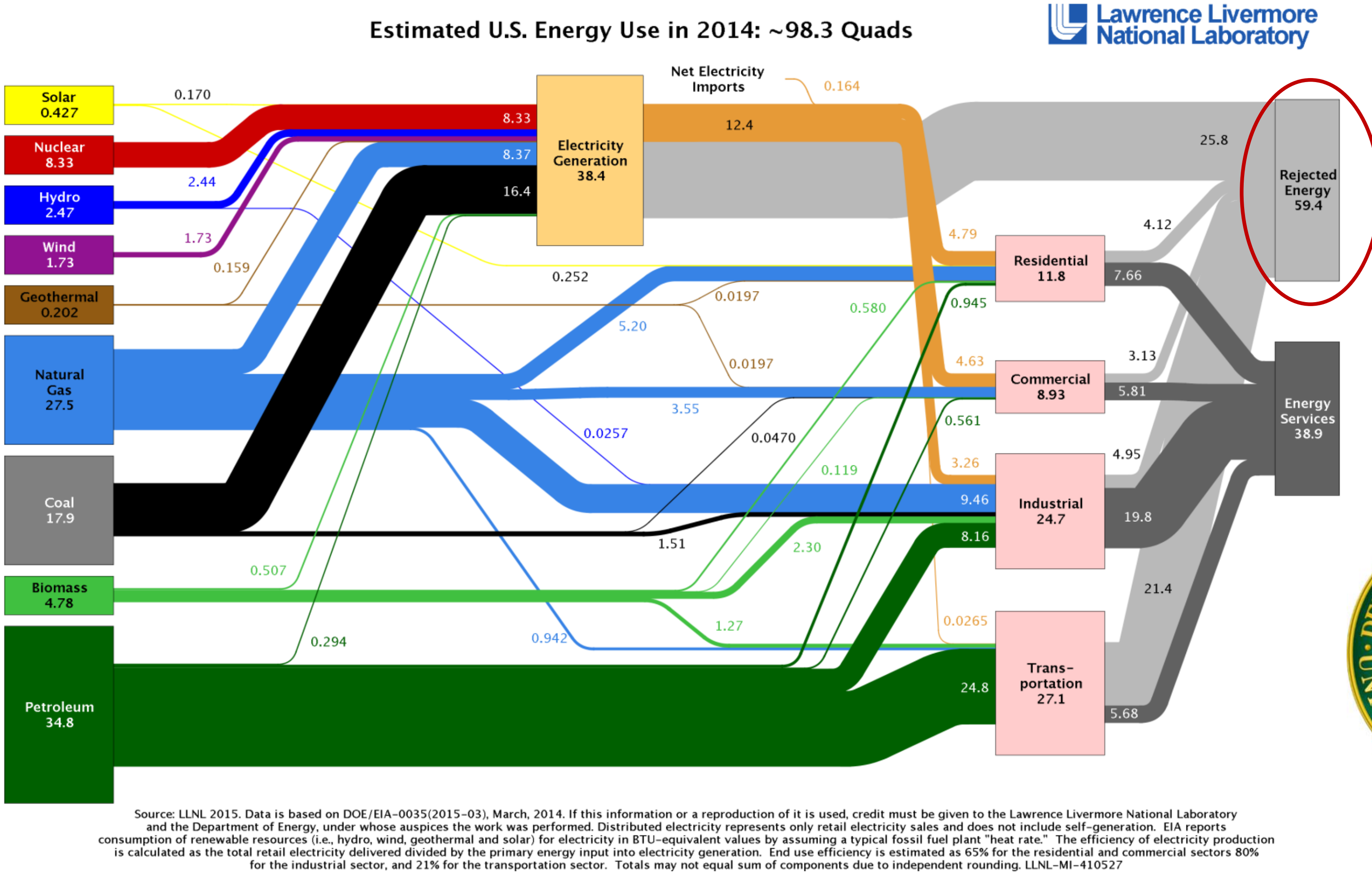
Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov

United States Energy Flow



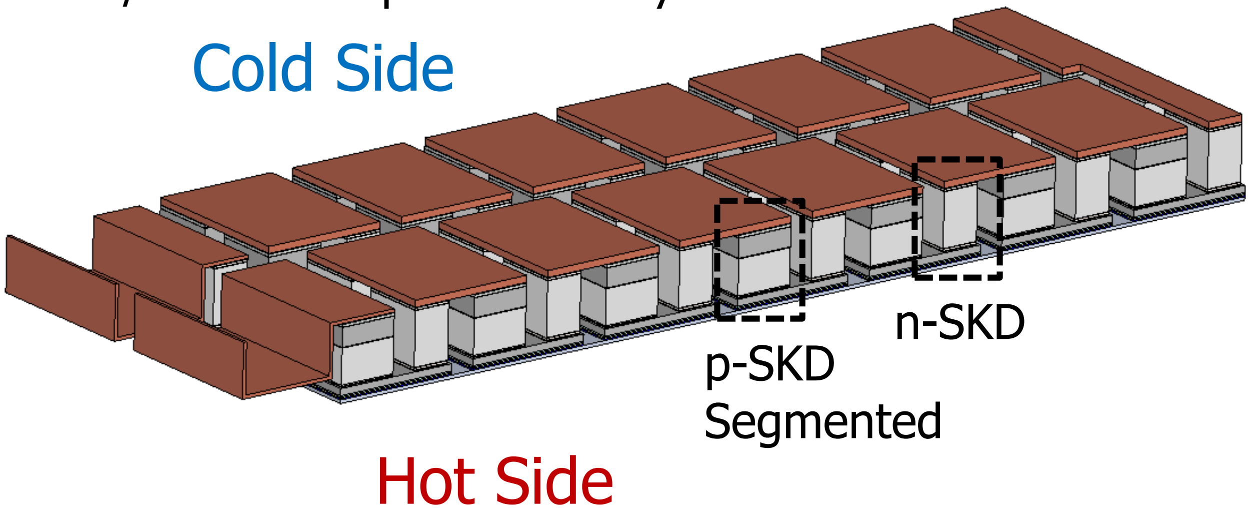
- Waste Heat To Be "Harvested"

  59.4 Quads

- Up ~ 5Quads From 2009

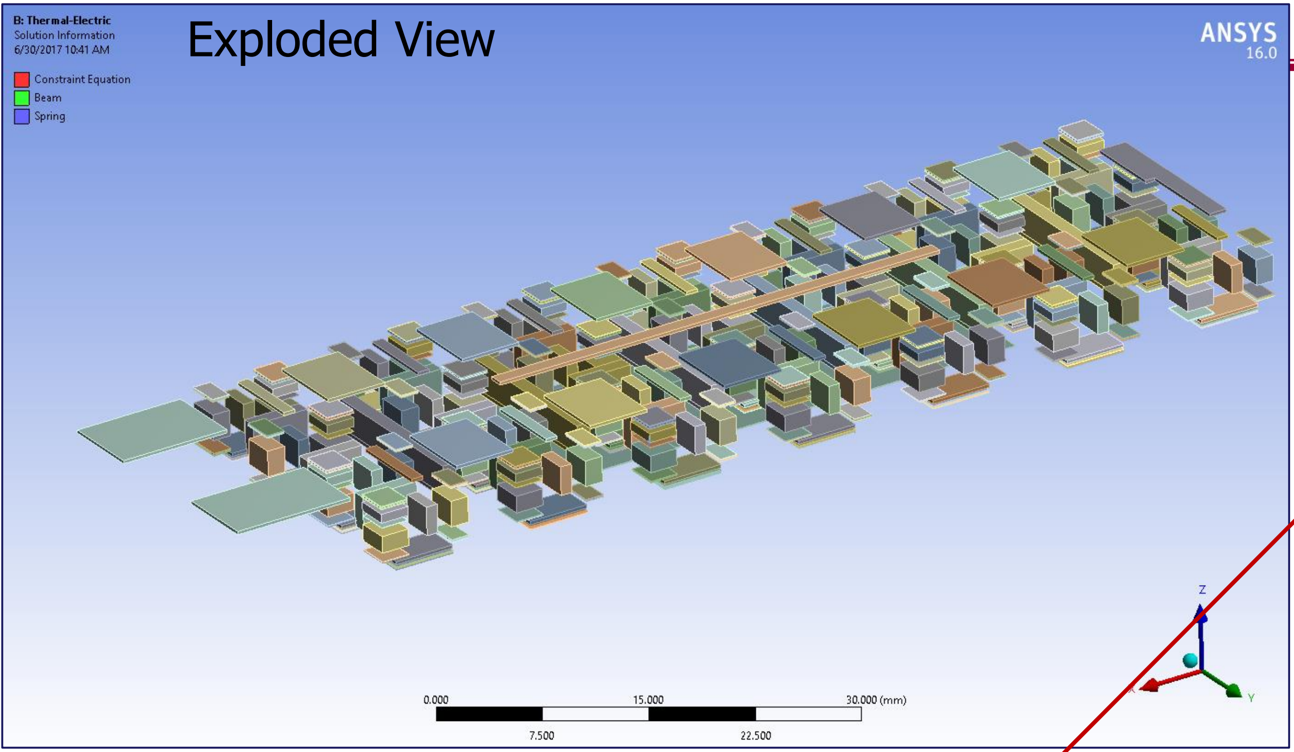
¼ Module CAD Description

- SolidWorks CAD Modeling
- SolidWorks CAD Information Transferred into Several FEA Environments
  - Electrical/Thermal/Thermoelectric Analyses
  - Structural Stress/Thermal Expansion Analyses



- 28 Couple Module
- Series/Parallel Connection
- Critical Interface Layers Designed In
  - Couple Electrical Isolation
  - Material Diffusion Layer
  - Bonding Metallization Layer

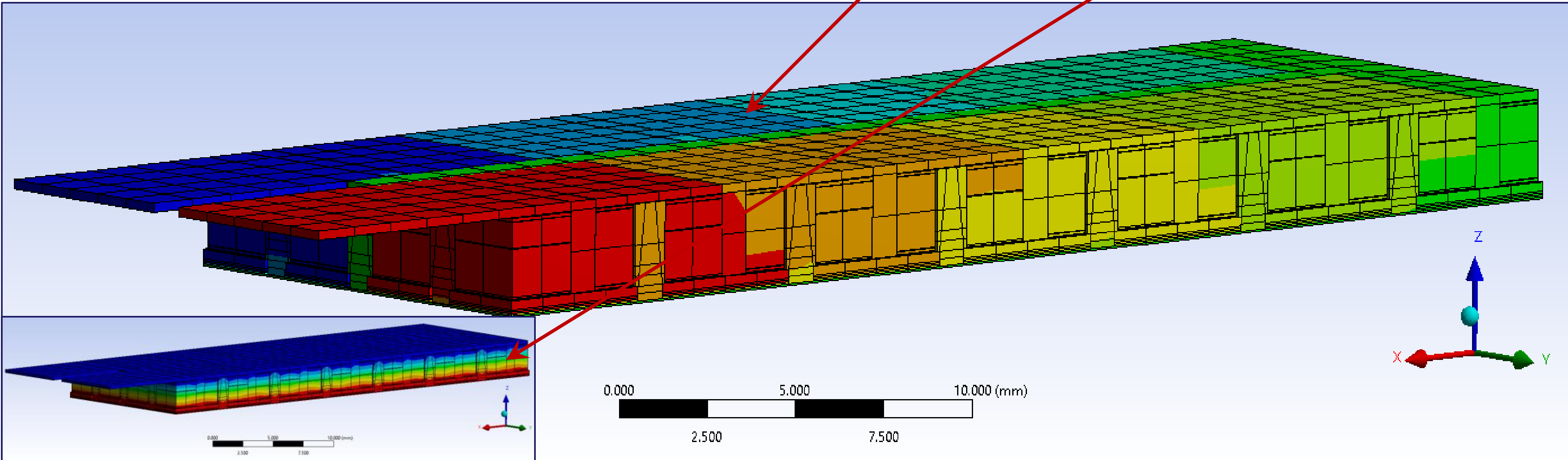
¼ Module FEA – High Resolution FEA Guiding Design



- Aerogel Incorporated in the Design.
- Bonded Contacts.
- Mesh Statistics, Nodes:27292, Elements: 46.39

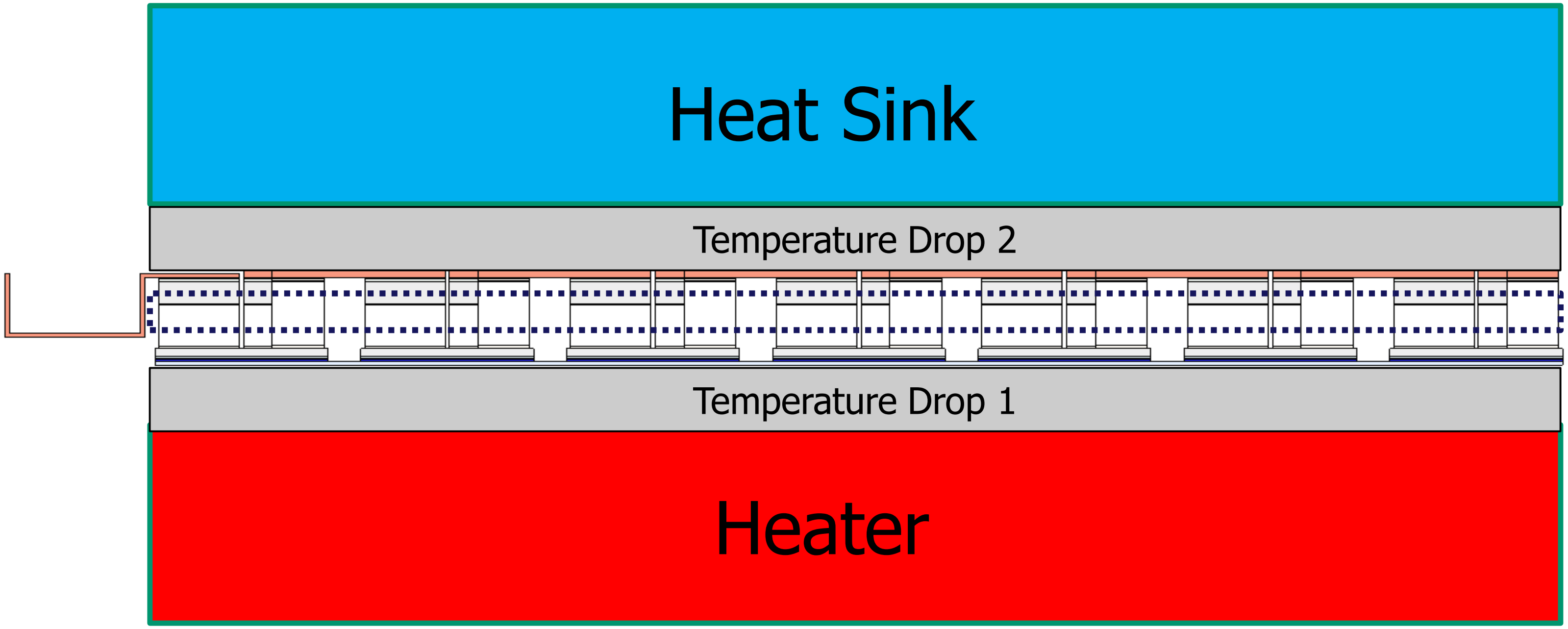
- Voltage Distribution
  Red: Voc
  Blue: Ground

- Temperature Distribution
  T_{Hot} ~ 700 K
  T_{Cold} ~ 290 K



¼ TE Module Technical Challenges

- ❑ Temperature Drops Across Hot and Cold Side Interfaces.
- ❑ Average Electrical Contact Resistance Between Components.



Analytic Approach

- ❑ Temperature Drops due to Interface Thermal Resistance are Estimated Based on Measured Value of Open Circuit Voltage (Voc) and Measured T_{Cold}. (Verified via testing)
- ❑ Hence, T_{Cold} is Kept Constant and T_{Hot} is varied until Calculated V_{oc} matches Measured Value.
- ❑ Average Electrical Contact Resistance Between Components is Subsequently Calculated Based on Measured I-V curve.