Advanced Soldier Thermoelectric Power System for Power Generation from Battlefield Heat Sources

SERDP Project #SI-1652

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SERDP

Our Project Team Would Like to Express our Sincerest Thanks to *Dr. John Hall, Sustainable Infrastructure Program Manager*, Strategic Environmental Research & Development Program Office and *Ms. Carrie Wood, Technical Monitor*, *HGL, Inc.* for their Support and Funding of this Project.

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Project Technical Objective

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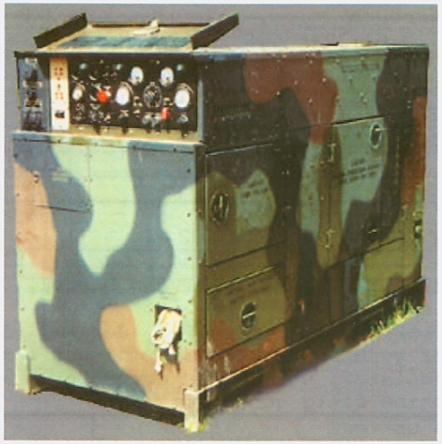
- **Develop a Light-Weight, Small-Form-Factor, Soldier-Portable Advanced Thermoelectric Power (TEP) System**
  - Develop Bench-Scale Prototype to Recover & Convert Waste Heat
  - Variety of Deployed U.S. Army and Marine Equipment
    - Diesel Generators/Engines, Incinerators, Vehicles, & Potentially Mobile Kitchens
- **Achieve Power Conversion Efficiencies of ~10% (Double Current TE System Efficiencies) With Operating Power System Output of ~1.6 kW**
- **Research & Solve Never-Before-Addressed System Integration Challenges**
  - Segmenting LAST (Lead-Antimony-Silver-Telluride) Compounds & Bi_2Te_3 TE Materials in Operating TEP System
  - Thermal Expansion, Thermal Diffusion, Electrical Interconnection, Thermal & Electrical Interfaces in Thin "TE power panels" With Segmented LAST/ Bi_2Te_3

Project Summary

- Advanced TE Materials and Micro-Technology Designs Combined into Operating 1.6 kW TEP System (3-Phase Program)
- Bench-Scale Prototype Testing (Phase 2)
- Application-Scale Testing @ U.S. Army Aberdeen Testing Center
  - Adapted to Tactical Quite Generator (TQG) in Phase 3 Application-Scale Testing
  - Potentially Applied to Several Battlefield Heat Sources, But TQG Being Used as the Test Bed Demonstrator
  - Reduce Base Fuel Consumption or Provide More Power Output

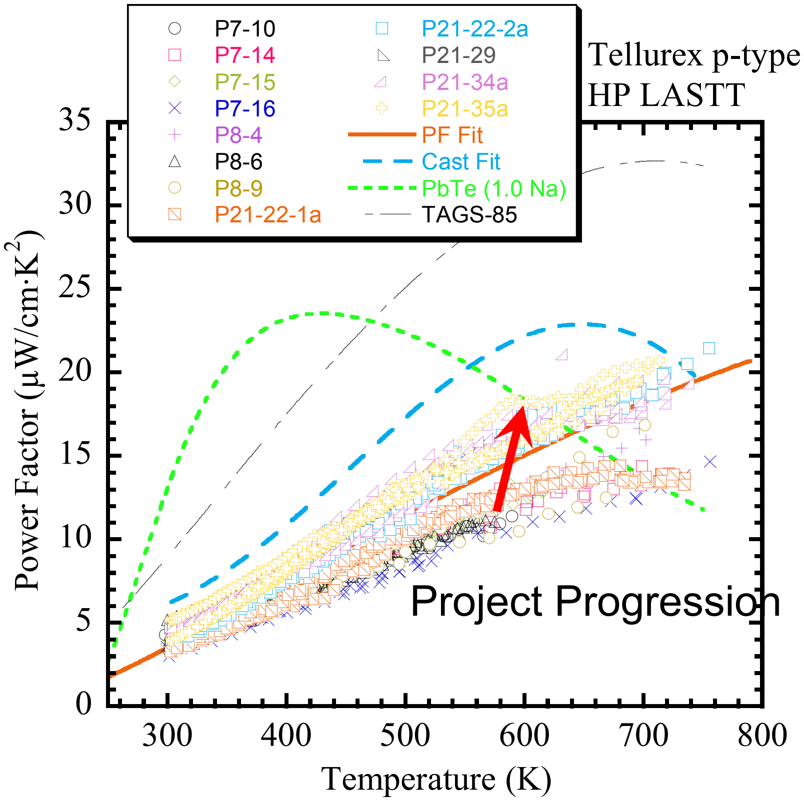
30 kW TACTICAL QUIET GENERATOR

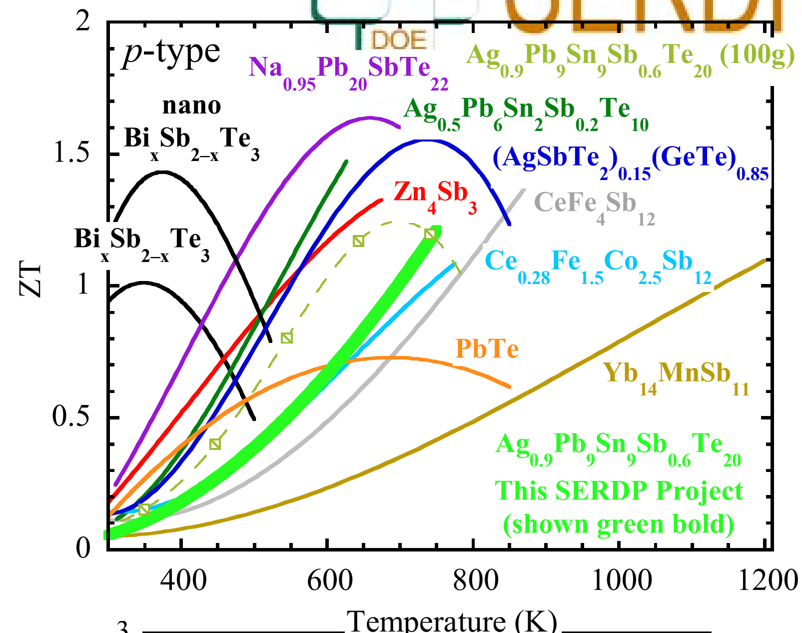


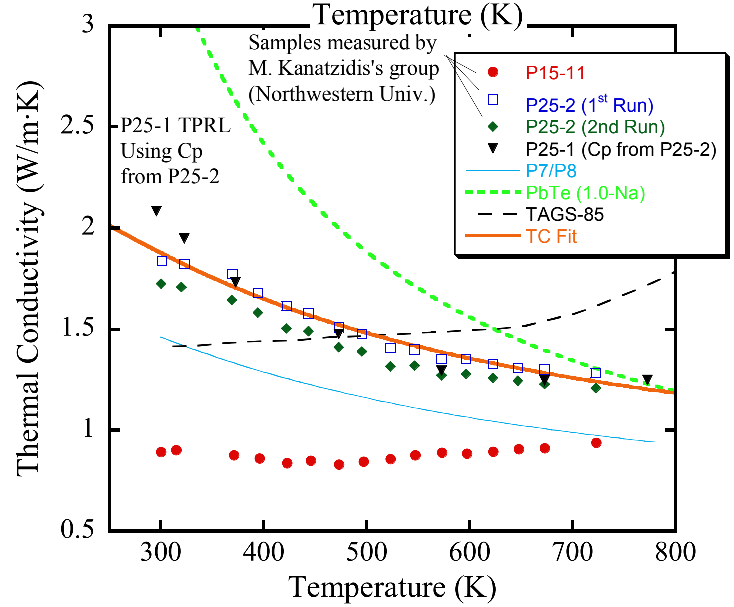
MEP-805A or MEP-815A

Segmented Element R&D Results

Properties of Tellurex P-type Samples





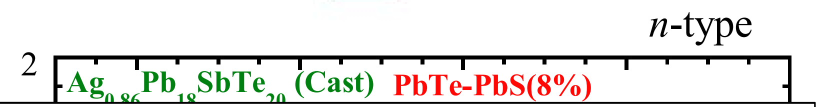


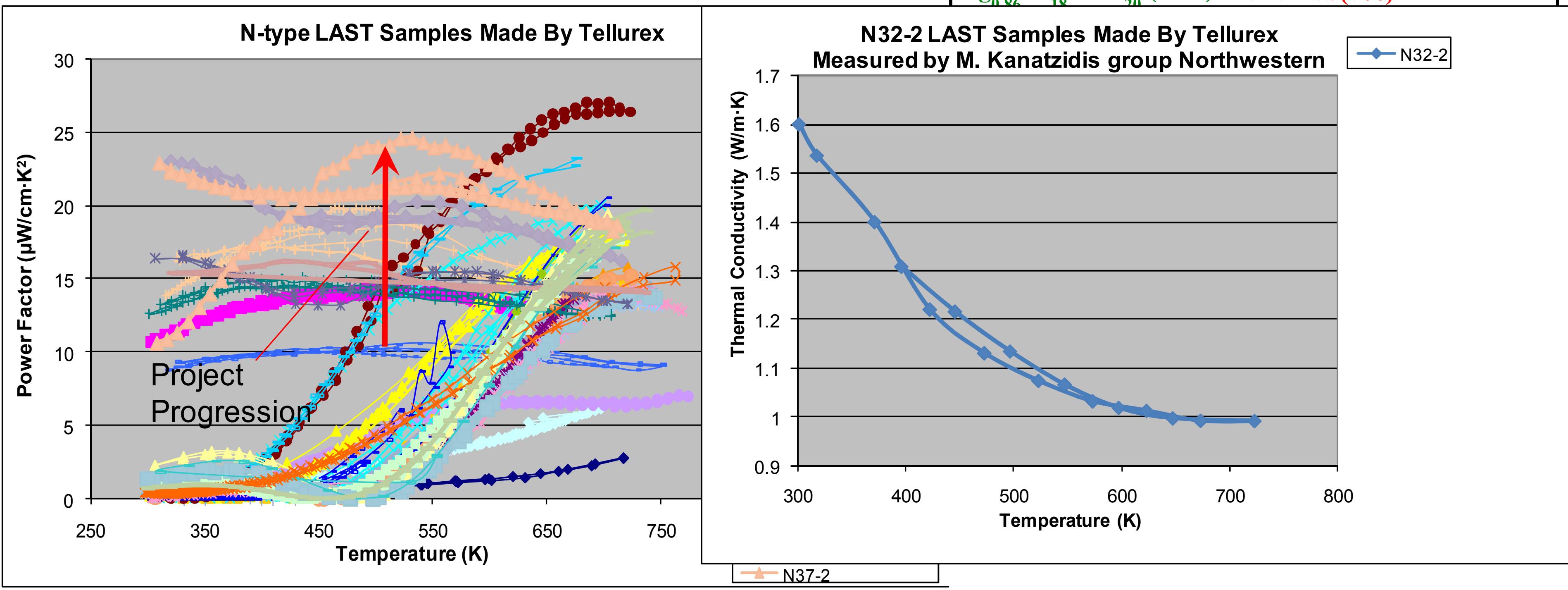
- P-type LASTT TE Materials Quite Reproducible & Showing Power Factor Improvements
- Starting to Approach the Performance Levels of Cast LASTT Materials

Segmented Element R&D Results

Properties of Tellurex N-type Samples

Higher Pb content has a doping effect and moves the peak of the power factor to higher temperatures





- N-type LASTT TE Materials Showing Power Factor Improvements
- Starting to Approach the Performance Levels of Cast LASTT Materials
  - Peak ZT Increasing
  - Shallower ZT Slope

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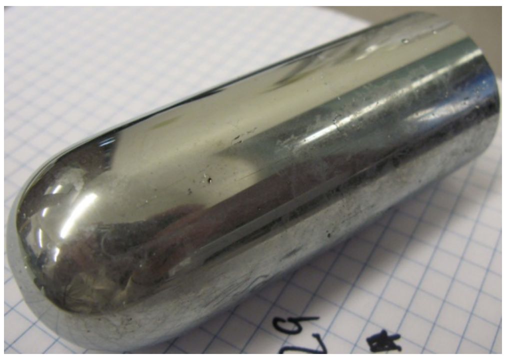
TE Material Thermal Stability Studies

Material Processing to Support Testing

Ingot



Material Processing

Powder

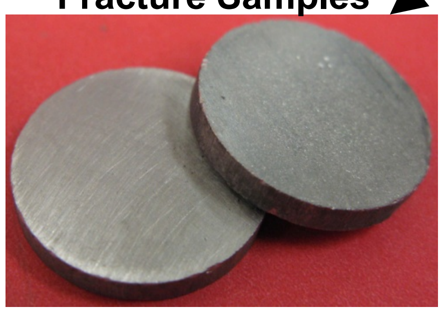
Cold Pressing

Hot Pressing

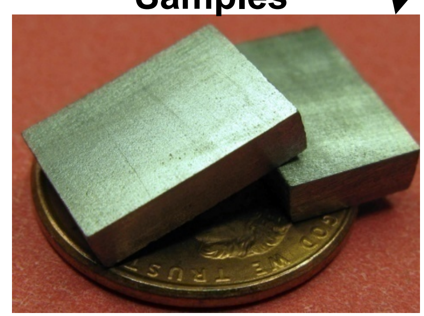
Sintering

Raw Wafers

Biaxial Flexure Fracture Samples



Thermal Fatigue Samples



Thermal fatigue testing

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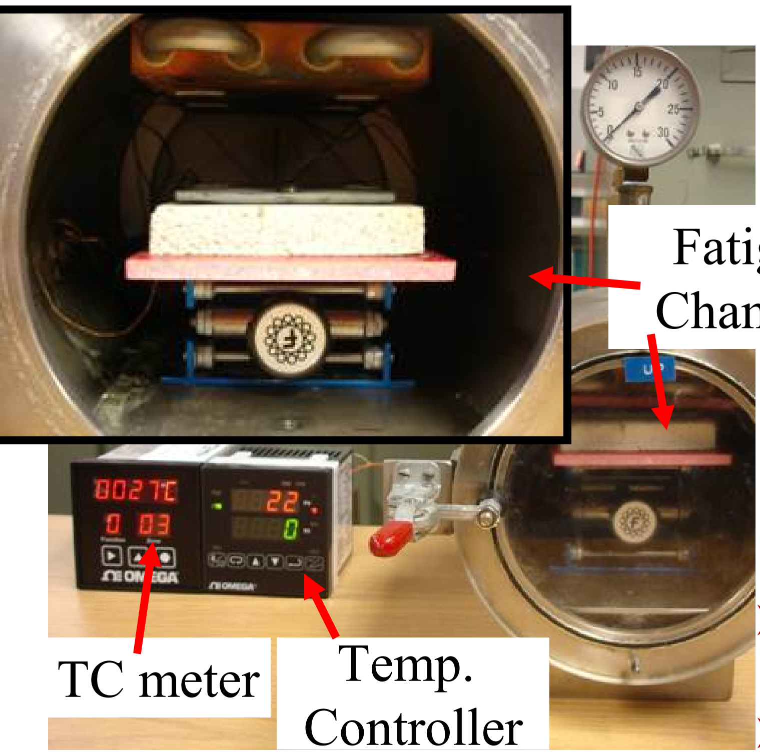
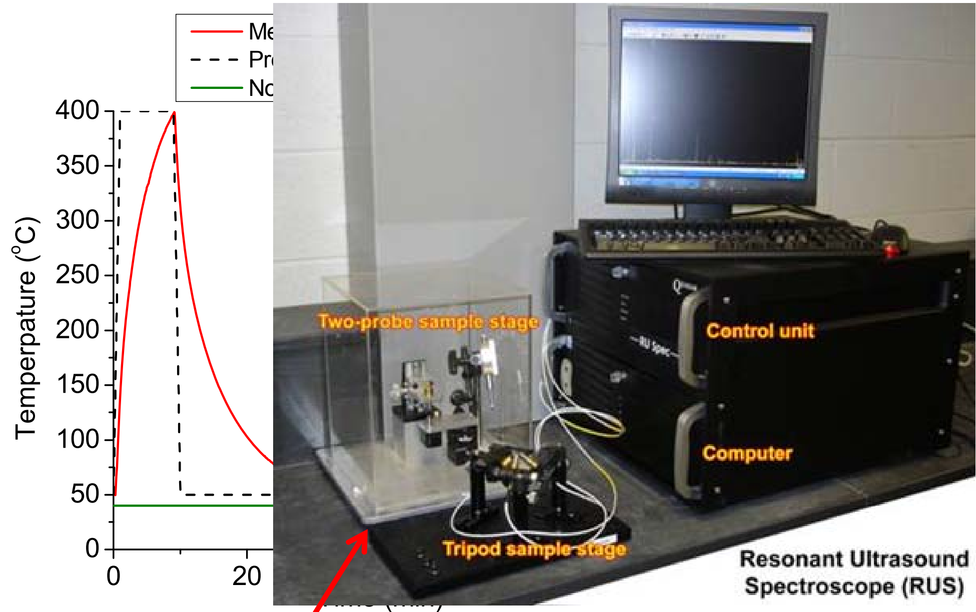
Evolution of Thermal Fatigue Damage Monitored Through Elastic Moduli

- LAST, LASTT and undoped PbTe specimens placed in a chamber - Argon gas
- Specimens undergo up to 200 thermal fatigue cycles (50 C – 400 C)
- Specimen temperature monitored during thermal fatigue process





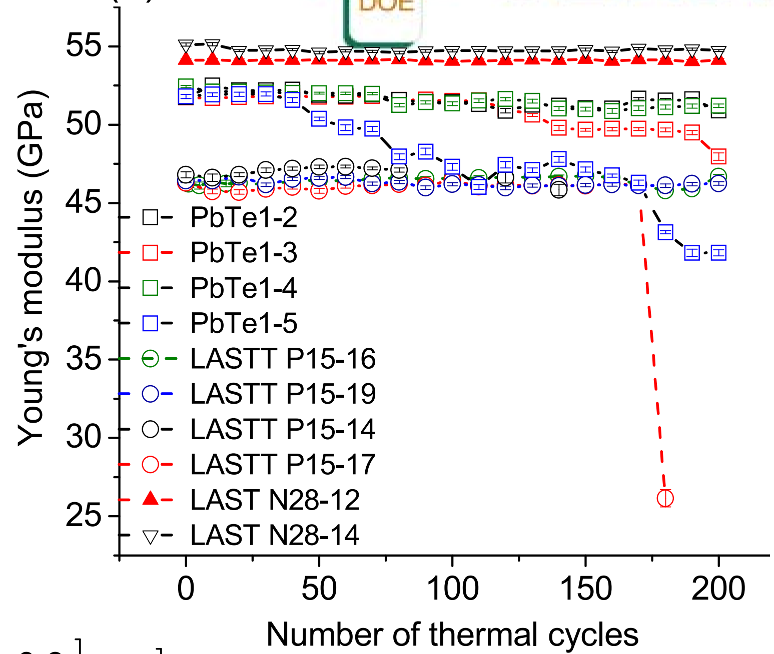
- Young's modulus and the Poisson's ratio measured using the Resonant Ultrasound Spectroscopy (RUS)
- Fracture strength in biaxial flexure -- accommodates disc-shaped specimens

Young's modulus, E, versus N results

Number of specimens tested: LASTT (4), PbTe (4), LAST (2)

LASTT results

- Latest specimens survived the 200 thermal cycles without appreciable decrease in E
- One specimen broke into two pieces following the 170th cycle.
- One specimen, E dropped from 46.4 GPa (N = 170) to 26.1 GPa (N =180 --> substantial increase in crack damage between 170 and 180 thermal cycles.

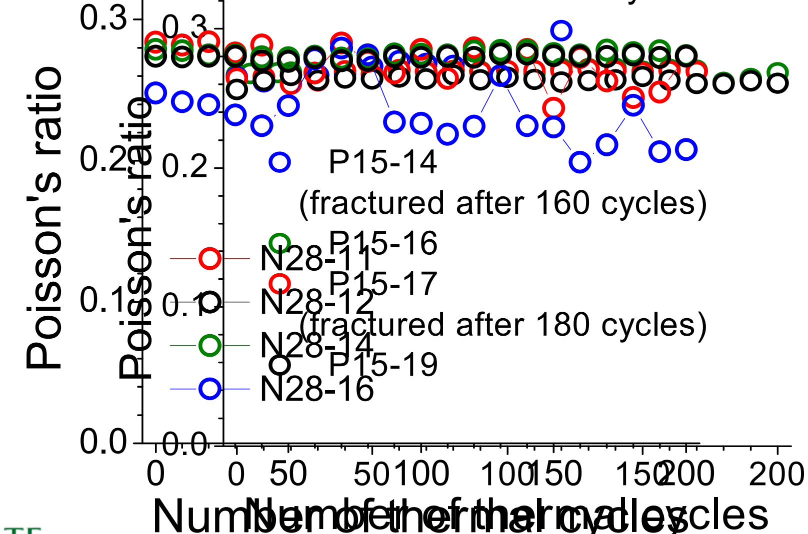


LAST results

- E for the two LAST specimens decreased by less than 0.7 % for N = 200.

Undoped PbTe results

- E for two of the PbTe specimens decreased by only about 2 percent for N = 200
- Other two specimens, E decreased by eight percent and 20 percent, respectively.



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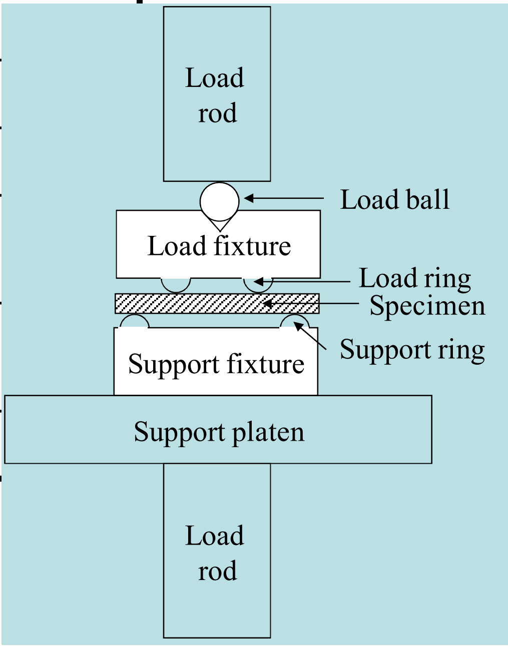
Mean biaxial fracture strength of specimens tested to date in this study

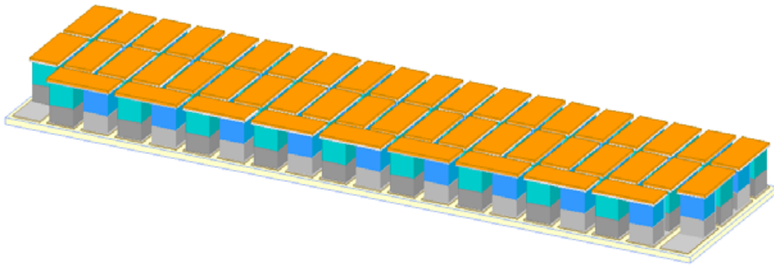
Material	Specimen	Condition	Test	N_{valid}/N_{total}	Strength (MPa)
LASTT	P14	As-received	BOR	6/10	46 ± 4
	P15	Polished	BOR	6/10	58 ± 8
	P15	As-received	ROR	9/10	32 ± 5
	P15	30 thermal cycles	ROR	9/10	30 ± 5
PbTe	PbTe1	As-received	ROR	10/10	19 ± 6
	PbTe1	30 thermal cycles	ROR	16/20	20 ± 3
	PbTe2	30 thermal cycles	ROR	10/10	15 ± 4
	PbTe2	Annealed 400°C 2hr	ROR	7/10	22 ± 3
	PbTe2	Annealed 500°C 2hr	ROR	10/10	15 ± 6
LAST	N37	As-received	ROR	7/8	26 ± 4.4

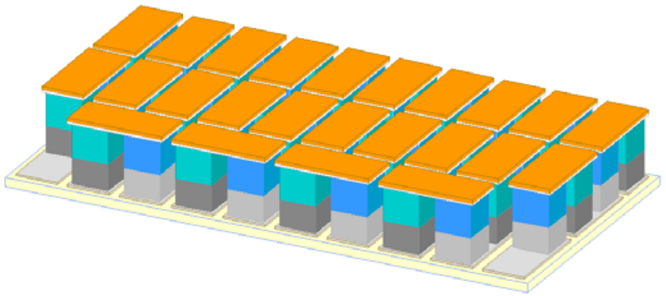


Ring-on-Ring Biaxial Flexure Test (ASTM Standard C1499-05)

R&D TE Device (design & circuit layout)

TE Module Fabrication with LAST/Bi_2Te_3

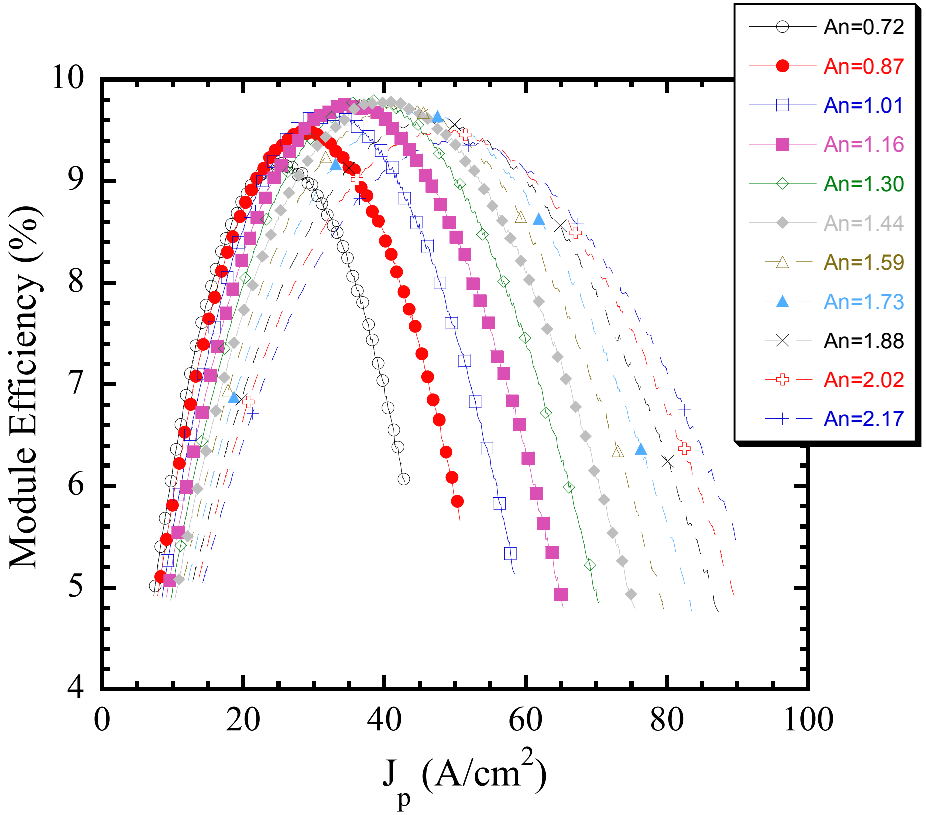


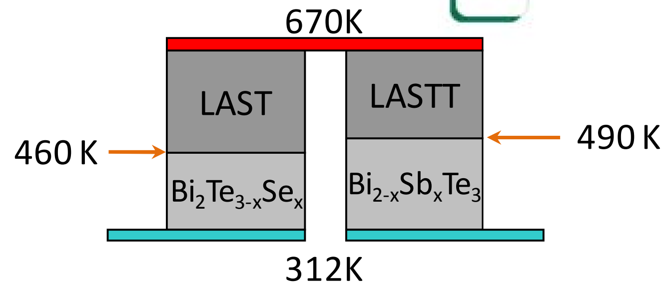


- Tellurex Working On 2 Segmented Module Designs
  - 49 Couples
  - 24 Couples
- Intended to Fit on 7.6 cm X 2.0 cm Heat Exchanger Footprint
- Module Efficiency ~9% (Including Contact Resistance Effects; 670 – 312 K)
  - Current Status with Current LAST/LASTT Material Performance
  - Seeking Further Material Progress to Allow us to Improve this Result to 10%

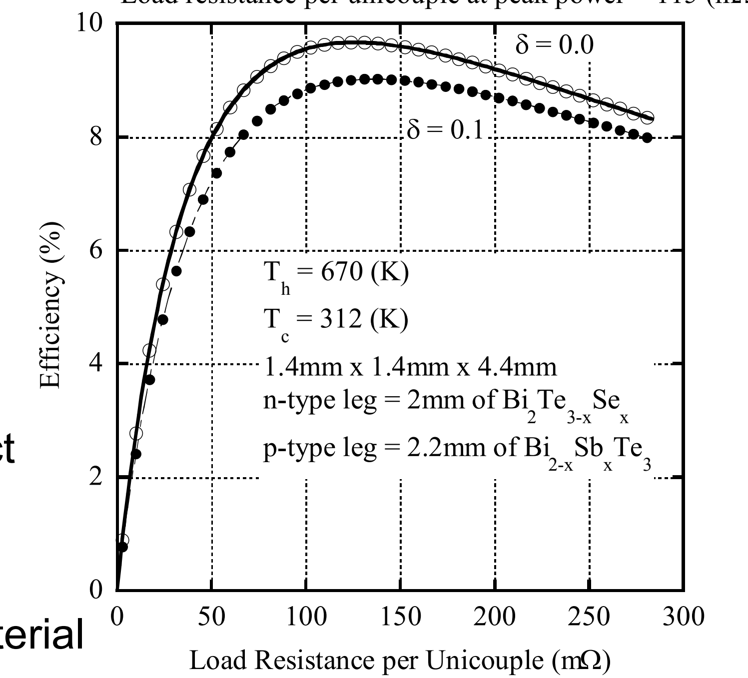
Segmented Element R&D Results

Efficiency for Segmented Legs with Tellurex Samples





For δ = 0.1
Current output at peak power = 0.73 (A)
Load resistance per unicouple at peak power = 115 (mΩ)



† Modeling software developed under ONR support.

- η = 9.8% (Ideal, No Contact Losses); 9.0% With Contact Losses)
- Heat flux to TE material hot side q_h = ~12 W/cm^2
- Module Efficiency Quite Good Given the Number of Material "Process Parameters" We Are Trying to Control

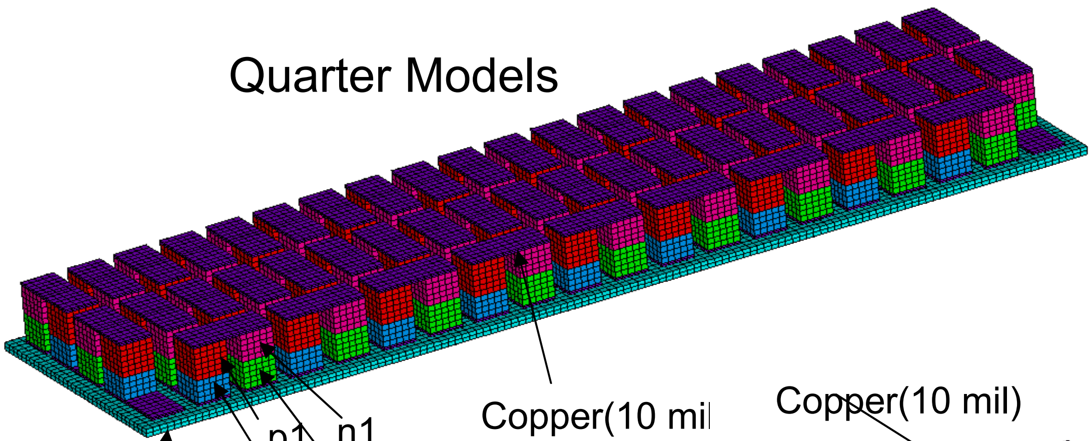
Thermal - Structural Analysis Results

p1: Tellurex LAST n1: Tellurex LAST

p2: p_Bi2Te3 n2: n_Bi2Te3

Configuration 1

Quarter Models



Module Dimensions:

Length: 72.91 mm

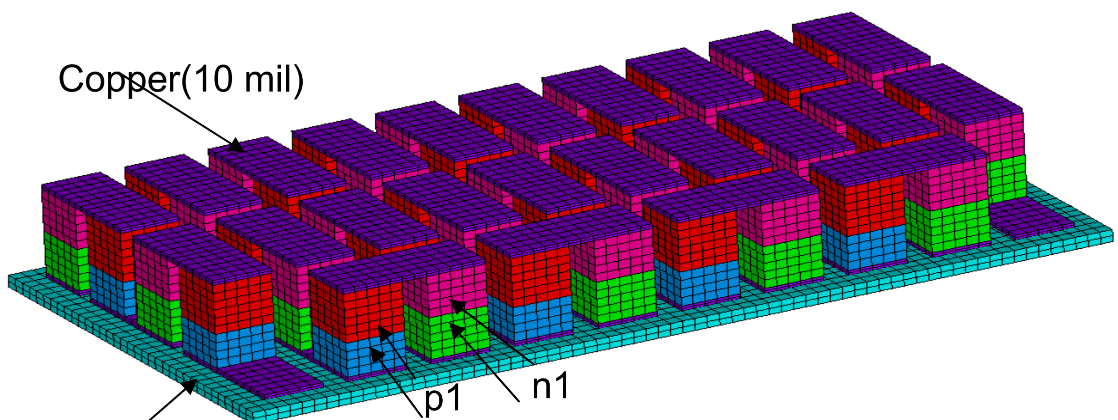
Width : 18.46 mm

Configuration 2

Module Dimensions:

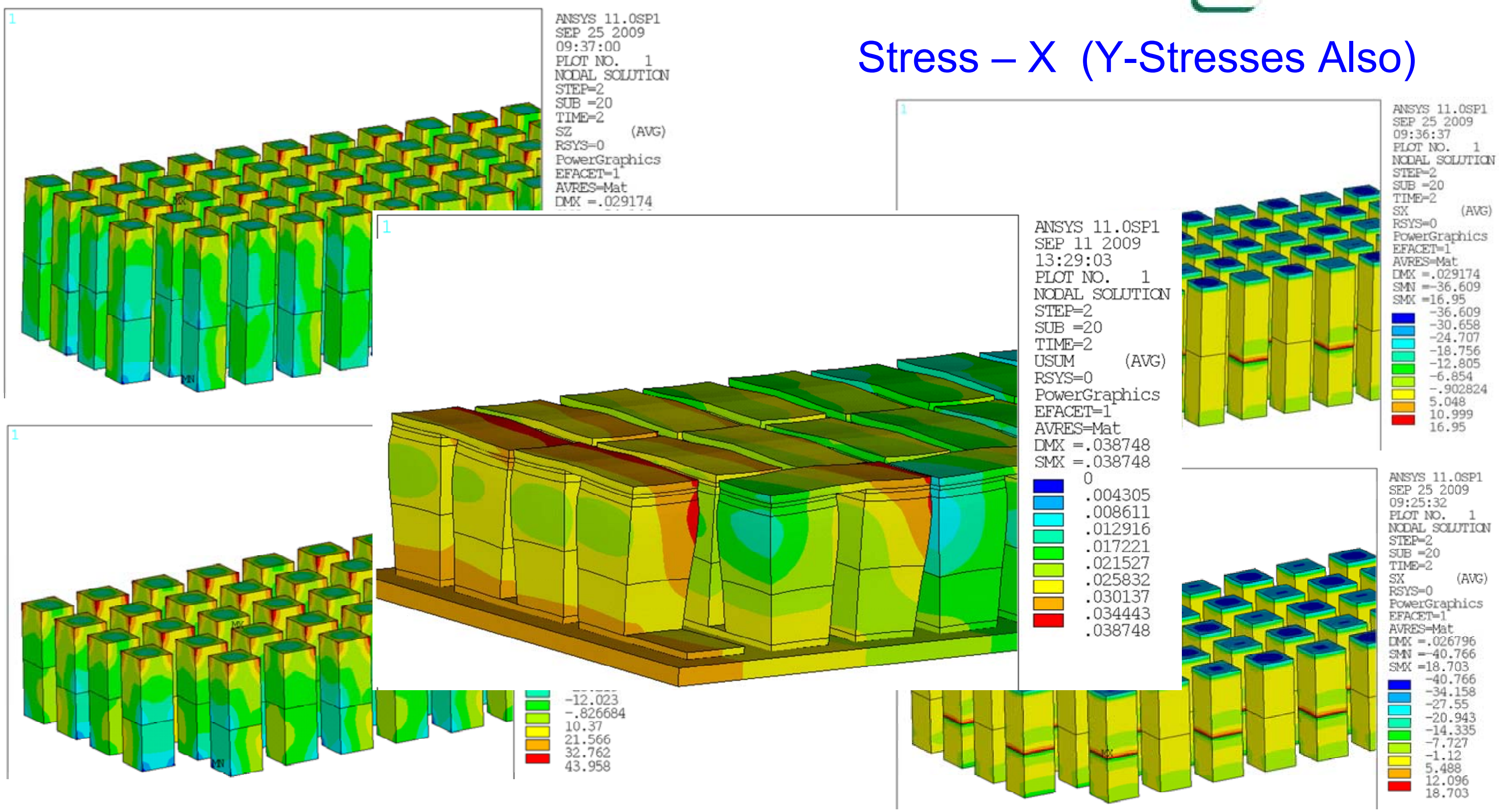
Length: 36.61 mm

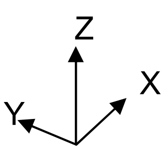
Width : 18.46 mm



Stress - Z

Stress – X (Y-Stresses Also)





- Using Structural Analysis to Define Critical Interface Materials & Element Design
- Structural Stresses Controlling Element Design as Much as TE Properties
- X- and Y-Stresses OK
- Z-Tensile Stresses Creating Small Challenges Due to Expanding Cu

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Microchannel Heat Exchanger Design Results

- Hot-Side & Cold-Side Heat Exchanger Designs Exhibit High Heat Flux Capability
  - 12 W/cm^2 on Hot-Side
  - While Providing:
    - 670 K TEG Hot-Side Temperature
    - 312 K TEG Cold-Side Temperature
  - Allows for Compact System Design
  - 11 W/cm^2 on Cold-Side
- Materials
  - Hot-Side Design: Stainless Steel 304 or 316
  - Cold-Side Design: Copper or Aluminum
- Each Heat Exchanger: 7.6 cm x 2.0 cm Heat Transfer Footprint

Hot-Side Microchannel Heat Exchanger Designs

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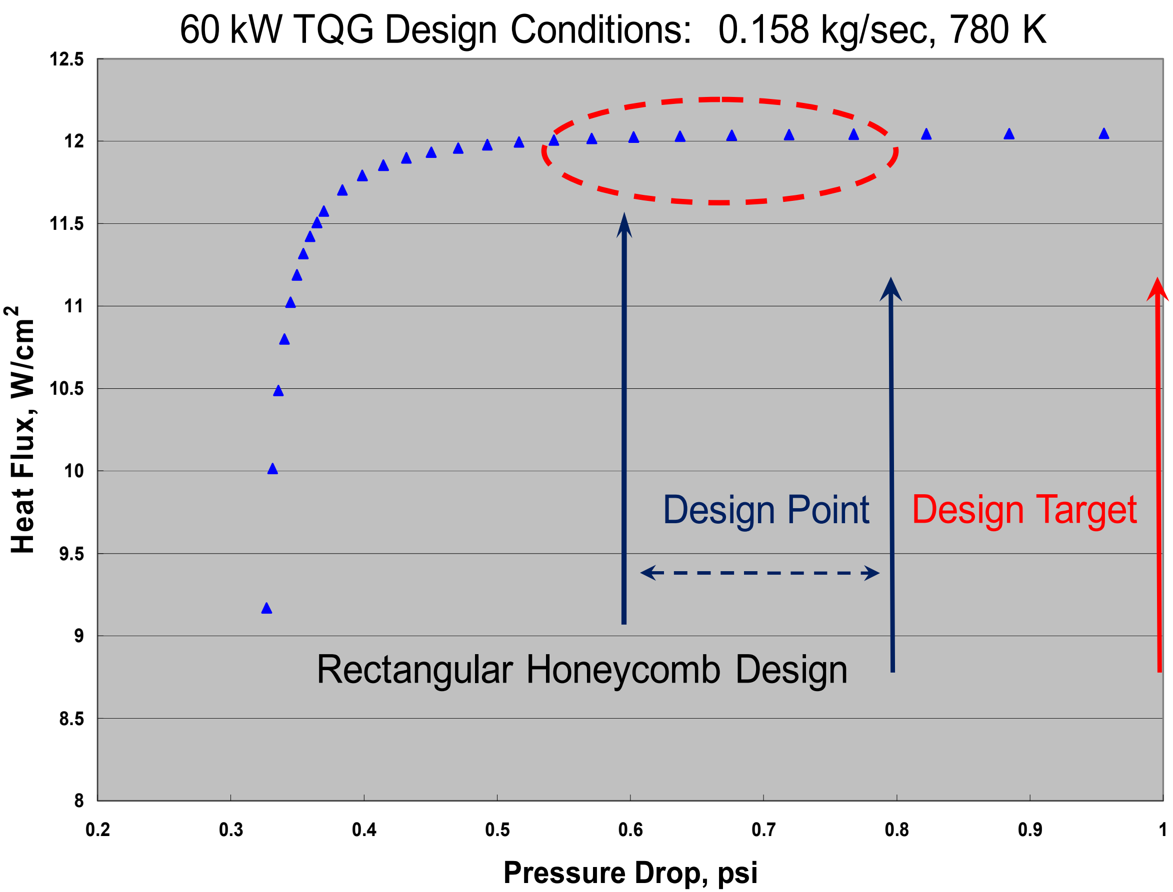
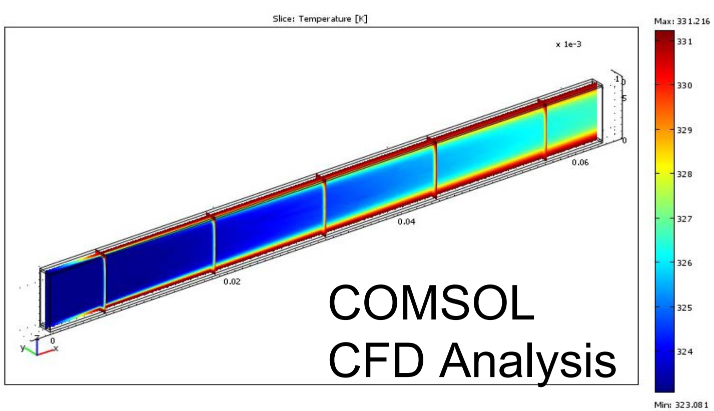
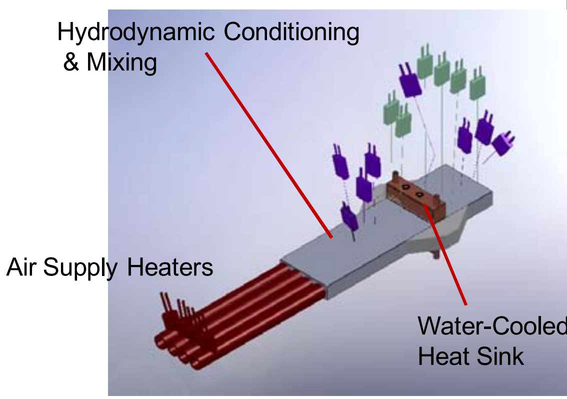


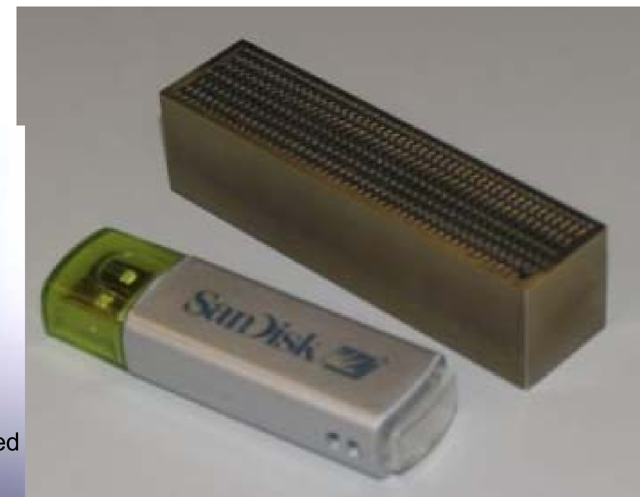
- Various Hot-Side Heat Exchanger Design Concepts Have Been Studied
- Anticipated Hot Side Heat Flux Determined
  - Pressure Differential Dependency Established
  - TQG Exhaust Flow Conditions
  - Given Exhaust – Device Hot Side Temperature Differential
- Hot-Side Heat Flux-Pressure Differential Tradeoff Is Clear

Microchannel Heat Exchanger Designs

- Exploratory Heat Exchanger Test Specimens Fabricated
- Hot-Side Heat Exchanger Design Developed & Being Refined
- Hot-Side Heat Exchanger Testing in Next Project Phase
- Performance Goals:
  - High Thermal Transfer Flux (~12 W/cm2) in Hot-Side Heat Exchanger
  - Low Pressure Drop (< 1 psi)
  - Heat Flux vs. Pressure Drop Characteristics Quantified for Different Design Approaches
- Integrate TE/HX Interface Design & Material







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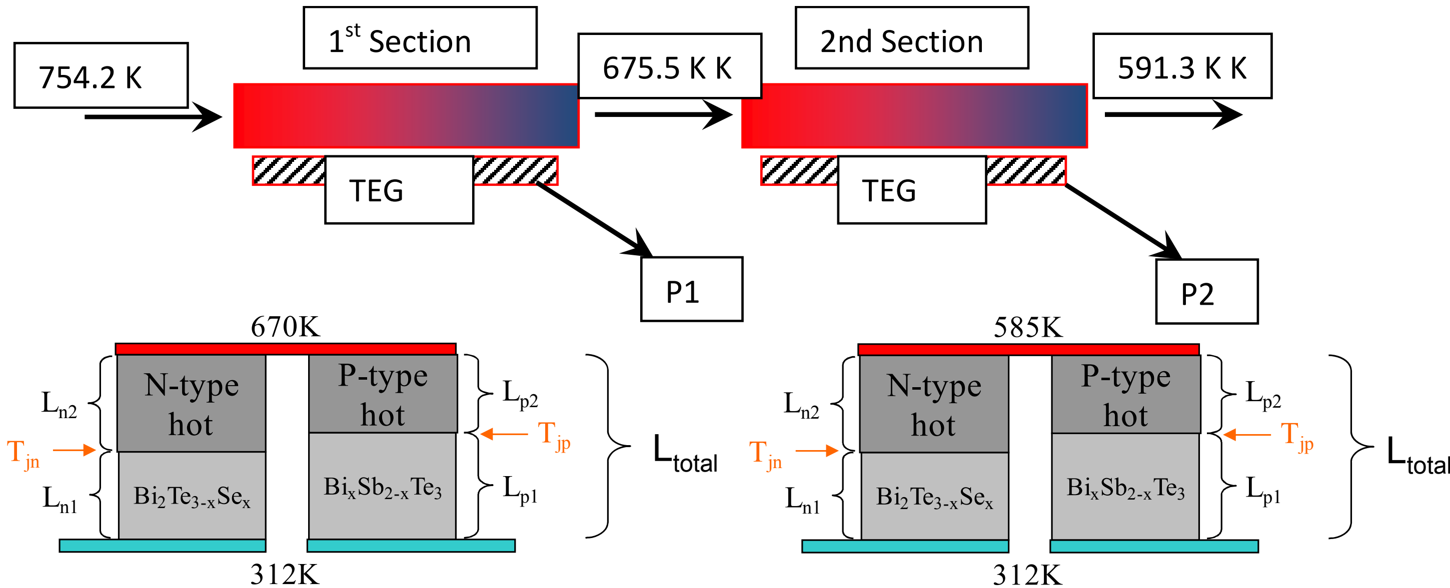
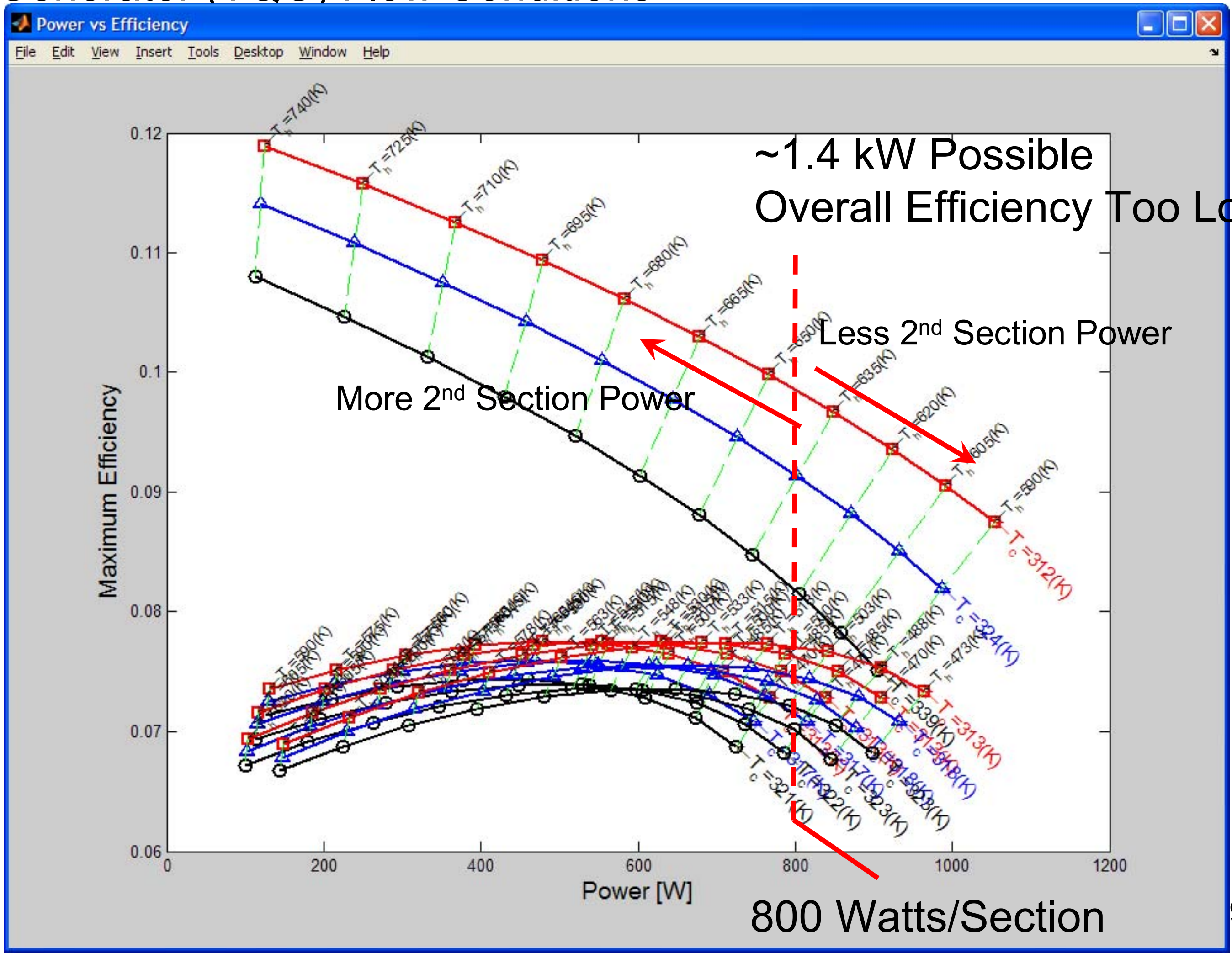
Dual Section Design Approach & Analysis



- Dual Section Design Allows Higher Power @ Highest Efficiency
- 30-kW Exhaust Conditions & Results Shown Above (754 K, 0.097 kg/sec)
- Important Design Tradeoffs Between the Two Sections
- 30-kW Exhaust Conditions Create Designs That Fall Short of Project Goals
  - 1.4 kW, ~8.1% Efficiency
  - Still Significant Opportunity in TQG's

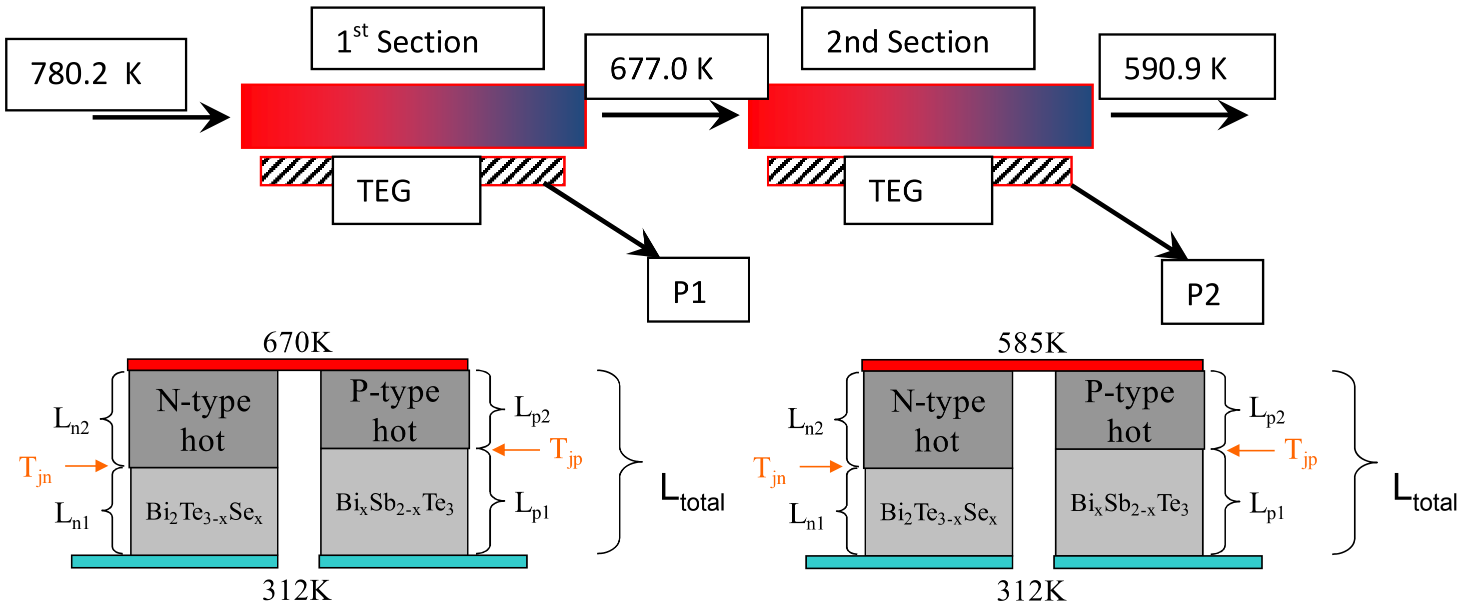
Dual - Section TEG Design Analysis

- LAST/LASTT/Bismuth Telluride Segmented in First Section; Bismuth Telluride In Second Section
- 30 kW Tactical Quiet Generator (TQG) Flow Conditions
  - 0.1 kg/sec
  - 754 K
  - ~1.4 kW @ 8.8% Possible With ~11% TE Module
  - ~1.4 kW @ 8.1% with 10% Module



Dual Section Design Approach & Analysis

SERDP



- Dual Section Design Allows Higher Power @ Highest Efficiency
- 60-kW Exhaust Conditions & Results Shown Above (780 K, 0.158 kg/sec)
- Important Design Tradeoffs Between the Two Sections
- 60-kW Exhaust Conditions Allow One to Achieve Very Close to Project Goals
  - Single-Section Design Can Almost Achieve Goals (~1.6 kW with a 10% Efficient TE Modules)
  - Dual-Section Design Creates More Power at Slightly Reduced Overall Conversion Efficiency
    - 2.6 kW @ 8.2% System Efficiency

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TEG System Analysis

- Detailed TE System Analysis Has Shown That:
  - 30 kW TQG Enthalpy Flow is Too Low to Achieve Project Objectives
  - Dual-Section Design Could Get 1.4 kW But Only at 8.1% Efficiency
    - Flow Temperature and Mass Flow Rate Simply Too Low
      - 0.1 kg/sec @ 754 K
    - TE Material Properties Simply Not High Enough
- 60 kW TQG Could Provide the Necessary Flow Conditions To Reach Close to Project Goals
  - 0.158 kg/sec @ 780 K
  - Single-Section TEP Design
- Current System Design Is Being Performed Around 60 kW TQG Flow Conditions
- Design Options/Approaches Now Exist for Multiple TQG's

Summary

- LAST/LASTT Materials Making Significant Improvements for Implementation into TE Devices
  - TE Material Properties Improving
  - Structural Properties & Thermal Fatigue Characteristics Being Quantified
- Micro-Technology Heat Exchanger Designs Identified and Test Articles Fabricated
- Flexible & Modular System Design Identified – Key Tradeoffs Quantified
- System Analysis Shows That Project Needs a 60 kW TQG Rather Than a 30 kW TQG
  - Enthalpy Flow is Too Low in 30 kW TQG Exhaust to Meet Original Project Goals
  - However, 30 kW TQG's Still Present a Significant Energy Recovery Opportunity
  - As do 100 kW TQG's
- This Project Provides Pathway for Flexible, Modular System Design to Address All TQG Opportunities and Other Battlefield Heat Sources

BACKUP MATERIAL

These charts are required, but will only be briefed if questions arise.

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Material Properties (Mechanical & Thermal) used in FEA

	Alumina	Copper	LASTT (p1)	LAST (n1)	p_Bi_2TE_3 (p2)	n_Bi_2TE_3 (n2)
*Young's Mod (GPa)	300	129	46.55	54.5	43.6	43.6
**Yield / Fracture Strength (MPa)	2100 (compressive)	~198	30-32(ROR) 46-58 (BOR)	26(ROR)	8-166	8-166
CTE ($x10^{-6}$ / °C)	8.2	Temp Dependent	18	21.3	18	21.3
Thermal Conductivity (W/m°C)	25	Temp Dependent	1.5035	1.25	2.27	1.103

* Properties are approximate averages over T_h to T_c range

** For information only. Not used in FEA.

1st Section Analysis – Th = 670 K, Tc = 312 K					2nd Section Analysis – Th=585 K, Tc = 312 K						
Material Case # / TE Materials	η1-Segmented (%)	Qh1 [W] ε=0.936	P1-Segmented [W]	ηtotal [%]	Material Case # / TE Materials	η2 (%)	Qh2 [W] ε=0.936	P2 [W]	Ptotal [W]	Qhtotal [W]	ηtotal (%)
2. Cast LAST & Bi2Te3 Materials – Best	12.1	.9*17585	1910.3	10.9	Bi2Te3 (only) 28.Best Tellurex LAST/LASTT & Bi2Te3 (Segmented)	7.37 8.34	.9*14398 .9*14398	955.0 1080.7	2865.3 2991.0	31983 31983	9.0 9.4
10. Cast LAST Materials – Average	10.5	.9*17585	1664.9	9.5	Bi2Te3 (only) 28.Best Tellurex LAST/LASTT & Bi2Te3 (Segmented)	7.37 8.34	.9*14398	955.0 1080.7	2619.9 2745.6	31983	8.2 8.6
14. SERDP Project - Average LAST/LASTT Materials	9.5	.9*17585	1503.5	8.6	Bi2Te3 (only) 28.Best Tellurex LAST/LASTT & Bi2Te3 (Segmented)	7.37 8.34	.9*14398	955.0 1080.7	2458.5 2584.2	31983	7.7 8.1
12. SERDP Project - Best LAST/LASTT & Bi2Te3 Materials	10.1	.9*17585	1598.5	9.1	Bi2Te3 (only) 28.Best Tellurex LAST/LASTT & Bi2Te3 (Segmented)	7.37 8.34	.9*14398	955.0 1080.7	2553.5 2679.2	31983 31983	8.0 8.4
8. SERDP Project - LAST/LASTT With Zhou-based Process on n-type, Best Tellurex LASTT & Bi2Te3 Materials	10.9	.9*17585	1725.1	9.8	Bi2Te3 (only) 25.Zhou Process on n-type, Best Tellurex LASTT & Bi2Te3 (Segmented))	7.37 8.76	.9*14398	955.0 1135.1	2680.1 2860.2	31983 31983	8.4 8.9
7. TAGS-85/PbTe & Bi2Te3 Materials	11.4	.9*17585	2001.2	10.2	Bi2Te3 (only) 21. TAGS-85 /PbTe & Bi2Te3 Materials	7.37 9.2	.9*14398	955.0 1192.2	2956.2 3193.4	31983 31983	9.2 10.0
4. n-type $Ba_xYb_yCo_4Sb_{12}$ Skutterudites & TAGS-85 & Bi2Te3 Materials	11.7	.9*17585	2055.7	10.5	Bi2Te3 (only) 28.Best Tellurex LAST/LASTT & Bi2Te3 (Segmented)	7.37 8.34	.9*14398	955.0 1080.7	3010.7 3136.4	31983	9.4 9.8
15. n-type $Ba_xYb_yCo_4Sb_{12}$ Skutterudites, Best Tellurex LASTT & Bi2Te3 Materials	10.7	.9*17585	1693.4	9.6	Bi2Te3 (only) 30. n-type $Ba_xYb_yCo_4Sb_{12}$ Best Tellurex LASTT & Bi2Te3 (Segmented))	7.37 8.8	0.9*14398	955.0 1140.3	2648.4 2833.7	31983	8.3 8.9

Room temperature mechanical properties for selected wide and narrow band gap semiconductors

Mat'l	E (GPa)	υ	K_c (MPa-$m^{0.5}$)	σ_f / (MPa)
Si	163 [p]	0.22 [p]	0.7 [a]	247 [s]
Ge	128 [l]	0.21 [l]	0.60 [j]	231-392 [q]
GaAs	117 [j]	0.24 [j]	0.46 [d]	66 [m]
PbTe	58	0.26		
LAST/-T (MSU)	24.6 – 71.2	0.24 – 0.28	--	15.3 – 51.6
PbTe (Tellurex)	51.7 – 52.5	0.26 – 0.28	--	15 – 20 (ROR)
LAST (Tellurex)	54 – 55	0.27 – 0.28	--	~ 21-30 (ROR) Average: 26
LASTT (Tellurex)	46.3 - 46.8	0.26 – 0.27	--	30 – 32 (ROR) 46 – 58 (BOR)
ZnSe	76.1[n]	0.29[n]	0.9 [f]	~60 [r]
Zn_4Sb_3	57.9 – 76.3		0.64 – 1.49	56.5 – 83.4
Bi_2Te_3	40.4 – 46.8	0.21 – 0.37		8 – 166
Skutterudites (n and p)	136 (n) 133 (p)	0.14-0.25 (n) 0.22-0.29 (p)	1.7 (n) 1.1 - 2.8 (p)	86 (n) 37 (p)