Development of High Efficiency Segmented Thermoelectric Couples for Space Applications

Fivos Drymiotis[1], Jean-Pierre Fleurial [1], Sabah Bux [1], Samad Firdosy [1], Kurt Start [1], Ike Chi [1], Vilupanur Ravi [1,2], Billy Chun-Yip Li [1], Sevan Chanakian [3], Dean Cheikh [1], Kathy Lee[1], Kevin Yu [1], Obed Villalpando [1], Kevin Smith [1], David Uhl [1], Chen-Kuo Huang [1], Jong-Ah Paik [1], Knut Oxnevad[1], David Neff[1], Sutinee Sujittosakul[1], Kevin Smith[1]

[1]**Jet Propulsion Laboratory-California Institute of Technology, Pasadena CA 91109**

[2]California State Polytechnic University Pomona, Pomona CA 91768

[3]Michigan State University, East Lansing MI 48824,

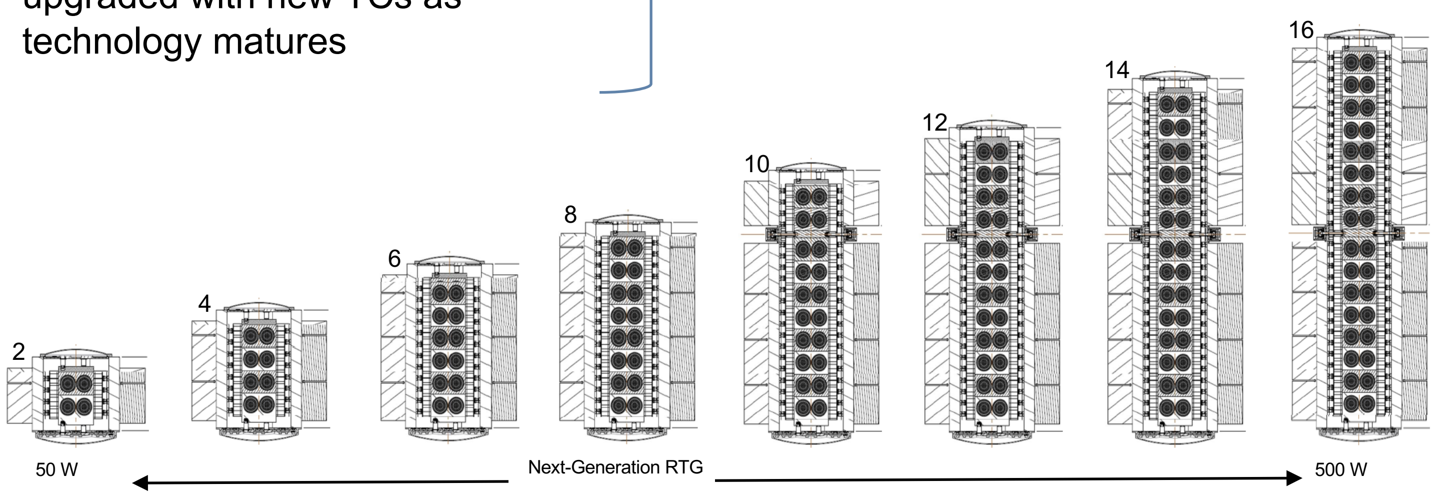
Jet Propulsion Laboratory
California Institute of Technology

Next Generation RTG Study Recommendations

- **NG-RTG:**
  - Vacuum Only
  - Modular
- **Variants**: **2, 4, 6, 8, 10, 12, 14**, and **16 GPHS** variants
  - 16 GPHSs (largest RTG variant)
  - P_{BOM} = **400-500 We** (largest RTG variant)
  - Mass goal of < **60 kg** (largest RTG variant)
  - Degradation rate **< 1.9 %**
  - System to be designed to be upgraded with new TCs as technology matures

Three (3) couple configurations have been selected, with conversion efficiencies ranging from *e=13%* to *e=16.4%*

Conversion efficiencies for heritage systems is e~ 7%



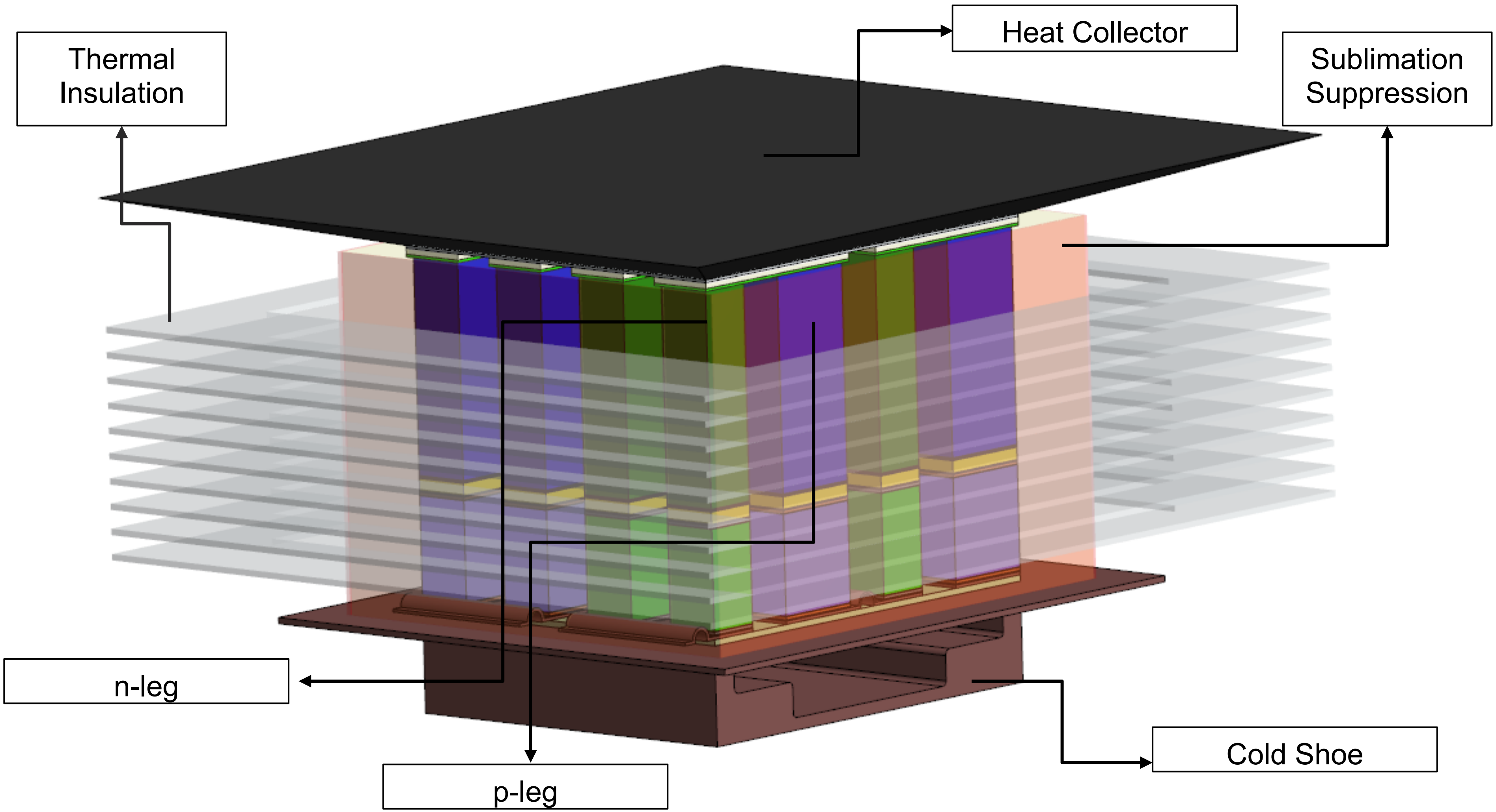
NG-RTG Couple Configurations

Configuration #	n		p		Current (study*) Predicted Materials-based Couple Efficiency (%)	Current (study*) Estimated BOL RTG Efficiency (%)	Current (study*) Estimated BOL RTG Power (W)
	Low	High	Low	High		*16-GPHS, 250W per GPHS*	
1	1-2-2 Zintl	$La_{3-x}Te_4$ /composite	9-4-9 Zintl	14-1-11 Zintl	**14.7** (16.4*)	**12.8** (14.3*)	**513** (572*)
3	SKD	$La_{3-x}Te_4$ /composite	SKD	14-1-11 Zintl	**13.9** (15.6*)	**12.1** (13.6*)	**485** (544*)
14		$La_{3-x}Te_4$ /composite		14-1-11 Zintl	**11.1** (13.0*)	**9.7** (11.3*)	**387** (452*)

- Efficiency calculated during Next Gen RTG study used higher ZT $La_{3-x}Te_4$/composite material produced by small batch synthesis (15 gr).
    - Current Project baseline (April 2018) produced by large batch synthesis process (100 g)
    - **Process optimization to reproduce these original results is in progress**
- Couple efficiency based on couple operating $T_{hot\ junction}$ = 1273 K, $T_{inter\text{-}segment}$ = 773 K and $T_{cold\ junction}$ = 450K
    - **Lower temperature segments, such as SKDs, would operate no higher than 773 K (500 C)**
    - **Most of hot side interface degradation risk would be for 14-1-11 Zintl and La_{3-x}Te4/composite**
- Estimated BOL system-level efficiency based on heritage RTG performance (derating factor)
    - GPHS-RTG: couple (7.5%) ; system (6.5%)
    - MMRTG: couple (7.1%); system (6,3%)

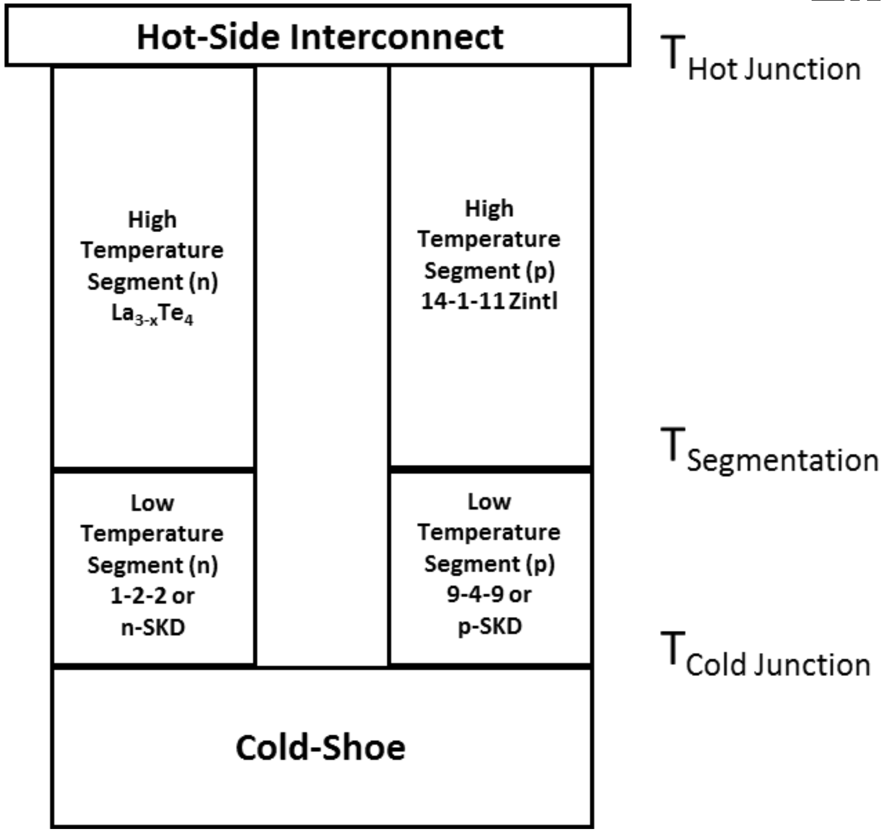
NG-RTG Multicouple

- ≥ 11% system conversion efficiency (≥ 60% improvement over MMRTG at BOL)
- ≥ 6-8.5 We/kg specific power (2-3 x improvement over MMRTG)
- 1.9%/year or lower power degradation average over 17 years (including isotope decay)



Managing Technology Development Risk

Ex. All Zintl Segmented Couple



T_{HOT} (K)	T_{COLD} (K)	Efficiency* (%)
1273	450	15.8
1223	450	15.2
1173	450	14.5
1123	450	13.7
1073	450	13.0
1023	450	12.2
973	450	11.4

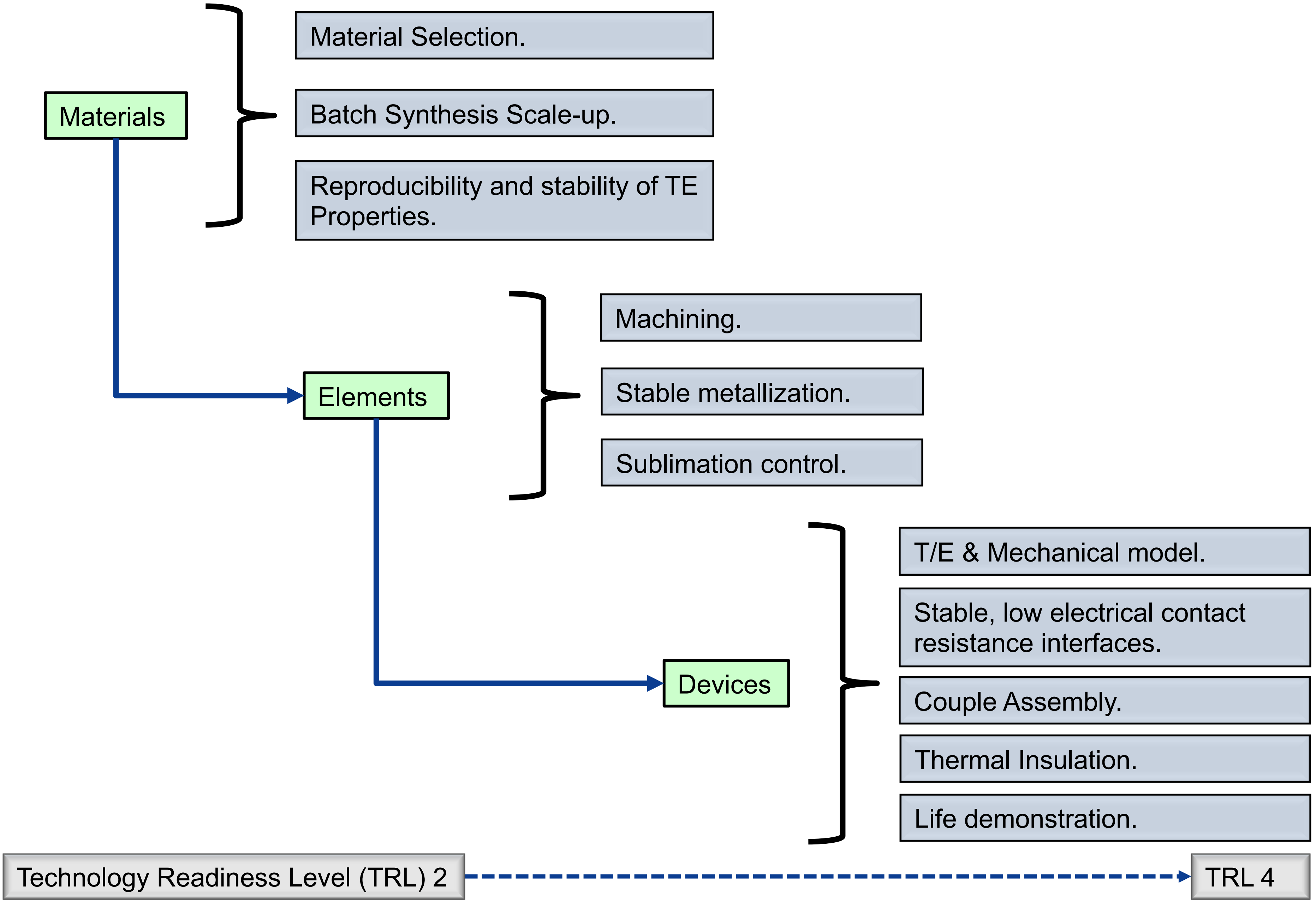
1223 K: 500W target

1023 K: 400W target

Preliminary prediction – will be updated periodically

…We can reduce hot-junction temperature and subsequently minimize degradation rate

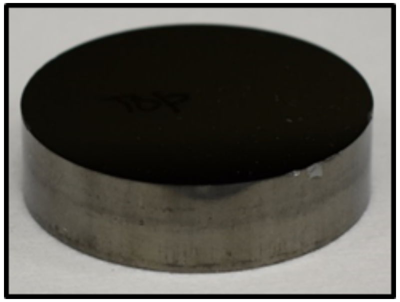
Overlap Between Tasks Ensures Concurrent Development



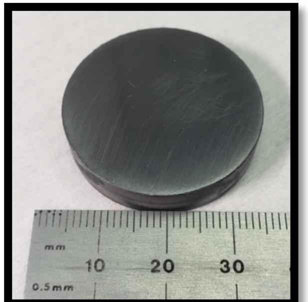
Materials Highlight

Successfully sintered 32mm diameter pucks of 14-1-11 Zintl, LaTe, LaTe Composite, 1-2-2 Zintl and 9-4-9 Zintl.

14-1-11 Zintl



1-2-2 Zintl



9-4-9 Zintl

$La_{3-x}Te_4$

$La_{3-x}Te_4$ /composite

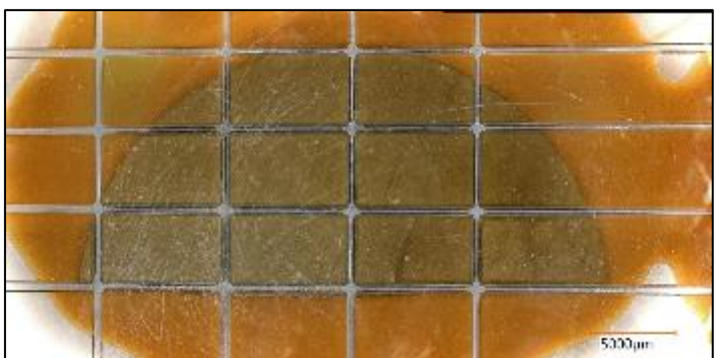
- **Large pucks enable rapid TE leg production to feed the device fabrication effort.**
- **Based on current TE leg dimensions (8-couple multicouple configuration), puck size sufficient to support production of legs and devices for full scale generator.**

Elements Highlight

- **Completed Scale Up Fabrication of Metallized Pucks of TE Materials for 14-1-11 Zintl and SKDs**
- Currently Developing Dicing Procedures

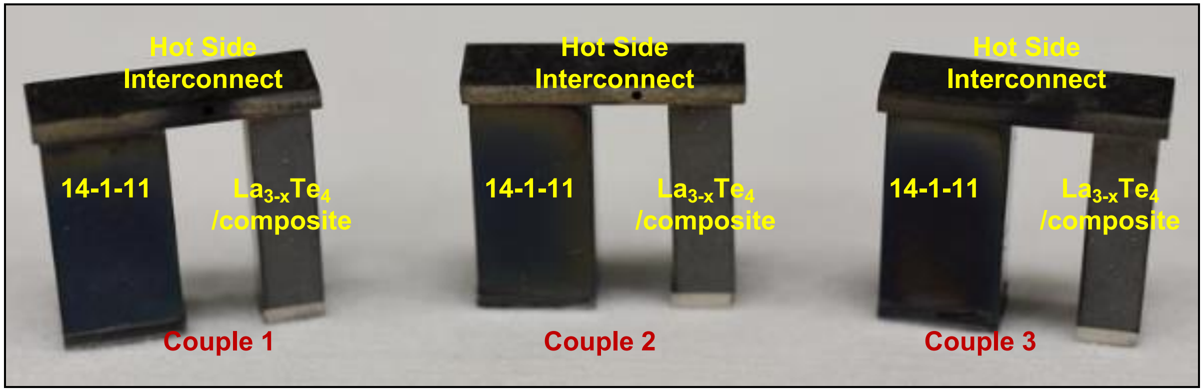
Metallized 14-1-11 32mm diameter puck

Metallized p-SKD 32mm diameter puck



Diced puck – wax side

Devices Highlight

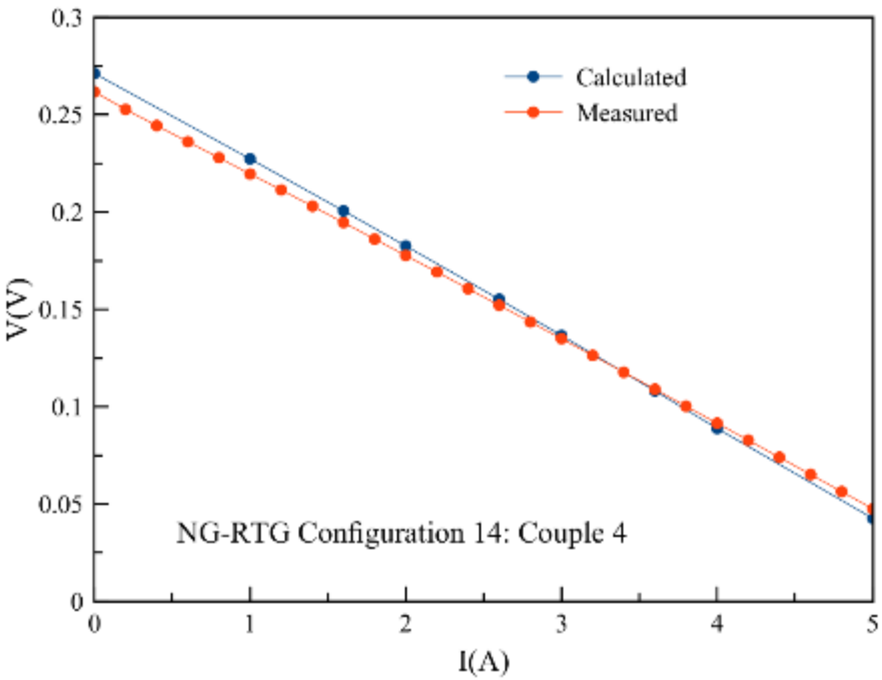


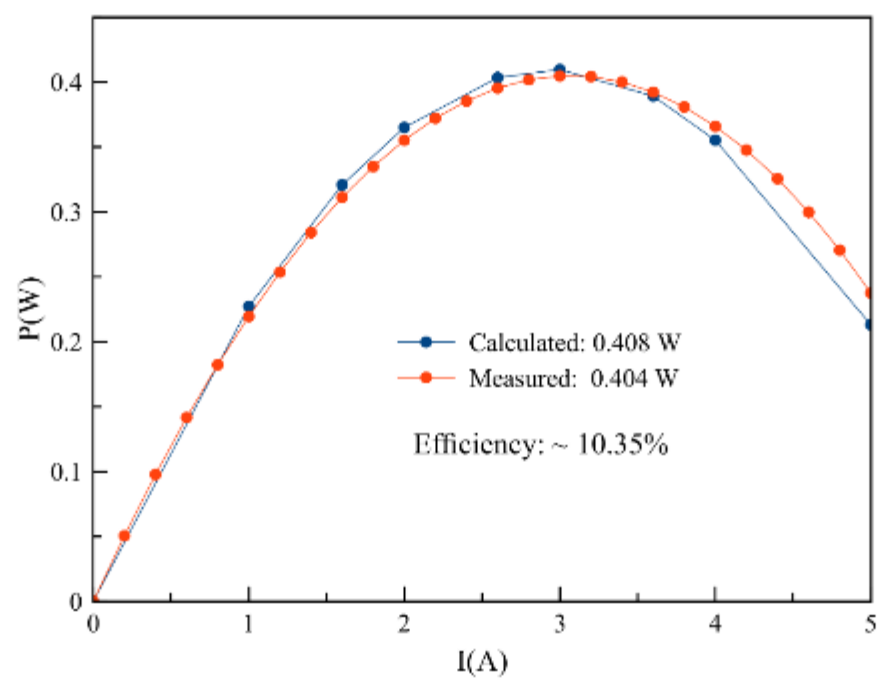
	Couple Resistance (mOhm)
Couple 1	15.50
Couple 2	15.61
Couple 3	15.45

- Consistent room temperature end-to-end resistance in all three couples.
- Couples are tested at 1000˚C, 900˚C, and 800˚C hot junction temperatures in order to evaluate long term stability and kinetics of degradation rates.

Devices Highlight

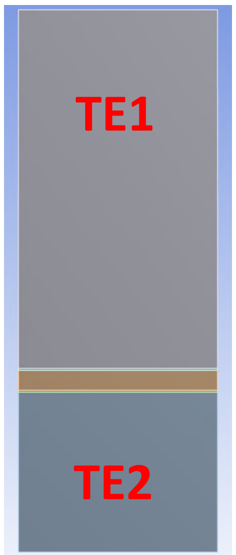
BOL Data Device Level Verification – Long Term Testing Currently In Progress





- T_{hj} ~ 1000 °C, T_{cj} ~ 200 °C
- Good agreement between experimental data and FEA calculations.
- Pmax~ 0.410 Watts @ I=3 A
- Efficiency e ~ 10.35%

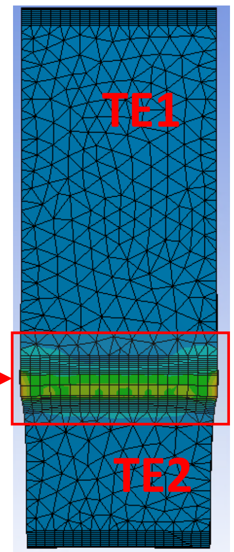
Technology Highlight: Development of Compliant Interfaces



Compliant Structure is bonded between the high-temperature (HT) and low temperature (LT) TE sections

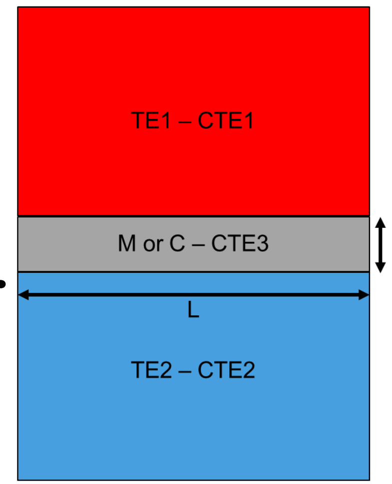
Reduced Mechanical Coupling between TE components

Deformation on cooldown (HT to RT)



During Cooldown, because of CTE mismatch, the LT TE contracts more than the HT TE, which leads to high stress and subsequently crack formation. *The compliant structure mechanically isolates the HT TE form the LT TE Components, hence reduces stress transfer and eliminates crack formation.*

Generic Physical Model



TE: Thermoelectric Element
CTE: Coefficient of Thermal Expansion
M: Metal
C: Compliant

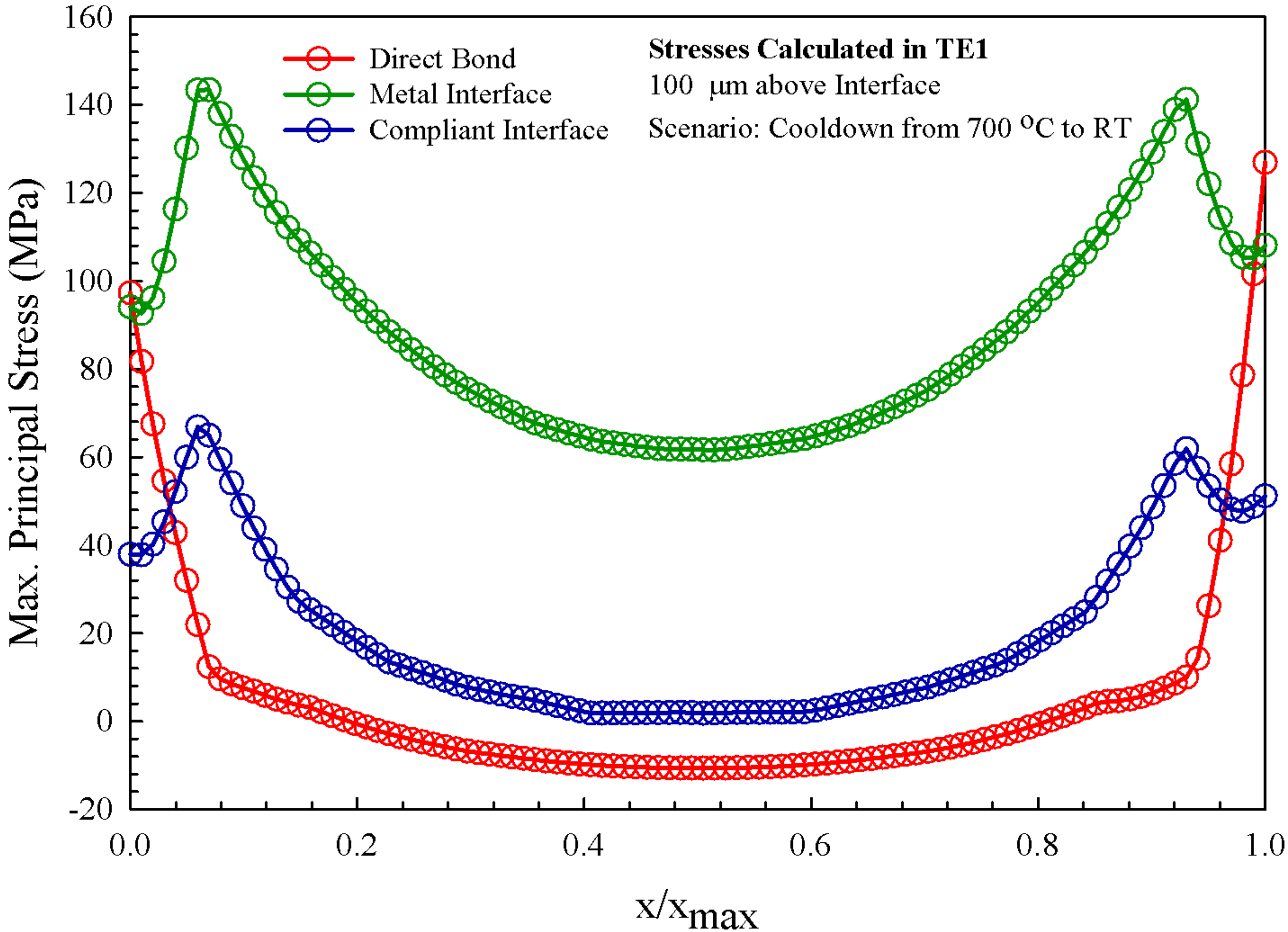
Stress in TEs Is Reduced When

- CTE1 ~ CTE2 ~ CTE3 (CTE Matching)

Or

- Presence of Low Modulus Intermediate Layer (Compliant Layer)

Technology Highlight: Development of Compliant Interfaces



Conclusions

- Set of thermoelectric materials have been selected for Next Gen RTG device technology development.
  - Scale-up synthesis has been demonstrated for all materials.
  - Considerable progress has been made measuring relevant material properties (TE Properties, Mechanical Properties, Bare Sublimation Rates).
  - Extended (1-2 years) thermoelectric property stability testing has been completed for several of these materials.
  - Targeting completion of all materials development and characterization work in FY19.

- Device-level technology development is in progress
  - Focus is on two segmented and one unsegmented couple configuration.
  - Developed Compliant Interfaces that Minimize Stress Due to CTE Mismatch.
  - Developed FEA models for Thermomechanical Analysis and Thermoelectric Analysis to help guide design trades.
  - First round of extended device performance testing is underway.

- Selected Next Gen RTG device configurations offer ample margin against initial performance target
  - Will help minimize initial technology development risks.

Acknowledgements

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