Jet Propulsion Laboratory
California Institute of Technology

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 [13], Kevin Smith [1], David Uhl [1], Chen-Kuo Huang [1], Jong-Ah Paik [1], Zi-Kui Liu [4], Jorge Paz Soldan Palma [4], Yi Wang [4], XiaoYu Chong [4], Frances Hurwitz [5], Dongming Zhu [5], Haiquan Guo [5], Gustavo Costa [5].

[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,
[4]Penn State University, State College, PA 16801
[5]NASA Glenn Research Center, Cleveland, OH 44135

Historical RTG-Powered U.S. Missions

Mission	RTG type (number)	TE	Destination	Launch Year	Mission Length	Power Level*
Transit 4A	SNAP-3B7(1)	PbTe	Earth Orbit	1961	15	2.7
Transit 4B	SNAP-3B8 (1)	PbTe	Earth Orbit	1962	9	2.7
Nimbus 3	SNAP-19 RTG (2)	PbTe	Earth Orbit	1969	> 2.5	~ 56
Apollo 12#	SNAP-27 RTG (1)	PbTe	Lunar Surface	1969	8	~ 70
Pioneer 10	SNAP-19 RTG (4)	PbTe	Outer Planets	1972	34	~ 160
Triad-01-1X	SNAP-9A (1)	PbTe	Earth Orbit	1972	15	~ 35
Pioneer 11	SNAP-19 RTG (4)	PbTe	Outer Planets	1973	35	~ 160
Viking 1	SNAP-19 RTG (2)	PbTe	Mars Surface	1975	> 6	~ 84
Viking 2	SNAP-19 RTG (2)	PbTe	Mars Surface	1975	> 4	~ 84
LES 8	MHW-RTG (2)	Si-Ge	Earth Orbit	1976	15	~ 308
LES 9	MHW-RTG (2)	Si-Ge	Earth Orbit	1976	15	~ 308
Voyager 1	MHW-RTG (3)	Si-Ge	Outer Planets	1977	40	~475
Voyager 2	MHW-RTG (3)	Si-Ge	Outer Planets	1977	40	~475
Galileo	GPHS-RTG (2)	Si-Ge	Outer Planets	1989	14	~ 574
Ulysses	GPHS-RTG (1)	Si-Ge	Outer Planets/Sun	1990	18	~ 283
Cassini	GPHS-RTG (3)	Si-Ge	Outer Planets	1997	20	~ 885
New Horizons	GPHS-RTG (1)	Si-Ge	Outer Planets	2005	12 (17)	~ 246
MSL	MMRTG (1)	PbTe	Mars Surface	2011	6 (to date)	~ 115
*Mars 2020***	*MMRTG (1 baselined)*	*PbTe*	*Mars Surface*	*2020*	*(5)*	*> 110*

#Apollo 12, 14, 15, 16 and 17
**Planned

**Total power at Beginning of Mission (W)*

From a few watts up to ~ 900 W, up to 40 years of operation (and counting)

Request for the NG-RTG Study

Was motivated by the need for larger RTGs than presently available or near-term improvements

- **Serve NASA for 2-3 decades** to come
- To address the needs of future Decadal Survey missions

  ✓ An RTG that would be useful **across** the **Solar System**

  ✓ An RTG that **maximizes** the types of **missions**: flyby, orbit, land, rove, boats, submersibles, balloons

  ✓ An RTG that has **reasonable** development **risks** and **timeline**

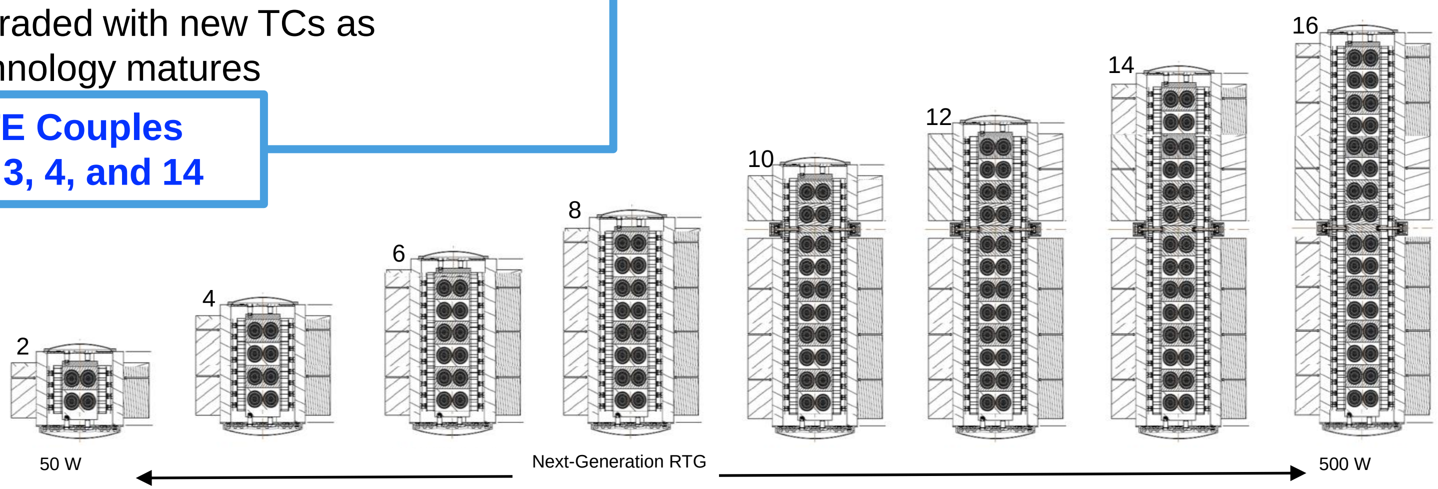
"**OPAG** is in support of pursuing the advancement and maturation of segmented thermoelectric converter technology for development of a modular Next Generation RTG …" (La Jolla, 2017)

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 W_e** (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

Configuration	n		p		~Couple Efficiency at T_{cj} = 450K	~ Generator Efficiency (16 GPHSs)
	Low	High	Low	High		
1	1-2-2 Zintl	$La_{3-x}Te_4$/composite	9-4-9 Zintl	14-1-11 Zintl	16.6	14.8
2	1-2-2 Zintl	$La_{3-x}Te_4$	9-4-9 Zintl	14-1-11 Zintl	15.3	13.6
3	SKD	$La_{3-x}Te_4$/composite	SKD	14-1-11 Zintl	15.7	13.9
4	SKD	$La_{3-x}Te_4$	SKD	14-1-11 Zintl	14.3	12.7
14		$La_{3-x}Te_4$/composite		14-1-11 Zintl	13.6	12.1

•Selected TE Couples
•1, 2, 3, 4, and 14



Technology Objective and Work Element Organization

Technology Objective:

- **Develop and demonstrate advanced thermoelectric couples capable of supporting the Next Generation RTGs with:**
  ≥ 11% system conversion efficiency
  (≥ 60% improvement over MMRTG at BOL)
  ≥ 6-8.5 We/kg specific power
  (2-3 x improvement over MMRTG)

- **Prediction of 1.9%/year or lower power degradation average over 17 years (including isotope decay)**

- **Develop and maintain technology maturation plan for module development**

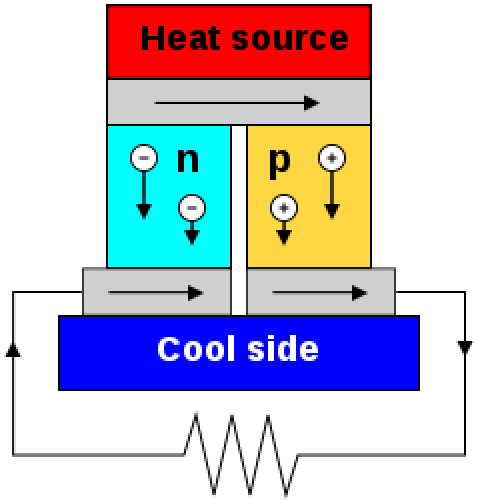
Work Element Organization

- Lead: Jet Propulsion Laboratory
- Collaborators: Glenn Research Center (GRC)
- Subcontractors: *ATA Engineering*, *University of Southern California (USC)*, University of Mississippi, Penn State University, *Harvard*

Basic Thermoelectric Couple

Power Generation Mode - Seebeck Effect

$V = S\Delta T$

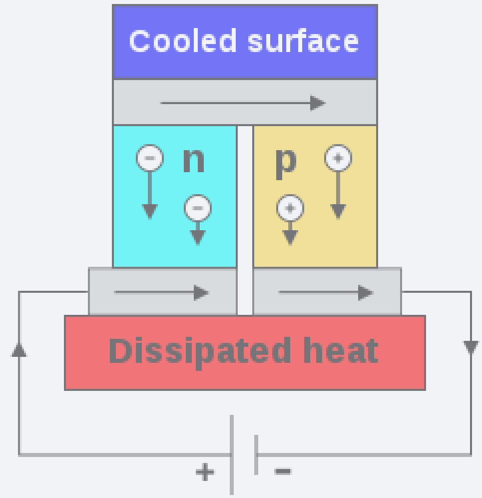


- Charge carriers move from hot side to cold side (high energy to low energy)

- Current is generated when circuit is closed

Cooling Mode – Peltier Effect

$dQ/dt = (\Pi_A - \Pi_B)I$



- Electrical work is required to move charges from cold side to hot side.

zT and Conversion Efficiency

$$zT = \frac{\alpha^2 T}{\rho\kappa} \longrightarrow \eta_{\max} = \frac{\Delta T}{T_h} \cdot \frac{\sqrt{1+zT}-1}{\sqrt{1+zT}+1}$$

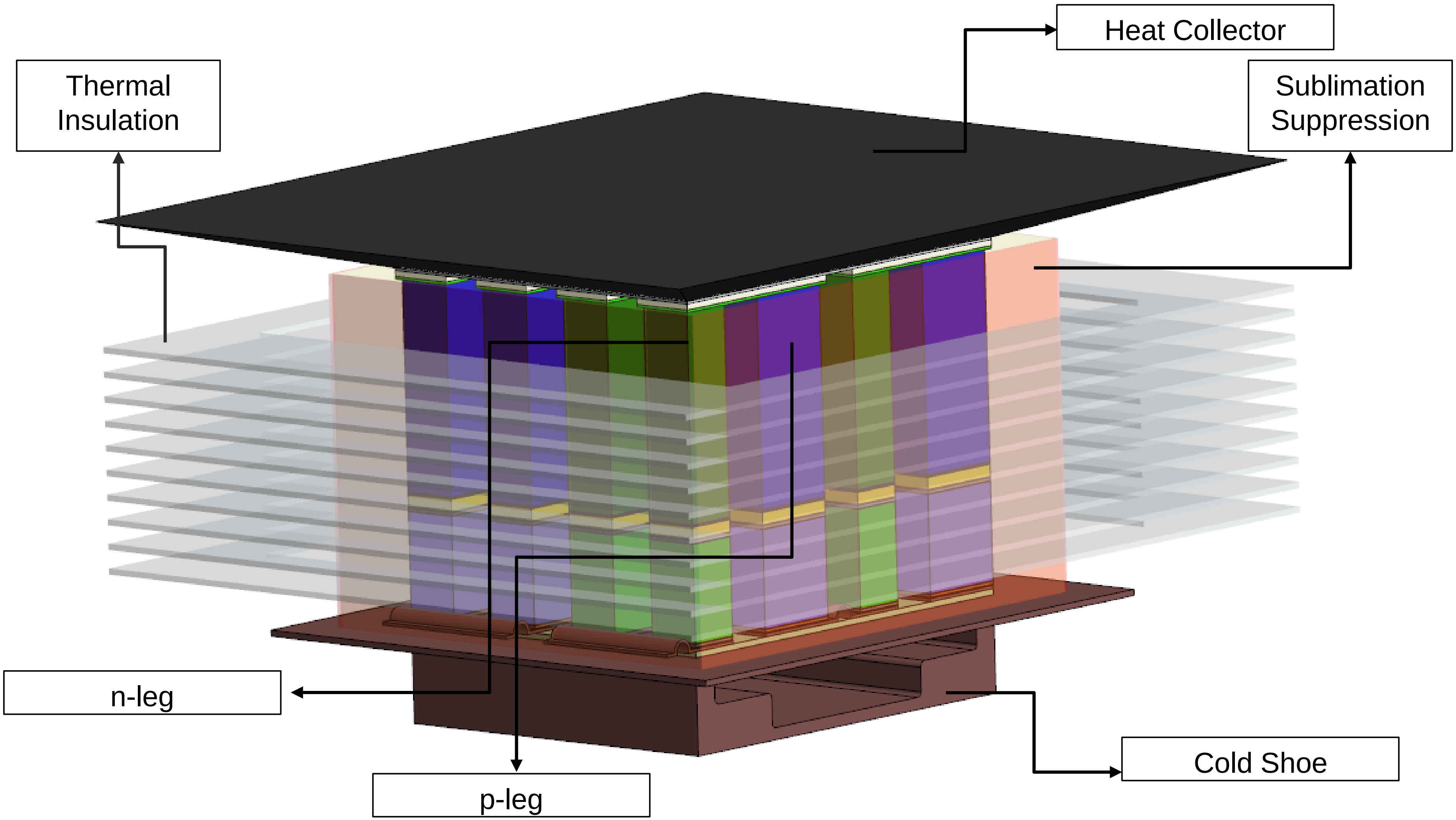
- Dimensionless Figure of Merit
  - Depends on Material Properties

- Conversion Efficiency
  - Fraction of the Carnot Efficiency
  - Increases with increasing *zT*
  - For *zT*>>> $\eta = \eta_{Carnot}$

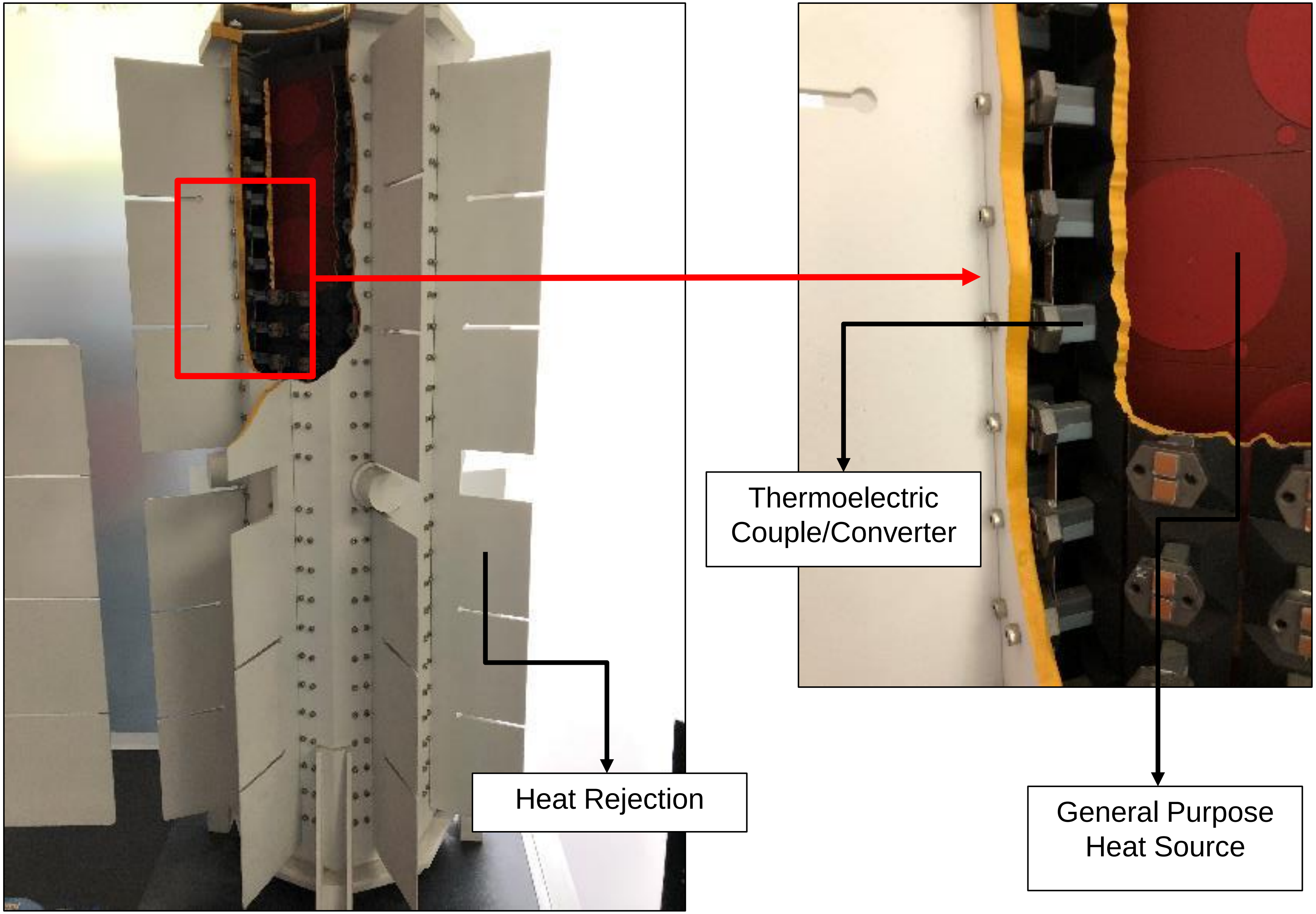
http://thermoelectrics.matsci.northwestern.edu/thermoelectrics/index.html

Thermoelectric Multicouple Converter

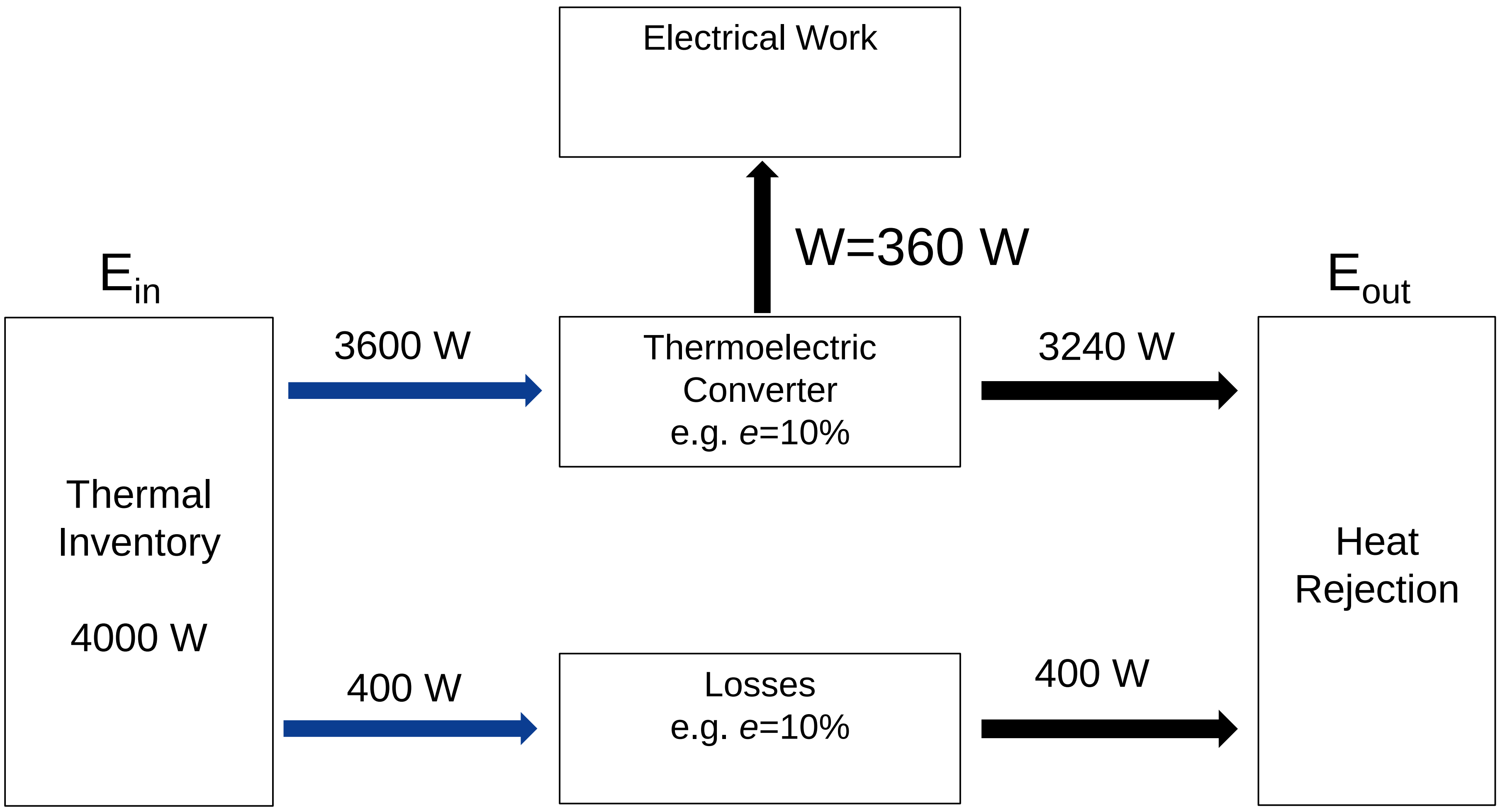
Many Thermoelectric Couples Electrically in Series (and parallel) and Thermally in Parallel



Radioisotope Generator



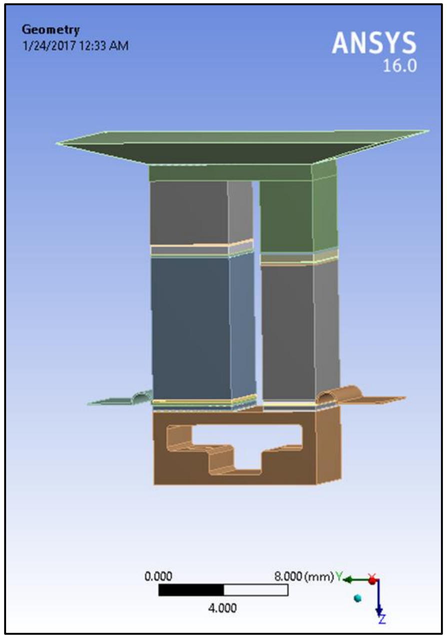
Solid State Heat Engine: $E_{in} = W + E_{out}$



Couple Configurations For Next Generation RTG

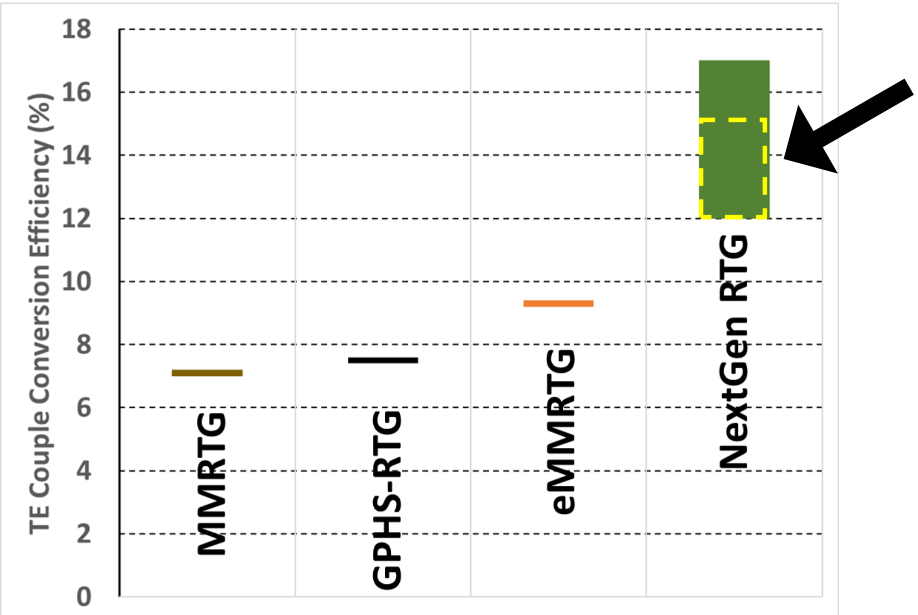
Configuration #	n		p		Predicted Materials-based Couple Efficiency (%)	Estimated Generator Efficiency (16 GPHSs)
	Low	High	Low	High		
1	**1-2-2 Zintl**	**$La_{3-x}Te_4$/composite**	**9-4-9 Zintl**	**14-1-11 Zintl**	**16.4**	**14.3**
2	1-2-2 Zintl	$La_{3-x}Te_4$	9-4-9 Zintl	14-1-11 Zintl	14.6	12.7
3	**SKD**	**$La_{3-x}Te_4$/composite**	**SKD**	**14-1-11 Zintl**	**15.6**	**13.6**
4	SKD	$La_{3-x}Te_4$	SKD	14-1-11 Zintl	13.6	11.8
14		**$La_{3-x}Te_4$/composite**		**14-1-11 Zintl**	**13.0**	**11.3**

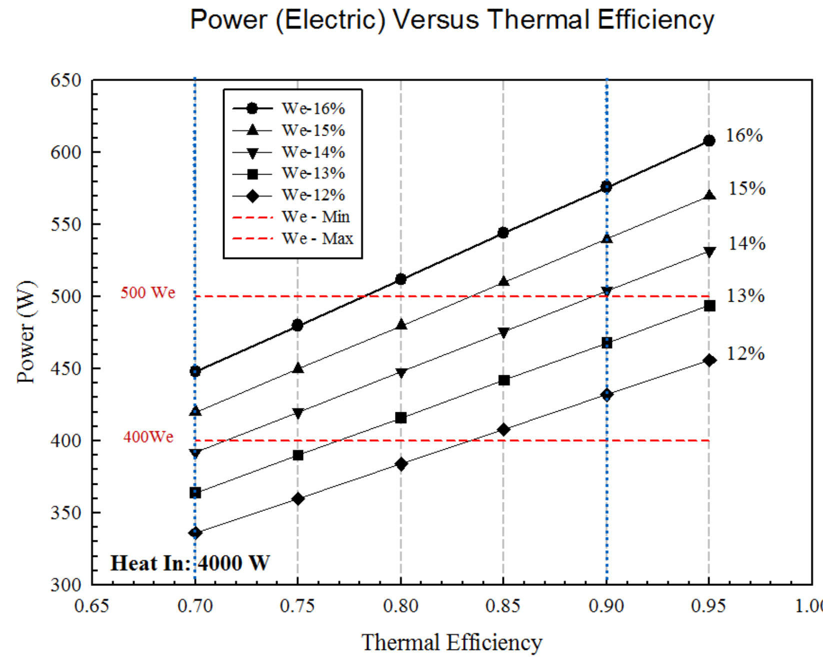
- *Couple efficiency based on couple operating $T_{hot\ junction}$ = 1273 K, $T_{inter\text{-}segment}$ = 773 K and $T_{cold\ junction}$ = 450K*
  - *No bottom Bi_2Te_3-based segments*
- *Estimated system-level efficiency based on heritage RTG performance (derating factor)*



- **14-1-11 Zintl** – *High Temperature p-leg (14-Mn-11 composition is further developed; 14-Mg-11 compositional modification has lower sublimation rates but is less developed).*
- **$La_{3-x}Te_4$** Composite – *High Temperature n-leg (Matrix baseline compound further developed – but composite has higher ZT and improved mechanical robustness)* .
- **1-2-2 Zintl** – *Low Temperature n-leg* (CTE matches that of high-temperature component)
- **9-4-9 Zintl** – *Low Temperature p-leg* (CTE matches that of high-temperature component)
- **Skutterudites (SKD)** – *Low Temperature n- and p- legs (Completed development – but low CTE values require engineering solution).*

New Segmented Thermoelectric Technologies Offer Ample Margin Against Initial Performance Target



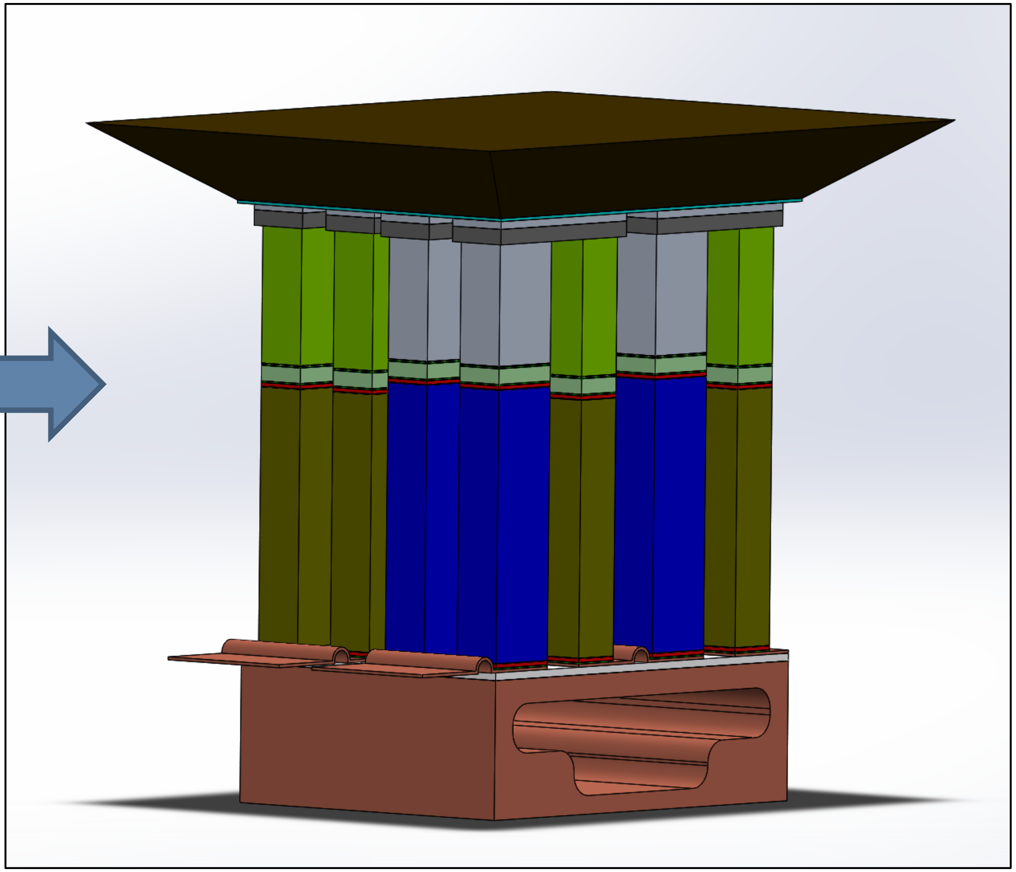


Example: *All-Zintl segmented couple hot junction temperature performance trade*

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

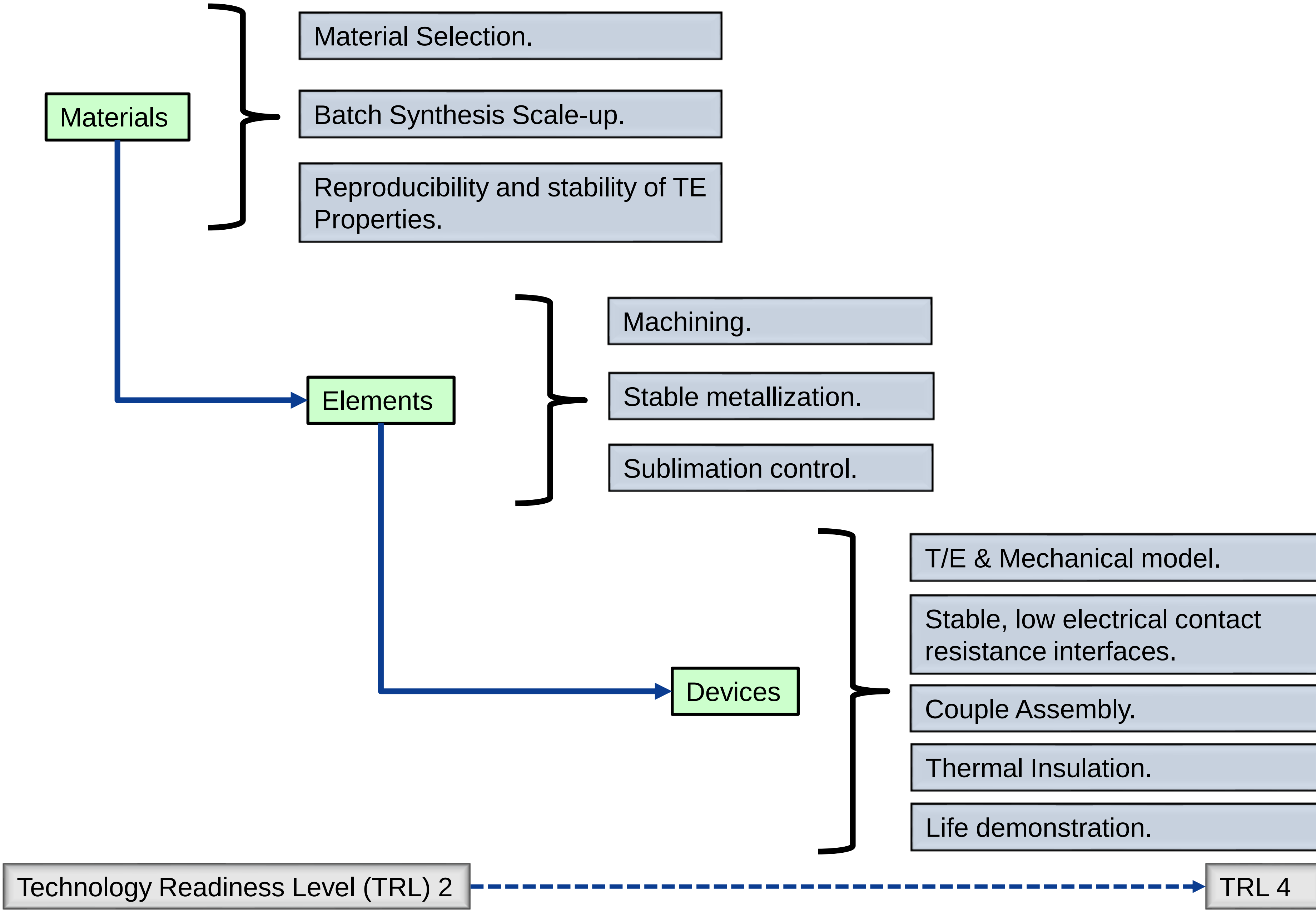
- *Technology **development risks** can be **minimized** by:*
  - *Trading higher efficiency against lower hot-side operating temperature*
  - *Adjusting hot side temperature of lower segments*
  - *Use of more robust composite materials*
  - *Thermal insulation performance and device configuration trades*

Technical Challenges

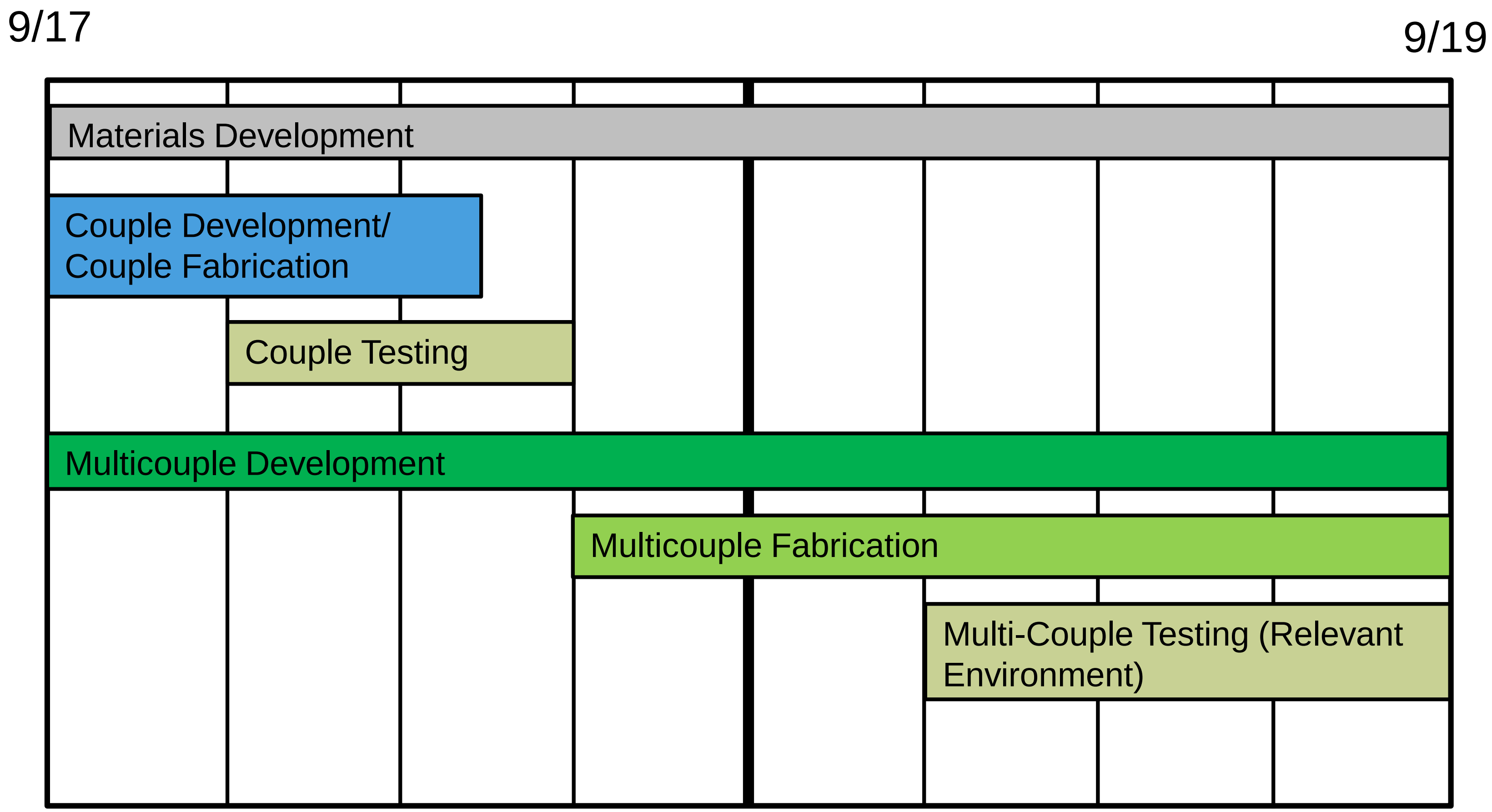


Long Life Thermoelectric Converter

Overlap Between Tasks ensures concurrent development



Two Year Development Plan

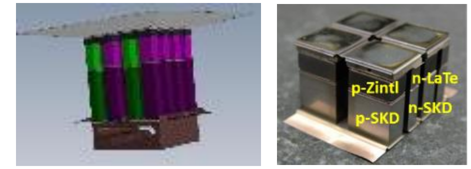


- Initial Couple Development and Couple Fabrication Allow us to Assess Fabrication Feasibility and Fabrication Process.
- Materials Development – Continuous Activity to End of 9/19.
- Multicouple Development Continuous Activity to End of 9/19.
- Multicouple Testing – Requires testing in relevant environment of device packaged with “near prototypic” thermal insulation and sublimation suppression control

Segmented Thermoelectric Device Technology:
Remaining Challenges for Achieving Low Power Degradation Rates

Alternate interconnect material(s) - JPL

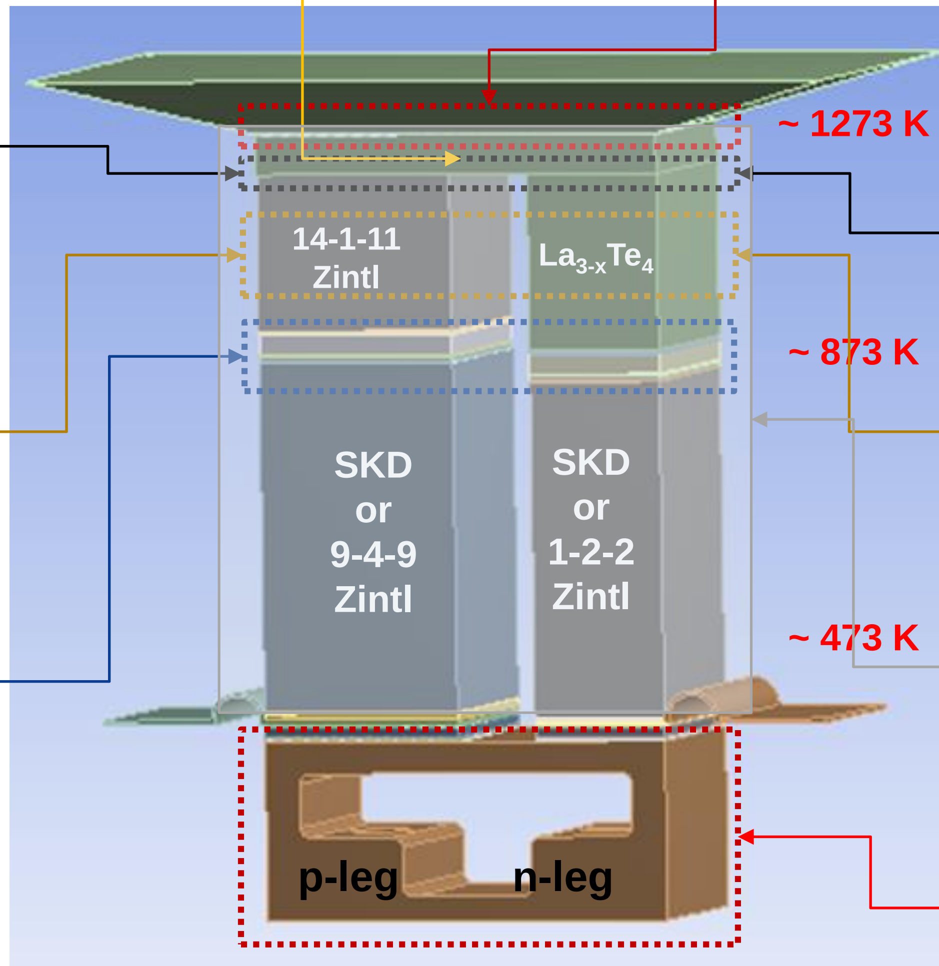
Hot shoe with dielectric layer (multicouples)



ATEC Segmented Module Technology Advancement

Mechanically robust & chemically stable, hot side interface for 14-1-11 Zintl and composites – **JPL/PSU**

Mechanically robust hot side interface for $La_{3-x}Te_4$ and composites – **JPL/PSU**



Strengthening and stable TE properties for 14-1-11 Zintl and composites - **JPL**

Strengthening and stable TE properties for $La_{3-x}Te_4$ composites - **JPL**

Mechanically compliant, high electrical/thermal conduction segment interfaces - **JPL**

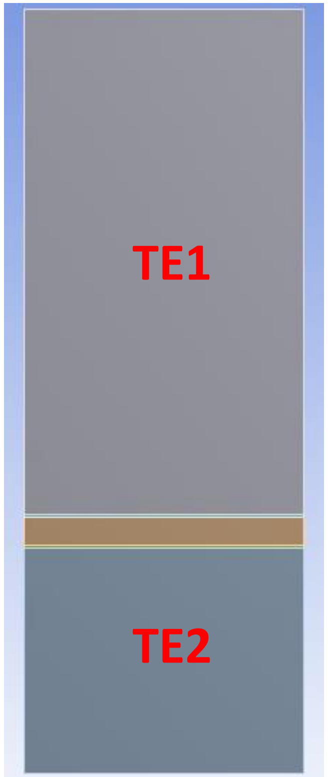
Aerogel thermal insulation / sublimation suppression - **GRC**

Cold shoe with dielectric layer (cantilevered devices, modules)

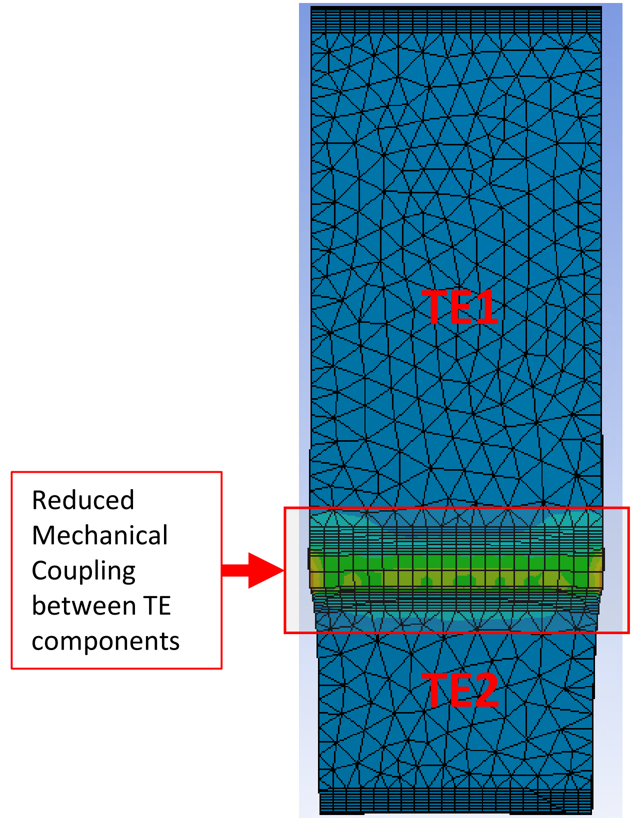
Development needed

In progress

Compliant Interfaces: Reduction of Mechanical Coupling Between Bonded Components



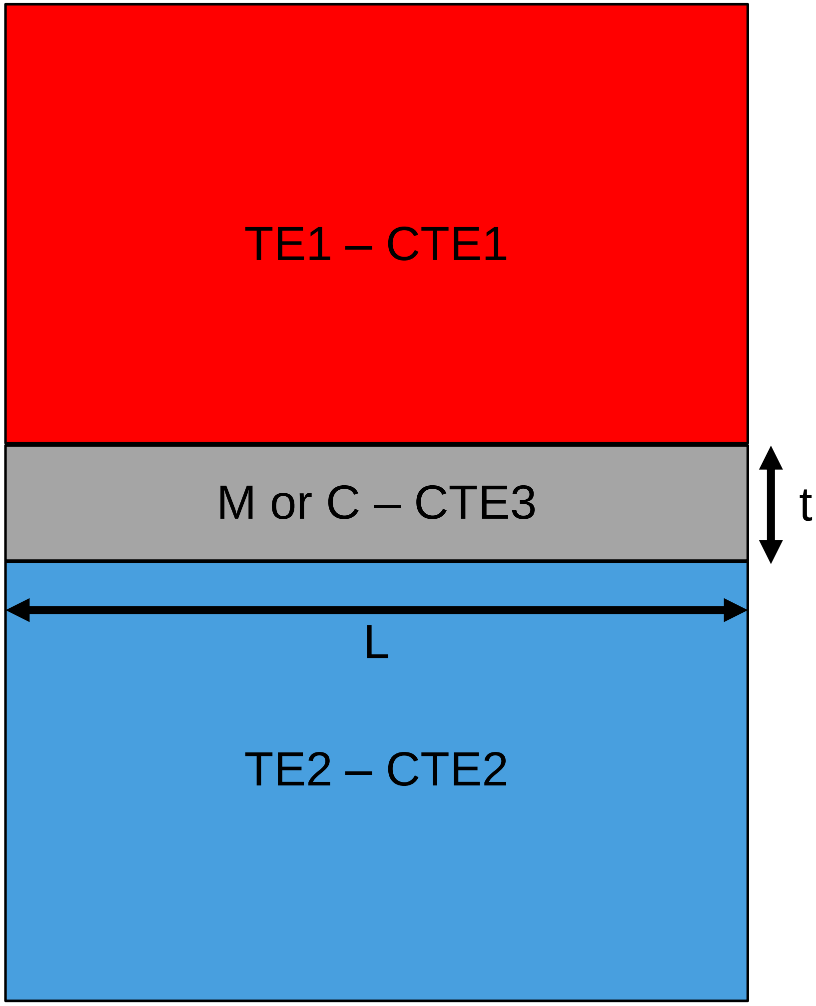
Deformation on cooldown (HT to RT)



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

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.*

Compliant Interfaces: Generic Layout



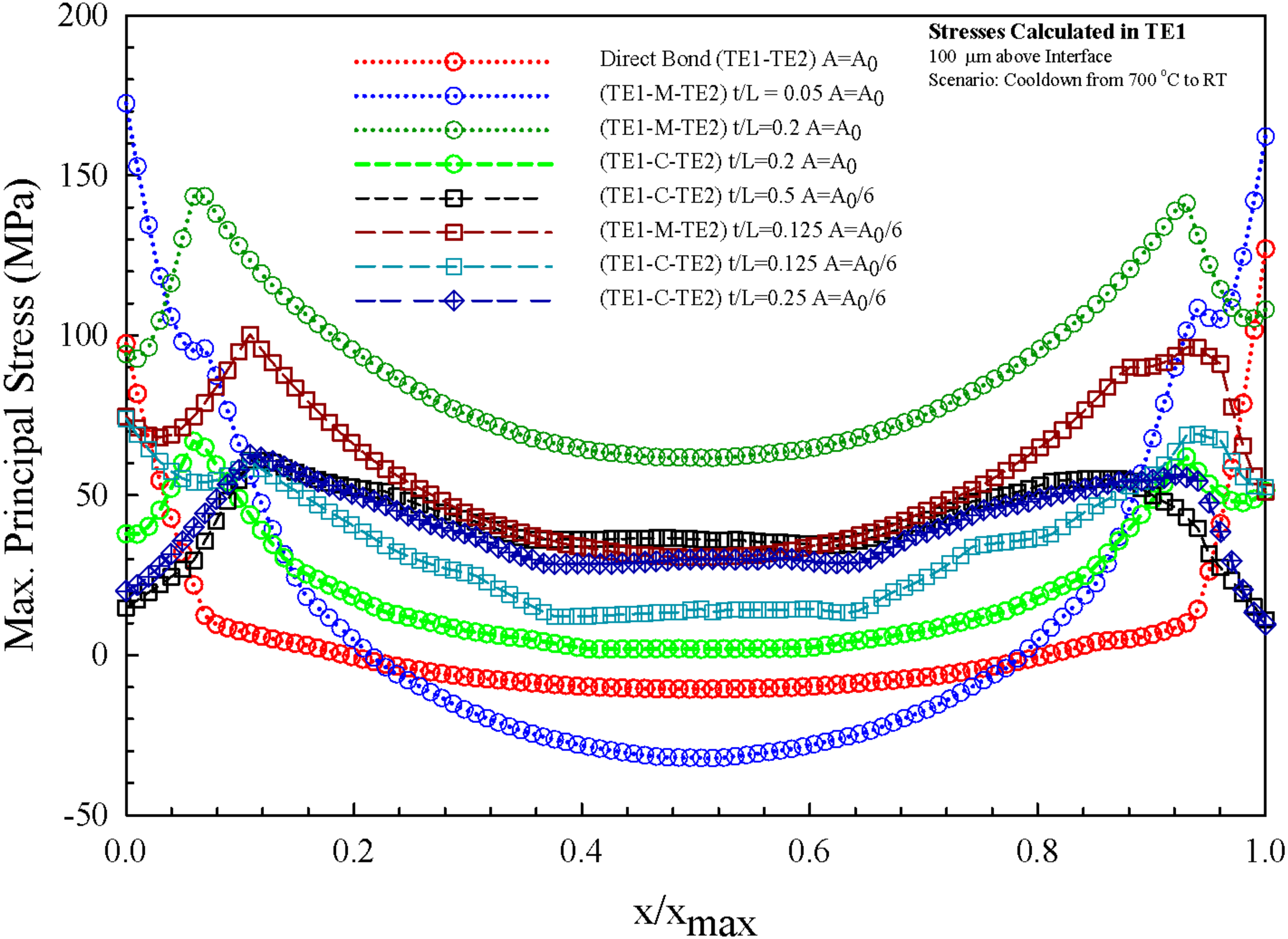
TE: Thermoelectric Element
CTE: Coefficient of Thermal Expansion
M: Metal
C: Compliant

Stress in TEs Is Reduced When

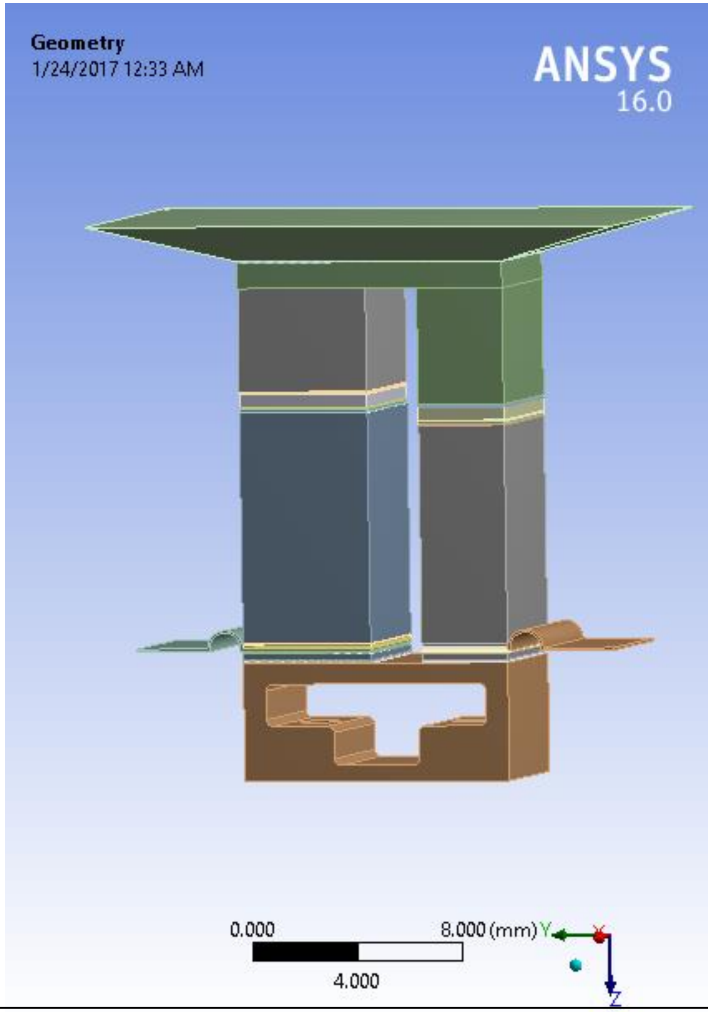
- CTE1 ~ CTE2 ~ CTE3 (CTE Matching)

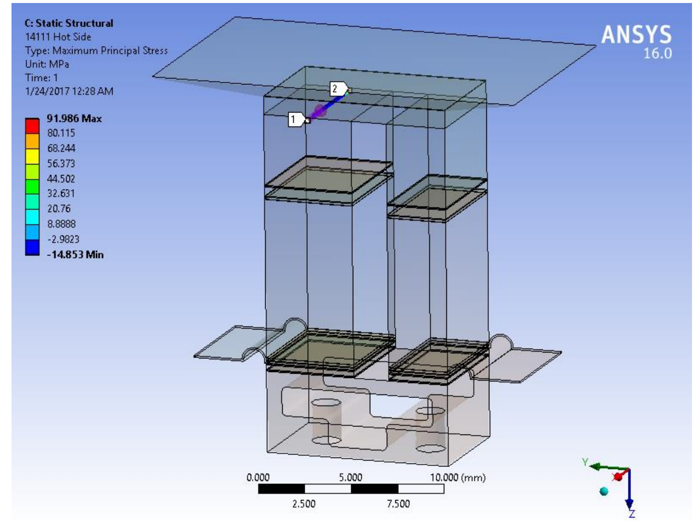
Or

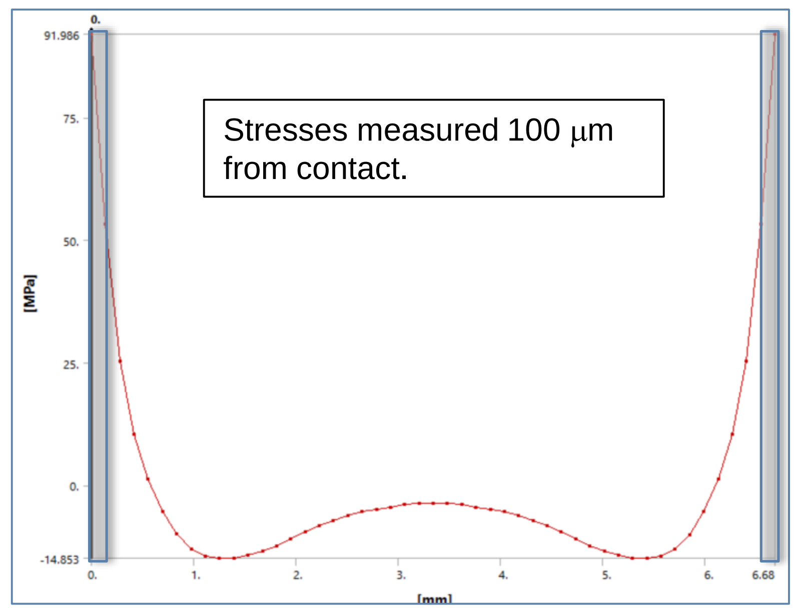
- Presence of Low Modulus Intermediate Layer (Compliant Layer)


Stresses Calculated in TE1
100 μm above Interface
Scenario: Cooldown from 700 °C to RT
Direct Bond (TE1-TE2) A=A0
(TE1-M-TE2) t/L = 0.05 A=A0
(TE1-M-TE2) t/L=0.2 A=A0
(TE1-C-TE2) t/L=0.2 A=A0
(TE1-C-TE2) t/L=0.5 A=A0/6
(TE1-M-TE2) t/L=0.125 A=A0/6
(TE1-C-TE2) t/L=0.125 A=A0/6
(TE1-C-TE2) t/L=0.25 A=A0/6
Max. Principal Stress (MPa)
200
150
100
50
0
-50
0.0
0.2
0.4
0.6
0.8
1.0
x/xmax

Segmented Couple – Cantilevered Configuration Thermomechanical Response

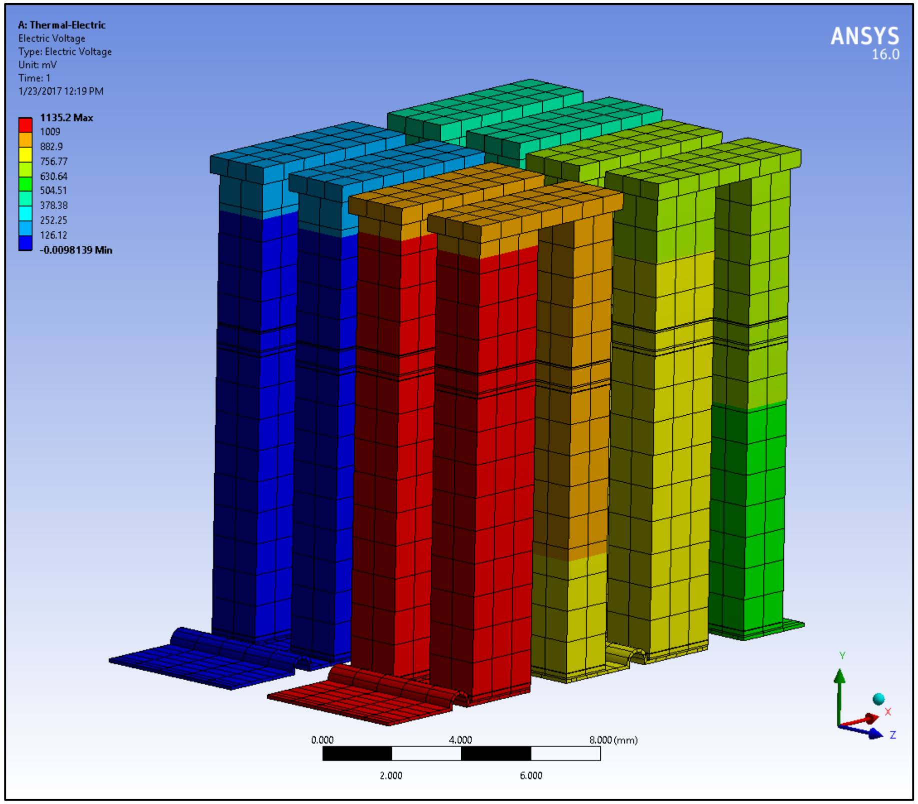


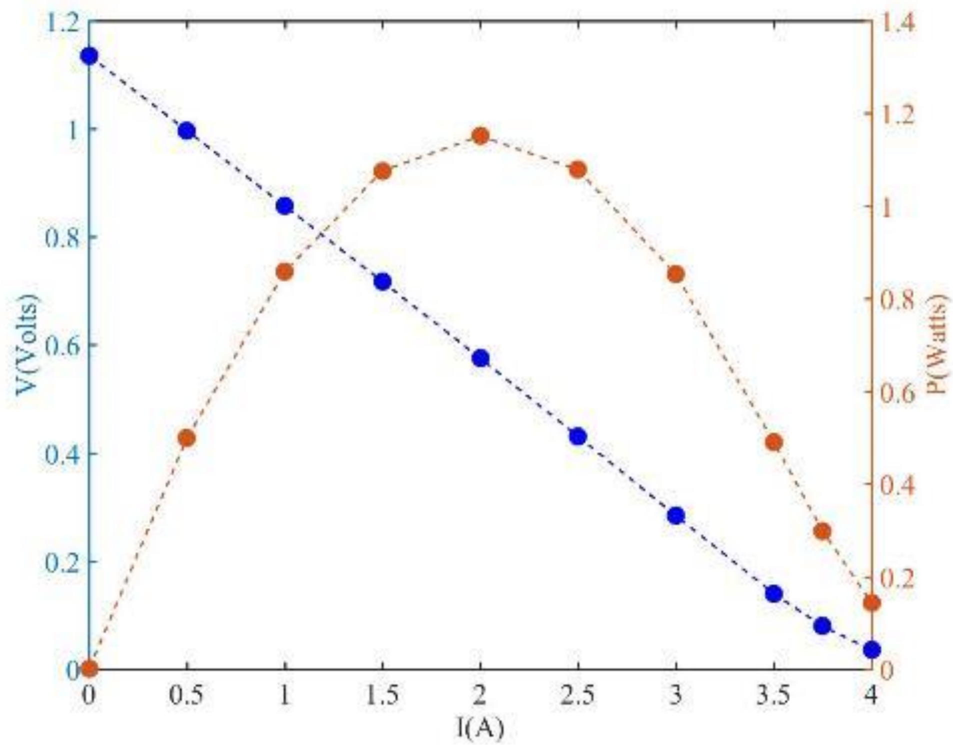




- Analysis to evaluate stress values, and make changes to reduce below UTS (Ultimate Tensile Strength ~ 100 to 200 MPa)

Segmented Couple – Prediction of Thermoelectric Performance





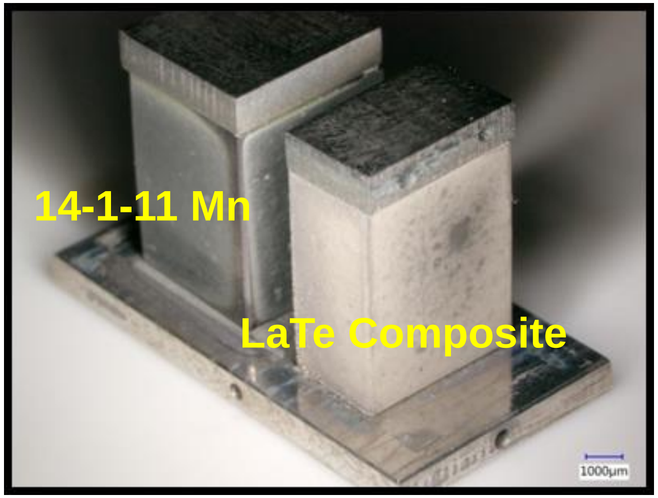
ATEC 8 – couple module, series/parallel configuration: V_{Open} = 1.14 V, I_{Short} =4 A, P_{Max} = 1.15 Watts
FEA allows for concurrent Thermomechanical Analysis and Thermoelectric Analysis – Thermoelectric performance prediction is essential for evaluating measured module performance.

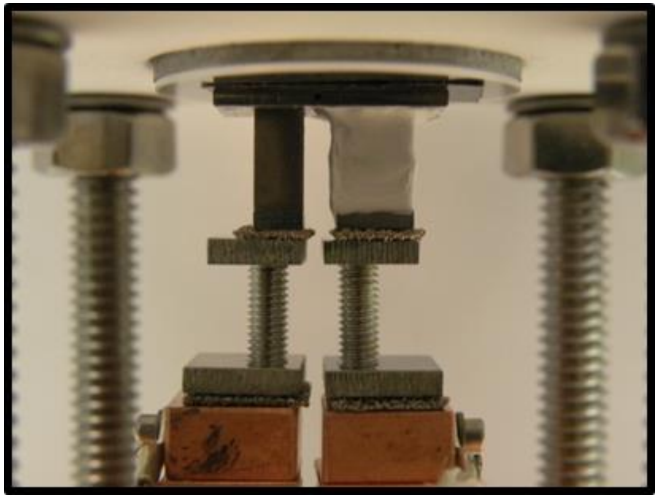
Thot = 1000 C
Tcold= 200 C
Pin =8.6 Watts
Pout = 1.15 Watts
Efficiency = 13.4%

Device Fabrication

Next Generation Configuration 14

- One of the proof-of-principle high temperature Next Generation RTG couple configurations being developed under TTDP/ATEC (NG-RTG) has demonstrated reasonably stable operation for 3000 hours under nominal hot side temperature of 1275 K





- Couple remained on test for 3000 hours.
- *No sublimation coating was used on the n-leg.*
- Maximum Power after 3000 hours ~ 90% of BOL

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 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

This work was performed at the California Institute of Technology/Jet Propulsion Laboratory under contract with the National Aeronautics and Space Administration. This work was supported by the NASA Science Mission Directorate under the Radioisotope Power Systems Program's Thermoelectric Technology Development Project

Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov