An Update on the Skutterudite-Based Thermoelectric Technology Maturation Project for the Proposed eMMRTG

ICT 2016
Wuhan, PR China

T. Caillat[1], I. Chi[1], S. Firdosy[1], C. –K. Huang[1], K. Smith[1], P. Gogna[1], J. Paik[1], C. Erverline[1], J. - P. Fleurial[1], R. Bennett[2], S. Keyser[2]

[1]Jet Propulsion Laboratory/California Institute of Technology, Pasadena, CA
[2] Teledyne Energy Solutions, Hunt Valley , MD

What is being enhanced in the Proposed eMMRTG?

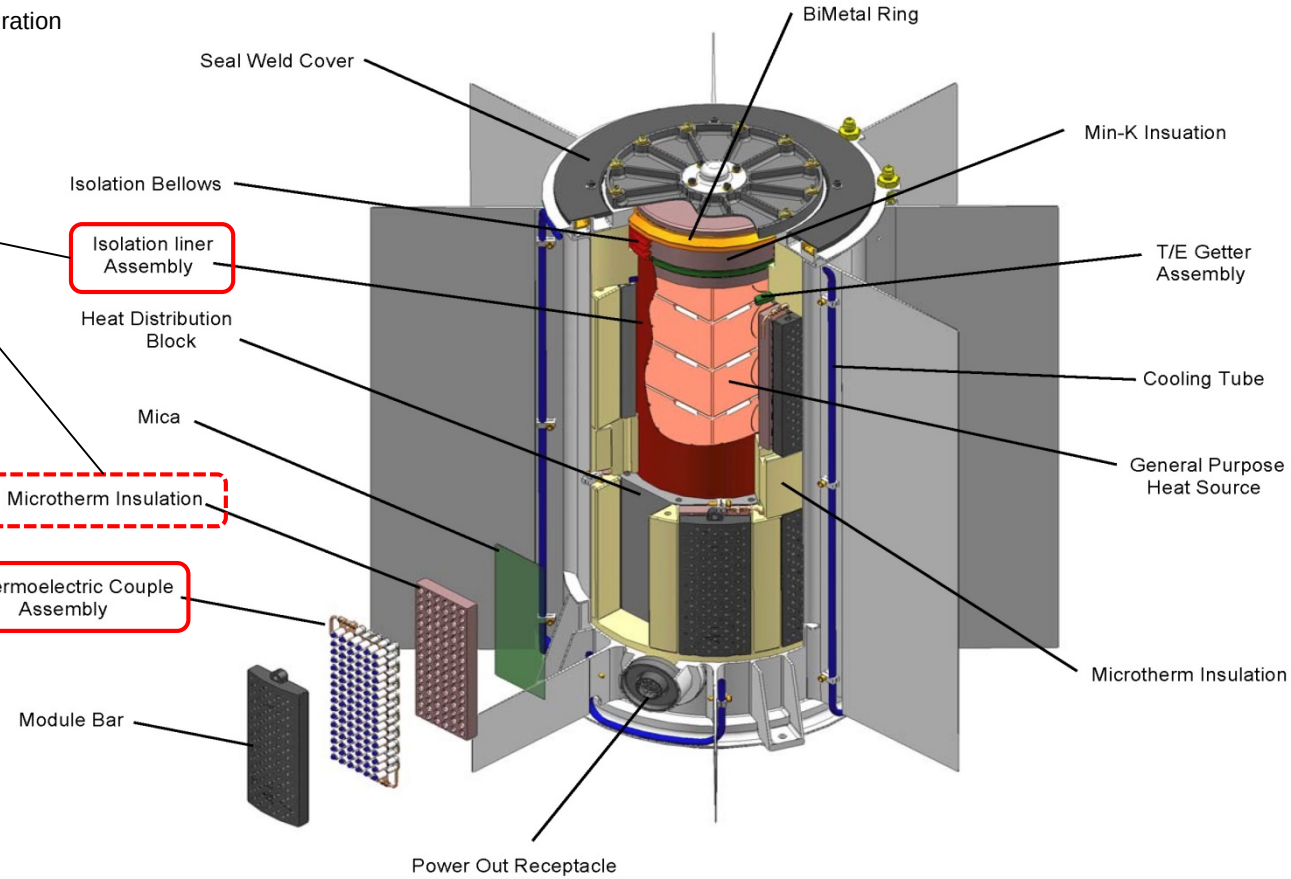
Enhancements under consideration

Known enhancements

Engineering: emissivity change to liner, substitute part of insulation

Changes needed to MMRTG

New Technology: Substitute skutterudite couples



Retrofitting the MMRTG with new skutterudite thermoelectric couples

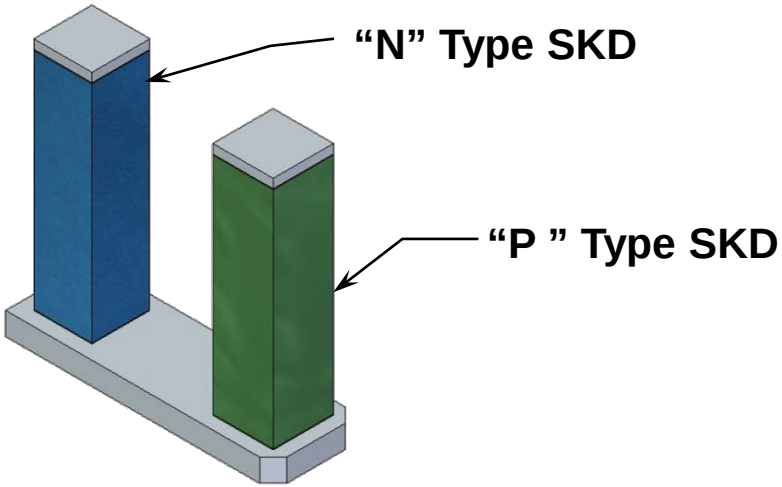
- Skutterudite couples fit within the space available (no change in number of couples)
- Simple emissivity change to heat source liner will enable use of MMRTG end insulation system
- Volume, mass, and external interfaces remain unchanged
- Multi-mission capability preserved

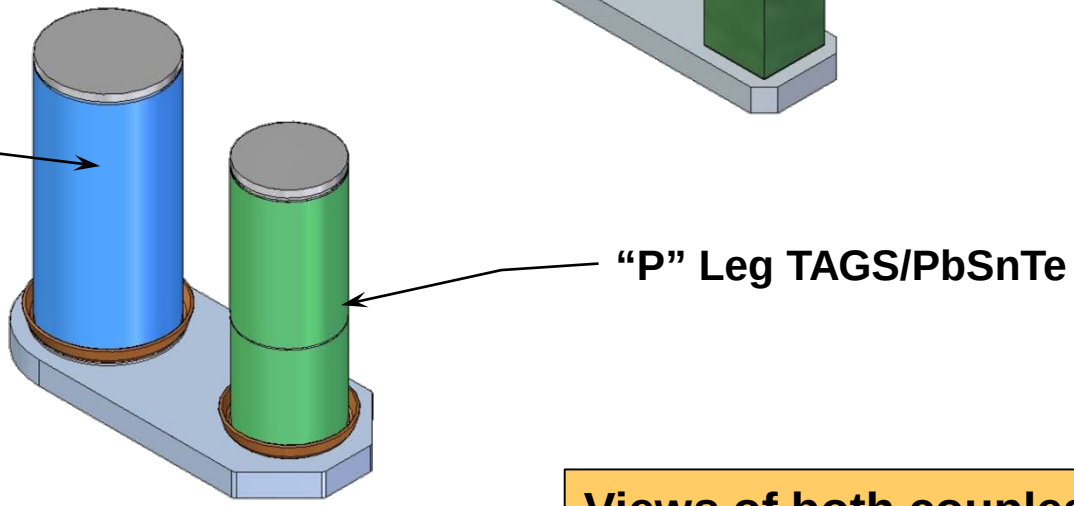
T/E Couple Assembly Comparison

<u>"Drop-in Replacement" Couple</u>

- **Better high temperature capability**
- **Non-segmented**
- **Cut to shape (not pressed)**
- **Equivalent or better mechanical properties**
- **Smaller element cross section**
  - *Required to increase hot side temperature*

Proposed eMMRTG Couple

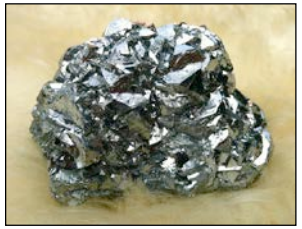




MMRTG Couple

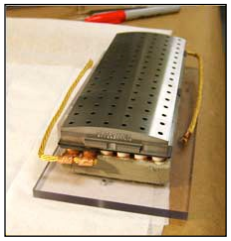
Views of both couples are to scale relative to each other

The proposed enhanced MMRTG (eMMRTG) : A Boost in Conversion Efficiency



Skutterudite (SKD) materials

SKD couples



eMMRTG modules

New SKD materials with higher performance and maximum operating temperature than MMRTG TE materials

10% increase in conversion efficiency over MMRTG couples

+

Operating Temperature rises from 800K to 873K

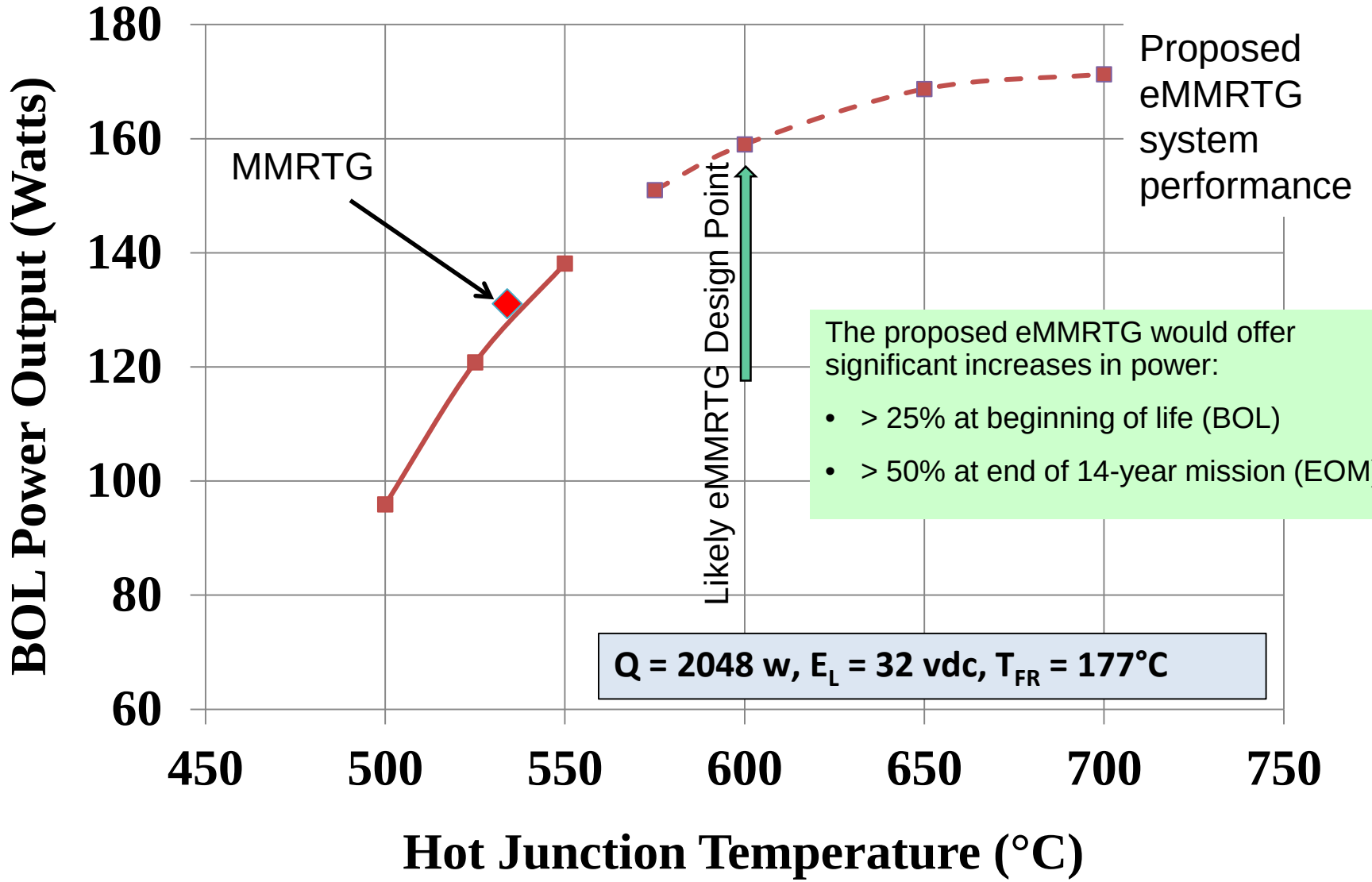
Cross-section change boosts operating temperature

14% increase in conversion efficiency over MMRTG couples

Proposed eMMRTG

24% increase in conversion efficiency over MMRTG at BOL

eMMRTG Study Result – Power vs. T_{HJ}



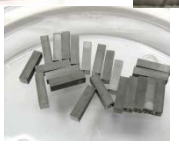
The proposed eMMRTG would offer significant increases in power:

- > 25% at beginning of life (BOL)
- > 50% at end of 14-year mission (EOM)

Phased Technology Transfer and Maturation

- **Phase A key objectives**
  - Transfer JPL developed TE materials, metallized elements and ambiently dried aerogel production procedures to TESI
  - Demonstrate manufacturability and validate performance for SKD materials and elements
  - Demonstrate initial manufacturability and performance for 1st iteration SKD couples
  - Assess thermal insulation options for modules
  - Initiate life assessment of SKD materials, coupons, couples

Phase A
~ 2 years

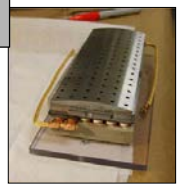


- **Phase B key objectives**
  - Finalize couple design and module insulation/sublimation suppression at the end of the 2nd iteration of couple development
  - Further establish lifetime performance database through SKD materials, coupons, couples, and modules under nominal and accelerated testing conditions

Phase B
~ 1.5 years

- **Phase C key objectives**
  - Design and demonstrate manufacturability and initial performance for SKD 48-couples modules
  - Establish a lifetime performance database through SKD materials, coupons, couples, and modules under nominal and accelerated testing conditions
  - Develop a high reliability lifetime performance prediction (LPP)
  - Initiate validation of LPP through 48-couple module testing under nominal and accelerated testing conditions

Phase C
~ 1.5 years



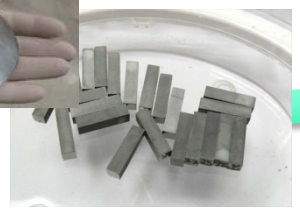
STM Team

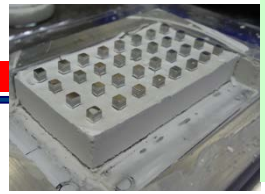
- JPL (Lead), NASA/GRC (support), DOE (Guidance)
- Subcontractors: Teledyne Energy Systems Inc., UDRI, ATA

Task scope overview

Phase A

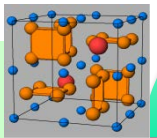
Metallized TE elements
- Demonstrate manufacturability and validate performance for SKD elements (TE

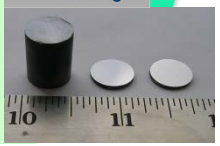




Module insulation
- Evaluation of various insulation options
  - Module integration feasibility
  - Thermal conductance
  - Aging characteristics
  - Mechanical properties
  - Vibration testing

Couples
- Demonstrate manufacturability and validate initial performance for SKD couples
- Evaluate couple strength





Skutterudite TE materials
- Demonstrate manufacturability and validate performance for SKD materials

Increased level of confidence in life Performance Prediction

LPP database development ; testing of coupons, couples and modules under nominal and accelerated thermal conditions; LPP development

Gate 1
Oct 2015

Phase B

Couples
- 2nd iteration couples
- Demonstrate manufacturab and performance
- Finalize couple design and module insulation

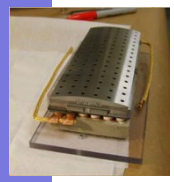
Gate 2
Jun 2017

Phase B

Multi-couple life test boxes
- Assess degradation rate in a more prototypic environment
- Sublimation rate of TE materials
- Insulation thermal conductance testing

Phase C

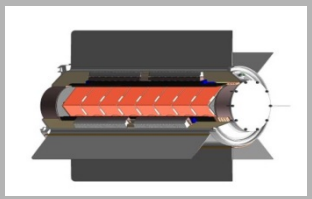
48-couple module
- Design and demonstrate manufacturability and performance for SKD modules
- Validate life performance prediction



Gate 3
Oct 2018

Lifetime performance prediction (LPP)

Potential eMMRTG flight program development (DOE)



eMMRTG

SKD TE Materials Manufacturing (TESI)

- JPL's initial procedures for the synthesis of SKD materials transferred to TESI
- Equipment and procedures for the synthesis of p- and n-SKD TE materials established at TESI
- Mechanical properties of TESI produced SKDs consistent with materials made at JPL
- 3.8 kgs of p-SKD and 4.5 kgs of n-SKD made at TESI to date
- Batch and yield to date sufficient to support the fabrication of a generator
- Performance of TE materials produced by TESI independently verified by JPL and ORNL

SKD TE materials manufacturing capabilities successfully established at TESI

Glovebox System

High Energy Ball Mill

Metallized Element Fabrication

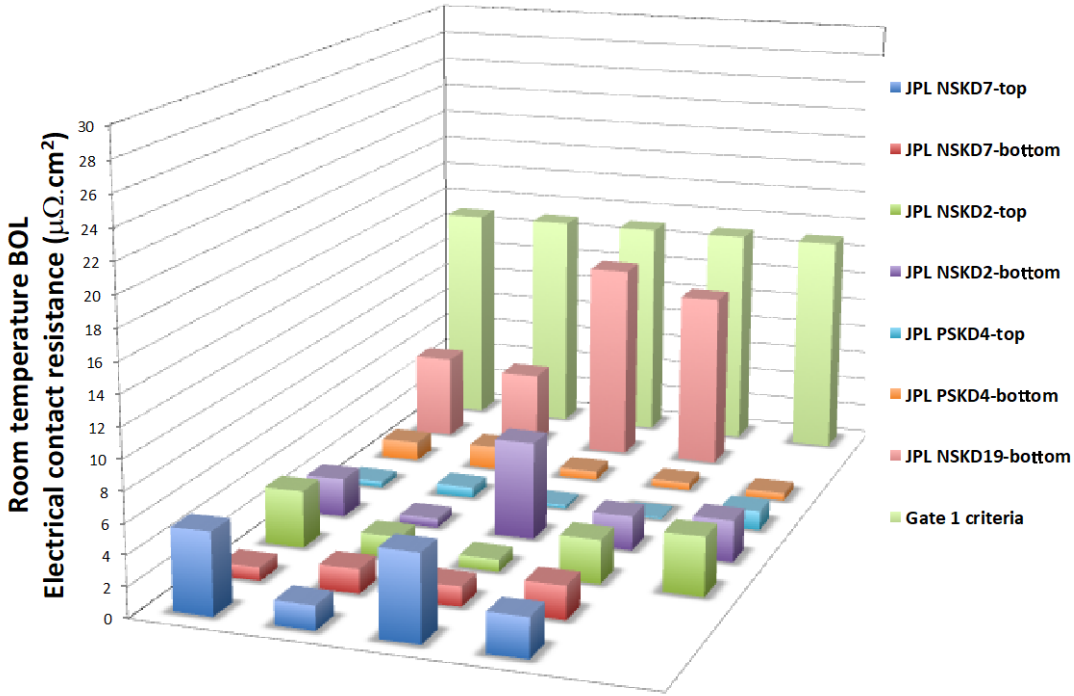
- JPL's initial procedures for the fabrication of 1st iteration SKD elements transferred to TESI
- Equipment (hot-press and dicing saw) and procedures for the fabrication of SKD metallized elements established at TESI
- Batch and yield to date sufficient to support the fabrication of a generator
- Performance of elements verified by JPL

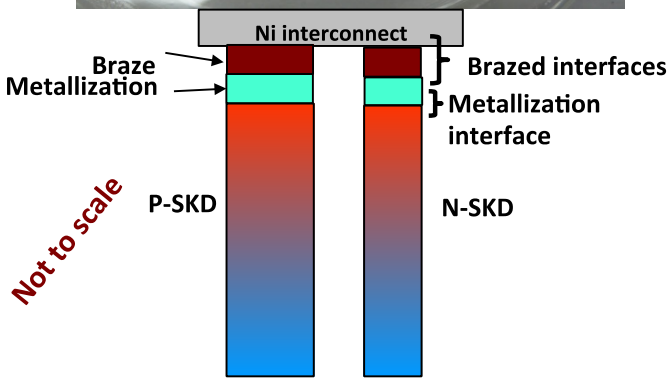
SKD metallized elements manufacturing capabilities successfully established at TESI

Diced metallized puck before removal of elements

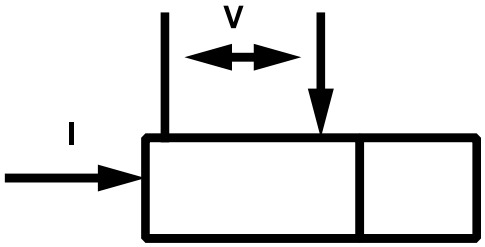
Elements in storage container

Metallization interface electrical contact resistance





- 4 brazed interfaces in one SKD couple
- 4 metallization interface sin one couple



Room temperature electrical contact resistance value < 15 μΩ.cm²

Couple Fabrication (TESI)

- JPL's initial procedures for the fabrication of 1st iteration SKD couples transferred to TESI
- Equipment and initial procedures for the fabrication of SKD couples established at TESI
- Performance of couples verified by JPL

Initial SKD couples manufacturing capabilities successfully established at TESI

1st iteration couple fabricated at TESI

Initial SKD Couple Performance

- **TESI Power Testing – 200 to 600° C gradient**
  - Tested 1st iteration couples
  - All couples exceeded 206 mW threshold
  - All four couples exceed 225 mW target for average power at matched load

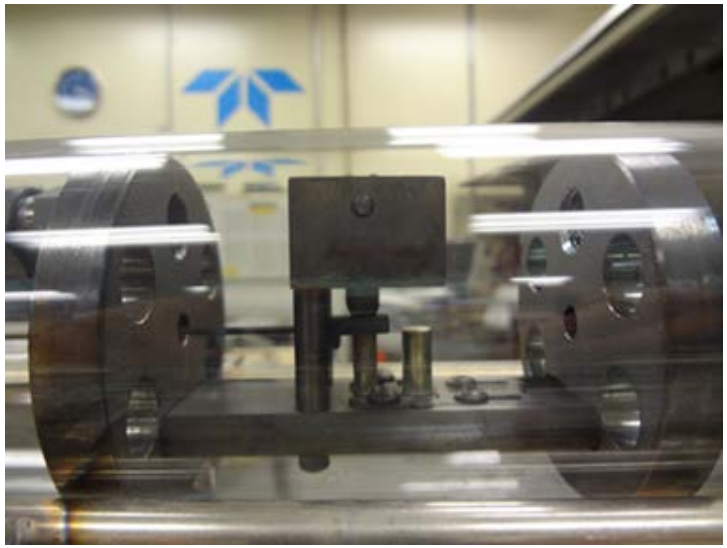
				Power at match-load			
Couple ID	**T_{Hot}**	**$T_{Cold\text{-}AVG}$**	**V_{OC}**	**V_{load} (mV)**	**I (A)**	**P (mW)**	**Adj. P (mW)**
SKD-64-1	601.6	199.9	133.6	66.55	3.57	237.7	234.0
SKD-64-2	601.2	199.9	130.8	65.07	3.49	227.0	235.1
SKD-64-3	601.1	199.9	134.2	66.66	3.60	240.0	234.3
SKD-64-4	601.3	199.9	133.2	66.37	3.60	239.0	239.0

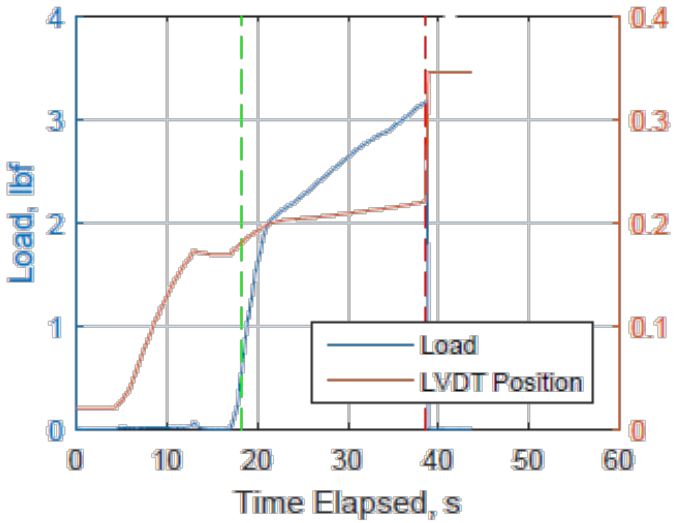
All couples exceeded power output criteria

- **Power output of couples also validated at JPL**

Couple Strength Testing Results

- **SKD couple passes acceptance criteria**
  - Combined SKD leg strength > MMRTG N-leg strength
    - MMRTG P-leg provides no strength at temperature



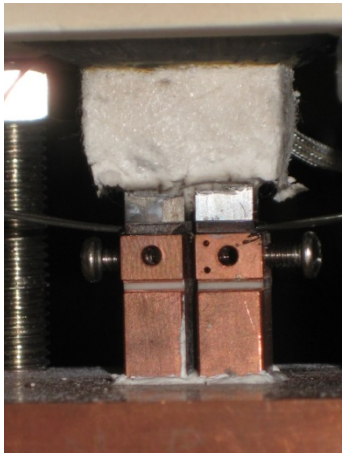


SKD 5.92 lbf
>
MMRTG 5.75 lbf

Test Condition	Peak Load (lbf, avg)	StDev Load (lbf)	Range of Peak Load	# of Tests
SKD N-Leg, 600°C	**2.59**	1.36	0.71 to 4.46	10
SKD P-Leg, 600°C	**3.33**	0.79	1.63 to 4.13	10
MM N-leg, 537°C	**5.75**	0.66	5.01 to 6.48	10

Phase A SKD Couple Testing

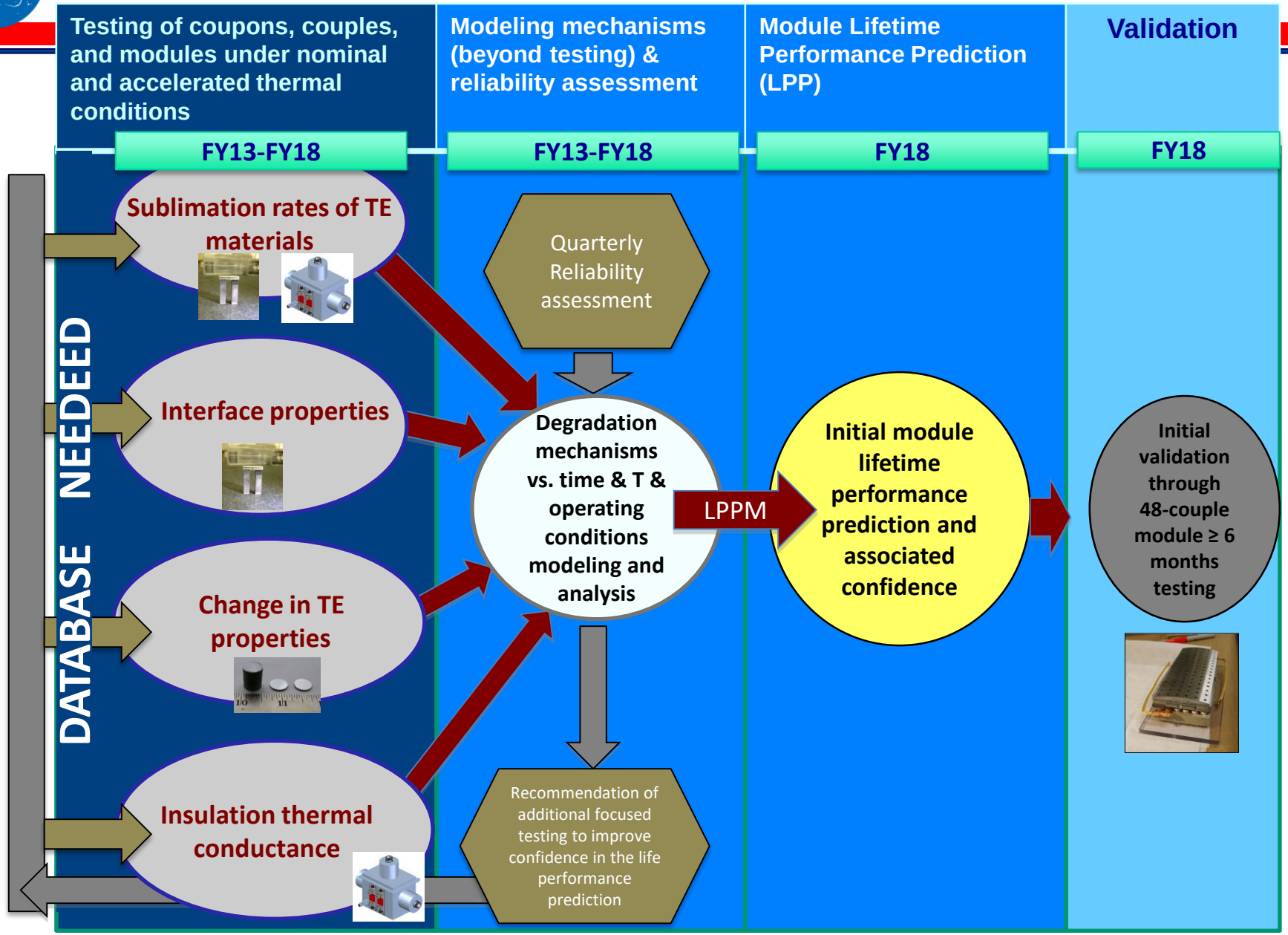
- **1st iteration couples in vacuum**
  - Four couples tested for 9888 hrs at Th up to 625C
  - Encapsulated in ambiently dried aerogel
  - Primarily for sublimation suppression



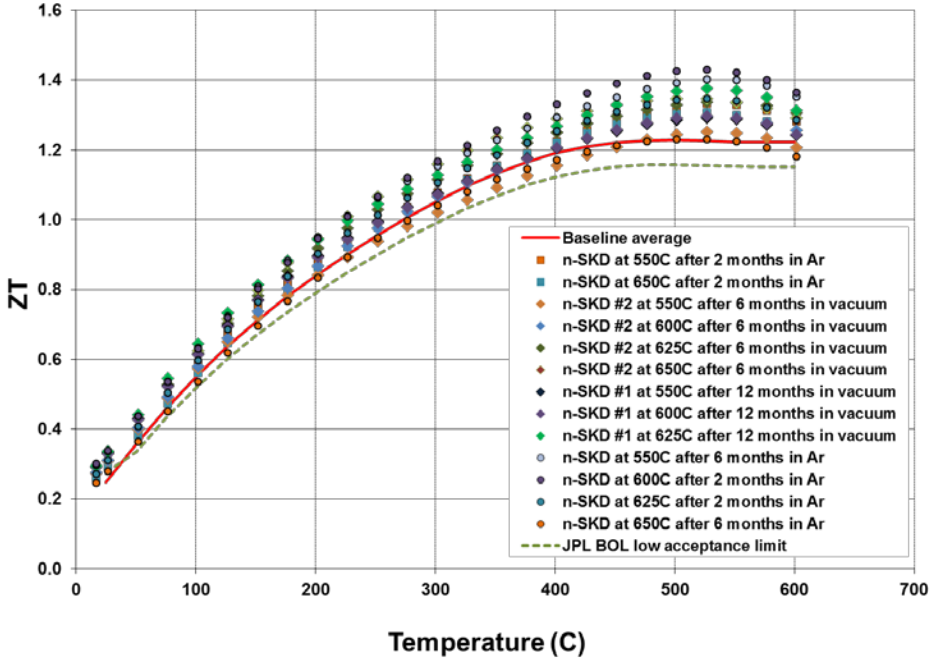
SKD couple tested for 9888 hrs at Th = 600C and Tc = 200C

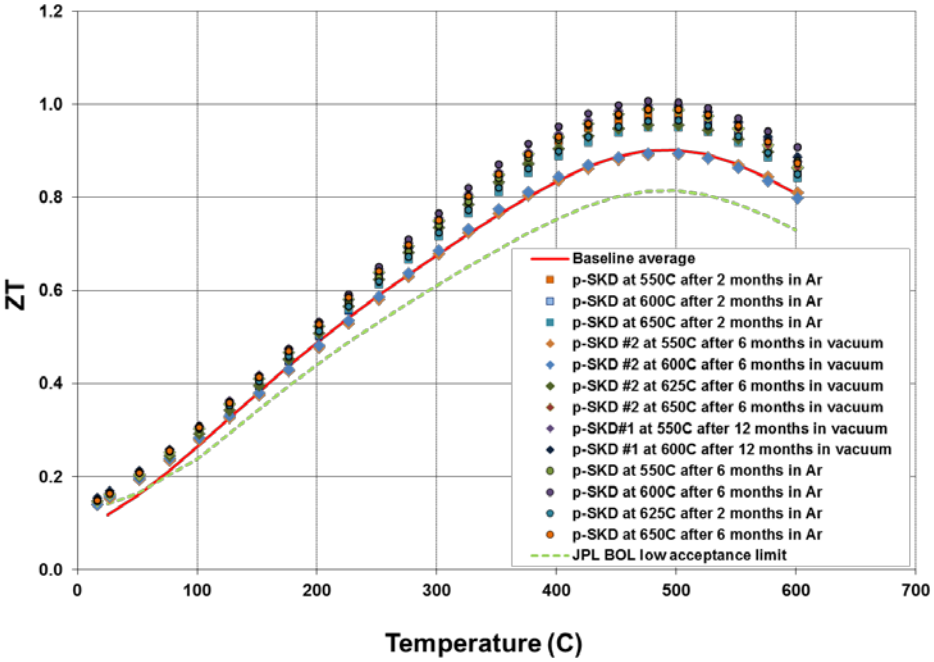
Couple ID	Test duration	Hot-junction T	Cold-junction T
SKD 6 V2	9888 hrs	550 C	200C
SKD 7 V2	9888 hrs	600 C	200C
SKD 9 V2	9888 hrs	600 C	200C
SKD 5 V2	9888 hrs	625 C	200C

Physics-Based Proposed eMMRTG Lifetime Performance Prediction & Validation Flow Diagram



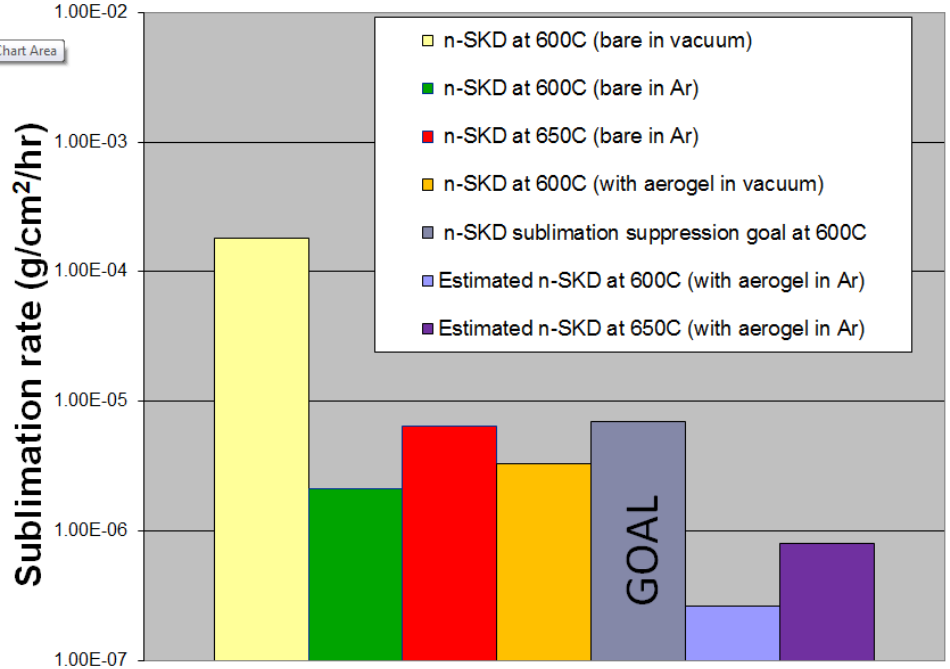
TE properties life testing - skutterudite in Ar and vacuum

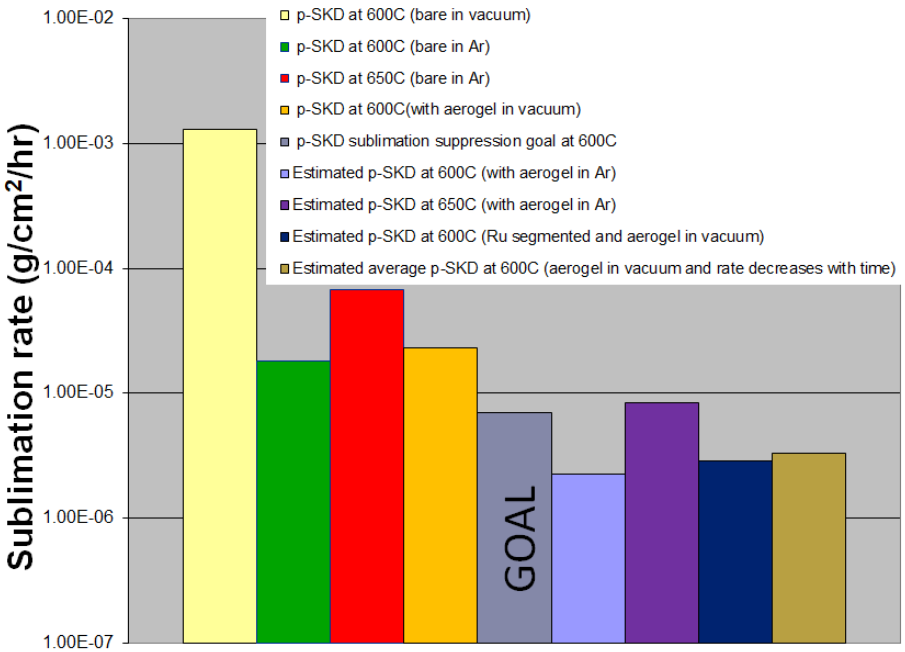




- **TE properties of n- and p-skutterudite show no change after 52 weeks of aging in vacuum up to 650C**
- **TE properties of n- and p-skutterudite show no change after 26 weeks of aging in Ar up to 650C**

Sublimation rate for SKD materials

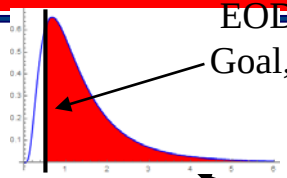




- **Key findings**
  - Sublimation rate of p-SKD decreased by ~ 8 times with aerogel
  - Sublimation rate of both p and n-SKD in Ar decreased by ~ 100 times (compared with the values in vacuum)
- **Estimated sublimation rate with both Ar and aerogel**
  - p-SKD at 600C with Ar and aerogel: 2.2×10^{-6} g/cm^2/hr
  - n-SKD at 600C with Ar and aerogel: 2.6×10^{-7} g/cm^2/hr

Proposed eMMRTG Life Performance Prediction Reliability Estimation

Probability Density Function for EODL Power$_E$



EODL Goal, G

Reliability

eMMRTG Model (e.g., LPPM)

SKD Material Properties

- Seebeck coefficient
- Sublimation flux
- Electrical resistivity
- Thermal conductivity

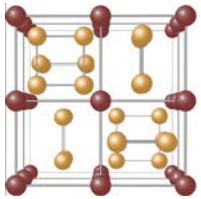
Couple Properties

- SKD Properties
- :
- Contact resistance$_E$
- Contact resistance$_T$

Insulation Properties

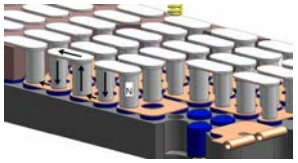
- Insulation Properties

SKD Testing



Wikipedia

Couple/Module Testing

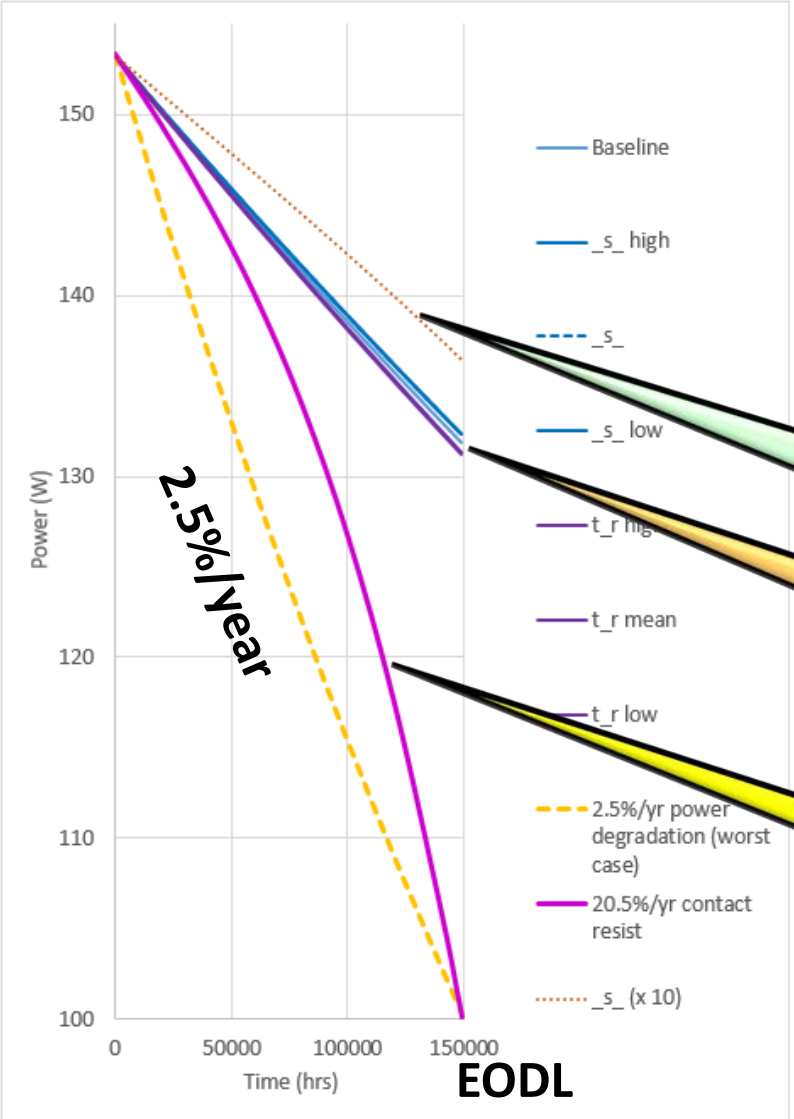


Insulation Testing

Photo credit: Cabot

Proposed eMMRTG-level LPP Sensitivity Analysis Initial Results

BOL



EODL

Key:
t: TE property uncertainties (Seebeck coefficient, electrical resistivity, thermal conductivity)
s: Sublimation uncertainty
r: Contact resistance time dependence

low: 0.14th percentile (corresponds to μ-3σ for normal)
high: 99.86th percentile (corresponds to μ+3σ for normal)

Increased sublimation increases necking can result in couple failure.

Additional testing of TE properties probably not needed at this time.

Thermal and electrical interface resistance data are needed.

Summary

- JPL has transferred the processes for the fabrication of SKD materials, metallized elements, and couples, and aerogel to TESI
- TESI has successfully developed manufacturing capabilities for SKD materials, metallized elements, ambiently dried aerogel, and couples
- Two additional iterations of couples are planned with a couple down-select scheduled at the end of Phase B (~ June 2017)
- A life database is being simultaneously developed to be used in a physics-based model to allow for the prediction of the power output of the propsoed eMMRTG as a function of time and different operating conditions

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