2018 Conference on Advanced Power Systems for Deep Space Exploration

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OVERVIEW OF SYSTEMS ENGINEERING INTEGRATED WITH TECHNOLOGY DEVELOPMENT WORK TO INFORM FUTURE RTG DESIGNS

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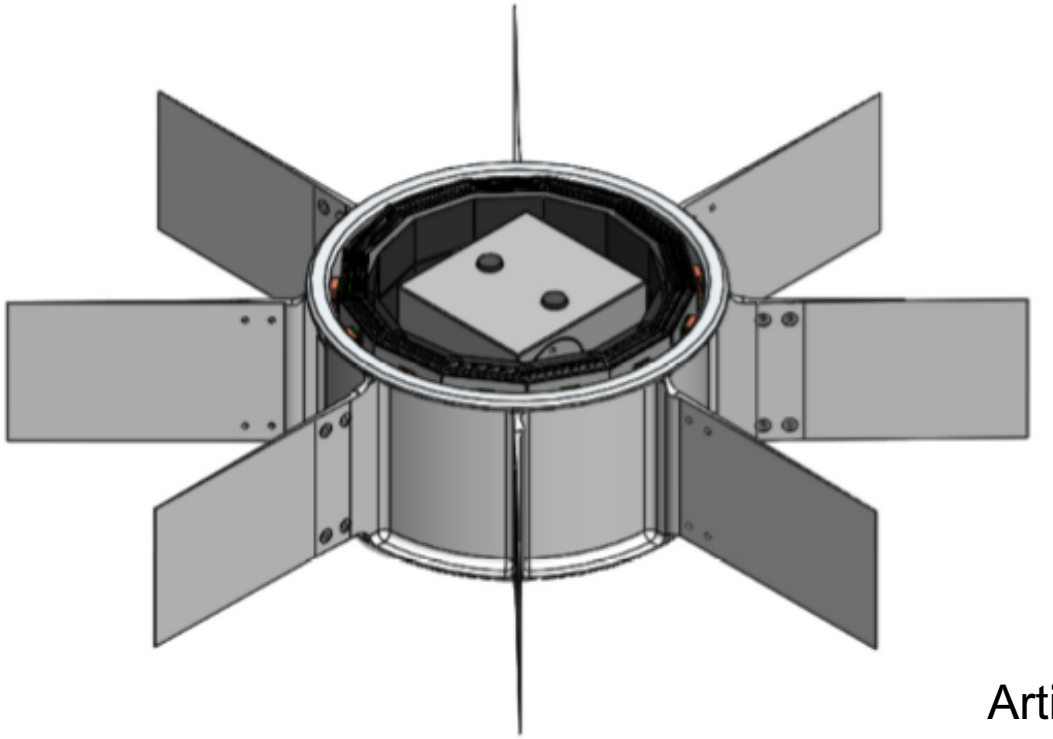
RTG Systems Engineering Approach



Artist's Concept

Terry J. Hendricks – Generator Systems Engineering Lead
NASA – Jet Propulsion Laboratory

RPS Systems Engineering Objectives

- Inform and guide Technology Development efforts with system-level design criteria, critical environments assessments and requirements, and key design constraints
- Provide key information and guidance to RPS Technology Development
  - Define the relevant device chemical, thermal and structural environment
- This is critical aspect of maintaining/sustaining RTG design and development capability
  - No Technology is viable without RTG design configuration to implement it
  - System engineering ensures successfully and efficient implementation of TE technology
  - TE technology design and RTG system design are INHERENTLY linked together

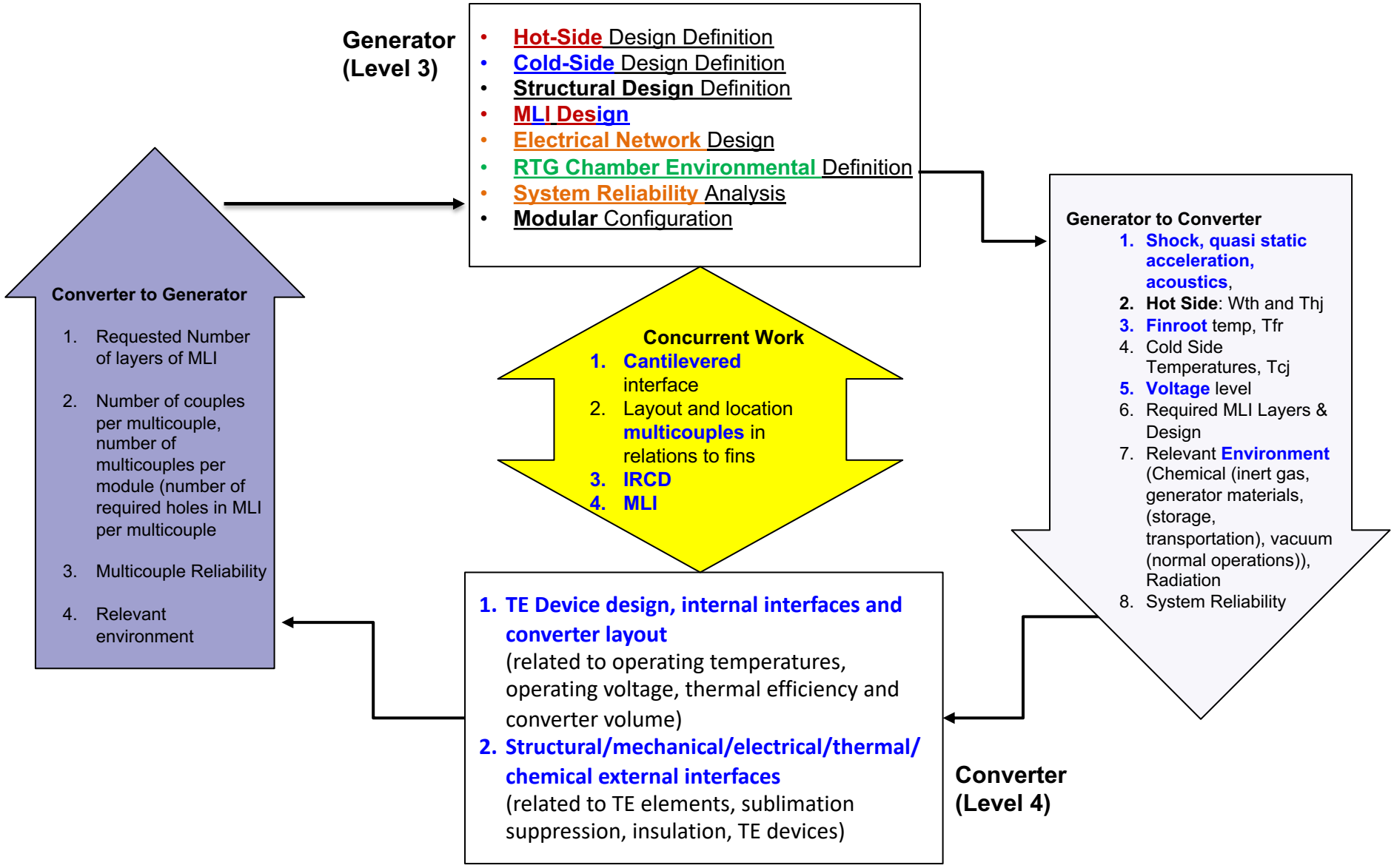
System Requirement Assumptions

- Assumptions/Constraints for Trades Provided by the RPS Program
  - Assumption/Constraints
  - GPHS Step-2 at BOL: 250 $W_{thermal}$
  - Vacuum-only RTGs
  - Modular
  - Series-parallel circuit architecture in RTGs
    - » Cantilevered couples/multicouples
  - 16 GPHS modules (largest variant)
  - PBOM = 400-500 $W_{electric}$ (largest variant)
  - Mass goal of < 60 kg (largest variant)
  - Allowable Flight Temperature (AFT): Tfr_avg = 50 – 200ºC
  - Degradation rate ≤ 1.9% average per year over design life
  - Design Life: 17 years
  - Largest variant fits in one DOE shipping cask, 9904

Generator Tradeoffs & Sensitivity Analyses

- RTGs for NASA – List of Currently Identified System Trades; All project level trades
  - Risk to Benefit trades, design sensitivities, & tasks:
  - Coupling to heat source and heat sink (Design Tradeoffs & Sensitivities On-Going)
  - Gases in generator environment (types, life, sealing) (Planned for FY 2019)
  - System Thermal Engineering trades (On-Going)
    - » Voltage trades require us to look at lifetime considerations & are integrated with temperature/thermal trades
  - System Structural Engineering trades (Planned for Starting in Qtr 1 FY 2019)
  - System Structural Dynamics trades (Planned for Starting in Qtr 1 FY 2019)
  - System Reliability trades (Voltage vs. System Electrical Network Configuration)
  - Radiation, Planetary Protection, Electronics, Safety, Contamination (FY 2019)

Systems Engineering Dataflow and Analysis & Design Work Generator to/from Converter



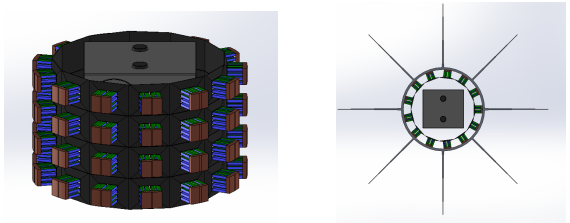
Current Work and Accomplishments

- RTG Thermal System Tradeoff Studies & Analyses
  - Developed 2 GPHS, 8 GPHS and 16 GPHS Thermal System Configuration Models (Thermal Desktop)
  - SolidWorks CAD files integrated and transferred into Thermal Desktop formats
  - Accomplishments & Plans:
    - » Hot-Side Thermal Absorption and Distribution Materials & Configurations
    - » Insulation Materials & Configurations – MLI Studies
    - » Cold-Side Dissipation Materials & Configurations
    - » Internal Chemical Environments (Fueling, Ground Operations & Pre-Launch Conditions)

Modularity

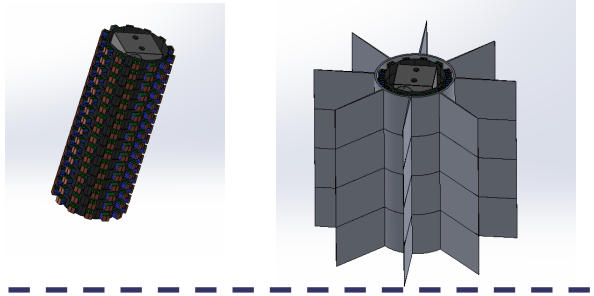
Design Targets

2 GPHS Next Generation RTG



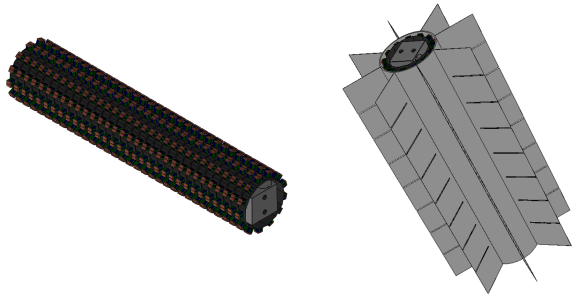
~50 W_e (BOL)
~4-5 W_e/kg
T_h = 800-1000° C
V = 34 Vdc

8 GPHS Next Generation RTG



~200-250 W_e (BOL)
~6-7 W_e/kg
T_h = 800-1000° C
V = 34 Vdc

16 GPHS Next Generation RTG



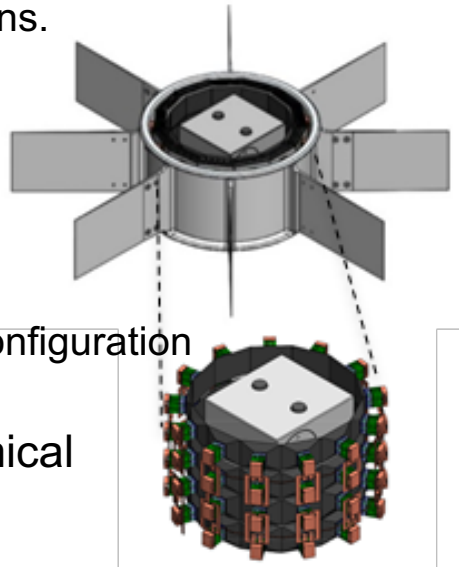
~400-500 W_e (BOL)
~8-9 W_e/kg
T_h = 800-1000° C
V = 34 Vdc

Systems Engineering Development (L3)

Modeling

- Refining Generator Thermal Models & Performing Tradeoff / Sensitivity Analyses
  - These models make it possible to estimate, for example, Hot Side and Cold Side Designs within the Generator for delivering and dissipating thermal energy, respectively, to/from the TE multicouples
  - Multiple models being developed for 2, 8 and 16 GPHS configurations.
  - Thermal models will include:
    - » Critical thermal interface conductances
    - » MLI insulation thermal performance
    - » Electrical conductances
    - » Internal & external radiative thermal models
    - » TE power producing simulations (from Converter work)
  - Configurations shown here provide preliminary starting generator configuration
- Program Requirements Document completed and incorporated
- Structural Stress, Structural Dynamics, and Radiation and Chemical Environment Analysis being planned and scheduled
- Preliminary Generator / Converter Risk Assessments completed

The NG-RTG uses MLI and aerogel for insulation. MLI is the most efficient. The MLI area to TE couple area ratio will be a major design criteria and discriminator.



TRL Advancement: Upcoming Milestones

TRL 3

Target system conceptual design defined and operating environment updated

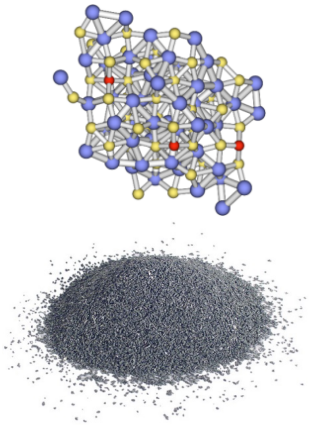
Completed: September 2019

- Complete Thermal Model development & preliminary trade results
  12/30/2018
- Chemical & Radiation Model development & preliminary trade results and environments
  6/30/2019

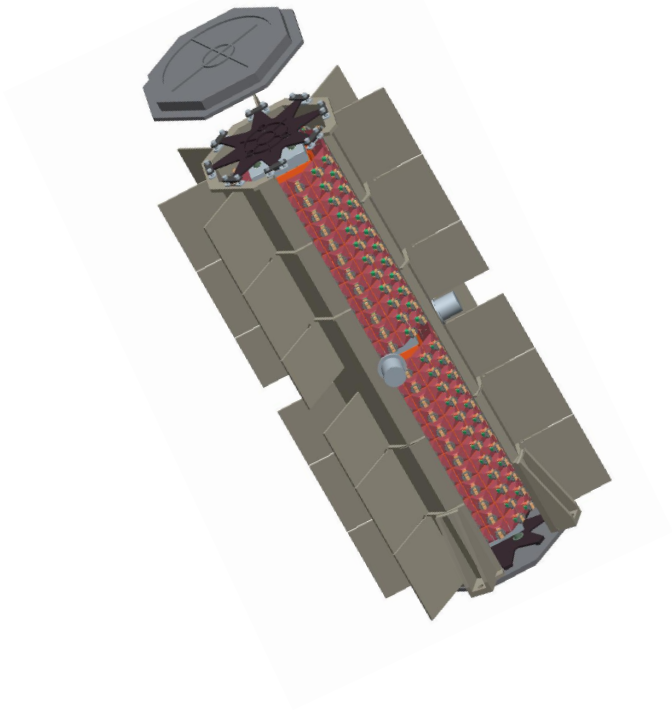
RPS Sponsored Converter Technology Development

Long Life, High Reliability and "More Capable" Thermoelectric Generator

Advanced TE Materials



Need to "live up" to heritage technologies …and do one better!



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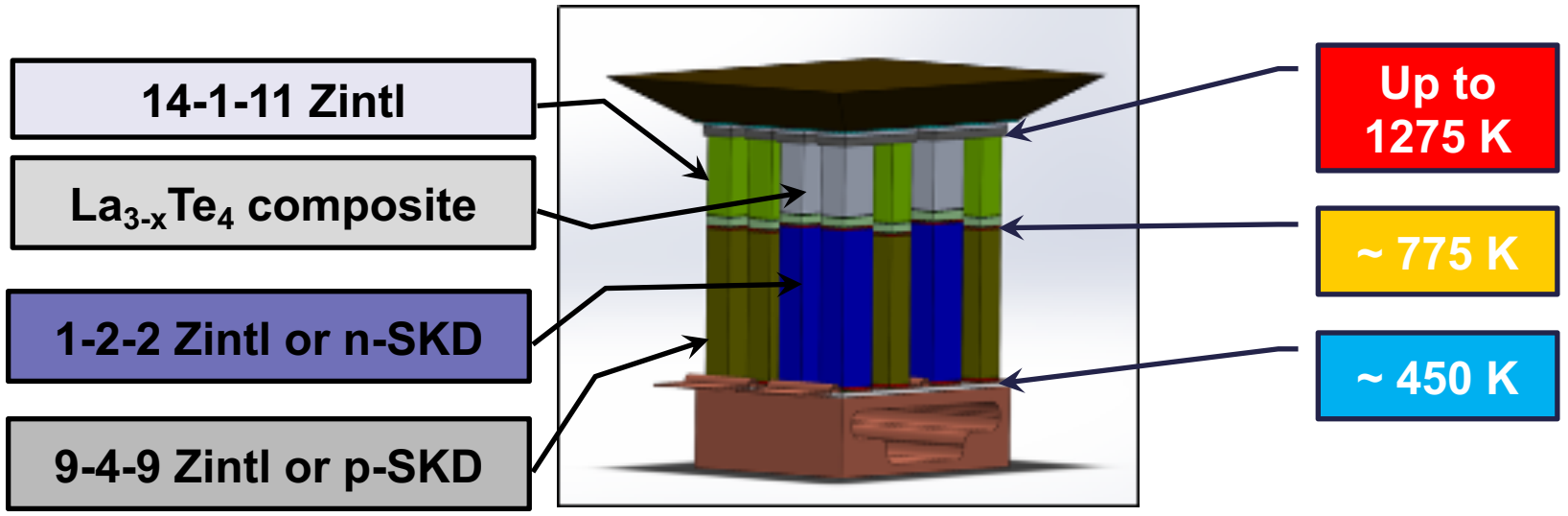
Couple Configurations Currently Being Explored

Configuration	n		p	
	Mid	High	Mid	High
Segmented	1-2-2 Zintl	$La_{3-x}Te_4$/composite	9-4-9 Zintl	14-1-11 Zintl
Segmented	SKD	$La_{3-x}Te_4$/composite	SKD	14-1-11 Zintl
Unsegmented		$La_{3-x}Te_4$/composite		14-1-11 Zintl

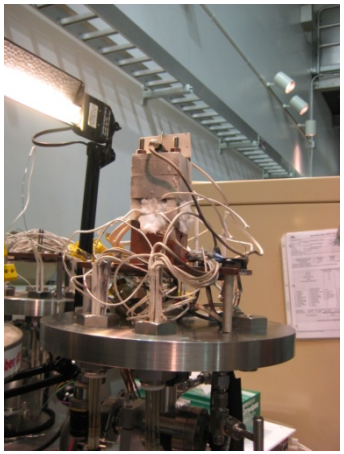
Cold side segment (Bi_2Te_3 alloys) not considered due to radiator size limitations

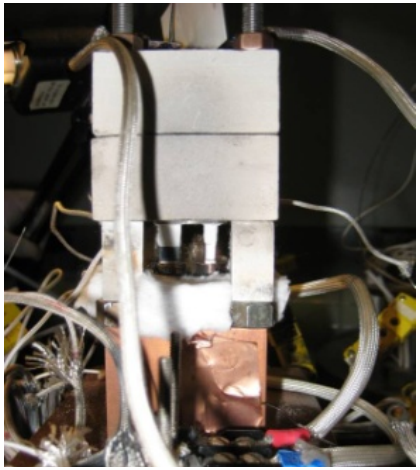


Multicouple device for supporting modular RTG capability

BOL Single Couple-level Materials Performance Verification

Up to 15% conversion efficiency for 1275-475 K Operation

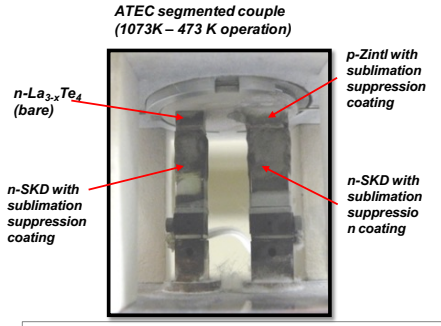


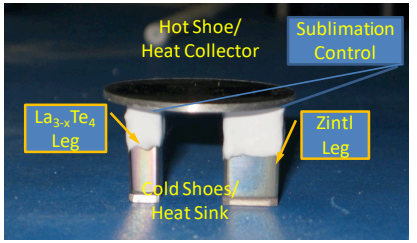


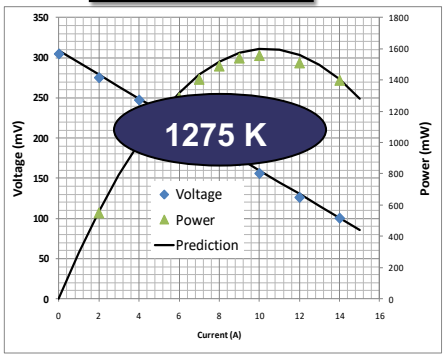
Testing Setups at JPL for Spring-Loaded Devices

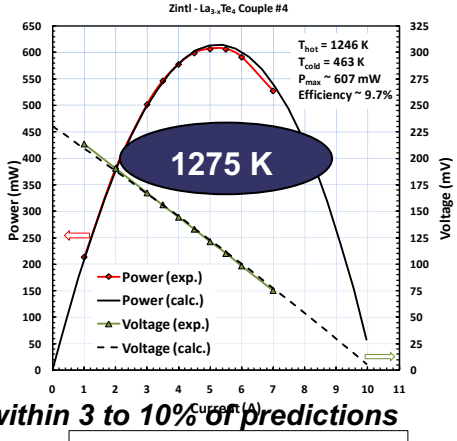
Segmented

Unsegmented







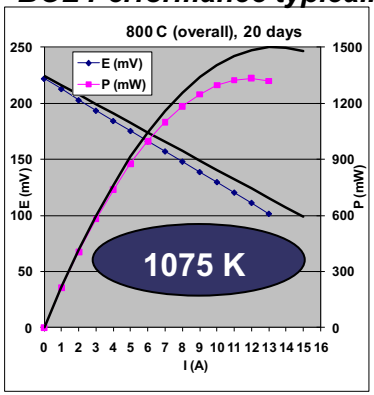


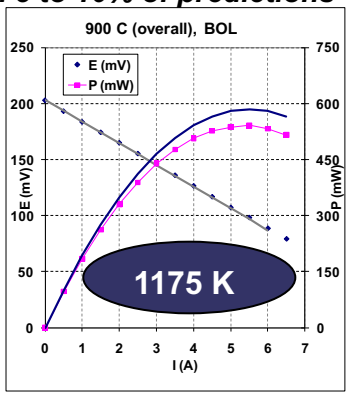
Proof-of-Principle Devices

BOL Performance Baseline established in 2012

- **Un-segmented couple efficiencies ranging from 8.7% (1175 K) and 10% (1275 K)**
- **Segmented couple efficiencies ranging from 11% (1075 K) and ~15% (1275 K)**
- ➢ ***475 K cold junction temperature***

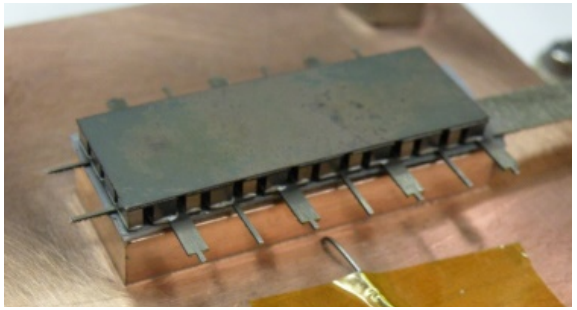
BOL Performance typically within 3 to 10% of predictions



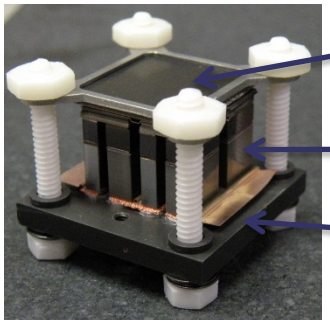


Proof-of-Principle TE Module Demonstrations Based on Segmented TE Technology

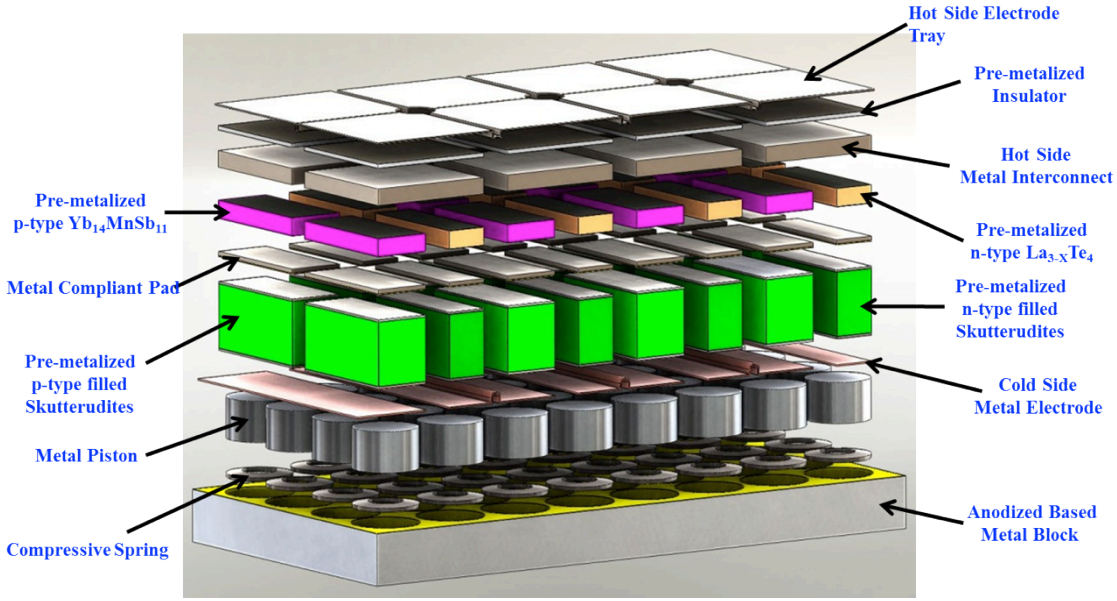
- Based on Segmented TE Couple Technology
  - Includes multiple compliant interfaces to minimize thermally induced mechanical stresses
  - Mechanically compliant designs with aerogel-based thermal insulation
- 1st Generation 4-couple and 8-couple modules fabricated & tested (solar furnace, Na HP heat sources)
  - Efficiencies up to ~ 10% measured to date
  - 15% possible for 1275/475 K operating temperatures

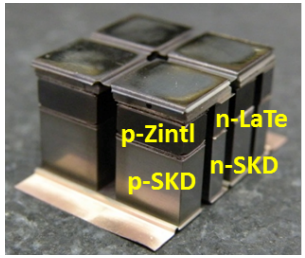


15 W 28-couple SKD Multicouple (JPL)



Fully segmented 4-couple TE Modules for Terrestrial and Space Applications (JPL)



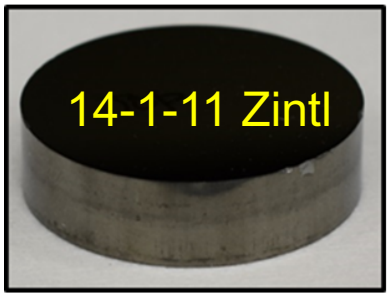


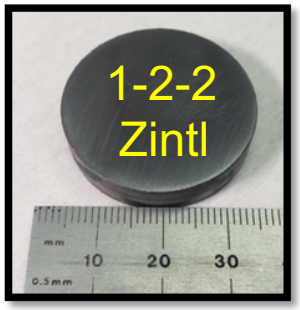
Basic Building Block: Segmented Multicouple "Skeleton Structure"

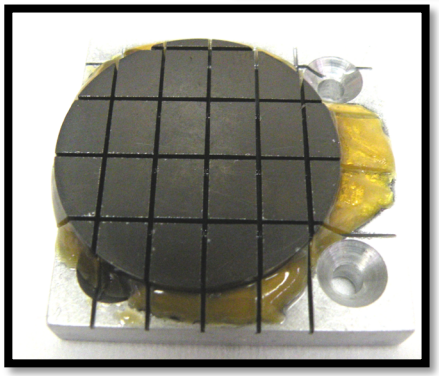
Technology Development
Thermoelectric Materials – Current Status

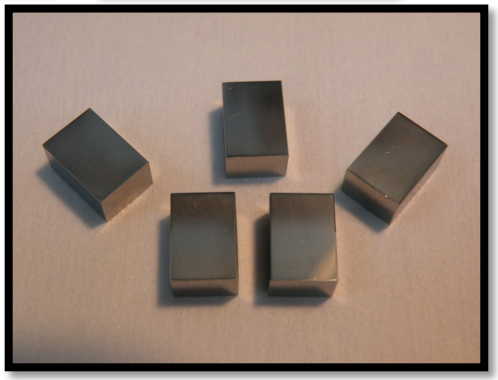
- Using high energy ball milling and high pressure high temperature sintering for all synthesis and fabrication processes
- Completing development for scaling up to TE materials large batch synthesis, large puck sintering and metallized TE elements dicing
- Completing set of long term stability and reactivity testing (TE properties, chemical and mechanical properties)

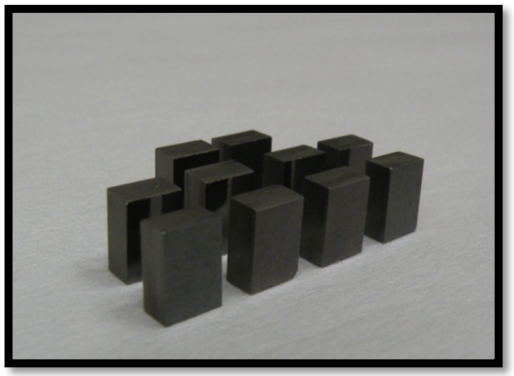
"bare" 32 mm sintered pucks of TE materials









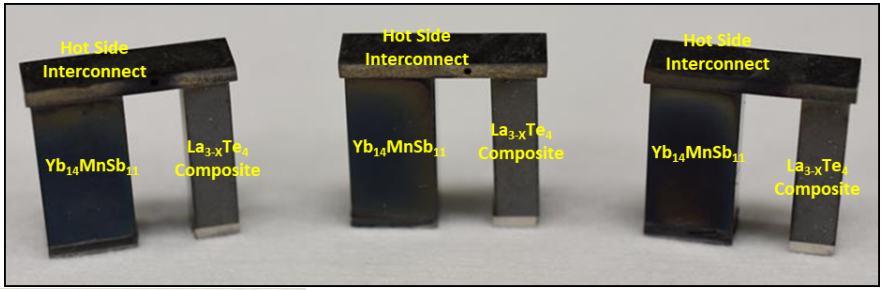


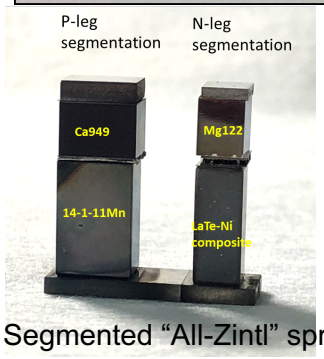
Metallized pucks and diced legs ready for device fabrication

Technology Development
Thermoelectric Devices – Current Status

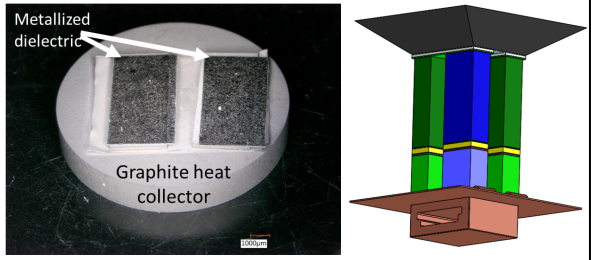
- Development of segmented and unsegmented devices
- Completing cycle for spring-loaded low fidelity devices
  - Conduct extended performance test to identify and quantify dominant degradation mechanisms
  - Develop and implement design changes to reduce or even eliminate these mechanisms
  - Develop aerogel encapsulation techniques for sublimation suppression and to serve as thermal insulation
- Initiating cycle for cantilevered multicouples
  - Developing fabrication processes for key elements: metallized legs, hot shoe, cold shoe and insulation
  - First proof-of-principle devices expected to be tested starting FY19 Q3

Unsegmented, spring-loaded single couples

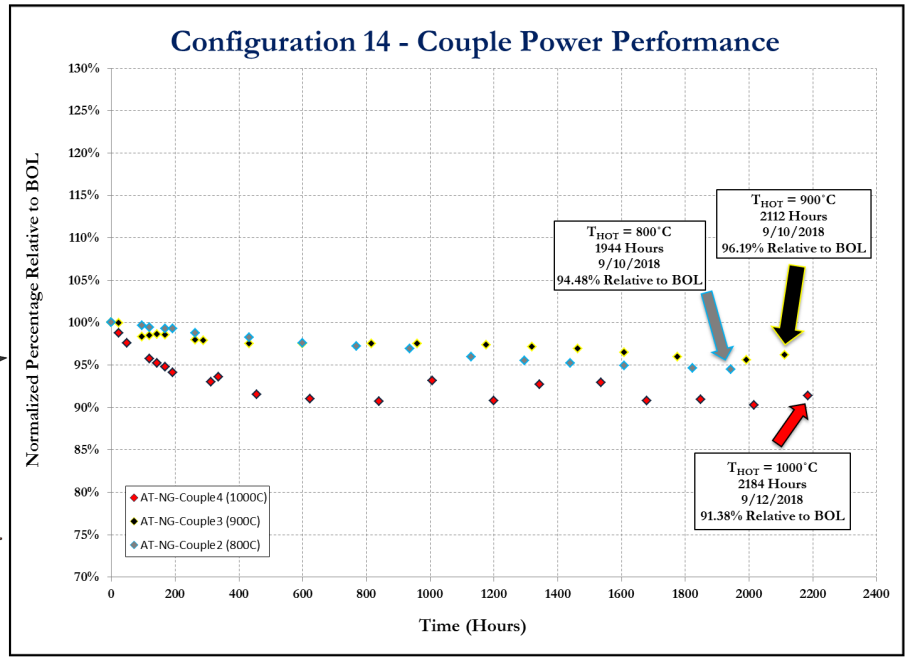




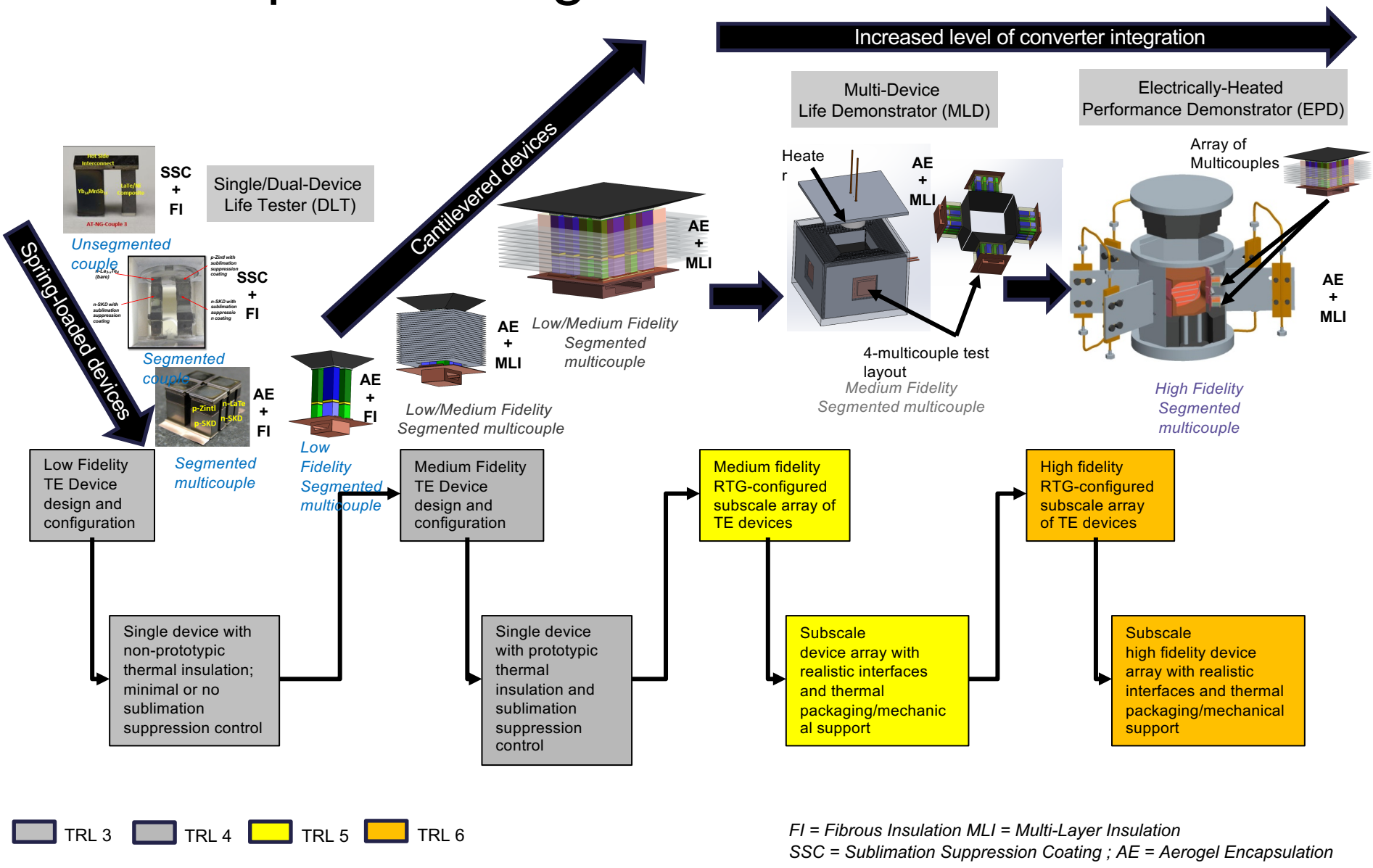
Segmented "All-Zintl" spring-loaded single couple



Hot Shoe development for cantilevered multicouple



Next Gen RTG – Converter Technology Development Progression to TRL 6



FI = Fibrous Insulation MLI = Multi-Layer Insulation
SSC = Sublimation Suppression Coating ; AE = Aerogel Encapsulation

Summary

- JPL is performing system studies and trades in parallel with technology development work sponsored by the RPS program that inform the relevant environment for the TE devices and generators