2011 THERMOELECTRICS APPLICATIONS WORKSHOP

Thermoelectrics: From Space Power Systems to Terrestrial Waste Heat Recovery Applications

Jean-Pierre Fleurial, Thierry Caillat, Bill J. Nesmith,
Richard C. Ewell, David F. Woerner, Gregory C. Carr and Loren E. Jones

Jet Propulsion Laboratory/California Institute of Technology

jean-pierre.fleurial@jpl.nasa.gov

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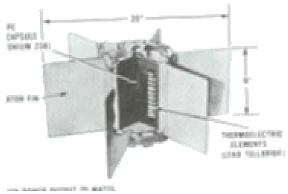
Outline

- **U.S. RTG-powered NASA Science & Exploration Missions**
- **MMRTG-powered Mars Science Laboratory mission**
  - Overview of power subsystem architecture
- **Development of high temperature TE couple technology for next generation RTGs**
  - Need for 2x to 4x improvement in RTG conversion efficiency and specific power (W/kg)
- **Potential of new TE technology for terrestrial applications**
  - High grade waste heat sources

RTG Technology - Missions

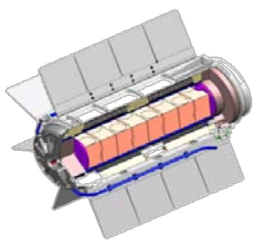
PbTe-based

SNAP-19



40 W_e, 3 W/kg
6.3% Efficiency
Deep space and planetary surface operation
➢30 Year life demonstrated

MMRTG



120 W_e, 2.8 W/kg
6.3% Efficiency
Deep space and planetary surface operation

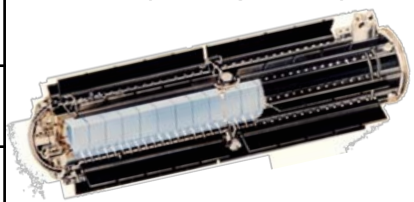
Mission	RTG	TE	Destination	Launch Year	Mission Length
Transit 4A	SNAP-3B7(1)	PbTe	Earth Orbit	1961	15
Transit 4B	SNAP-3B8 (1)	PbTe	Earth Orbit	1962	9
Apollo 12	SNAP-27 RTG (1)	PbTe	Lunar Surface	1969	8
Pioneer 10	SNAP-19 RTG (4)	PbTe	Outer Planets	1972	34
Triad-01-1X	SNAP-9A (1)	PbTe	Earth Orbit	1972	15
Pioneer 11	SNAP-19 RTG (4)	PbTe	Outer Planets	1973	35
Viking 1	SNAP-19 RTG (2)	PbTe	Mars Surface	1975	4
Viking 2	SNAP-19 RTG (2)	PbTe	Mars Surface	1975	6
LES 8	MHW-RTG (4)	Si-Ge	Earth Orbit	1976	15
LES 9	MHW-RTG (4)	Si-Ge	Earth Orbit	1976	15
Voyager 1	MHW-RTG (3)	Si-Ge	Outer Planets	1977	31
Voyager 2	MHW-RTG (3)	Si-Ge	Outer Planets	1977	31
Galileo	GPHS-RTG (2) RHU(120)	Si-Ge	Outer Planets	1989	14
Ulysses	GPHS-RTG (1)	Si-Ge	Outer Planets/Sun	1990	18
Cassini	GPHS-RTG (3) RHU(117)	Si-Ge	Outer Planets	1997	11
New Horizons	GPHS-RTG (1)	Si-Ge	Outer Planets	2005	3 (17)
MSL	MMRTG (1)	PbTe	Mars Surface	2011	3

SiGe-based

MHW-RTG

158 W_e, 4.2 W/kg
6.5% Efficiency
Deep space operation
➢30 Year life demonstrated

GPHS-RTG



285 W_e, 5.1 W/kg
6.5% Efficiency
Deep space operation
> 18 Year life demonstrated

RTGs have been successfully used on a number of long-life missions

MMRTG-powered Mars Science Laboratory mission

Mars Science Laboratory (MSL) Launch System and Payload

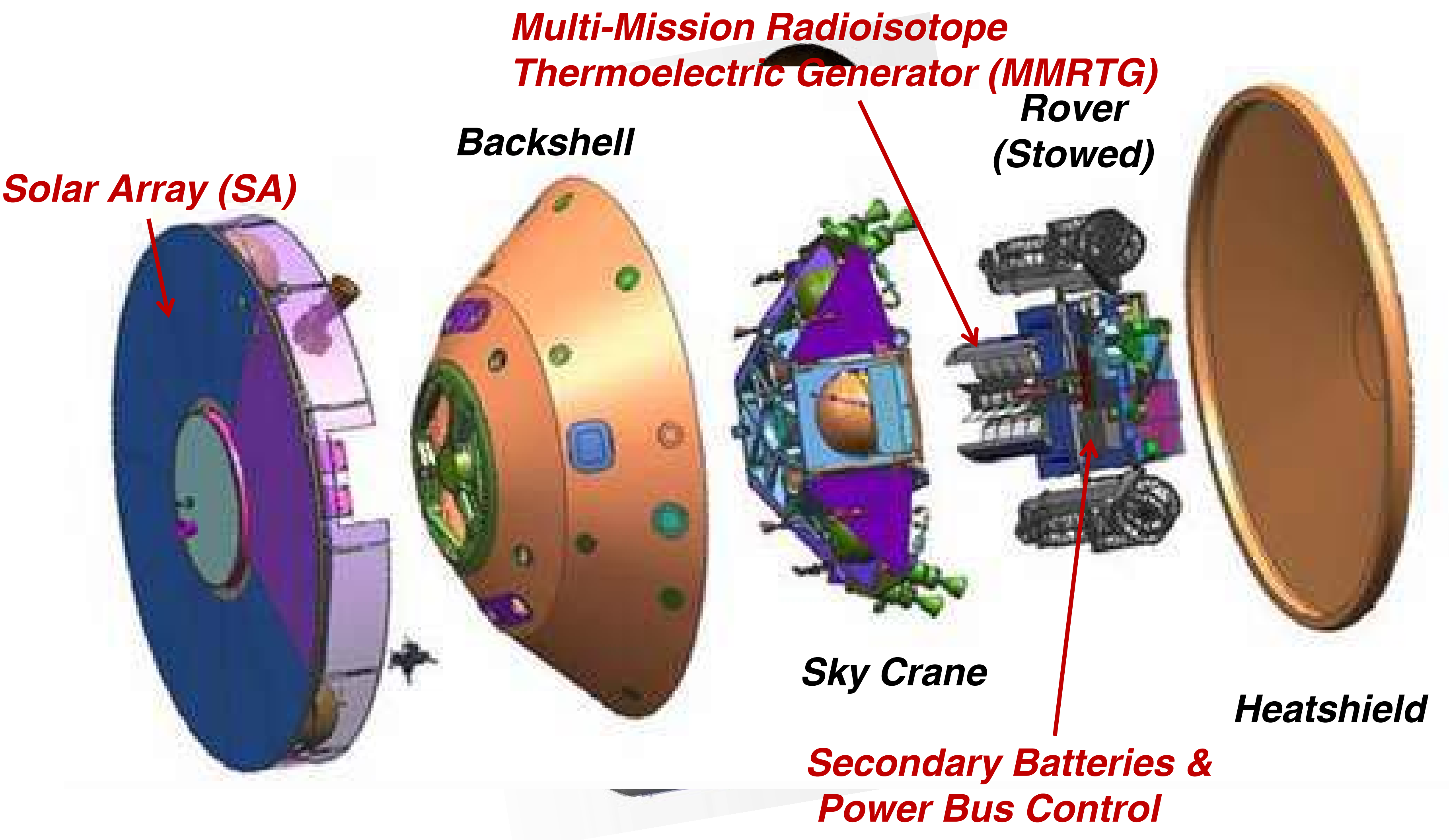
Mars Science Laboratory is part of NASA's Mars Exploration Program, a long-term effort of robotic exploration of the red planet. Mars Science Laboratory is a rover that will assess whether Mars ever was, or is still today, an environment able to support microbial life. In other words, its mission is to determine the planet's "habitability."

Launch window - Nov. 25 to Dec. 18, 2011
Mars Rover (Curiosity) arrival - Aug. 2012

Launch vehicle - Atlas V 541

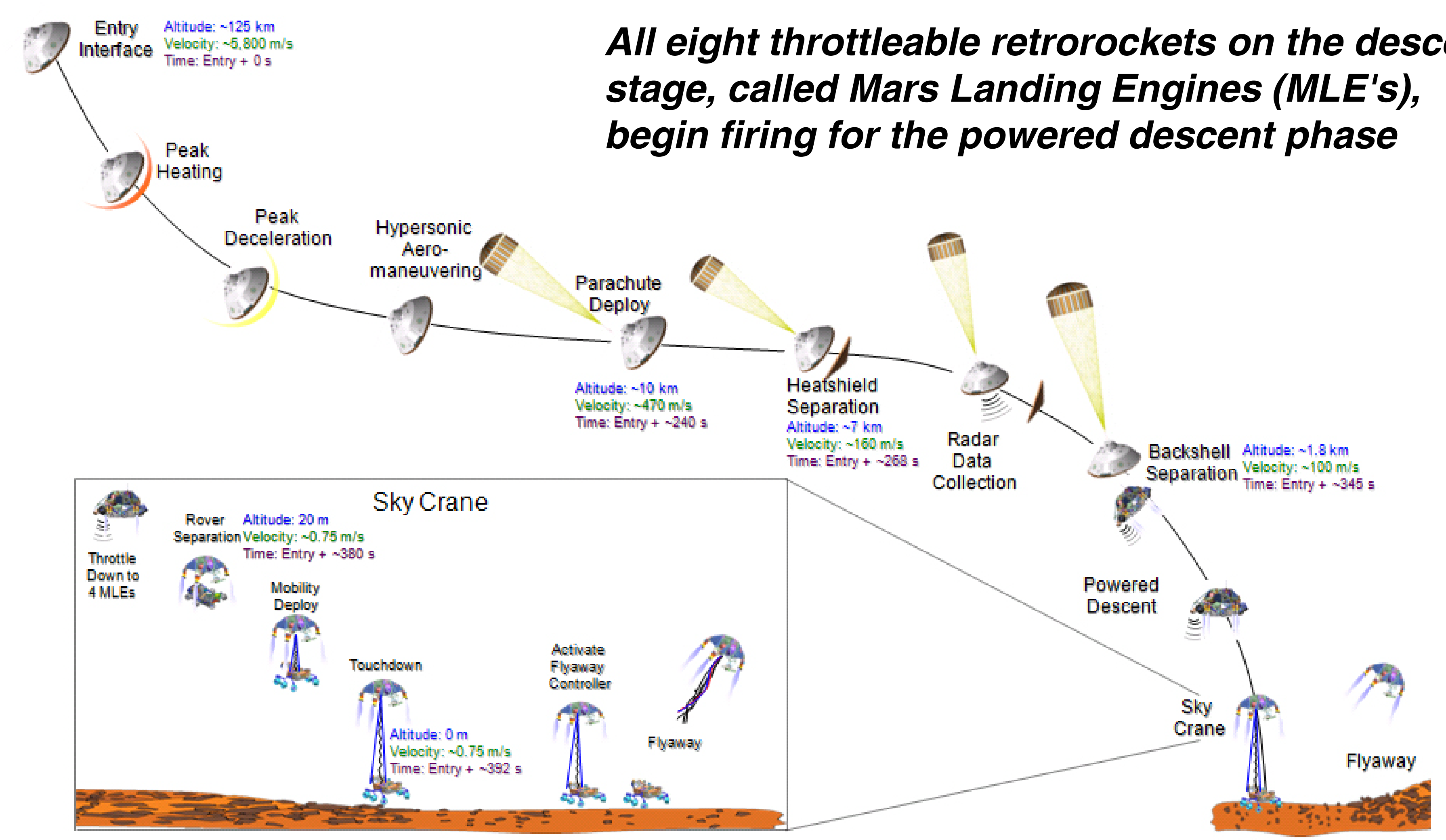
Rover	850 kg (1,875 lbs)
Descent stage (dry)	829 kg (1,830 lbs)
Descent Stage Propellant	390 kg (860 lbs)
Heat Shield	382 kg (842 lbs)
Cruise Stage (wet)	600 kg (1,323 lbs)
Backshell	349 kg (770 lbs)

Cruise Stage



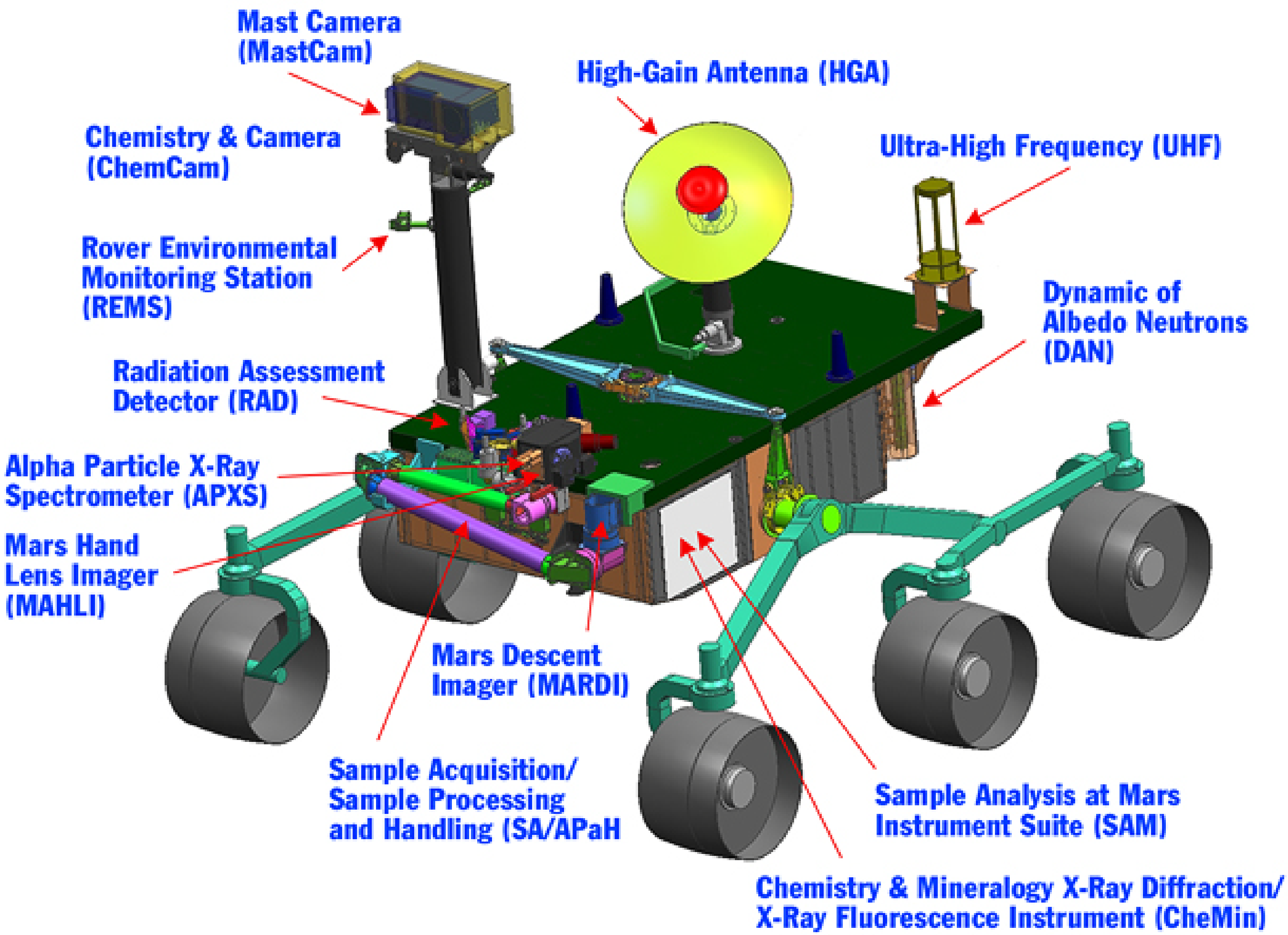
Entry, Descent, and Landing Stage

All eight throttleable retrorockets on the descent stage, called Mars Landing Engines (MLE's), begin firing for the powered descent phase



Surface Stage: MSL Science Instruments

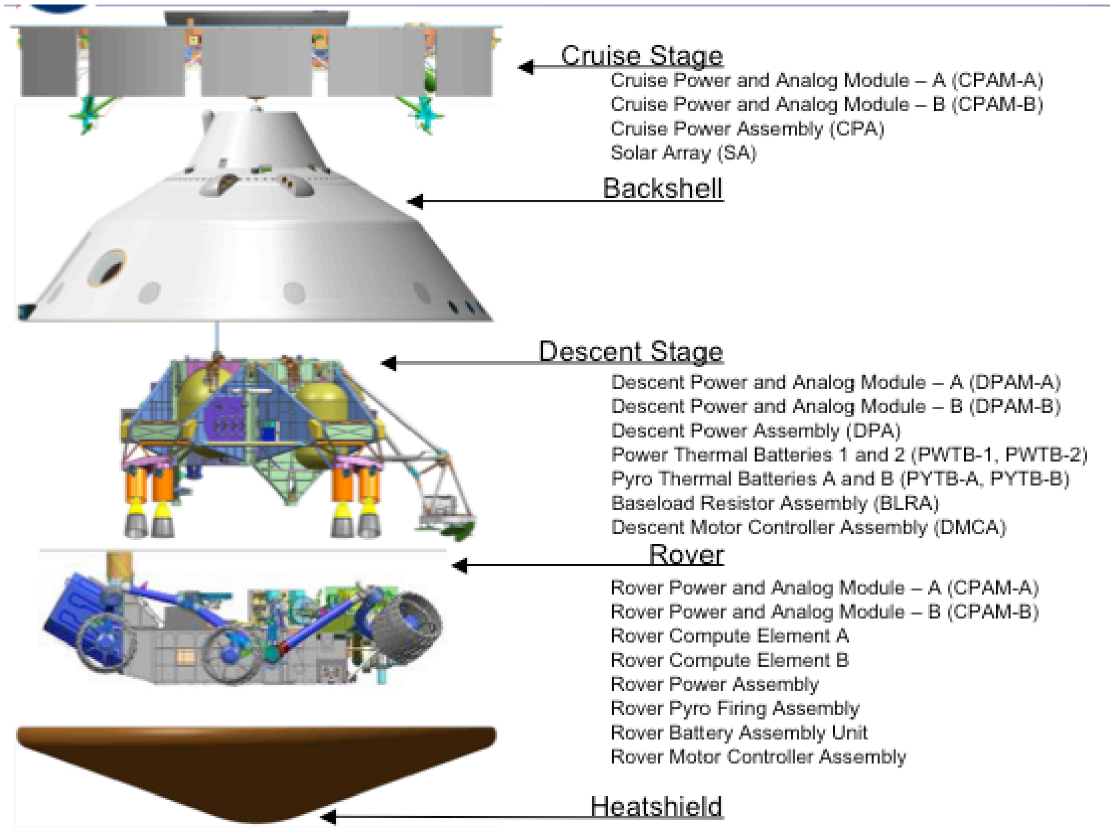
Current Rover Configuration



Overview of MSL Avionics Control Hardware
- Power Subsystem Architecture Design Challenges -

- **MSL has three stages that share one primary power bus**
  - First time that RTG, Battery and Solar Array elements are on same power bus
  - Bus stability over various configurations of the vehicle
  - Large solar array capable of high battery charge currents

- **Power system must function nominally in all three stages during all phases of the mission**
  - Descent and Rover stages are separated with cable cutters and must continue to function
- **Varying Power Bus configuration during MSL mission lifetime**
  - Large currents required throughout the vehicle and delivered to loads



MSL Power System Configurations

- **Cruise configuration**
  - All three stages physically and electrically connected.
  - Solar Array + MMRTG power supports all loads.

- **Entry-Descent-Landing configuration**
  - All three stages electrically separated via mechanical relays opening. Cruise Stage physically separated and non-functional at this point.
  - Descent Stage loads powered by thermal batteries.
  - Rover loads powered by MMRTG + Li-Ion Batteries.
  - During descent the Rover and Descent Stage are physically separated

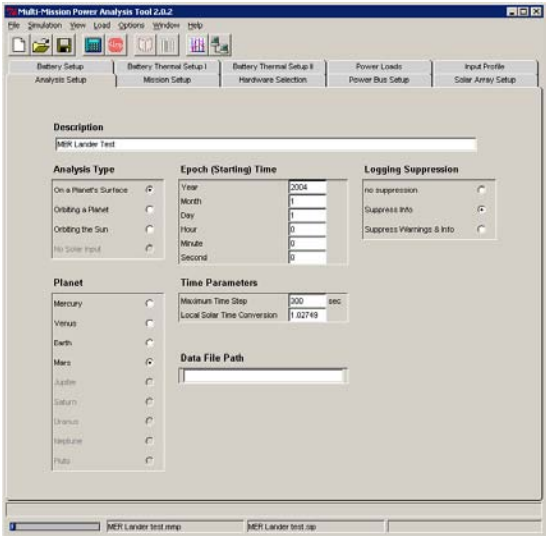
- **Surface configuration**
  - Descent stage non-functional.
  - Rover loads are powered by MMRTG + Li-Ion Batteries.

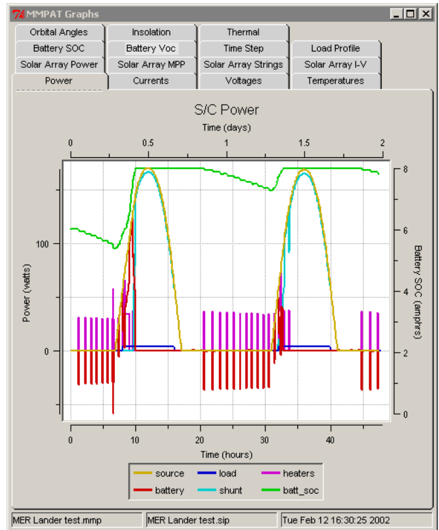
MSL Power System Modeling

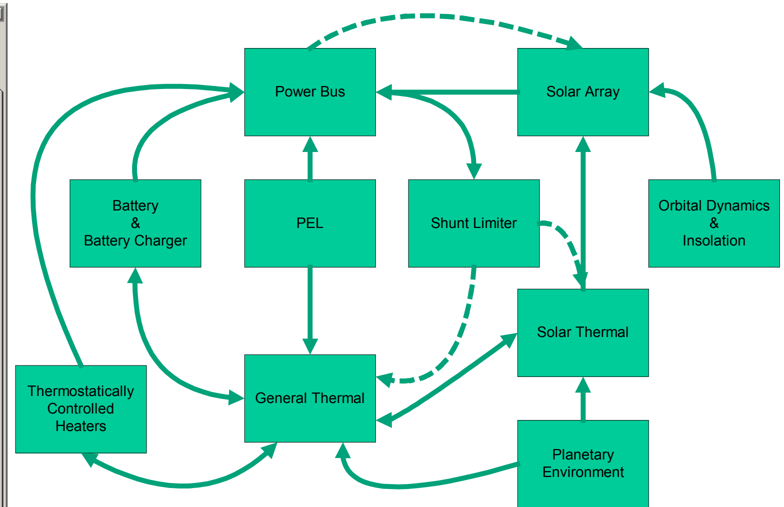
Power system modeling is performed two ways

- **High fidelity predictions using a custom tool called MMPAT.**
  - Multi Mission Power Analysis Tool (MMPAT)
    - Uses table based models for power sources
      - Battery voltage: Function of Temp, Current & state of charge (SOC)
      - Solar array: test data driven at solar cell level
      - MMRTG: table based on JPL DEGRA software tool
        Tables are accessed through:
        - » Age of Radioisotope Heat Source
        - » Age of Generator since fueling
        - » Generator Fin Root Temperature
    - Load power tracked in database style table
      - Each device has load power states defined in table
      - Device states are used to simulate mission scenarios
- **Simple power system analysis is performed using spreadsheet models**

MMPAT Overview







- Software Simulation of Spacecraft Electrical Power & Thermal Subsystems
  - Models the behavior of a power source and an energy storage device as they interact with the spacecraft loads over the mission timeline.
- Models Multiple Mission Types
  - Planetary Lander, Planetary Orbiter, Heliocentric Orbiter
- Used by Deep Impact (DI), MER, MRO & MSL Flight Projects.
  - Integrated with APGEN (mission planning tool) for MER & DI Operations planning

Surface Phase Bus Voltage Predictions

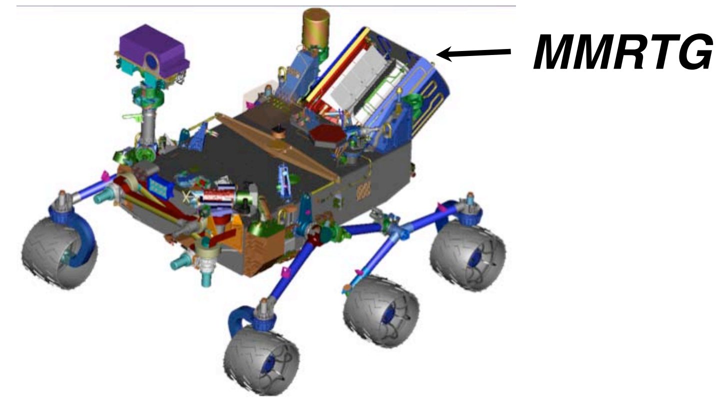
- **Bus voltage during surface follows battery discharge and recharge curves**
  - Unlike Cruise where solar array produces more than enough power to remain power positive and able to regulate the bus voltage

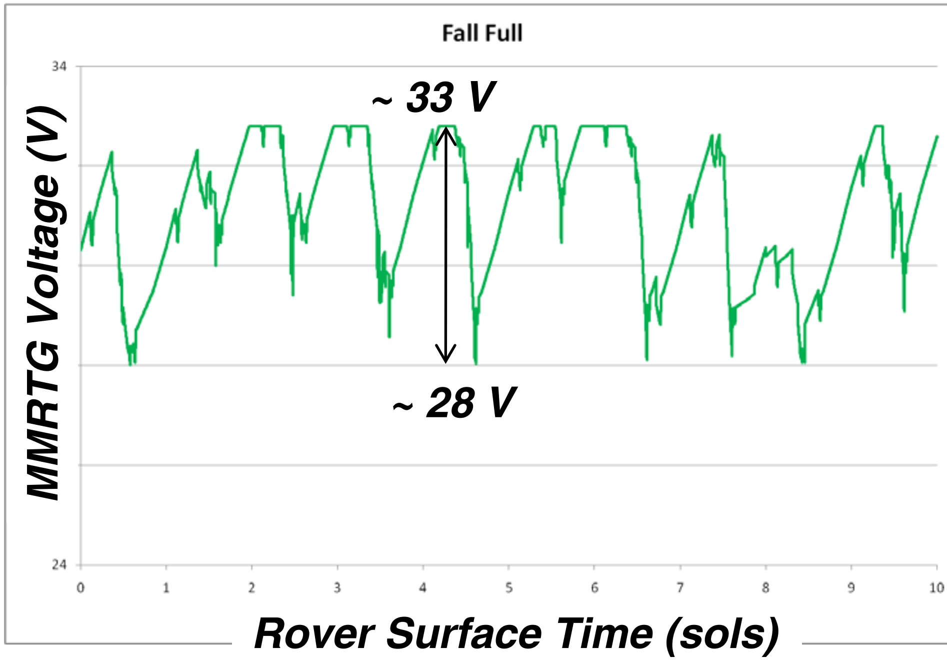
- **Battery performance varies with temperature and discharge rate**

- **Therefore, bus voltage predictions will vary for similar surface scenarios depending on Martian season and change in load power (usually heaters)**

MMRTG Power Model Workshop
Modeled Seasonal Variation

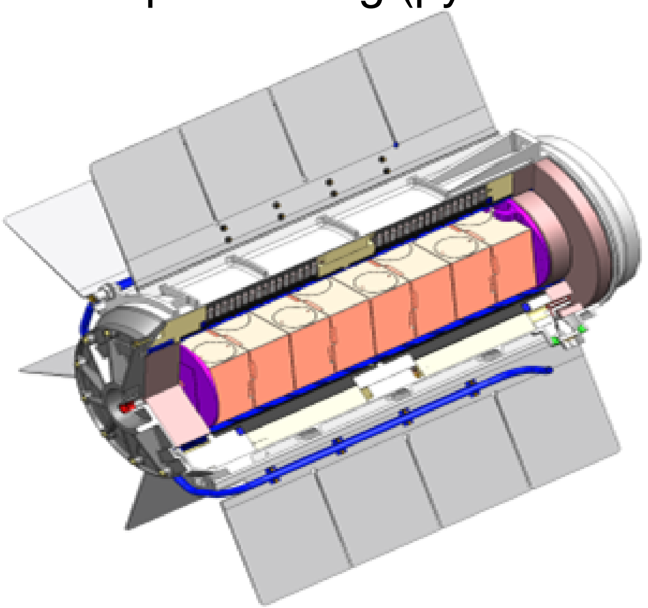
- Spring
  - Highest expected MMRTG power output
  - Highest battery capacity
  - Average heat energy required
- Summer
  - Above average MMRTG power output
  - Above average battery capacity
  - Lowest heat energy required
- Fall
  - Below average expected MMRTG
  - Below average battery capacity
  - Average heat energy required
- Winter
  - Lowest MMRTG power output
  - Lowest battery capacity
  - Highest heat energy required





Multi-Mission RTG Overview

- **Ability to operate in vacuum and planetary atmospheres**
  - 23-36 V DC capability, series-parallel circuitry
- **17 years lifetime requirement**
  - Up to 3 years of storage and up to 14 years of operation
- **Ability to withstand high mechanical loads**
  - ~ 0.3 g^2/Hz (random vibrations)
  - Up to 6000 g (pyrotechnic shock)

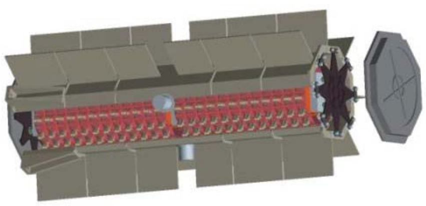


Beginning of Life Performance
~ 125 W
~ 2.8 W/kg

768 <PbTe + TAGS/PbSnTe> couples

High Temperature TE Couple Technology Development for next generation RTGs

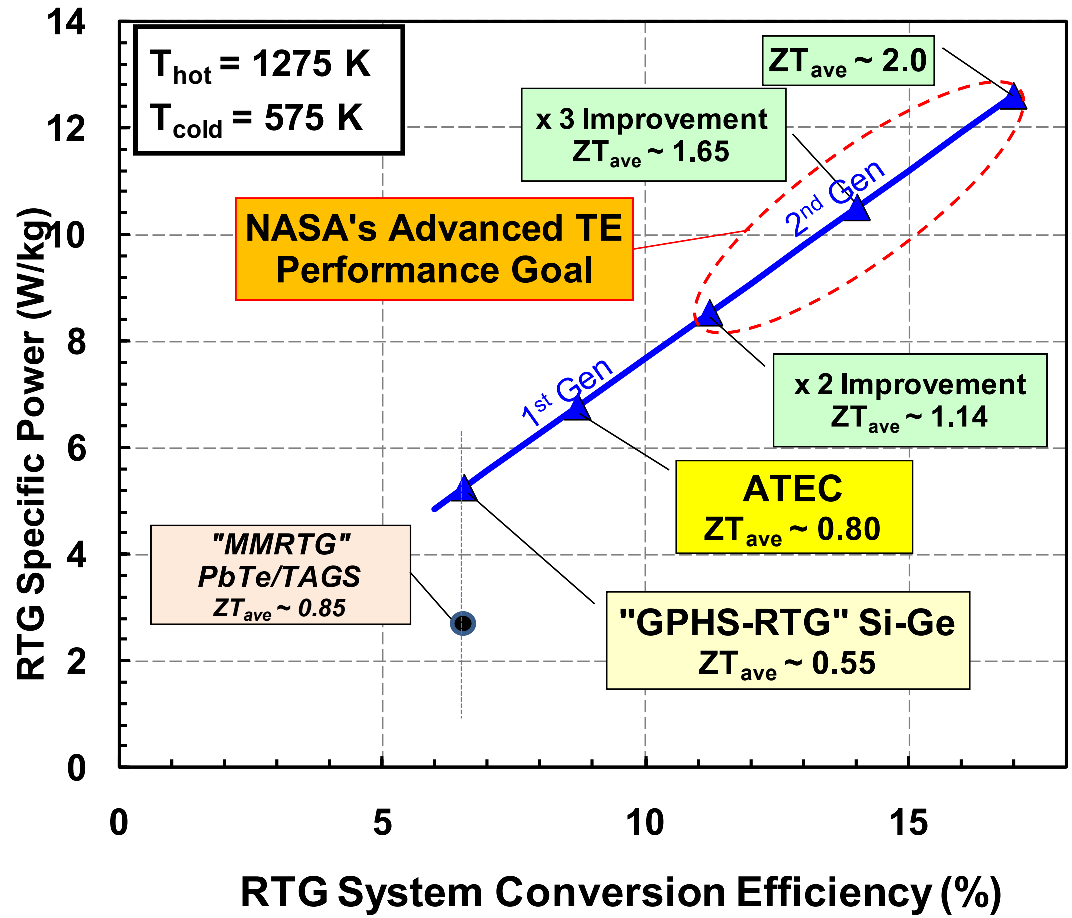
Impact of Advanced High Temperature Materials on Thermoelectric Power Systems for Space Exploration



T_{hot} = 1100 K to 1275 K

(higher is better!)

Lower System Mass and Conversion Efficiency Needed (x2 to 4)



Advanced RTG Specific Power vs. System Conversion Efficiency
(Based on radiatively coupled vacuum operation unicouple based RTG concept)

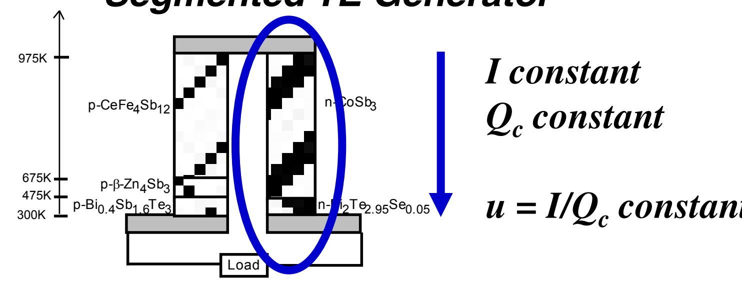
Ultimate goal: > 15% efficient, 10 W_e/kg Advanced RTGs

High Efficiency = High ZT & Wide ΔT

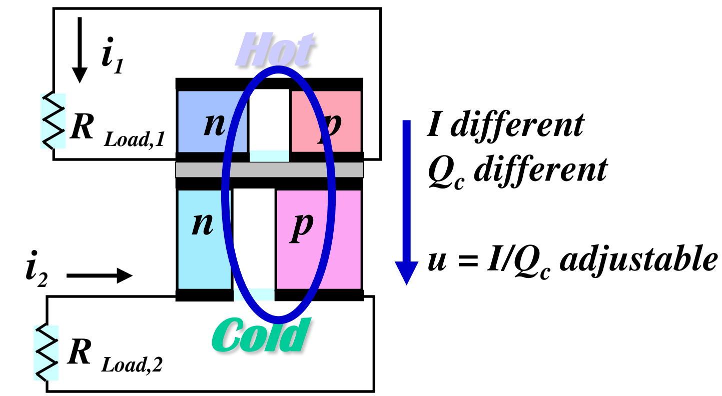
- **Need to combine several TE materials**
- **Segmenting vs. Cascading**
  - **Segmented Thermoelectric**
    - Constrained by constant current
      - $u = I/Q_c \approx$ *Constant*
  - **Cascaded Thermoelectric**
    - Independent circuits for each stage
      - Current different in each stage
      - Heat different in each leg
      - *u* optimized for each stage

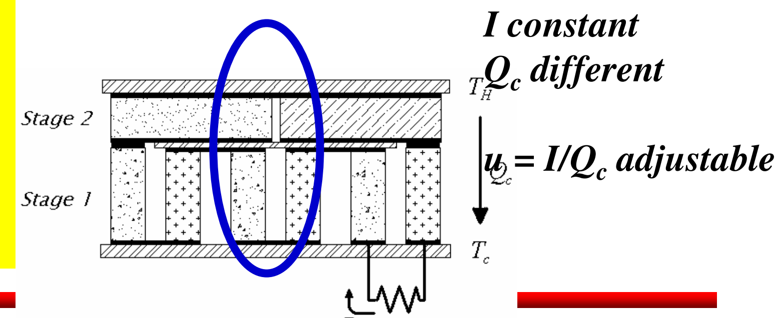
Both methods maximize ZT (efficiency) across wide ΔT, but segmenting has been preferred method for space systems (use couples, not modules)

Segmented TE Generator

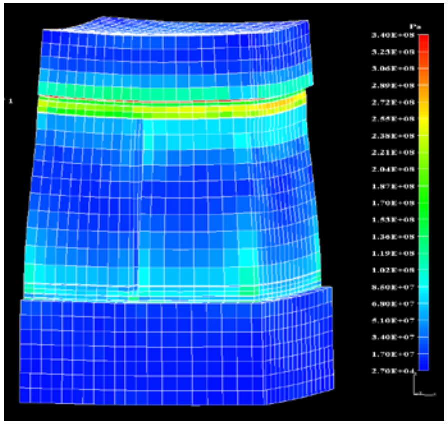


Cascaded TE Generators



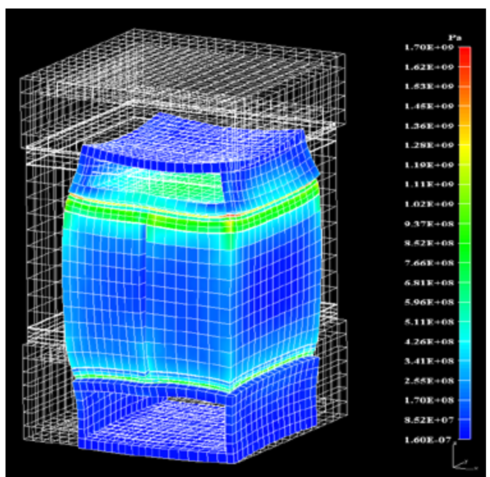


Thermal/Mechanical Considerations for Development of High Temperature TE Converters

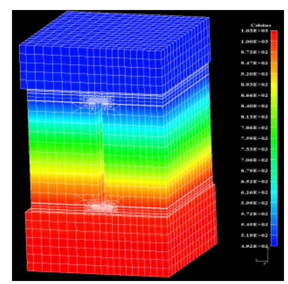


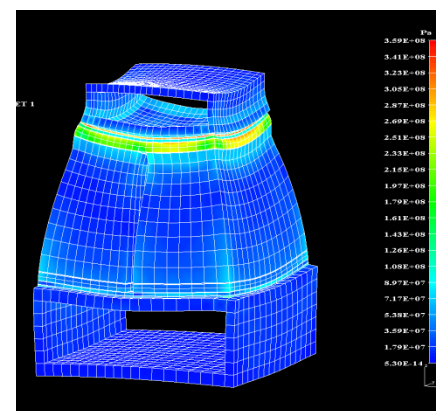
Stresses during high temperature fabrication steps

- ***Critical Structural Integrity Issues***
  - *Coefficient of thermal expansion mismatches within TE device stack (including segments), and between stack and heat exchangers (cold and hot "shoes")*
  - *"Bowing" of TE legs due to large ΔT*
  - *Surviving fabrication and assembly steps - and operation*
    - *Typically for space RTGs, only a few cycles (<20)*
    - *Hundreds to thousands for terrestrial applications*



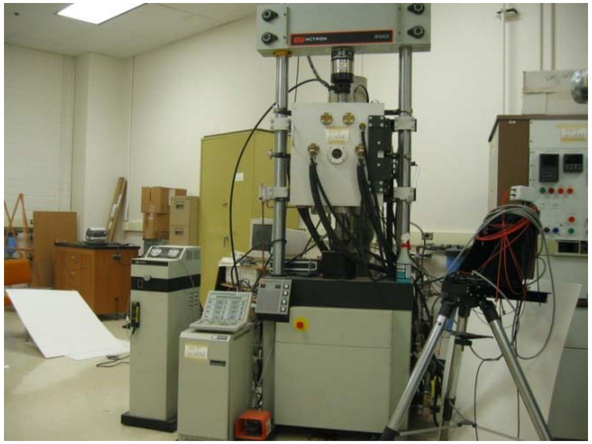
Stresses back at room temperature after fabrication

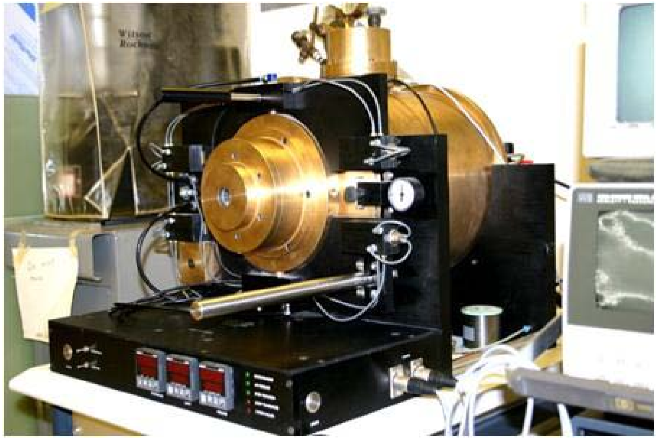


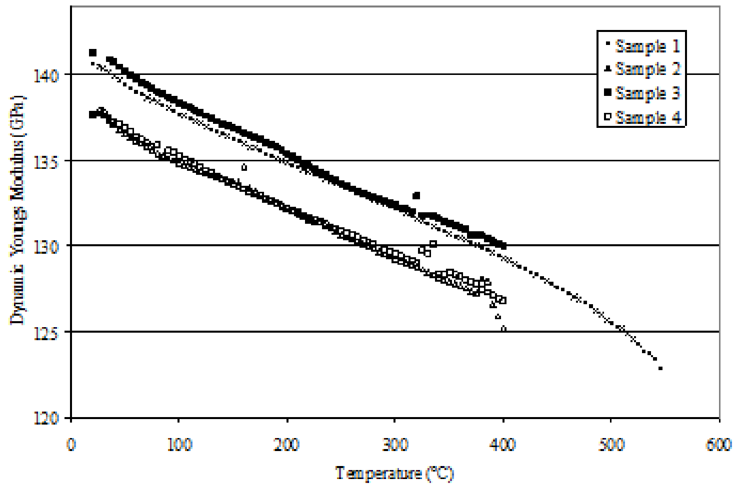


Stresses when operating across large ΔT Bonded to hot and cold side heat exchangers

High Temperature Mechanical Properties of TE Materials







Dynamic Young's Modulus - n-type $CoSb_3$

- ***Young's modulus at 20°C = 137 - 141 GPa***
- ***E decreases as T increases, reaching 127 GPa at 400°C***

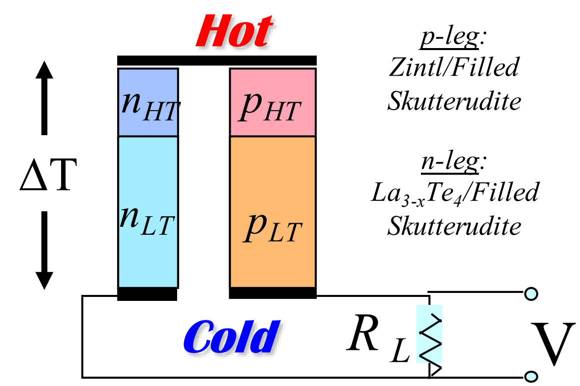
Determination of key mechanical properties required for prediction of short and long-term performance of thermoelectric devices: Strength, Stiffness and Toughness

- **Internal capabilities and external collaborations**
- **Types of measurements: flexural (4-point, biaxial), dynamic modulii, RUS, compression, etc**
  - High temperature flexural and modulus measurements
- **Thermoelectric materials tested to date:**
  - Skutterudites
  - Nanostructured silicon-germanium
  - $Yb_{14}MnSb_{11}$ (Zintl) and lanthanum telluride
  - Now evaluating advanced PbTe
    - *See 2009 publication for some of the results*

Projected Performance for Segmented Couple using Current Set of Advanced Materials: Zintl, $La_{3-x}Te_4$ and Skutterudites

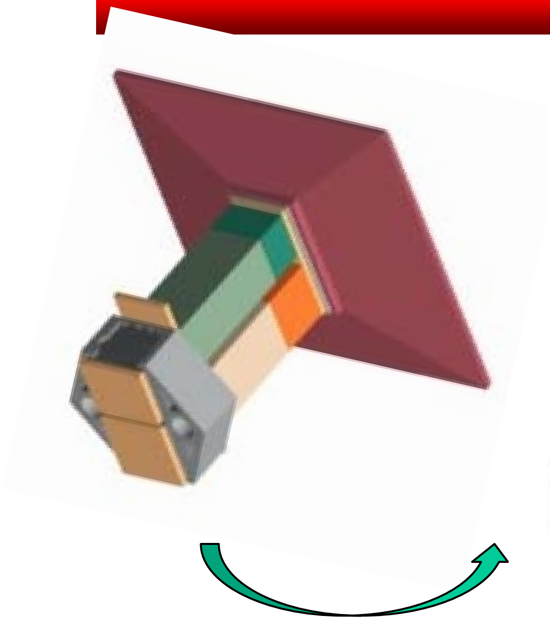
- **Using current in-house JPL-produced materials**
  - $Yb_{14}MnSb_{11}$ Zintl, $La_{3-x}Te_4$ and filled skutterudites (SKD)
  - All materials are produced in 50-100 g batches
- **Predicted efficiencies of up to ~ 14%**
  - Fixed temperatures for SKD segments (873 to 473 K)
    - 15% efficiency with Advanced PbTe
  - Hot side couple temperatures from 1073 K to 1273 K

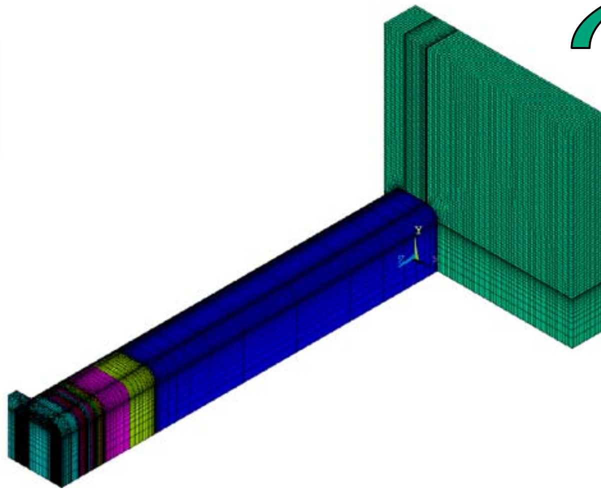
Segmented couple

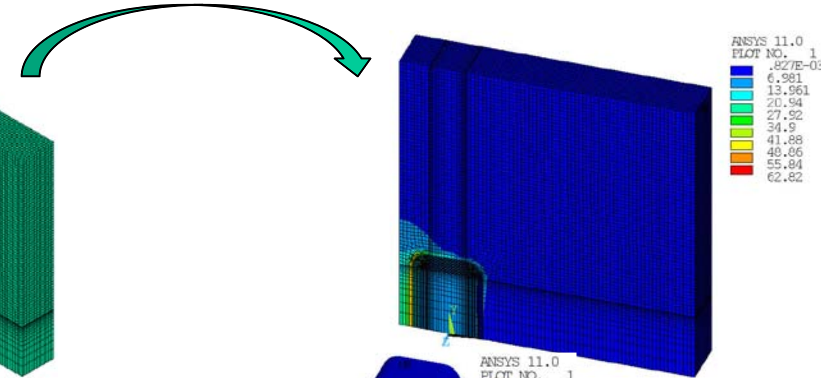


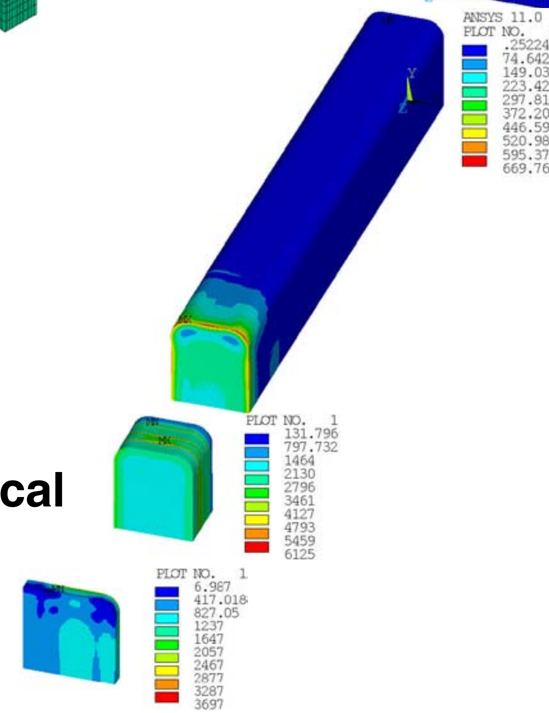
Temperatures				Performance
Hot Side	p-type segment interface	n-type segment interface	Cold Side	Device Efficiency
(K)	(K)	(K)	(K)	(%)
1273	unsegmented		473	10.2
1273	834	873	473	13.7
1173	837	873	473	12.4
1073	844	873	473	11.2

Design of Robust HT Segmented Couples



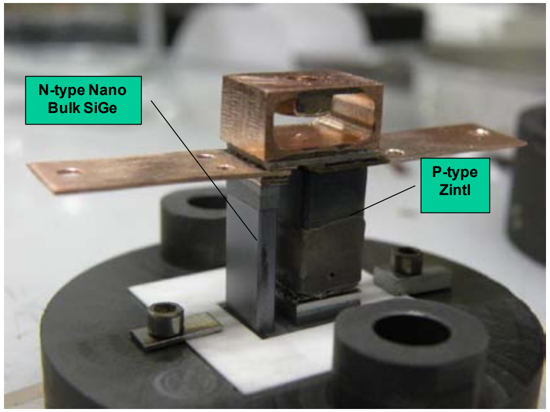




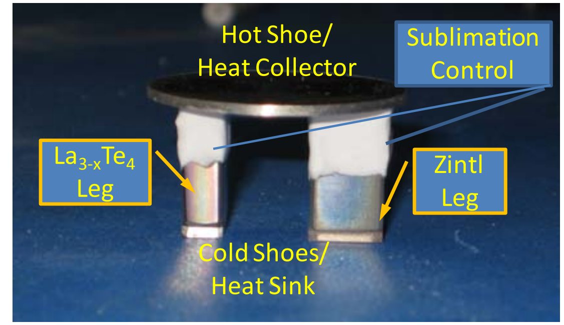


- **Detailed Finite Element Analysis**
- **Supported by experimental data on temperature dependent mechanical and thermal properties on TE materials, electrical and thermal interfaces**
- **Coupon-level demonstrations**
- **Prototype couple-level demonstrations**
- **Extensive life testing**

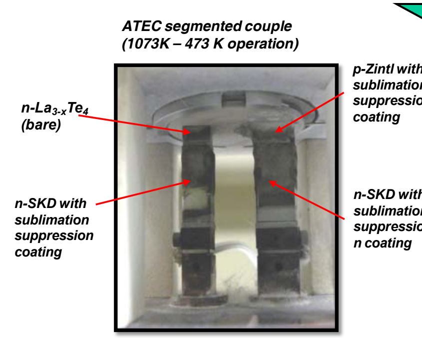
Couple Configurations in Development



Zintl ($Yb_{14}MnSb_{11}$) / NanoSiGe Couple (2007-2009)

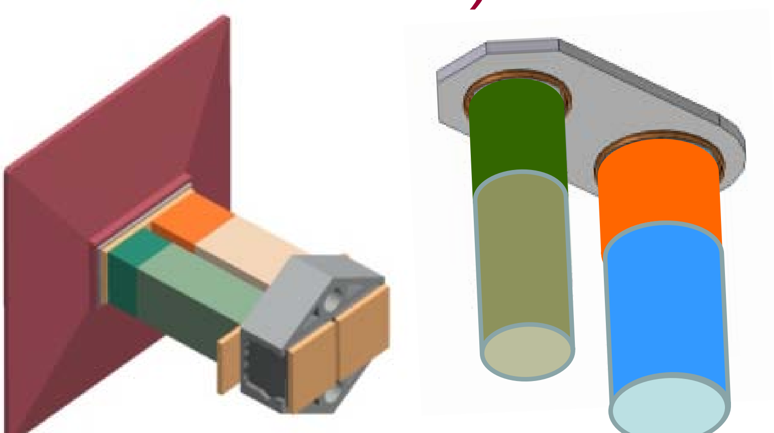


Zintl ($Yb_{14}MnSb_{11}$) / $La_{3-x}Te_4$ Couple (2009-2010)



Zintl/SKD // $La_{3-x}Te_4$/SKD Segmented Couple (2010)

Zintl/Adv.PbTe // $La_{3-x}Te_4$/Adv.PbTe Segmented Couple (2011)



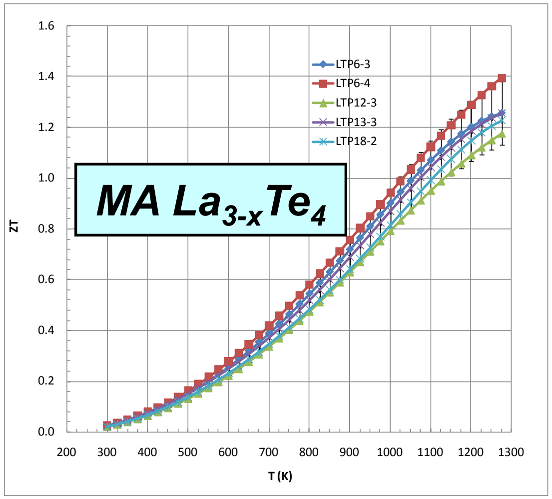
Zintl // $La_{3-x}Te_4$ Cantilevered and Spring-loaded Segmented Couples for Life Performance validation(2012-2014)

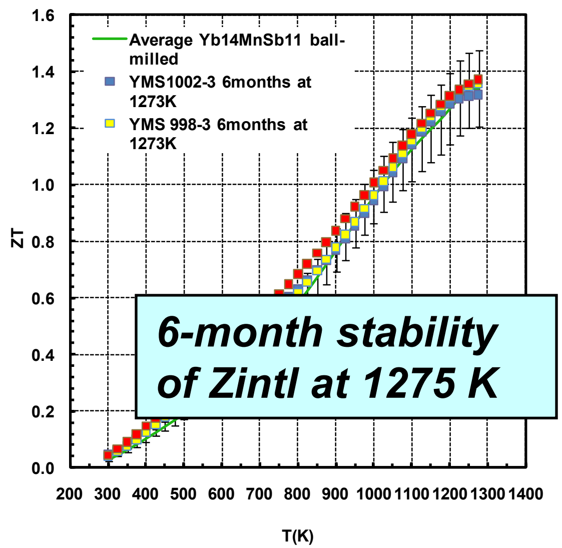
Maturity of Advanced Materials for Potential Infusion into Advanced Converters

	Nanostructured Si-Ge (p & n)	14-1-11 Zintl (p)	$La_{3-x}Te_4$ (n)	Skutterudite (p & n)	Advanced PbTe (n & p)	Heritage PbTe (n) TAGS (p)
Target ΔT (K) for operation	1273-573	1273-773	1273-773	873-473	773-473	n: 773-473 p: 673-473
Average ZT across relevant ΔT	n: 0.73 p: 0.55	p: 0.98	n: 0.88	n: 1.01 p: 0.78	n: 1.14 p: 1.28	n: 0.75 p: 1.06
Reproducible TE properties	☑	☑	☑	☑	☑	☑
Scale-up of synthesis	☑ (100 g batches)	☑ (15-50 g batches)	☑ (50-100 g batches)	☑ (100-200 g batches)	☑ (30-200 g batches)	☑ (MMRTG Production line)
Thermally stable TE properties	☑ (>12,000 hrs at 1273 K)	☑ (> 12,000 hrs at 1273 K)	☑ (>2,500 hrs at 1273 K)	☑ (>10,000 hrs at 873 K)	☐ (only preliminary data > 300 h)	☑ (750 K for TAGS, 825 K for PbTe)
Sublimation suppression feasibility demonstrated	☑ (same as heritage SiGe)	☑ (coating, up to 10,000hrs at 1273 K)	☑ (not required up to 1173 K)	☑ (aerogel, up to 9,000hrs at 1273 K)	☑ (Ar atm., assumes same as for heritage PbTe)	☑ (Ar atm., limited to 673 K for TAGS, 825 K for PbTe)
Stable low resistance metallizations	☑ (> 1000h at 1273 K)	☑ (> 5000h at 1273 K)	☑ (> 1000h at 1273 K)	☑ (>1500h at 873 K)	☐ (baseline is heritage PbTe)	☑ (> 200,000 hrs)
Temperature dependent mechanical properties	☑ CTE: 4.5 ppm	☑ CTE: 16-19 ppm	☑ CTE: 17-20 ppm	☑ CTE: 12-14 ppm	☑ CTE: 19-21 ppm	☑ CTE: 19-21 ppm

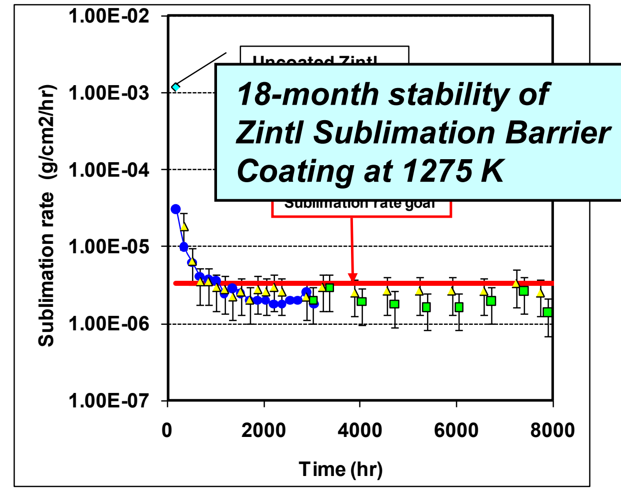
$Yb_{14}MnSb_{11}$/Nanobulk $Si_{0.8}Ge_{0.2}$ & $Yb_{14}MnSb_{11}$/$La_{3-x}Te_4$ HT TE Couple Technology Development

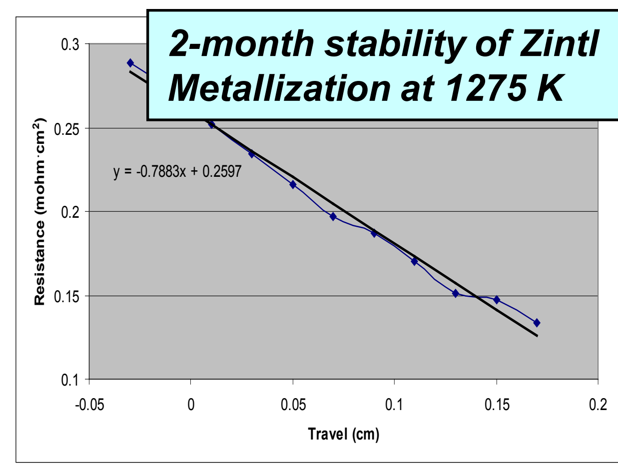
Powder Metallurgy Synthesis Scale-up and Reproducible TE properties





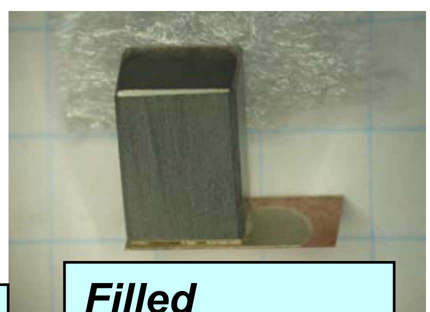
Thermal Stability of TE Materials and Low Electrical Contact Resistance Metallizations



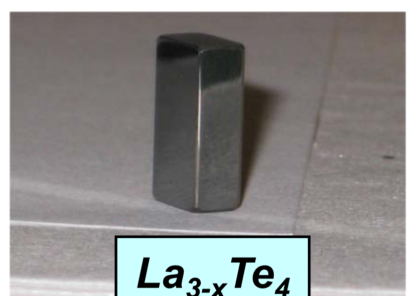


Metallized Leg Fabrication

$Yb_{14}MnSb_{11}$ Zintl



Filled Skutterudites



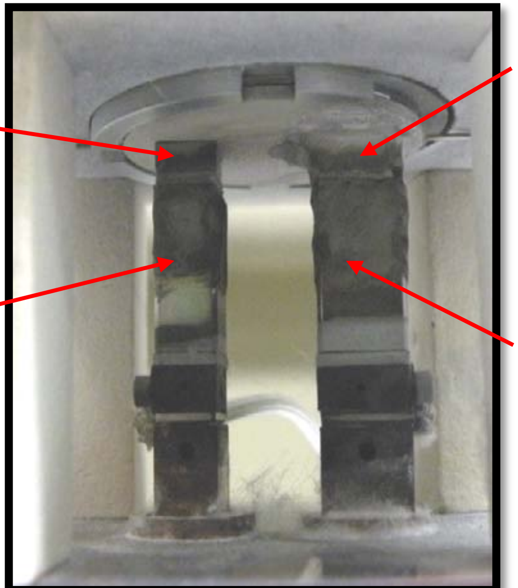
$La_{3-x}Te_4$

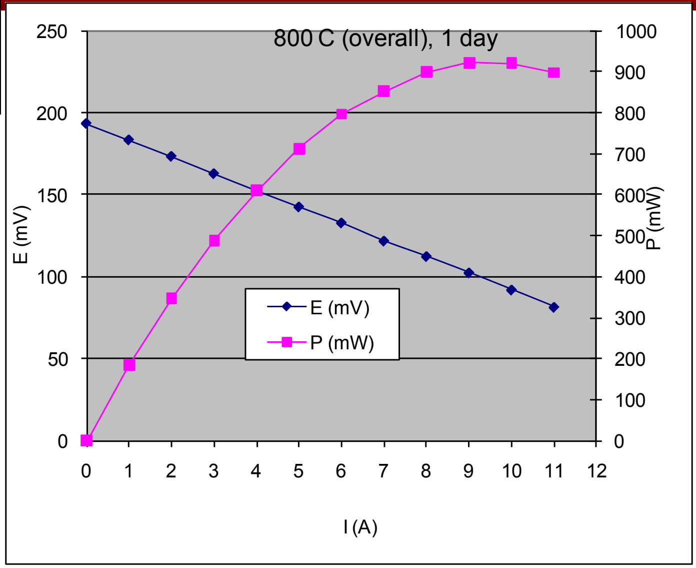
ATEC Segmented Couples ~ 11% Efficiency

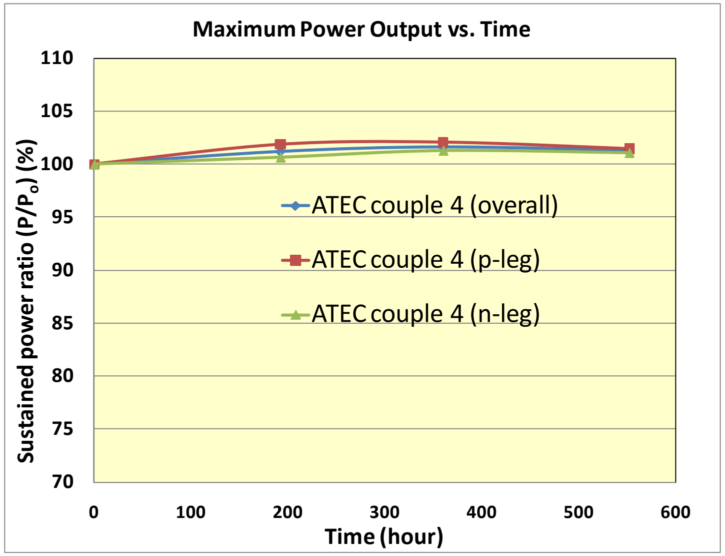
(Zintl/LaTe/SKD segmented couple testing – T_{hot} = 1073K)

- ***Assembled several couples***
- ***Long life operation at 800 C predicted***

ATEC segmented couple (1073K – 473 K operation)





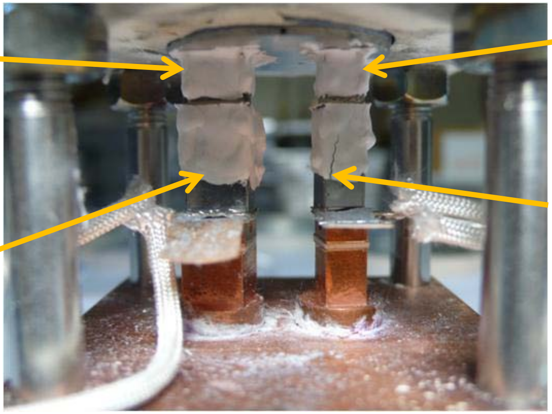


- ***Testing was initiated in late 2010***
  (600 hours of test to date, stable performance)
- ***Internal device resistance within 2% of predict***
- ***Open circuit voltage within 9% of predict***
- ***~ 11% couple conversion efficiency***

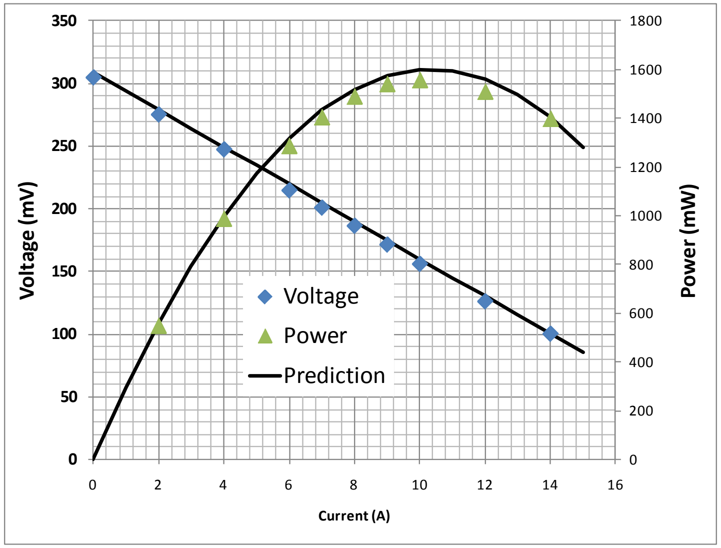
14-15% Efficient Segmented Couple Demonstration

- **Completed beginning-of-life performance test of 1275 K segmented couple**
  - First demonstration of segmented couple across full temperature range of interest
    - Spring loaded configuration (similar to MMRTG TE converter)
    - Legs sized for operation at 1273 K
    - Uses $Yb_{14}MnSb_{11}$ (Zintl) and $La_{3-x}Te_4$ for high temperature segments
    - Uses filled skutterudites for "low" temperature segments
- **~ 15% efficiency achieved with cold side temperature of 453 K**
  - Excellent agreement between experimental and predicted performance
    - Internal resistance within 1%, open circuit voltage within 1.5%
    - Maximum power output within 3%

p-leg: 14-1-11 Zintl/SKD
n-leg: $La_{3-x}Te_4$/SKD
T_{hot} ~ 1273 K
T_{cold} ~ 373 K
<u>Efficiency ~ 15.3%</u>



High Temperature Segmented Zintl/$La_{3-x}Te_4$/SKD Couple
Spring-loaded Performance Test Configuration

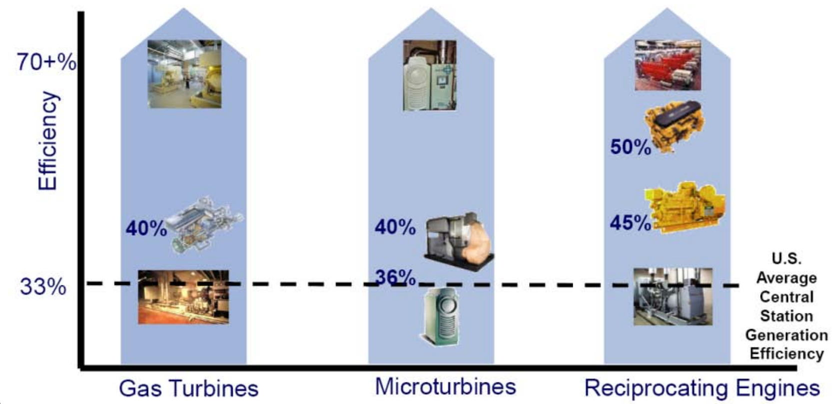


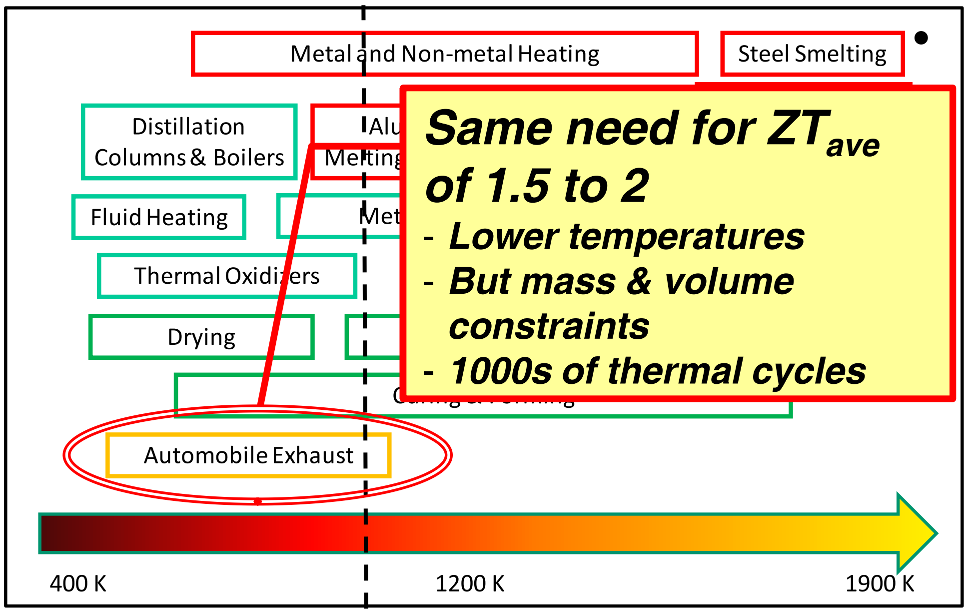
Beginning-of-Life (BOL)
Experimental vs. Predicted I-V and I-P curves
For Advanced TE Couple

Potential for Terrestrial High Grade Waste Heat Recovery Applications

Some "Large Scale" Opportunities for High Grade Waste Heat Recovery TE Power Systems

- **Thermoelectrics cannot compete "head-on" with dynamic technologies, but…**
- **…Some industrial processes are potentially attractive for TE systems**





Adapted from: Hendricks, T., Choate, W. T., Industrial Technologies Program, "Engineering Scoping Study of Thermoelectric Generator Systems for Industrial Waste Heat Recovery" (U.S. Department of Energy, 1-76, 2006).

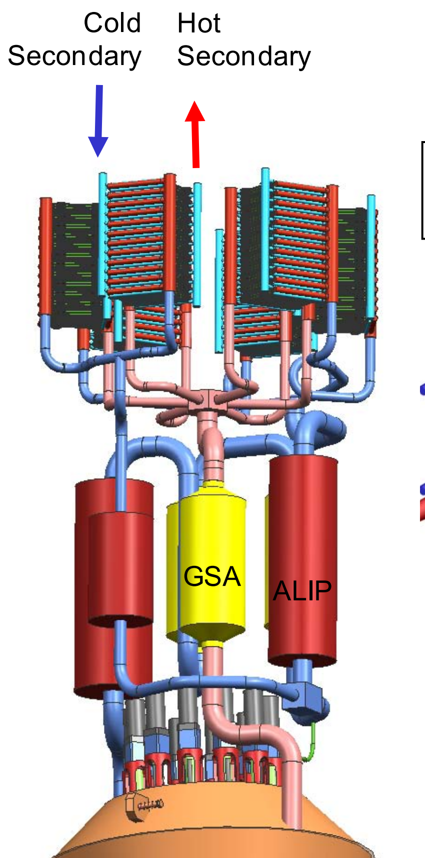
For near term applications in the US alone, between 0.9 and 2.8 TWh of electricity might be produced each year for materials with average ZT values ranging from 1 to 2

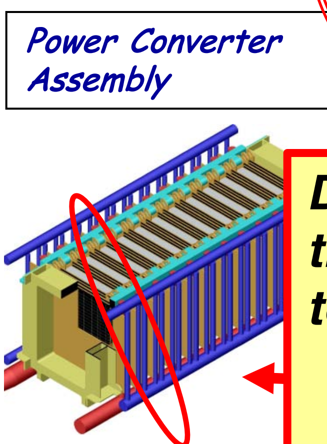
- *Medium to high grade heat for aluminum, glass, metal casting, non-metal melting, ceramic sintering and steel manufacturing*
  - *$T_{hot} > 1000$ K*
- *Limited opportunity to reuse the waste heat to improve process end-to-end efficiency*
- *Difficulties in effectively transporting that heat to separate energy conversion systems*

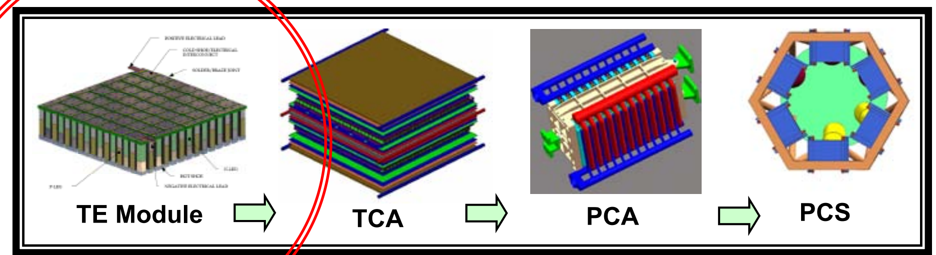
➢ *TE as a "passive "heat exchanger system in a stationary WHR system (no mass constraint!! fewer thermal cycles!)*

<u>Nuclear Electric Propulsion for Space Exploration Science Missions</u>

- Technology development was focused on arrays of thermoelectric couples grouped into power converter assemblies
- Used liquid metal heat exchangers to interface with reactor heat source and radiator heat sinks





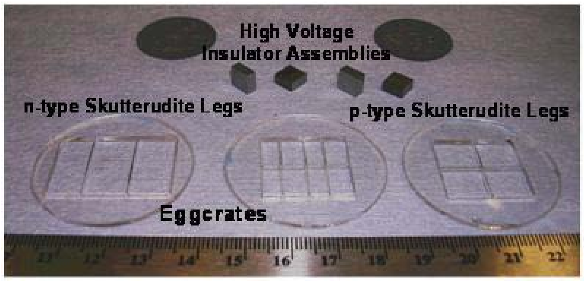


Development of robust high temperature thermoelectric module technology is critical to all applications

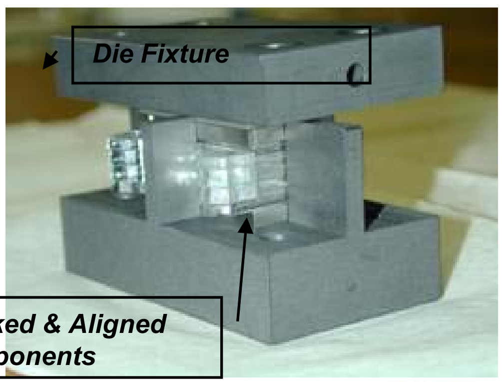
- ***Using low cost, practical fabrication techniques and relatively inexpensive materials (including thermoelectrics)***
- ***Ability to integrate with various heat exchangers***
- ***Ability to reliably survive thermal/mechanical stresses***

Assembly and Test of Aerogel-Filled Skutterudite TE Modules

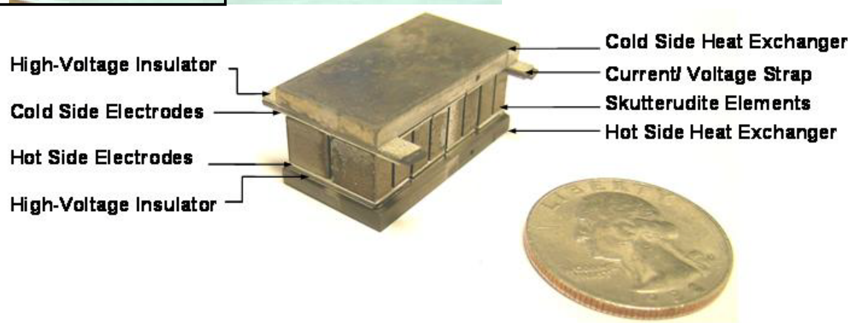
Module Technologies Developed under NASA/SMD In-Space Propulsion Program in 2004-2005



Assembled 2x4 Module after bonding cycle and egg-crate vaporized

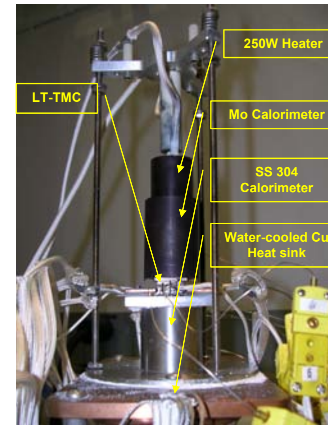


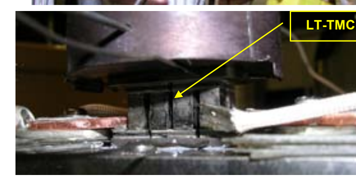
Stacked & Aligned Components

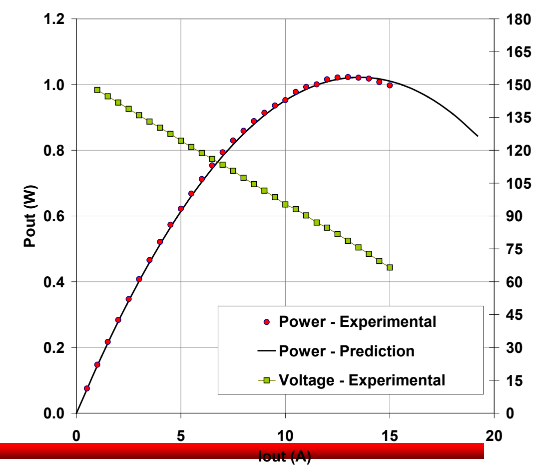


Designed for integration with flat plate HXs

Performance Test







Summary and Conclusions

- **Thermoelectrics have unique advantages for integration into selected high temperature waste heat recovery applications**
  - TWh-class opportunities available for some energy intensive industrial processes
- **TE materials efficiency is critical to TEG performance:**
  - x 2 to 3 increase in ZT_{ave} needed, especially for low to medium grade waste heat
  - But cost, environmental friendliness and availability are also key parameters (potential issues with elements such as Ge, Pb, Tl)
  - Terrestrial technology to date has used some form of encapsulation for the TE converters (no air operation) which reliability has been proven
- **Most of the technology risk lies in development of rugged TE couple & modular devices and is a must to enable new applications**
  - Without life, high ZT does not matter!
  - High temperature TE device development requires considerable, sustained support
- **Converter & heat exchanger designs are critical to efficient system implementation**
  - Typical heat fluxes delivered to the TE devices is in 5-30 W/cm^2 range
  - Efficient operation under large ΔT requires leg height > 5-10 mm
- **Demonstrated 10% to 15% efficient new high temperature couples based on new TE materials developed in last 5-10 years**
  - Extended performance testing and lifetime validation still require extensive work
  - Now developing segmented couples for more efficient next generation converters

Acknowledgments

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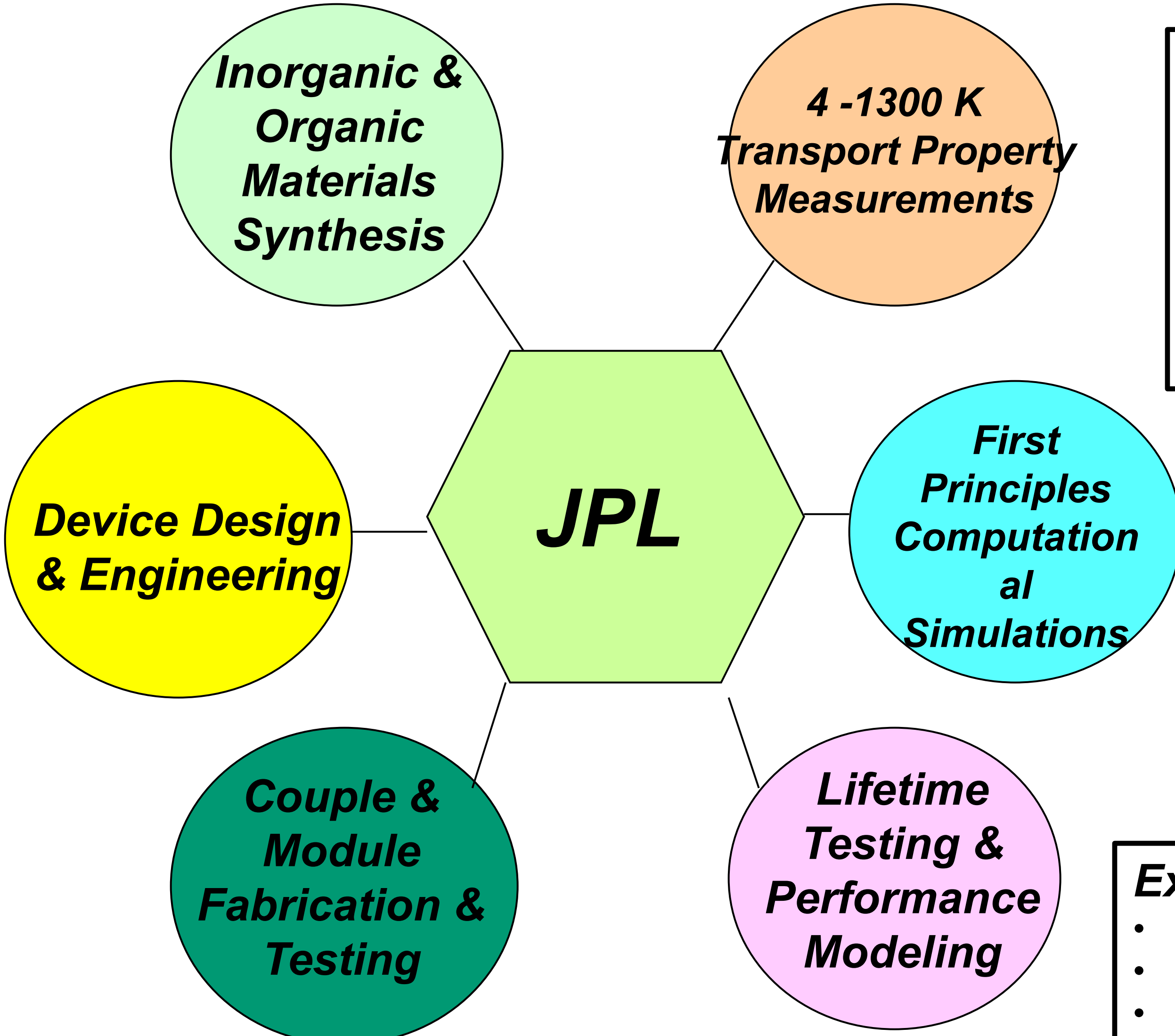
- **The work presented here benefited from contributions from a number of collaborators in the past few years**
  - California Institute of Technology
  - University of California at Los Angeles, University of California at Davis
  - California State Polytechnic University, Pomona
  - Ole Miss, University of Southern California
  - Boston College, Massachusetts Institute of Technology
  - Michigan State University
  - Teledyne Energy Systems
  - HS Rocketdyne

JPL's Capabilities in Thermoelectrics R&D



Unique set of capabilities

- *For high temperature materials & devices*
- *Extensive expertise in developing and testing designs for long life applications*
- *Robust collaborations with academia and industry*
- *TECT Group staff ~ 20*

Extensive collaborations

- *Universities*
- *Industry*
- *NASA/GRC*