Novel, High Efficiency Segmented Thermoelectric Unicouples for Space and Terrestrial Applications

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presented by
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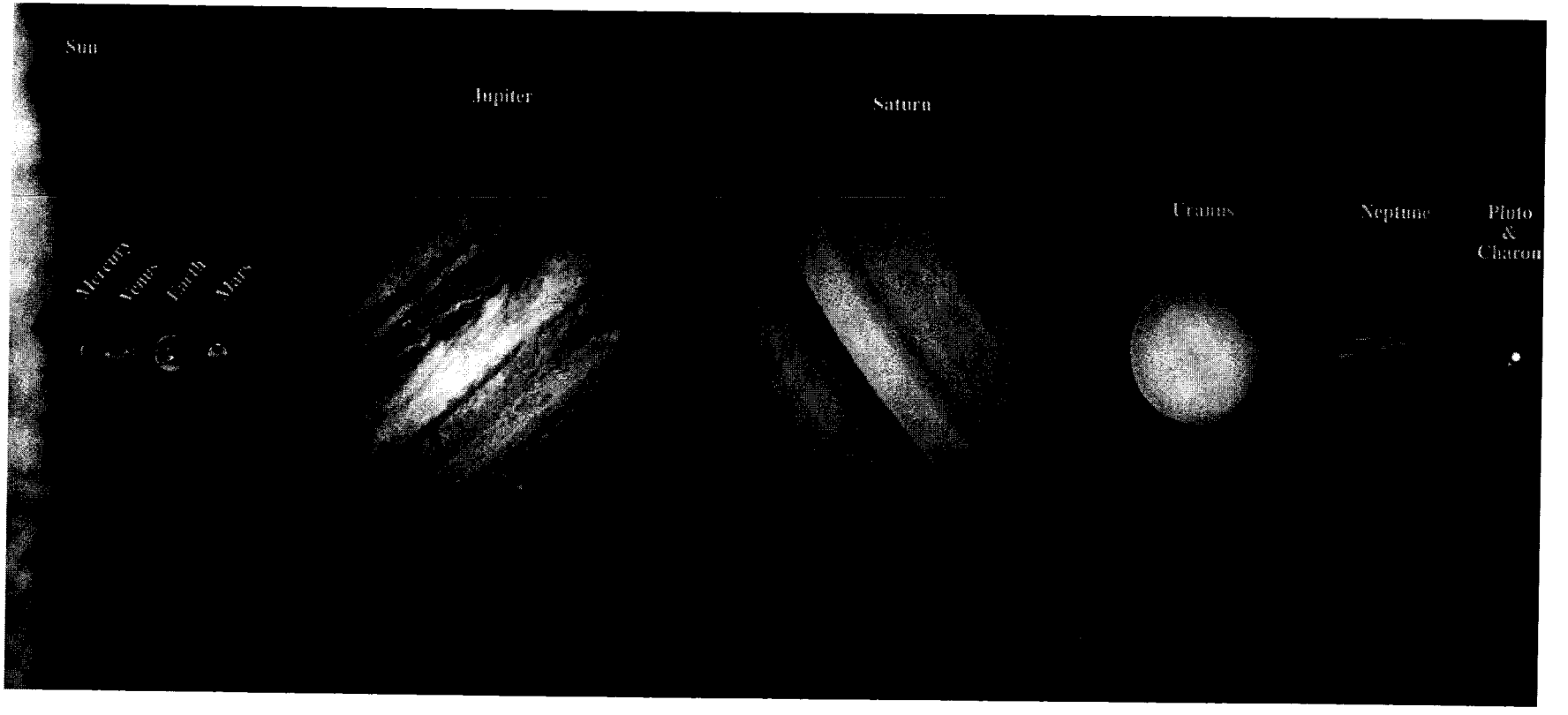
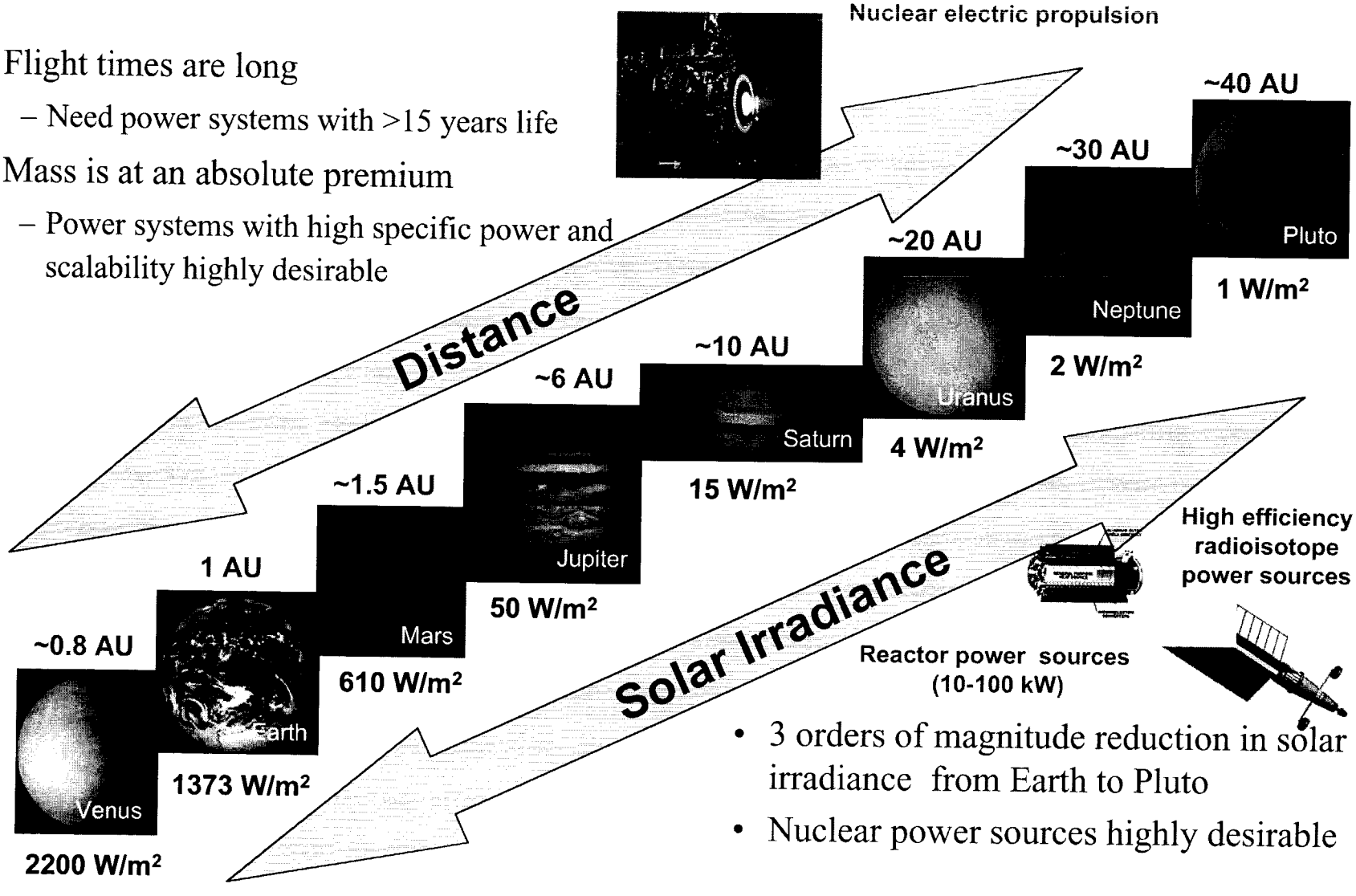
Deep Space Exploration



Power Technology

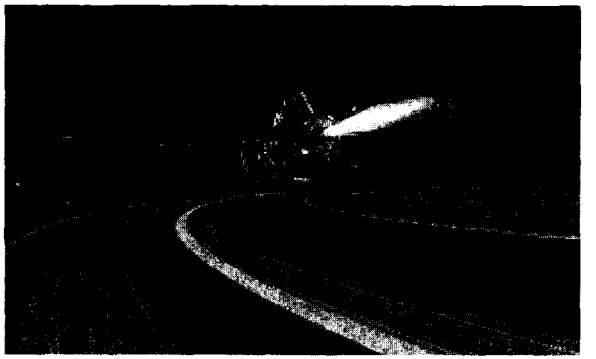
- Flight times are long
  - Need power systems with >15 years life
- Mass is at an absolute premium
  - Power systems with high specific power and scalability highly desirable



- 3 orders of magnitude reduction in solar irradiance from Earth to Pluto
- Nuclear power sources highly desirable

Radioisotope Thermoelectric Generators (RTGs) for Deep Space Missions

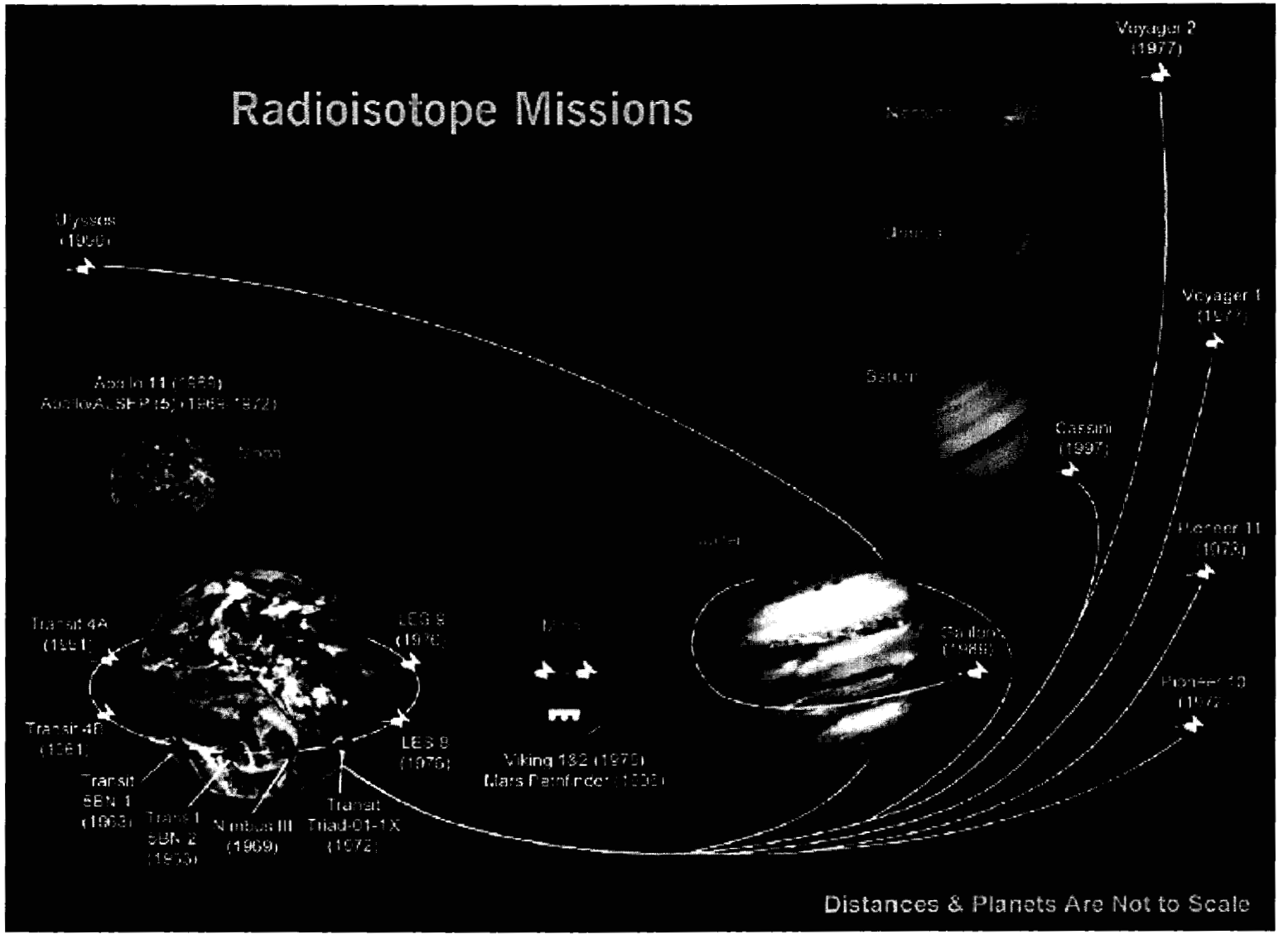
- **Cassini mission to Saturn electrical power requirements**
  - **600-700 Watts for 11 years (1.6 billion km from the Sun)**



	Possible solutions	
	Radioisotope Thermoelectric Generators (RTGs)	Solar Panels
Mass	■ 168 kg	■ 1,337 kg (598 m^2)
Advantages	■ Small size (1.13 m long, 043.m diameter ■ No moving parts ■ Easy maneuverability	■ Fewer regulations and agency interfaces
Disadvantages	■ Additional regulations ■ Additional agency interfaces	■ No rocket available ■ Slow maneuverability ■ Higher risk of failure

http://silver.neep.wisc.edu/~neep602/SPRING00/lecture6.pdf

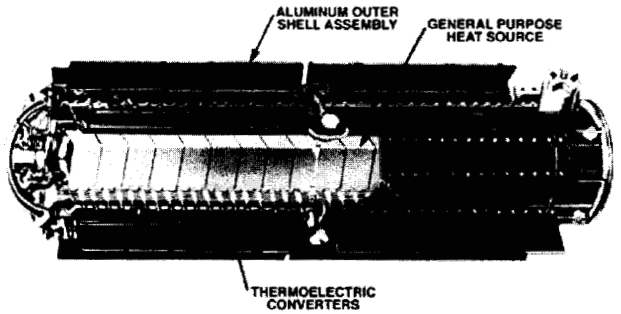
Radioisotope Thermoelectric Generators (RTGs) for Deep Space Missions (continued)



General Purpose Heat Source RTG

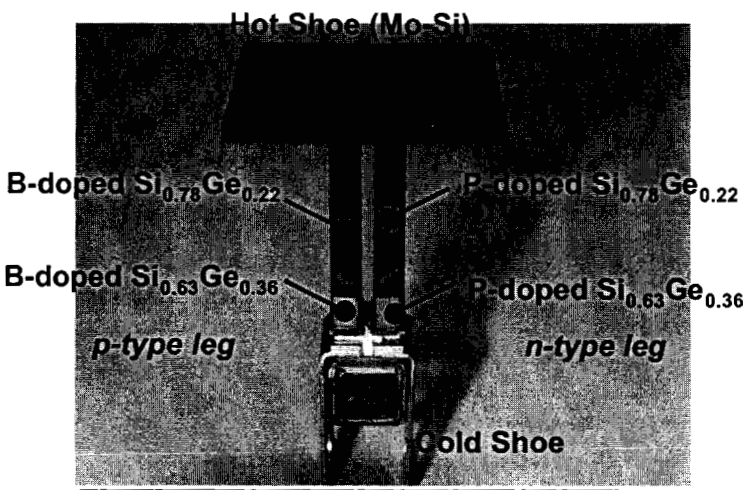
General Purpose Heat Source (GPHS)

Radioisotope Thermoelectric Generator (RTG)

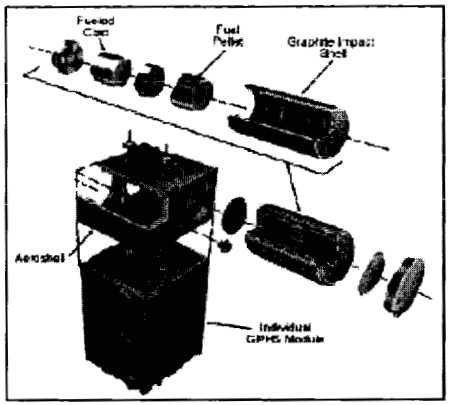


- POWER OUTPUT – 285 W(e)
- FUEL LOADING – 4400 W(t); 132,500 Ci
- WEIGHT – 124 lbs
- SIZE – 16.6 in x 44.5 in

The three Radioisotope Thermoelectric Generators (RTGs) provide electrical power for Cassini's instruments and computers. They are being provided by the U.S. Department of Energy.



MHW/GPHS SiGe unicouple



General Purpose Heat Source Module

GPHS-RTG Performance Data

Power output-We	290 beginning of life 250 end of life
Operational life - hrs	40,000 after launch
Weight-kg	55.5
Output voltage	28
Dimensions	42.2 diameter 114 long
Hot junction temperature-K	1270
Cold junction temperature-K	566
Fuel	PuO_2
Thermoelectric material	SiGe
Numbers of unicouples	572
Mass of Pu-238-g	7,561

http://silver.neep.wisc.edu/~neep602/SPRING00/lecture6.pdf

New Radioisotope Power System Major Requirements

- Modular generator (~100 We) to support variety of missions
- Shall operate in deep space and on the surface of Mars
- Shall provide power for missions up to 14 years
- Shall be as small and light as possible, maximizing specific power
- Shall be designed based on current GPHS heat source

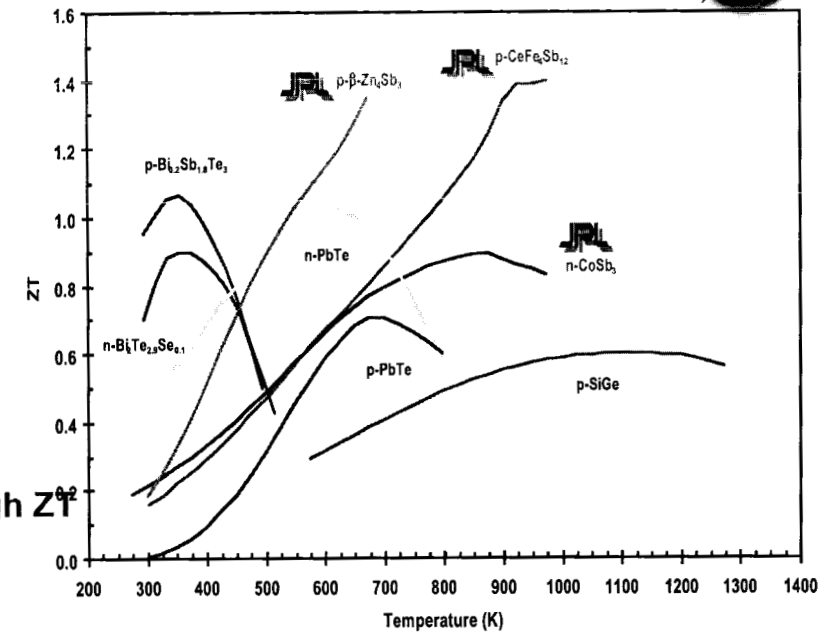
➤ Will require use of high efficiency materials if thermoelectrics to be an option

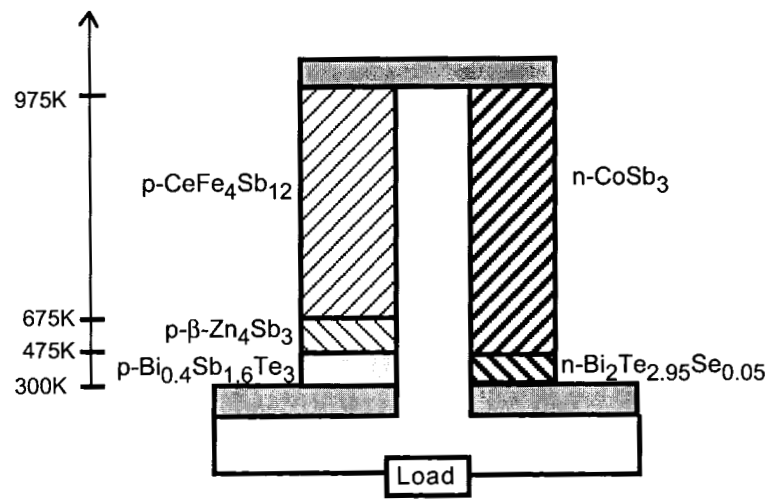
http://centauri.larc.nasa.gov/newfrontiers/July23_02_Future_Space_Missions.pdf

New bulk materials and concepts

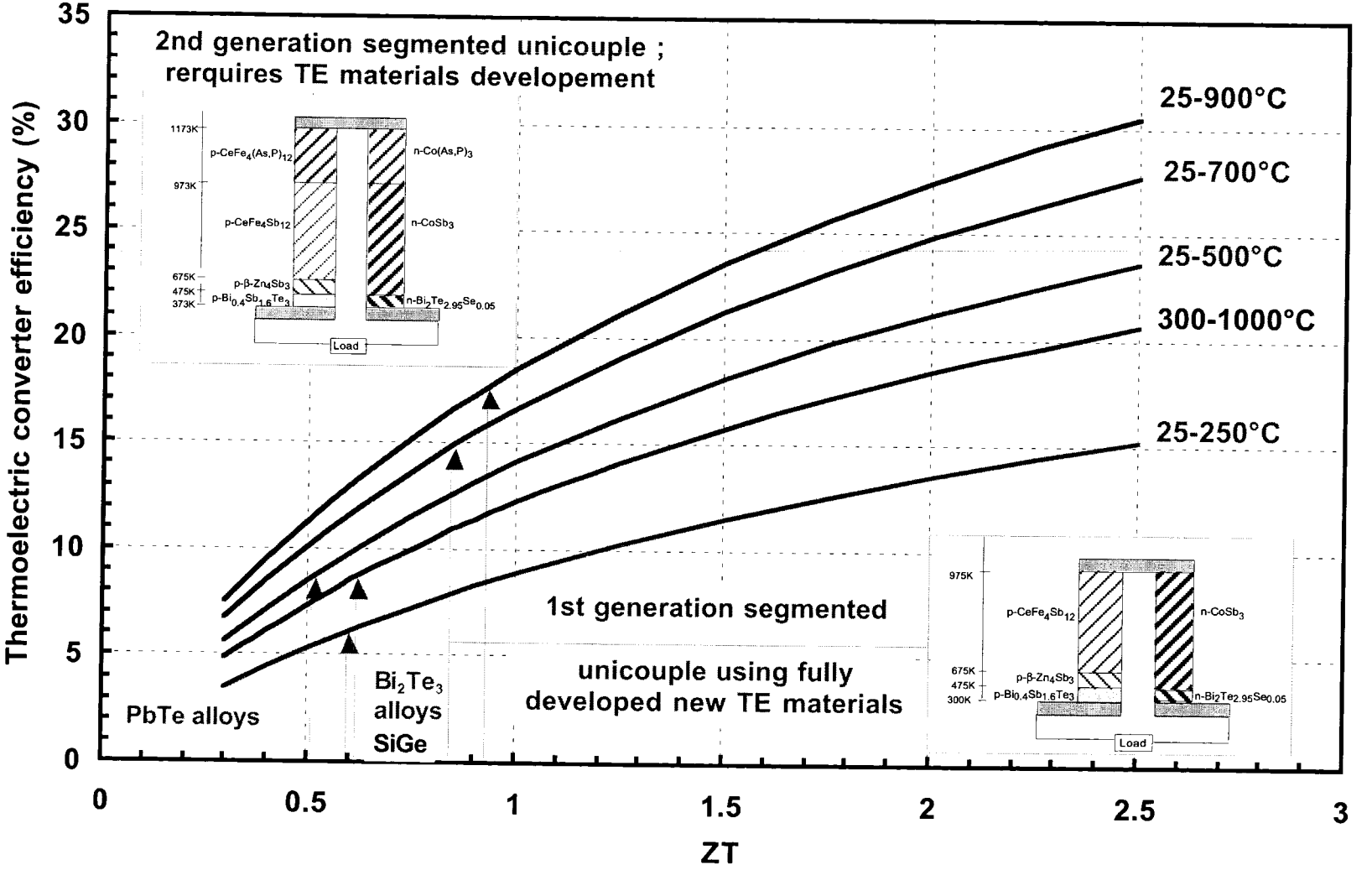
- **Improvement in ZT possible !**
  - Higher efficiency values
- **Segmented unicouples**
  - Large ΔT, high ZT -> high efficiency
  - Using a combination of state-of-the-art TE materials (Bi_2Te_3-based materials) and new, high ZT materials developed at JPL
    - Skutterudites : $CeFe_4Sb_{12}$ and $CoSb_3$
    - Zn_4Sb_3
  - Higher average ZT values
  - → Higher material conversion efficiency
    - → Up to 15 % for a 300-975K temperature gradient

$$\eta = \frac{T_H - T_C}{T_H} \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+\frac{T_C}{T_H}}$$

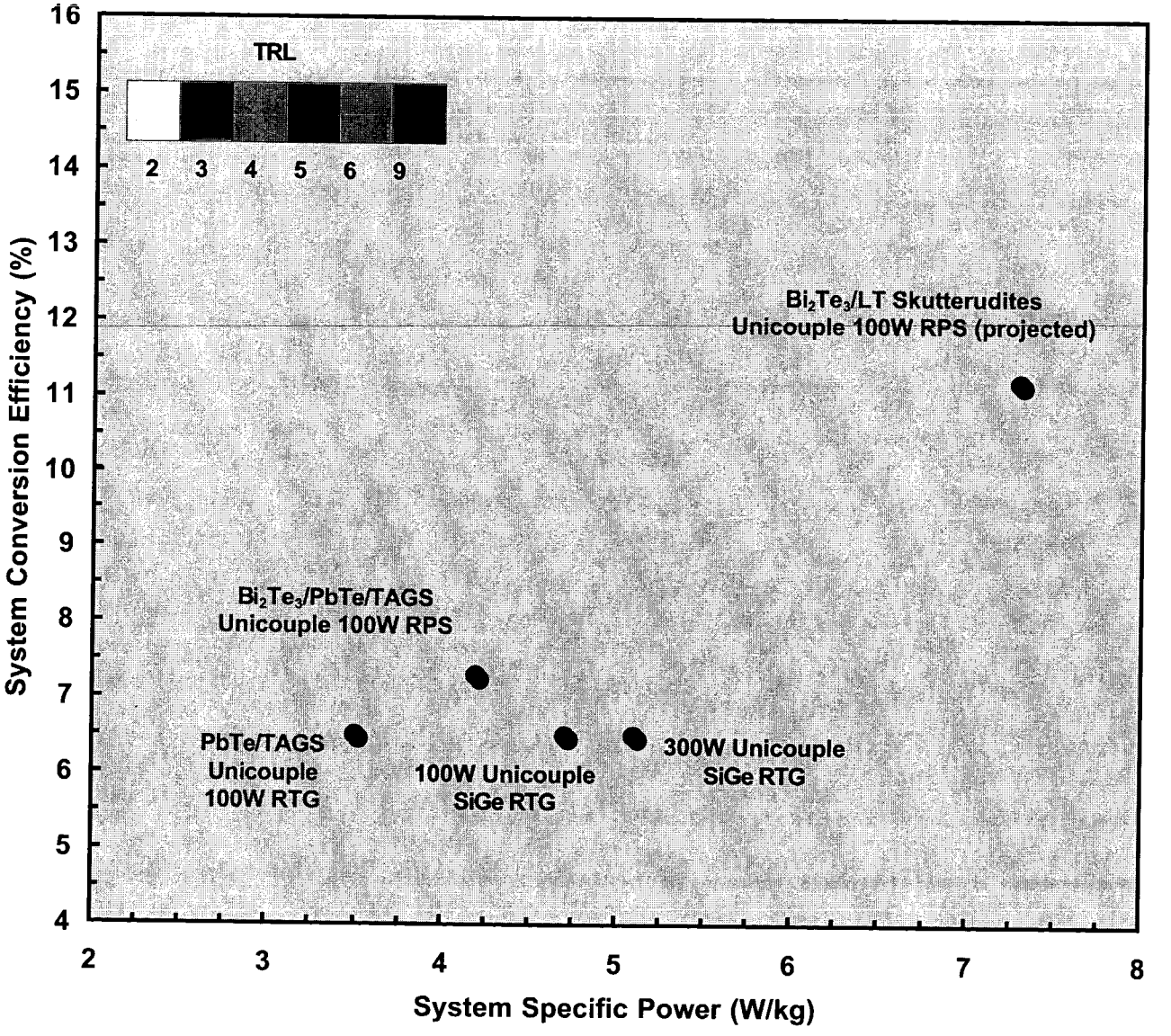




State-of-the-art vs. advanced thermoelectric technology



Efficiency & Specific Power: New Technology vs SOA

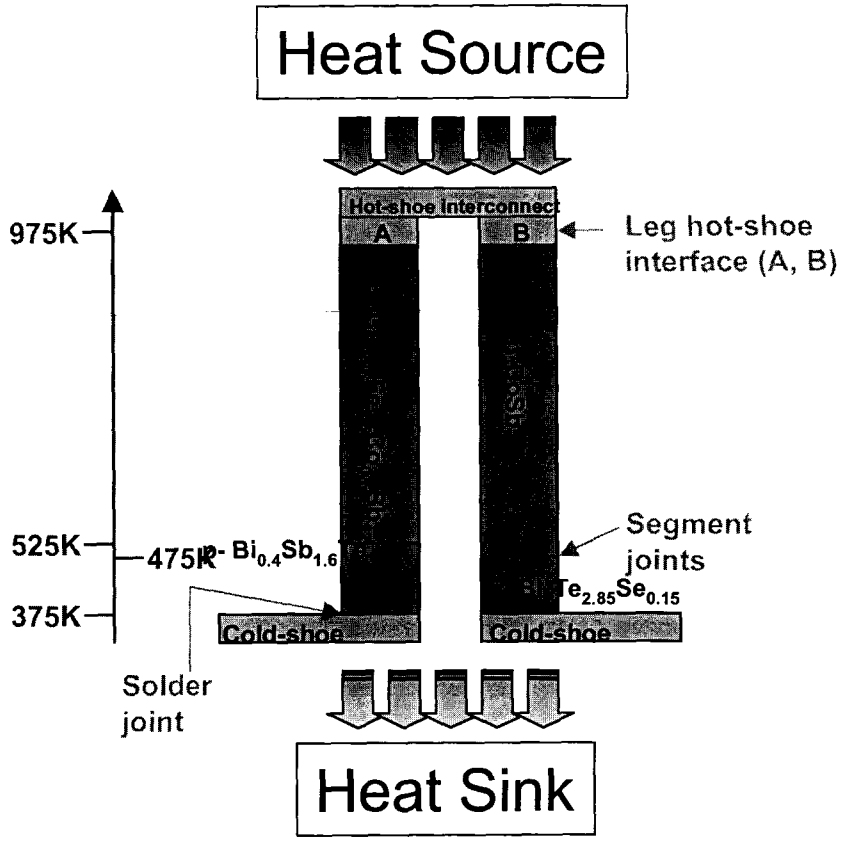


Projected Advanced RPS performance vs SOA

Item/Converter	SOA SiGe-RTG	Advanced Segmented RPS
Hot junction temperature (K)	1273	973
Cold junction temperature (K)	573	373
Converter efficiency (%)	7.2	12.5
System efficiency (%)*	6.5	11.18
Total thermal power (BOM) (W_{th})	2000	1250
System thermal efficiency (%)	85	85
Total electrical power (BOM) (W_e)	107	118.8
Number of GPHS	8	5
Total PuO_2 mass (kg)	5.02	3.138
Total system mass estimate (kg)	23.24	16.3
- GPHS mass (kg)	11.54	7.215
- Housing (Kg)	3.1	1.90
- Radiator fins (kg)	0.45	1.7
- Converter (kg)	5.65	3.9
- Other structure (kg)	2.5	1.6
Specific power estimate (W_e/kg)	4.6	7.3

* 90% of converter efficiency

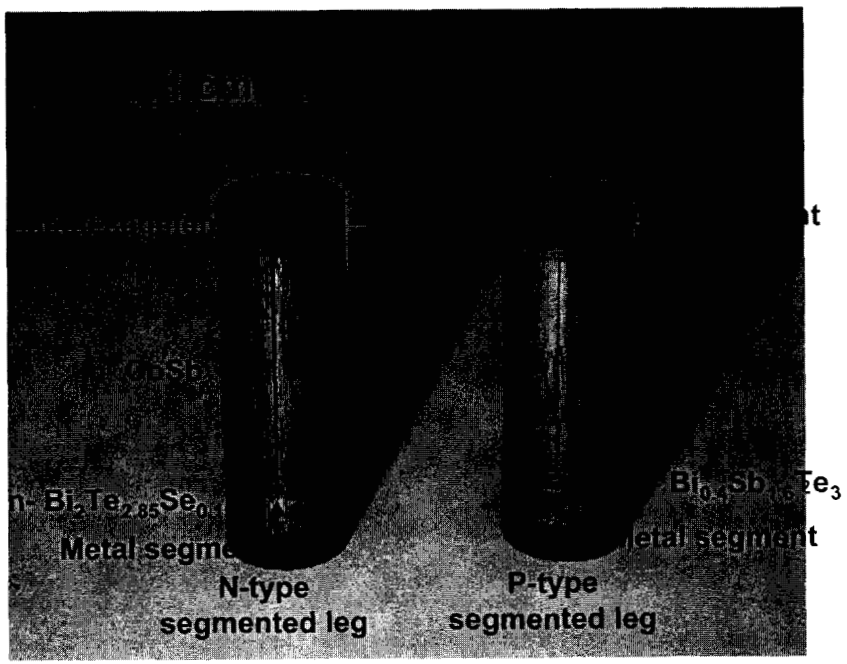
Segmented Technology Development Challenges



- TE materials processing and segmented leg fabrication
- Low electrical contact resistance between segments and between segments and cold- and hot-shoes
- Unicouple mechanical integrity
- Demonstrate unicouple performance
  - Testing and modeling
- Demonstrate TE materials stability
  - Sublimation control
  - Stable thermoelectric properties
- Lifetime

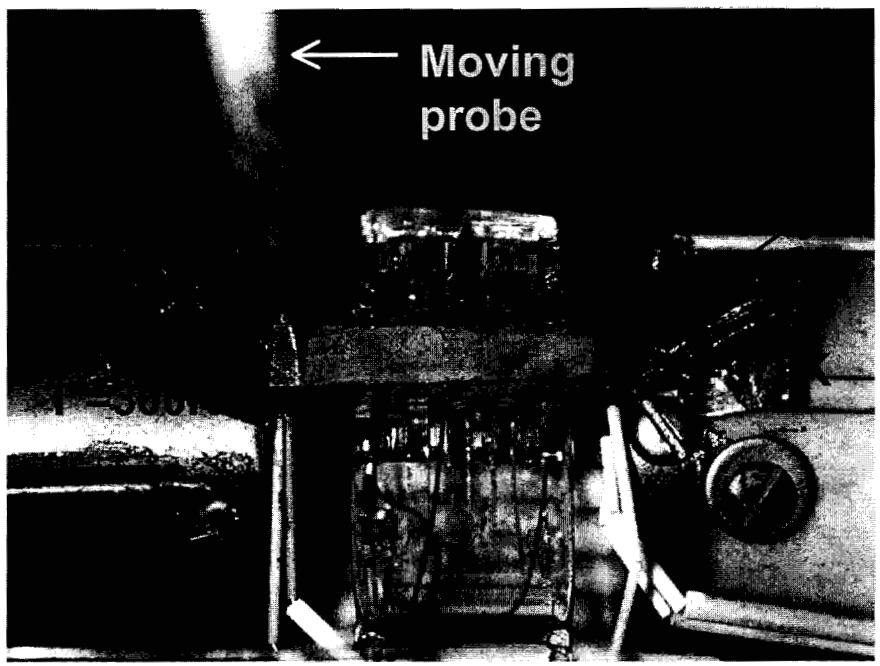
Unicouples legs fabrication

- Unixaxial hot-pressing of powdered materials stacked on the top of each other
  - Temperature optimized → density close to theoretical value
  - In graphite dies and argon atmosphere
- With metallic diffusion barriers Metallic contacts at hot- and cold-side between the different segments of the legs
  - Selected to compensate for coefficient of thermal expansion mismatch
  - Diffusion barrier
  - Should react chemically with both materials to be bonded
  - Low electrical resistance bond (<10μΩcm^2) to achieve negligible impact on overall unicouple performance



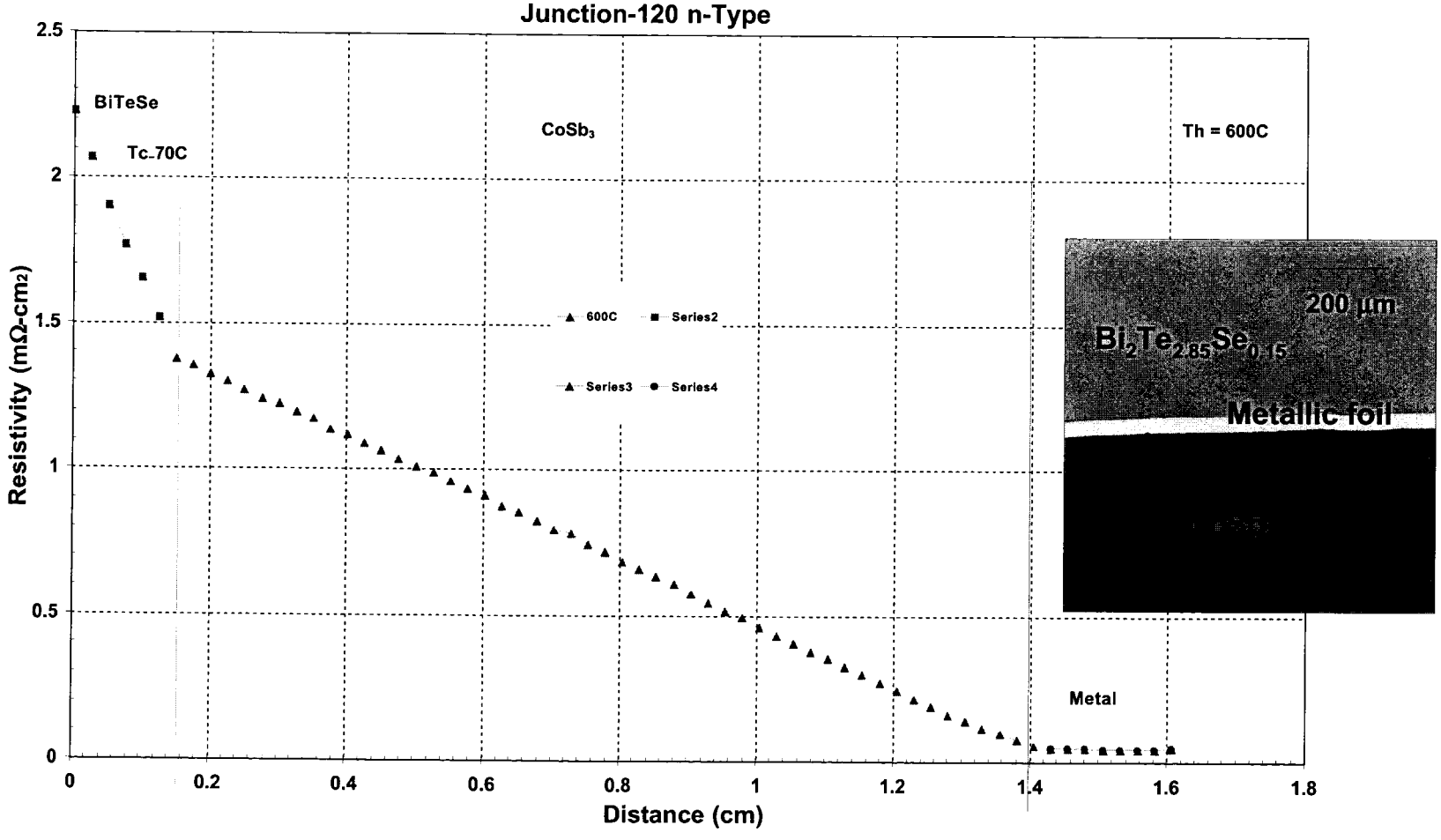
Segmented legs characterization

- Bond quality
  - Electrical contact resistance measurement
  - Microprobe analysis
    - Diffusion
    - Chemical reaction and interface layer analysis



Electrical contact resistance measurements set-up

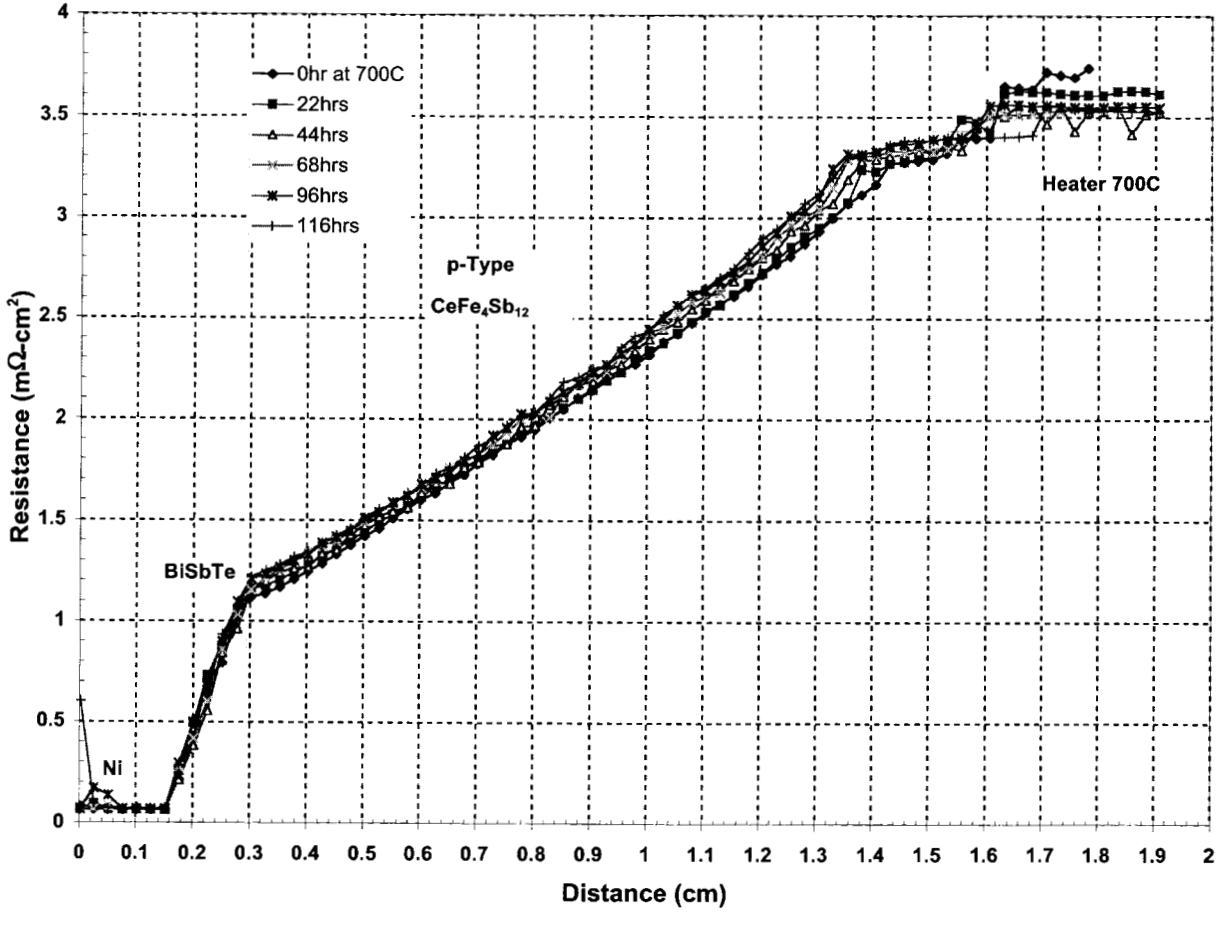
Electrical contact resistance measurements for n-type segmented leg



- Low electrical contact resistance achieved (< 5 $\mu\Omega cm^2$)

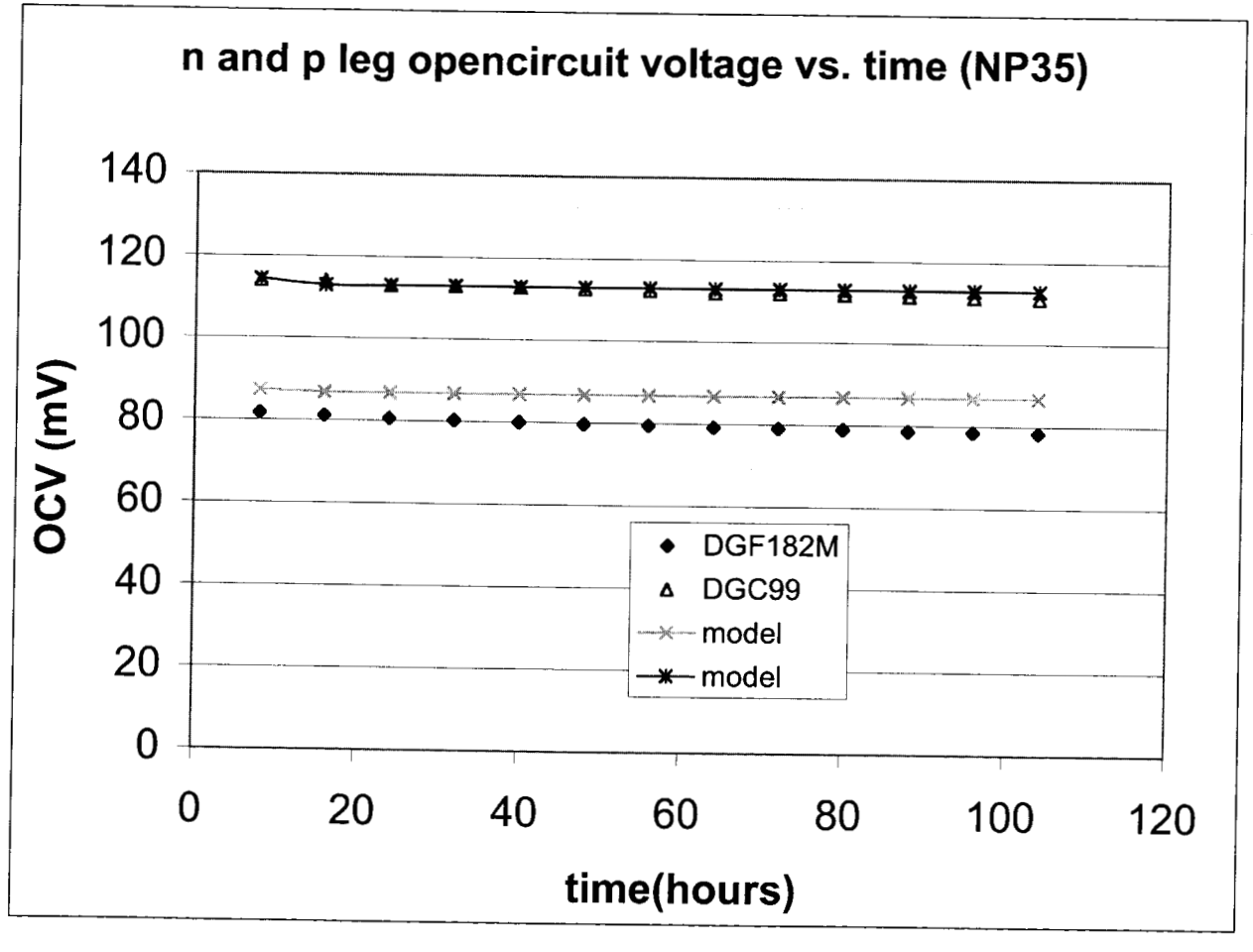
Electrical contact resistance measurements for p-type segmented leg

- Contact resistance measurements shows no degradation of contact after 116 hours of testing in dynamic vacuum



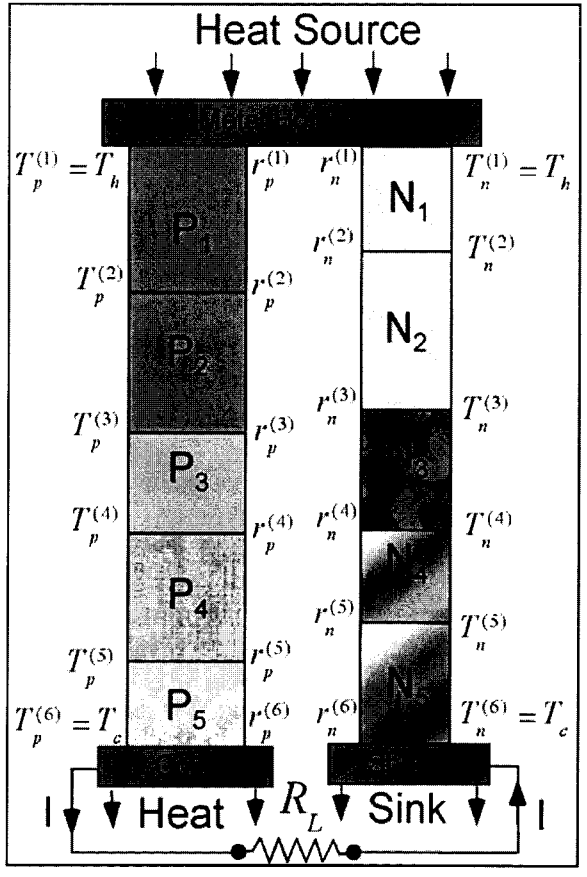
In-gradient voltage output testing

- In-gradient testing of p- and n-legs (975K-300K ΔT) shows good agreement with model predictions



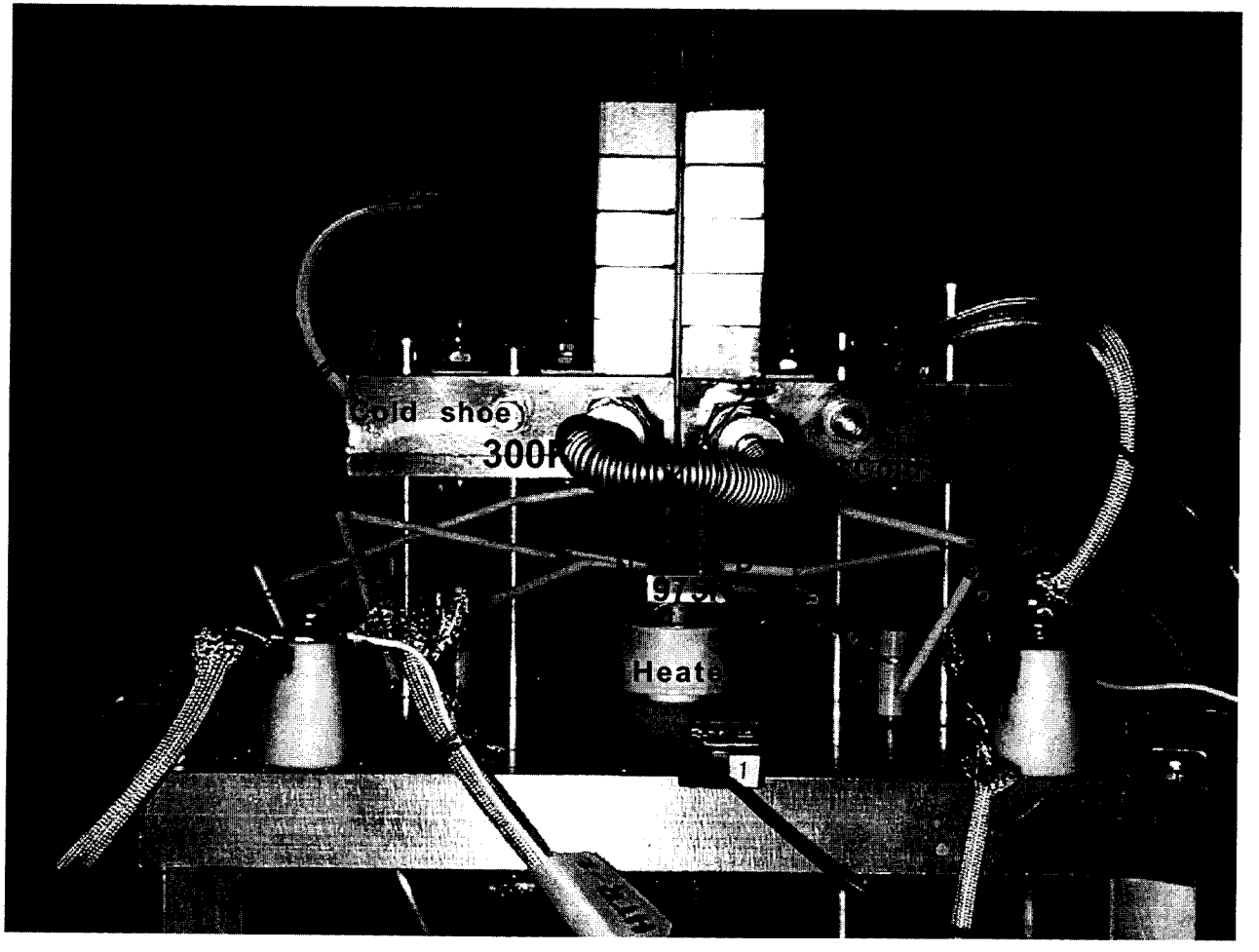
1-D Analytical Model of Segmented Thermoelectric Unicouples

- One-dimensional analytical model of STEs, with up to 5 segments per leg, is coupled to a *genetic algorithm* for maximizing either the electrical power of efficiency
- Input:
  - TE materials properties
  - Total length and composition of n- and p-legs
  - Cross sectional area of the p-leg (or the n-leg)
  - Hot and cold shoe temperatures
  - Total contact resistance per leg
- Output
  - Number of needed segments in n- and p-legs
  - Interface temperatures between various segments
  - Lengths of various segments in n- and p-legs
  - Cross sectional area of n-leg (or p-leg)
  - Electrical power and conversion efficiency curves
  - Operation I-V characteristics



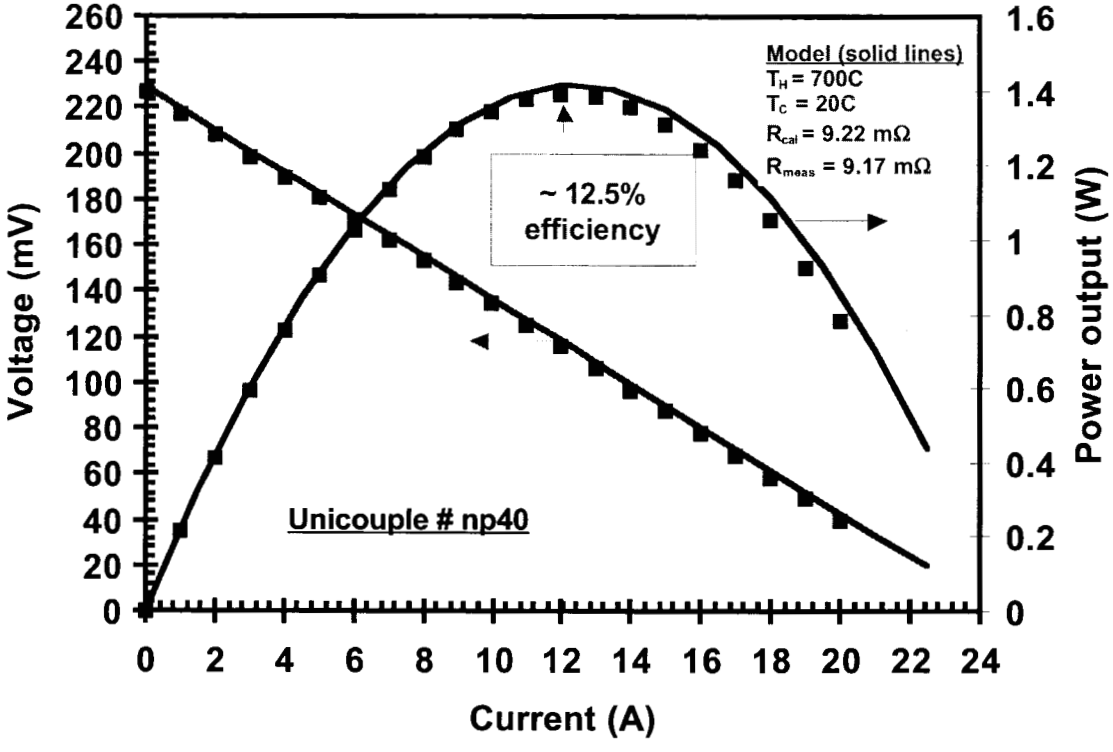
Unicouples testing

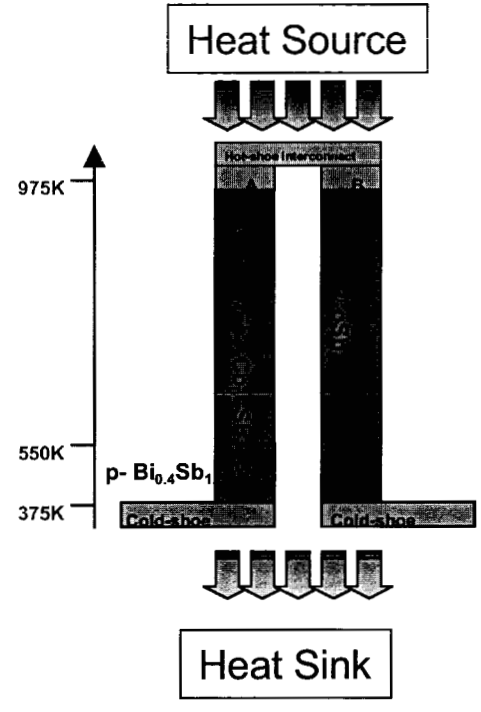
- In gradient-testing under vacuum or argon atmosphere
- Generate experimental I-V curve and compare to model prediction

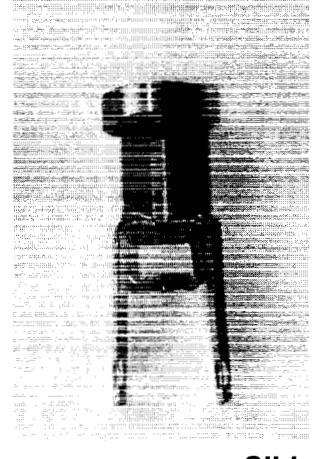


Unicouple test set-up

Thermal and electrical testing - Segmented unicouple



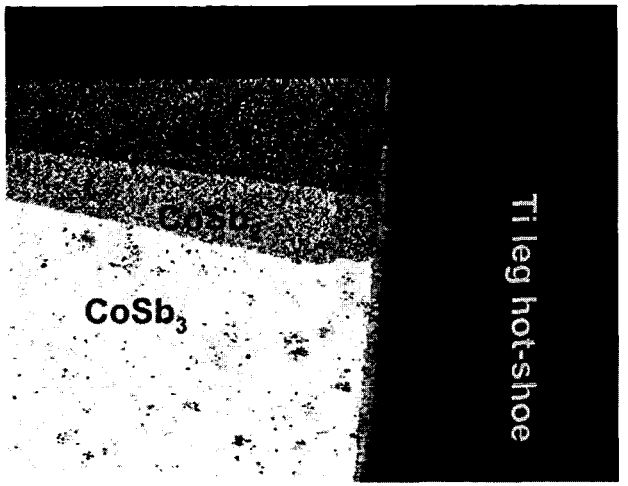




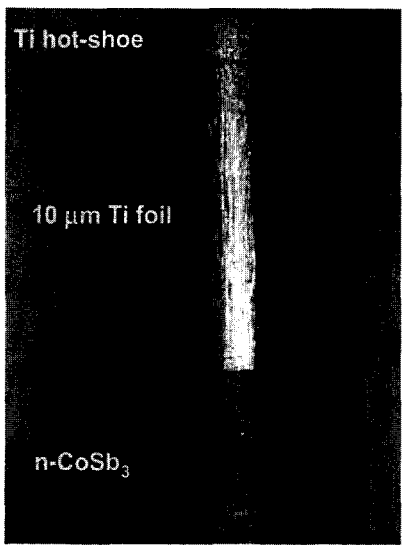
- Achieved 12.5% efficiency for 975K-300K ΔT
  - With p-segmented leg and n-skutterudite leg
  - Consistent with model prediction
  - Should achieve ~14% efficiency for 975K-375K ΔT with both p- and n-legs segmented

Sublimation control experiments

- **Uncoated samples**
  - **Sb sublimation in dynamic vacuum for T from ~ 875 to 975K**
  - **Decomposition into lower antimonide compounds**



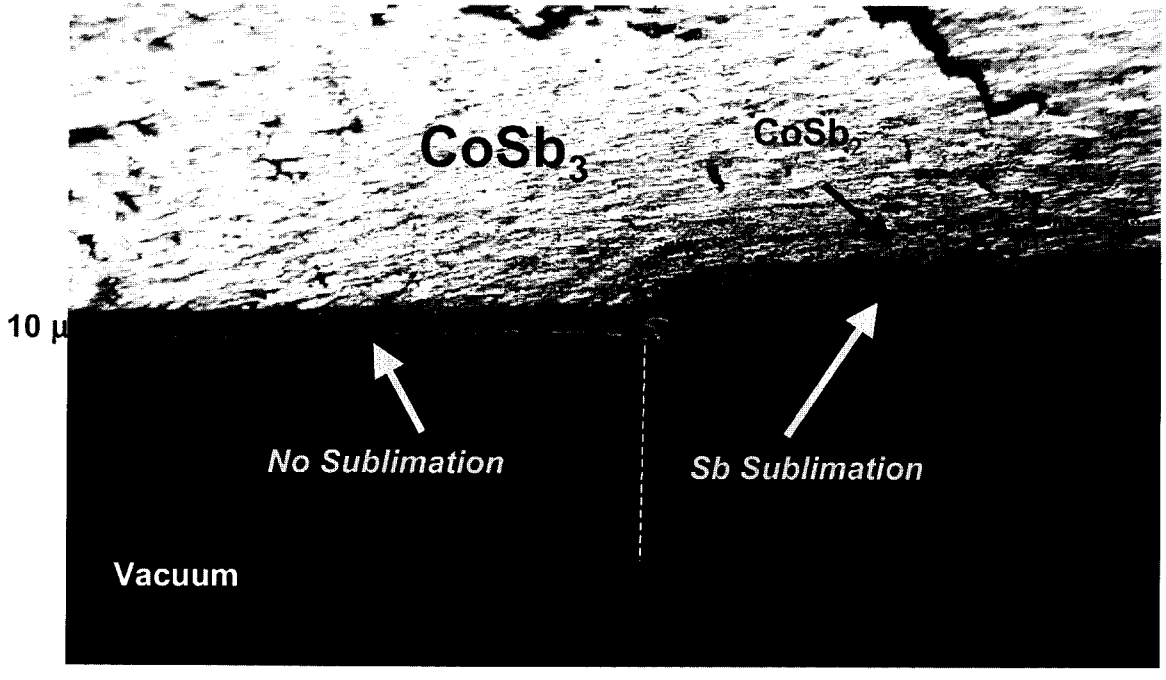
Photograph showing the decomposition of a $CoSb_3$ sample annealed at 875K for 3 months



N-type Ti coated skutterudite leg

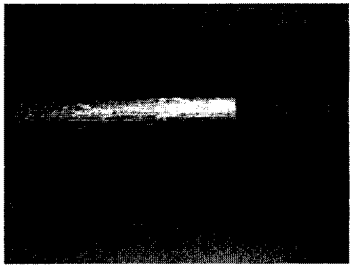
- **Sb sublimation control studies**
- **Use of cover gas significantly;ty suppresses Sb sublimation**
- **~ 10 μm metallic film applied during hot-pressing**
- **Performed in gradient Ti film-coated leg life tests**
- **Thermal/mechanical modeling performed to evaluate impact on unicouple performance**

Ti coating of $CoSb_3$

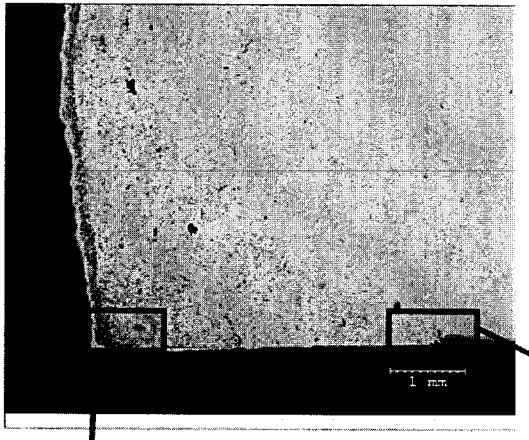


Photograph of $CoSb_3$ sample annealed at 975K for 5 days

Coated n-type tested in-gradient for 20 days



975K →

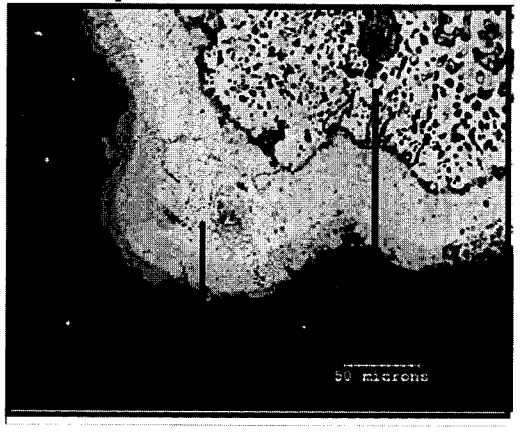


$CoSb_3$

$CoSb_2$

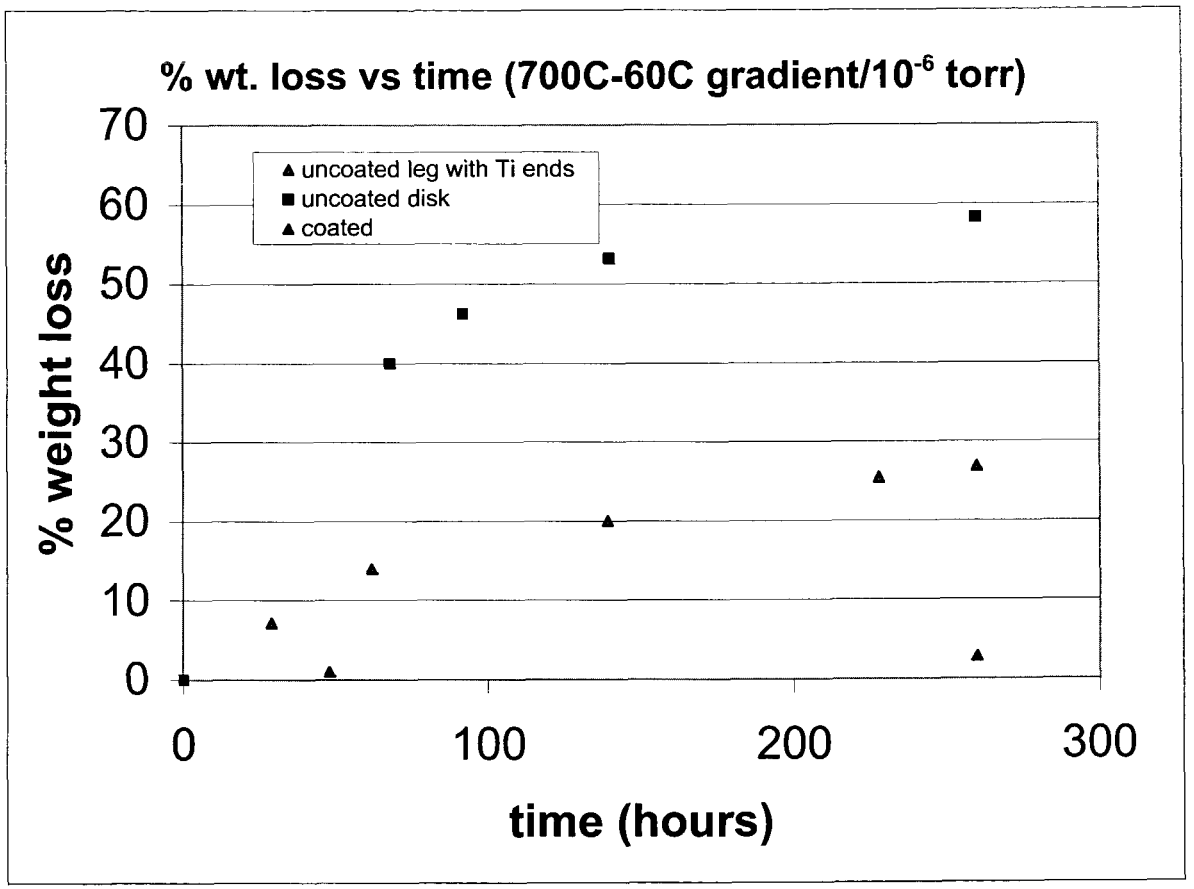
CoSb

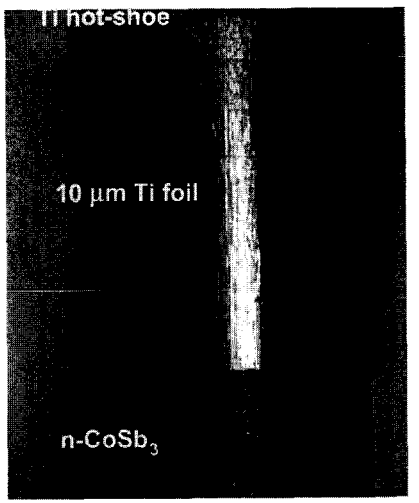
Coating stops



- No apparent degradation after 20 days
- Metal junction still intact
- Significant improvement over uncoated

Weight loss experiments

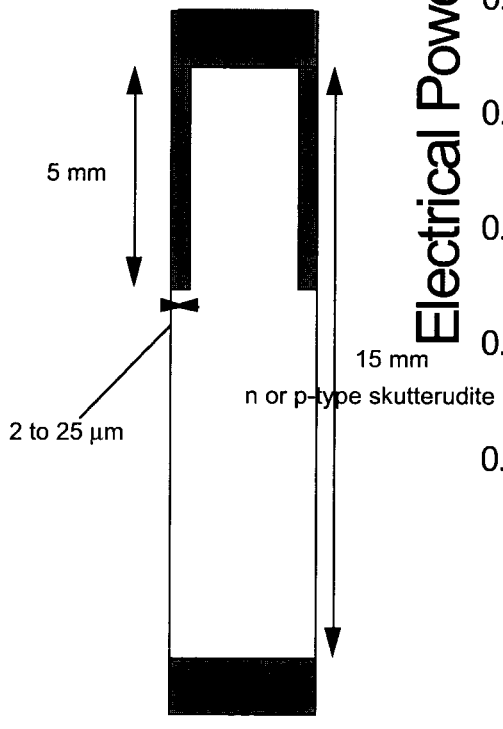


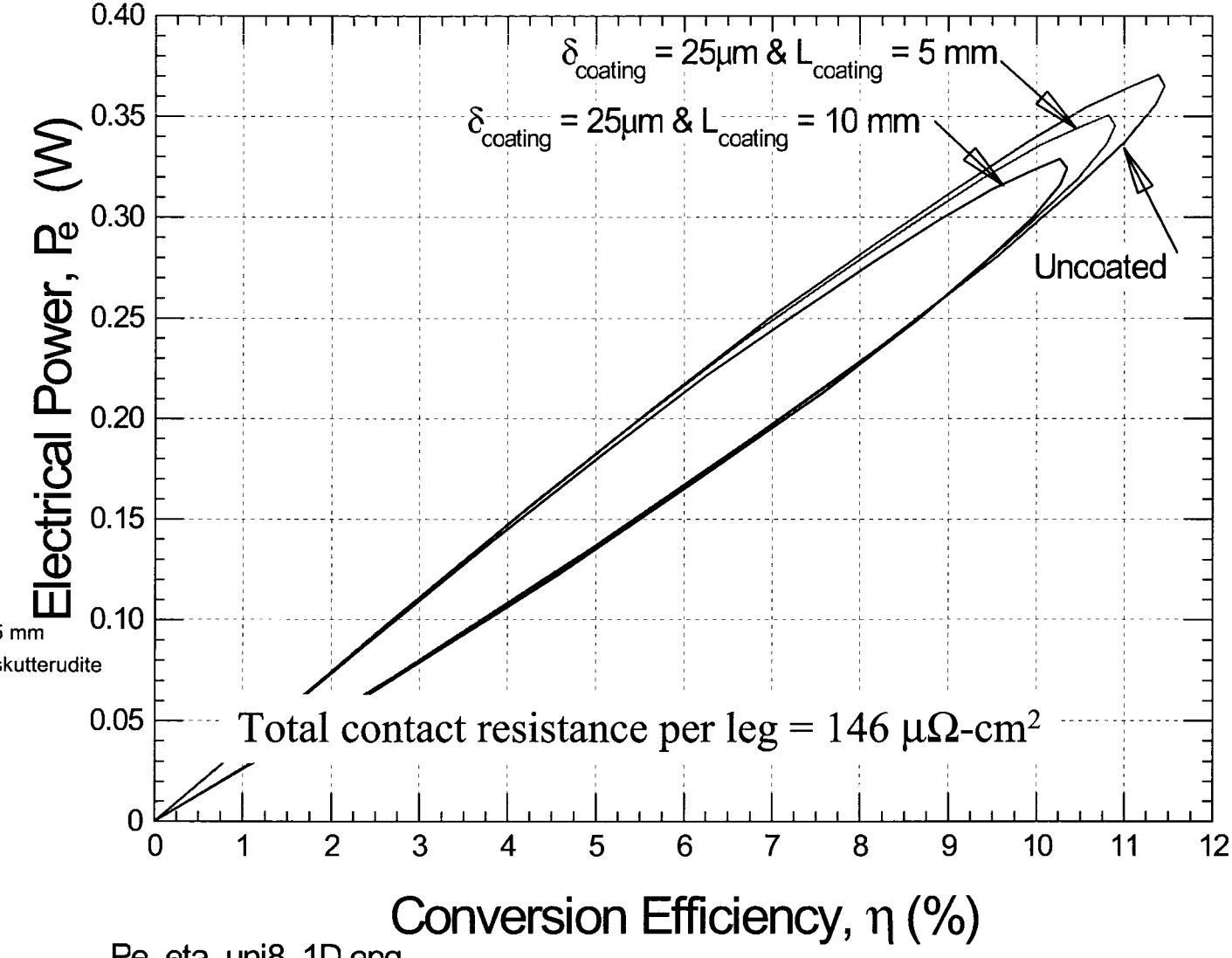


N-type Ti coated skutterudite leg

	Uncoated $CoSb_3$	Ti coated $CoSb_3$
Weight loss After 10 days in dynamic vacuum	27%	2.5%

Thermal/mechanical modeling
(University of New Mexico)





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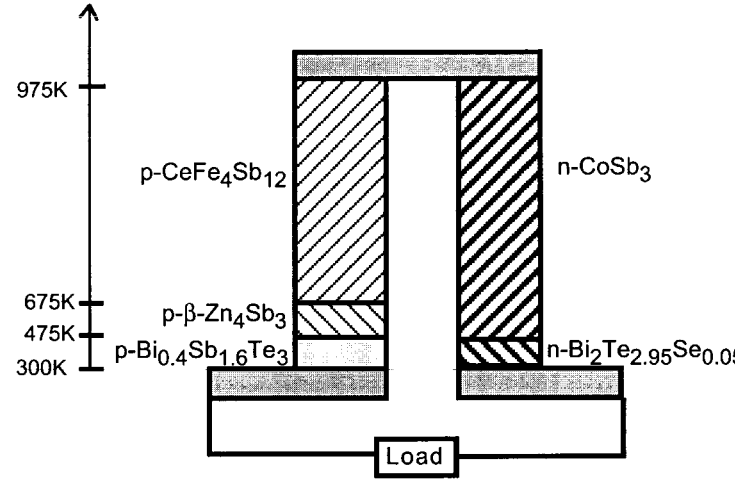
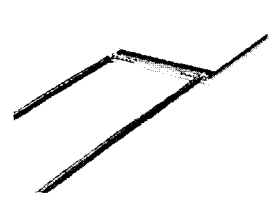
Potential applications

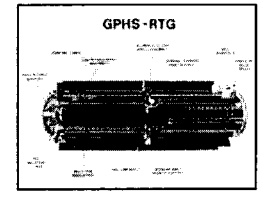
- Thermal to Electric Power Generation
  - Integration with any heat source
    - Combustors
    - Catalytic reactors
    - Radioisotope heat source
- Waste heat recovery
  - Automobile exhaust
    - Supplement or replace electrical power generator with electrical power generated from engine waste heat
    - T ~ 400 to 600°C downstream of the catalytic converter
    - ~1 kW power generator
    - Cost is critical (~$100/kW)
  - Power plants
  - Geothermal energy
- Solid State Advantage
  - No moving parts
  - No maintenance
  - Long life
- Scalability



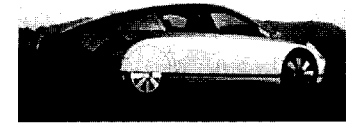
Advanced TE Segmented Unicouples



Advanced Power Generation TE Modules



Radioisotope Thermoelectric Generators



Waste heat Automobile

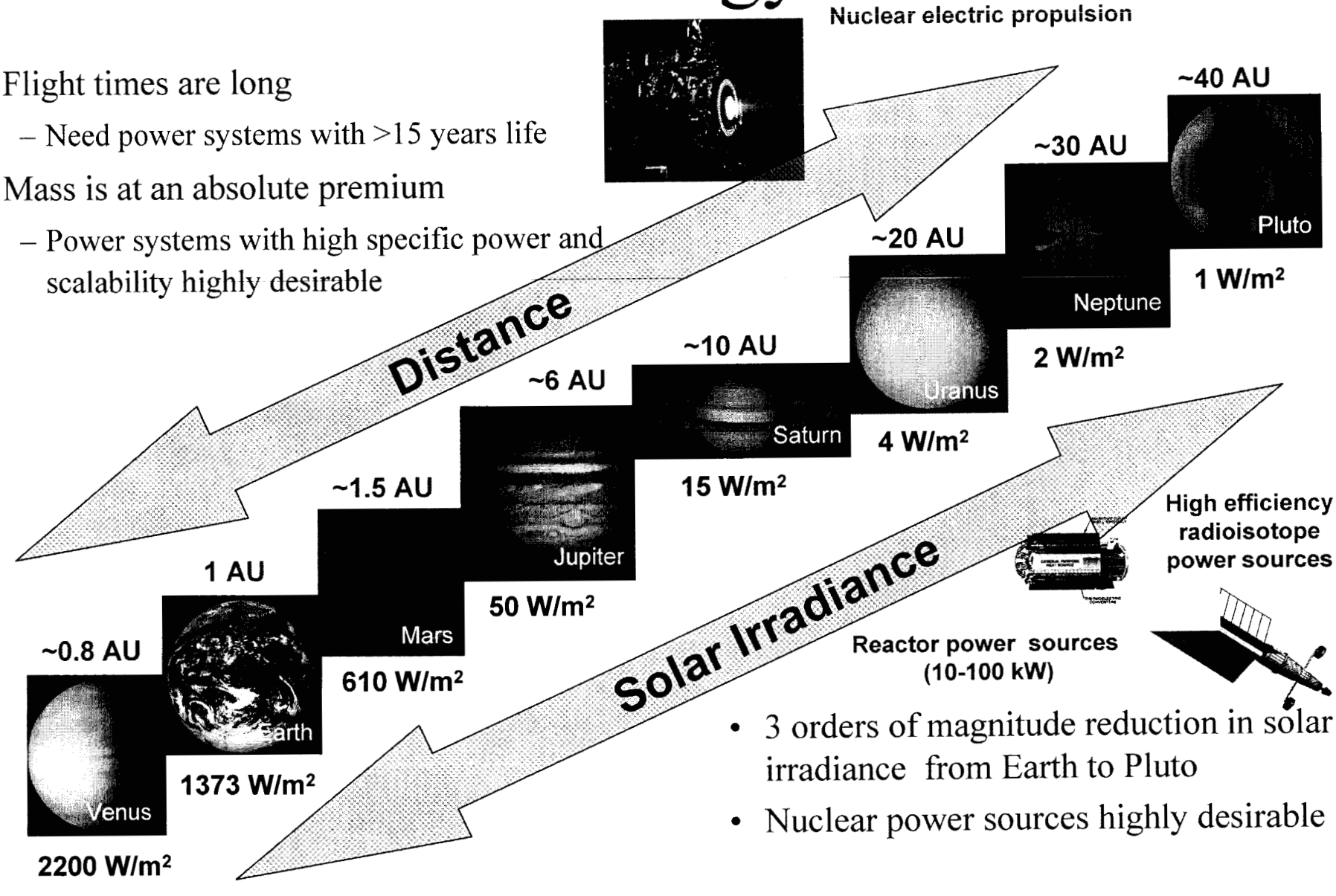
Conclusions

- Skutterudite-based segmented thermoelectric technology under development for space applications
  - Has the potential to double the efficiency and specific power of current SiGe-based RTGs
  - Further improvement in bulk thermoelectric materials a real possibility (skutterudite)
  - Future development work to focus on lifetime to ensure >14 years operation

- Thin-films materials development
  - Recent claims on Bi_2Te_3 nano-structured thin-films superlattices (RTI), SiGe/Ge quantum wells (Hi-Z) and PbTe quantum dot superlattice have the potential to revolutionize
  - Needs further understanding of underlying phenomena
  - Engineering and manufacturability issues may be a barrier to device implementation (parasitic losses)
  - May be an option in the future but bulk materials seem more promising in the near future

Power Technology

- Flight times are long
  - Need power systems with >15 years life
- Mass is at an absolute premium
  - Power systems with high specific power and scalability highly desirable



- 3 orders of magnitude reduction in solar irradiance from Earth to Pluto
- Nuclear power sources highly desirable