Thermoelectrics in Space: A Success Story, What's Next and What Might Be Possible

KISS Adaptive Multi-Functional Systems - Part II
California Institute of Technology

Jean-Pierre Fleurial
Jet Propulsion Laboratory/California Institute of Technology
Pasadena, California, USA

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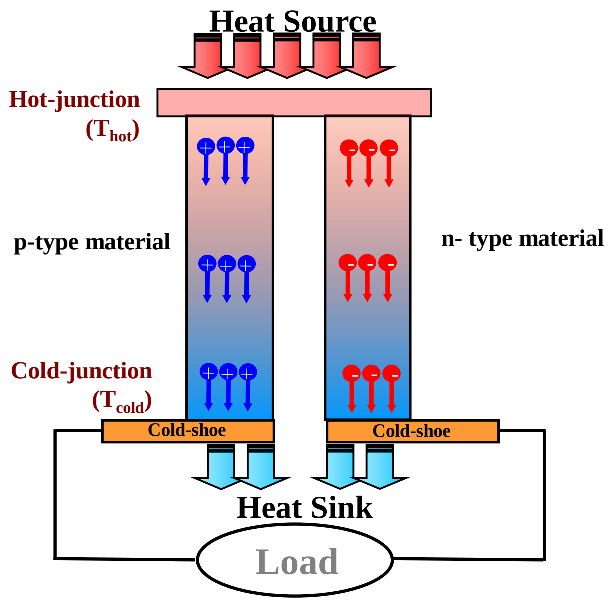
Thermoelectric Power Generation

Thermoelectric Couple



Thermoelectric effects are defined by a coupling between the electrical and thermal currents induced by an electric field and a temperature gradient

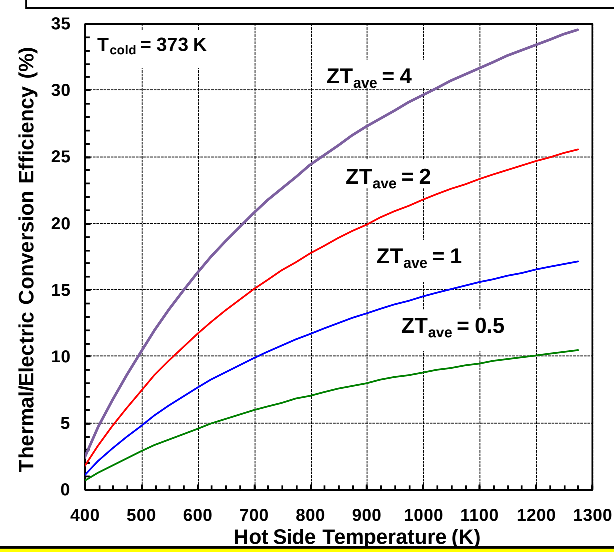
Dimensionless Thermoelectric Figure of Merit, ZT

$$ZT = \frac{\sigma S^2 T}{\lambda} = \frac{S^2 T}{\rho \lambda}$$

Seebeck coefficient S
Electrical conductivity σ
Electrical resistivity ρ
Thermal conductivity λ
Absolute temperature T

$$\eta_{max} = \overbrace{\frac{T_{hot} - T_{cold}}{T_{hot}}}^{\text{Carnot}} \; \overbrace{\frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + \frac{T_{cold}}{T_{hot}}}}^{\text{TE Materials}}$$

Conversion Efficiency



__Power generation__
(across 1275 to 300 K)
State-Of-Practice materials:
$ZT_{average}$ ~ 0.5

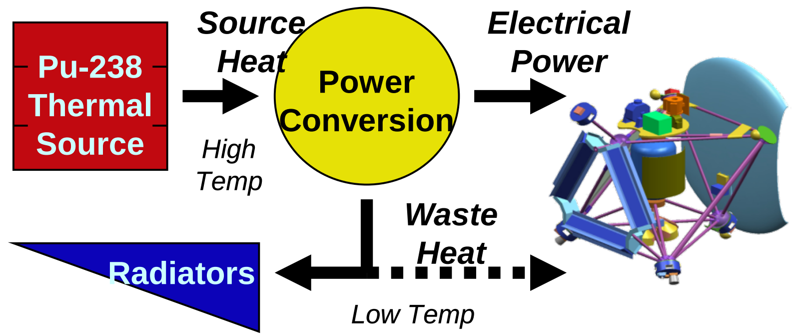
State-Of-the-Art materials:
$ZT_{average}$ ~ 1.2

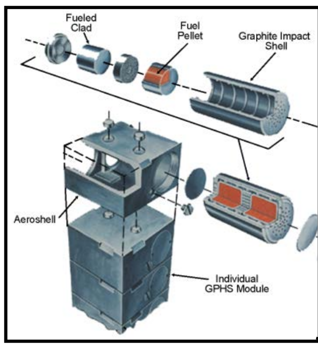
Best SOA materials:
ZT_{peak} ~ 2.6

Conversion efficiency is a direct function of ZT_{ave} and ΔT

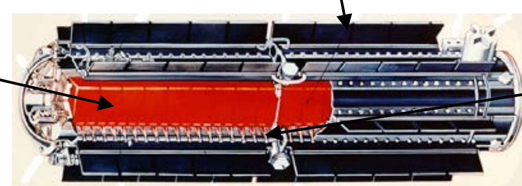
RTG Technology - What is a RTG?

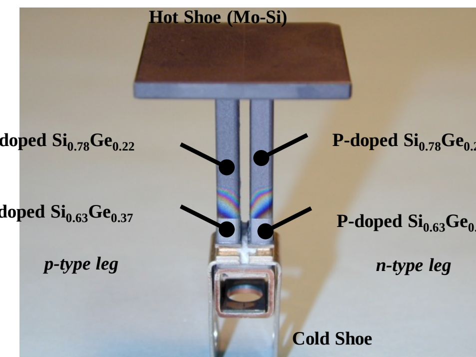
RTG is a thermoelectric conversion system that converts heat produced from natural alpha (α) particle decay of plutonium into electrical energy (DC)





Heat Source Assembly
(GPHS Modules)





Thermoelectric couple (572 couples used in the GPHS-RTG)

GPHS-Radioisotope Thermoelectric Generator (RTG)

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	37	~475
Voyager 2	MHW-RTG (3)	Si-Ge	Outer Planets	1977	37	~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	11	~ 885
New Horizons	GPHS-RTG (1)	Si-Ge	Outer Planets	2005	9 (17)	~ 246
MSL	MMRTG (1)	PbTe	Mars Surface	2011	3 (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)

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

The Success Story to Date

- For over 50 years, space nuclear power sources based on thermoelectric energy conversion have proved to be safe, reliable, sturdy, long-lived sources of electrical power.
- Since 1961, the U.S. has successfully launched 47 nuclear power sources (46 radioisotope thermoelectric generators and one nuclear reactor) on 28 space missions along with hundreds of radioisotope heater units (RHUs).
- The SNAP-10A space nuclear reactor power system demonstrated the viability of automatically controlled, liquid-metal-cooled reactors for space applications.
- RTGS have enabled some of the most challenging and scientifically exciting missions in human history
- In general, RTGs have exceeded their mission requirements by providing power at or above that required and beyond the planned mission lifetime.

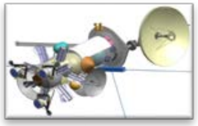
The Path Forward

High Temperature TE Materials & RTG Technology Development Timeline

Timeline	1960s	1970s	1980s	1990s	2000-2009	2010-2019	2020-2030





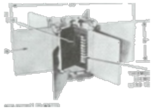


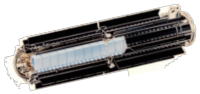
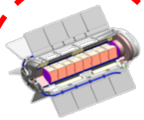
Mission

Pioneer 11 (1972-73); Viking (1975); Voyager (1977); Galileo (1989); Ulysses (1990); Cassini (1997); New Horizons (2005-2006); MSL (2012); Discovery (2016-17); Europa (>2021); Discovery & NF (2026); OPFM 2 (2030)

Generator

SNAPs (1961-1970); MHW (1975); GPHS (1985); MMRTG (2009); ARTG (>2020)




Technology

(~7 to 7.5 %)

PbTe (1958); TAGS (1965); SiGe (1968); "Fine-grained" Si-Ge, Rare earth chalcogenides and Boron Carbide; Skutterudites (1991-); Nano Bulk Si-Ge; 14-1-11 Zintls, $La_{3-x}Te_4$ and Adv PbTe

PbTe couples; SiGe "unicouples" (1968); MOD-RTG SiGe Multicouples; No Development; MMRTG couple (2003); 1st Gen Unsegmented ATEC couples; 1st Gen Segmented ATEC Couples; eMMRTG

2nd Gen Advanced TE; 2nd Gen Advanced TE; ARTG

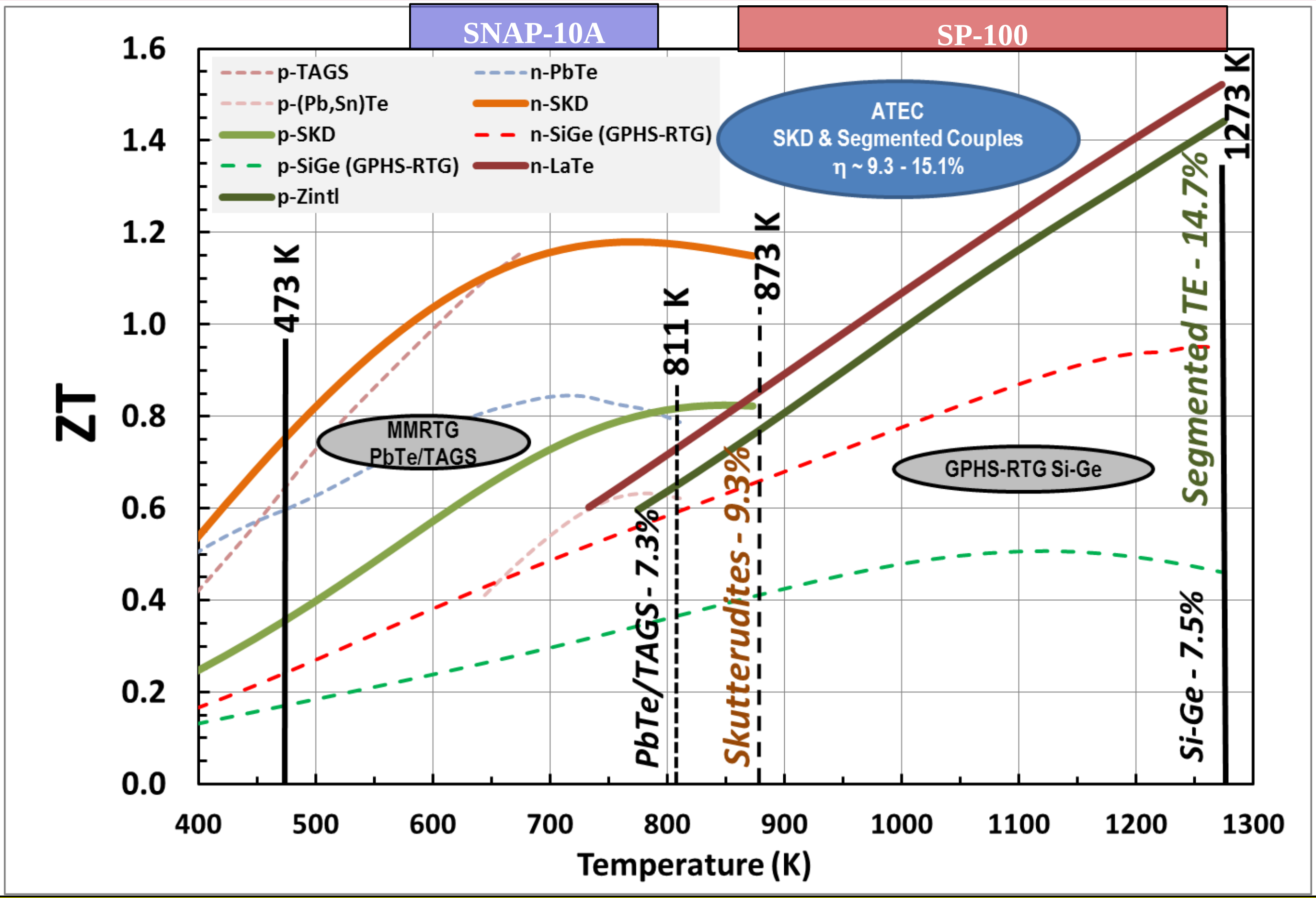
Segmented couples (10-15%)

>20%

?

Timeline	1960s	1970s	1980s	1990s	2000-2009	2010-2019	2020-2030

Thermoelectric Materials and Device-Level Performance: x2 Increase over State-of-Practice May be Now Possible



> 11% efficiency projected for ARTG based on 1273 K/523 K operating temperature differential *(GPHS-RTG: 6.5%)*

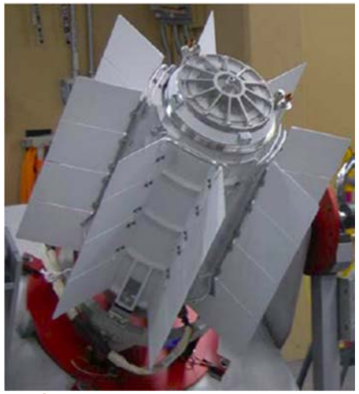
~ 8% efficiency projected for eMMRTG based on 873 K/473 K operating temperature differential *(MMRTG: 6.2%)*

~ 9% efficiency projected for Small FPS based on 1060 K/505 K operating temperature differential *(SP-100: 4.0%)*

x 2 increase in ZT_{ave} over SOA Si-Ge alloys *(1275 to 475 K ΔT)* **when combined through segmentation**

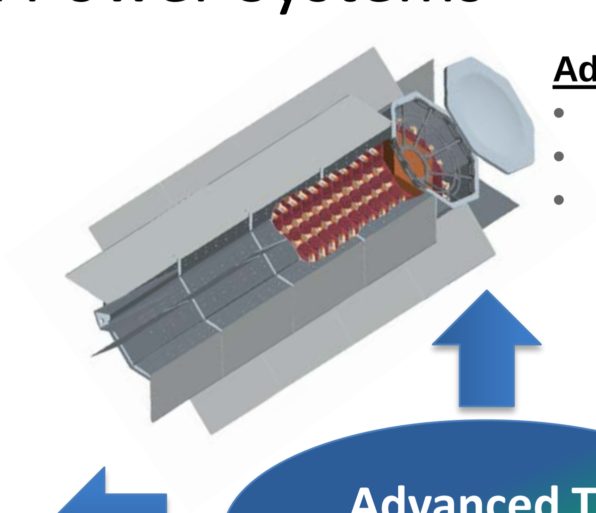
T_H / T_C (K)	1275 / 475	1075 / 475	975 / 475	875 / 475
Predicted TE Couple Efficiency	13.7%	11.2%	10.0%	9.3%
Demonstrated Efficiency (BOL)	14.8%	11.0%	10.0%	9.3%

Potential Near Term Space & Terrestrial Applications for Advanced TE Power Systems



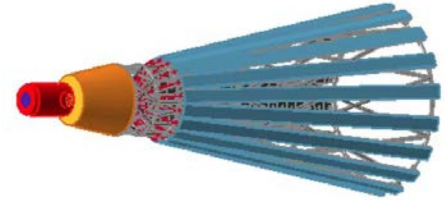
Early 2020's

Enhanced MMRTG
- ~ 160 W
- ~ 3.8 W/kg
- ~ 8% efficiency



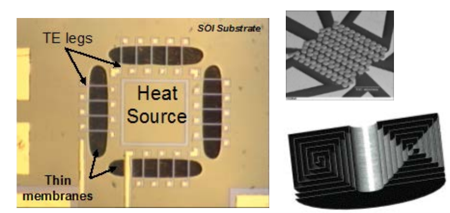
Advanced RTGs
- 200-500 W
- Up to 8.6 W/kg
- > 11% efficiency

Late 2020's



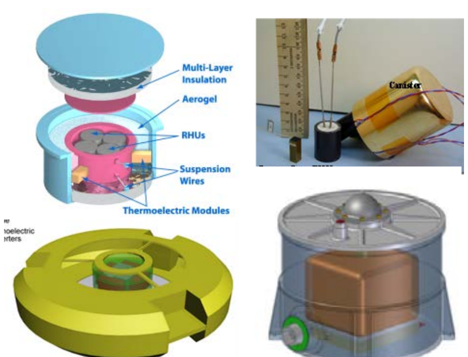
Fission Reactor Power System
- 0.5 to 10's of kW-class

Energy Harvesting
- Miniaturized devices
- Extreme environments

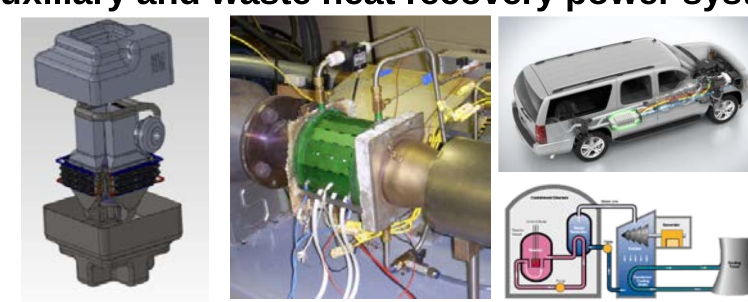


Advanced TE Technology

Small RTGs
- 0.1 to 20 W



Auxiliary and waste heat recovery power systems



Power Plants

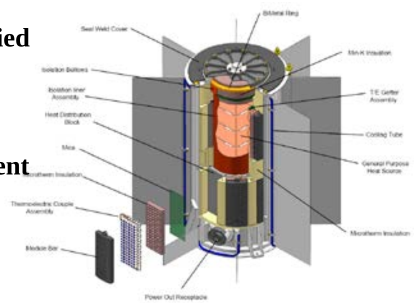
Large Scale Applications

Advanced high temperature TE technology being developed for space power systems could also be applied to terrestrial Waste Heat Recovery and auxiliary power systems

Power levels for Radioisotope Power Systems

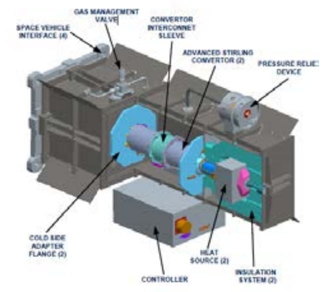
MMRTG
Flight Qualified
(on MSL)

eMMRTG
In Development
(~ 2022)

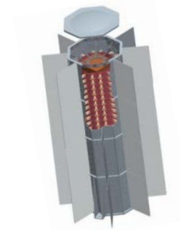


~ 120 to 160 W_e, 6.3% to 8% eff., 44 kg
~ 1880 W_{th} at 450 K T_{rej}

ASRG
In development
(~ 2028)



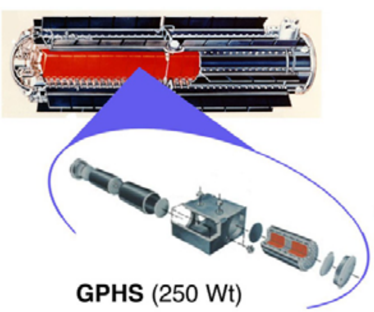
~ 140 W_e, 28% eff., 32 kg
~ 360 W_{th} at 350 K T_{rej}



Advanced RTGs (~ 2030)
At TE couple development stage

> 11% system efficiency
Potential for modular design
(1 to 16 GPHS 250 W_{th} blocks)
~ 23 to 500 W_e
~ up to 8.6 W/kg
~ 500 K T_{rej}

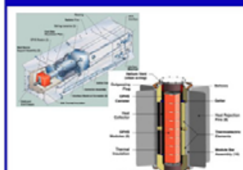
Existing Flight Qualified Heat Sources



GPHS (250 Wt)

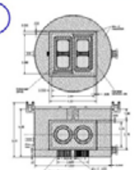
RHU (1 Wt)

Application Power Levels



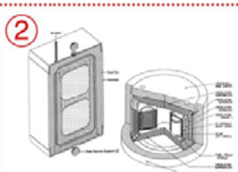
>100 Watts
- Under development – MMRTG & SRG
- >110 We & 35-40 kg per unit
- 2-8 GPHS per unit
- **Available by 2008-2009**

(1)



10 to 20 Watts
- Preliminary concept studies only
- 1 GPHS per unit
- Can use existing thermoelectric technology
- Requires systems engineering development

(2)

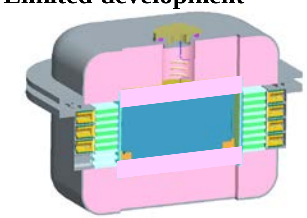


0.1 to < 10 Watts
- Some concept studies from early 1990's
- Fractional GPHS or assembly of RHUs
- Requires **redesigned thermal source aeroshell** and systems engineering development
- **More extensive development than options 1 or 3**

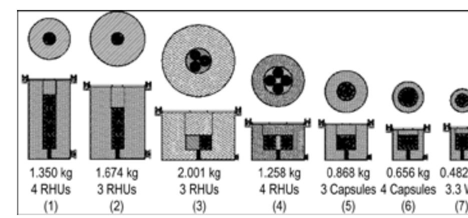
(3)

≥ 0.01 Watts
- Concept studies and technology development (Hi-Z)
- ≥1 RHU thermal source per unit
- Requires systems engineering development

Small RPS (RTG and SRG)
Limited development



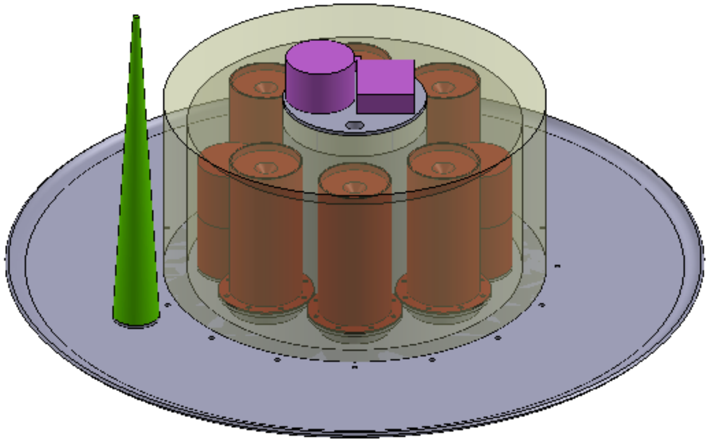
~ 20 to 50 W_e, 6-10 kg
~ 230 to 150 W_{th} at 400-350 K T_{rej}

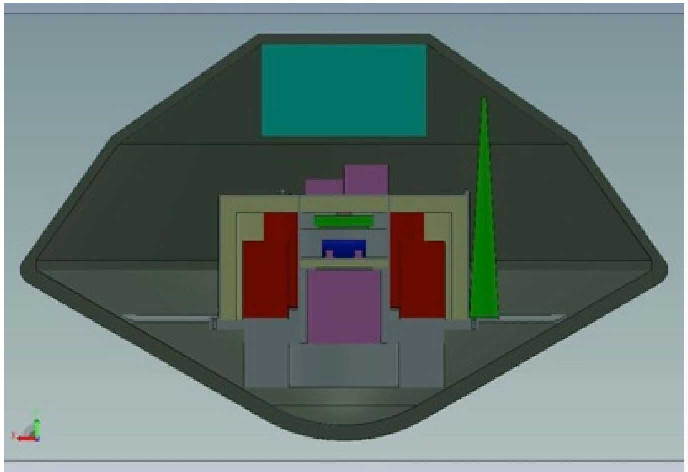


- **1.1 W_{th} per RHU**
- **4% efficient for 500 to 300 K operation**
- **~ 45 mW_e/RHU**
- **But could be 6-10% efficient between 300 and 100 K (Carnot!)**

Low Power (40 – 300 mW)
Radioisotope Thermoelectric Generators Concepts

Opportunities for Very Small RTGs





- Even at 40-250 mW of power, RHU-based very small RTGs could enable hard landers that house long duration sensors in challenging environments
  - Power/heat enables night-time operations
  - Power/heat enables polar winter operations
  - Power/heat simplifies in-space free flight (no solar arrays/batteries needed after carrier separation 1 Week before entry)
- The heat from the RHU-RTG, combined with capacitor systems and low temperature tolerable electronics (-40°C) are as important as the power output
- Due to the insulation required, the RHU-RTG power system dominates the interior volume of the lander
- RHU-based very small RTGs starting from 0.3 kg and 40 mWe
  - Single RHU-based concepts could use technology based on Bi2Te3 materials : TRL is already at 5;
  - Multi-RHU concepts could use Skutterudites: TRL ~ 3

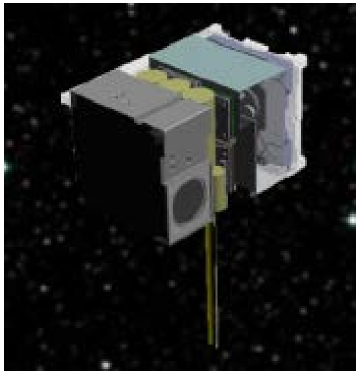
Potential Mission: Mars Sensor Network Concept

- Network of hard landers for a Mars Geophysical and Climate Network
- Long-life seismometry and climate monitoring enabled by RPS, RHU-RPS necessary to fit in Entry-Descent-Landing aeroshell
- Primary science objectives
  - Characterize the internal structure, thermal state, and meteorology of Mars.
- Targeted Measurements:
  - Temperature
  - Pressure
  - Seismometry
  - Optical (suspended dust and vapor)
  - Wind

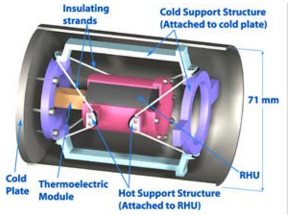
Pictured: Pascal hard lander

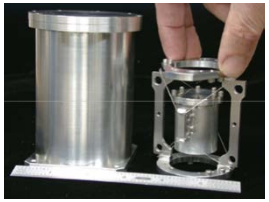
mW RPS for CubeSats and Micro Instruments

- Very small RTGs would enable CubeSats or micro instruments in support of long duration science and explorations missions.
  - Targeted Destinations
    - Mars – poles , craters, moons
    - Moon – shadowed craters, lunar night
    - Asteroids, Comets and other planetary moons
  - Targeted Micro Instruments
    - Surface (composition) or atmospheric (seismic or meteorological) measurement instruments

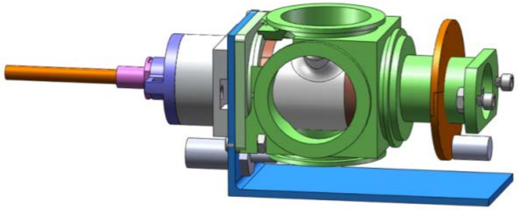


Notional S/C for MIRAGE Mission

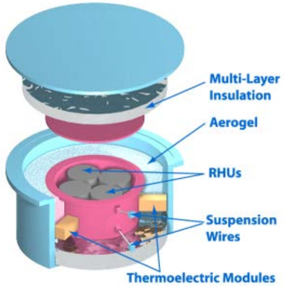




1-RHU mW-RPS Prototype



Compact Vector Helium Magnetometer



4-RHU mW-RPS concept

Enable and Encourage New Creative and Innovative Mission and Instrument Concepts with mW RPS Option to Meet Low Cost Missions Power Demands for NASA's Future Missions.

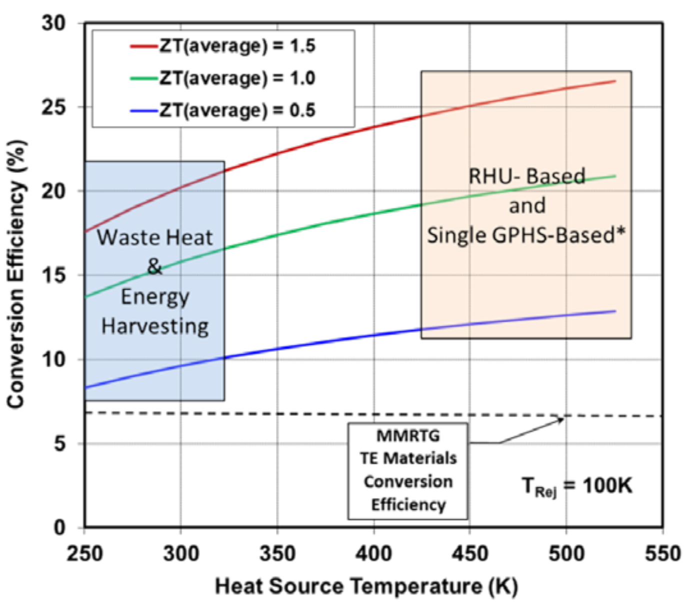
“non-RPS” Options

Thermal Energy Harvesting

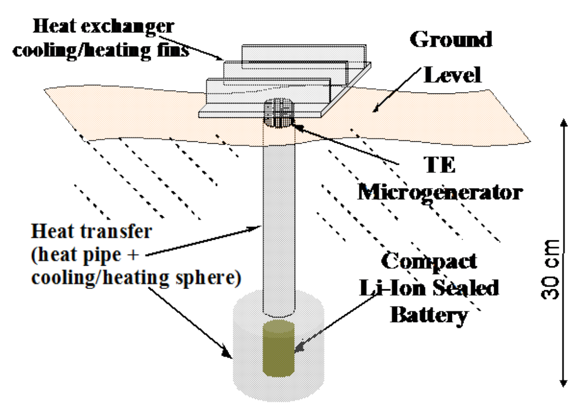
Technology	SOP	Performance Targets
Rechargeable batteries Supercapacitors	-30° C -40° C	-80° C -90° C
TE Generators	6.5% efficiency for >175° C heat sink	> 14% efficiency for heat sink > -20° C
Integrated Power System	> -55° C	-120° C

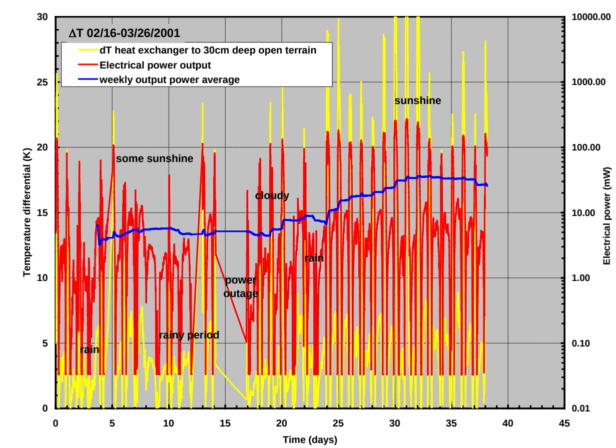
- High efficiency from high grade heat sources
  - Combustion/catalytic heat (Titan?)
  - Concept also applicable to fuel cells (ice)
- Low efficiency from low grade heat sources
  - Waste heat from “hot” components
  - Energy harvesting from “natural” temperature differential
- Could enable longer operation than just on primary batteries
  - Depends on required duty cycle – requires rechargeable energy storage component
  - Depends on thermal management requirements of other components and subsystems
  - Could be an intermediate, non-nuclear option of operation on icy moons

➢ Hybrid architecture possible (power tiles, power sticks…)



JPL demonstration of In-Ground Thermoelectric Energy Harvester for distributed sensor networks





Example: Titan In-Situ Energy Generator Options

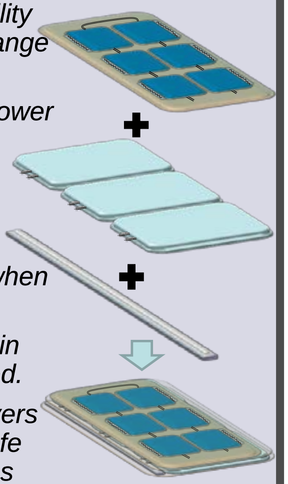
- First step is to capture thermal energy from atmospheric entry
  - Integrate entry vehicle surface with heat pipe
  - Transfer thermal energy from entry vehicle surface to thermal energy storage material
  - Capture thermal energy at capacity of thermal energy storage device
- Second step is to transfer thermal energy to system ‘start up’ phase
- Third step is to proceed through generator ‘start up’ sequence to reach steady state operation using catalytic combustor
  - Lander has stored oxygen (LOX) onboard (25 L -> 100 kWh thermal energy)
  - Assumes hydrocarbons on Titan are readily available to lander
- Fourth step is to charge the onboard secondary battery
- Fifth step is to synchronize the generator/battery state-of-charge/energy duty cycle for optimized use of stored oxygen

Example: PV/Battery Power Sheet Technology

MAIN CONCEPT:

Integrated modular hybrid power system that contains:

- *Power generation system - highly efficient, low cost ultra-thin photovoltaic cells (> 30% solar conversion efficiency)*
- *Energy storage system - high energy density rechargeable batteries(>250 Wh/kg) with fast charging capability and wide operating temperature range*
- *Power management system - integrated charge electronics for power regulation and distribution*



HOW IT WORKS:

- *Solar arrays charges the battery when sunlight is available*
- *Battery delivers power to loads in nighttime and daytime as needed.*
- *Power management system delivers power at 15/30 volts, insures safe recharging of batteries, provides energy metering capability and load management*

ASSUMPTIONS AND LIMITATIONS:

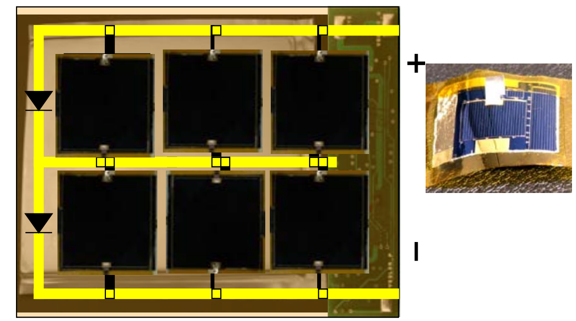
- *Availability of solar energy*
- *Availability of in-field charge time during mission*

<u>32 Wh Power Sheet Demo</u>
<u>(Single Module Built and tested)</u>

Uses Dual Junction thick solar cells and Li-Ion polymer pouch cells

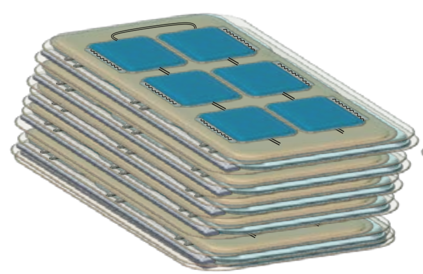
<u>6 Wh Power Sheet Demo</u>
<u>(Module Components tested)</u>

Uses Triple Junction ultrathin solar cells and Li-Ion polymer pouch cells

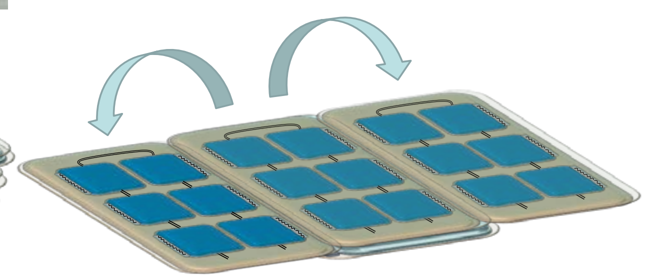


<u>720 Wh POP Target</u>
<u>(Projected Performance)</u>

Uses > 30% efficient ultrathin solar cells and 300 Wh/kg rechargeable pouch cells



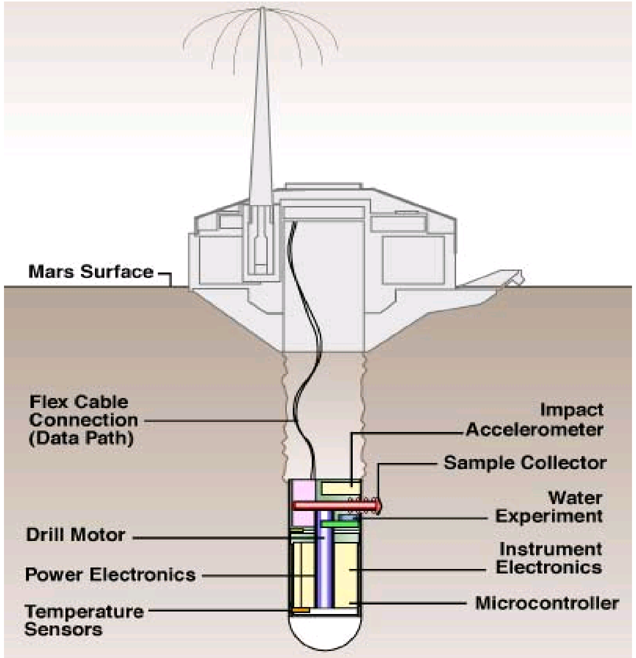
720 Wh
24-Module Stack Stowed
(less than 2 liters and 4 kg)

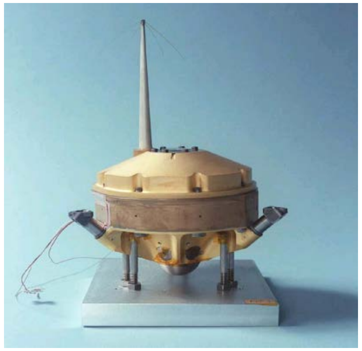


30 Wh Single Module Deployment of extra Ultrathin Solar Array "flaps"

Low Temperature Lithium Primary Batteries
Background: Mars DS2 Microprobe Spacecraft

- Launched on January 1999
- Two microprobes (2.4kg) piggybacked on Mars Polar Lander mission
- Intended as a low cost, high risk/high payoff mission
- Design:
  - No parachute: dropoff penetrator
  - Aftbody with batteries & telecom stays on surface
  - Forebody penetrates, ~ 1 meter
  - Drill scoops soil sample into chamber
  - Heat, vaporize, and analyze for H_2O
  - Transmit water and other science data





DS2 spacecraft

Battery technology development options

Development time frame	Energy Density	Estimated discharge temperature limits	Issues
Short term	~60 Wh/kg	-60°C at C/20	Charging <-40°C
	~40 Wh/kg	-60°C at C/5	Charging <-40°C
	~40 Wh/kg	-70°C at C/50	Charging <-40°C
Mid term	~200 Wh/kg (projected)	?	Charging <-40°C
Long term	200-250 Wh/kg	-130°C to -145°C	Primary battery, low TRL